CHARACTERIZATION OF AIRBORNE BRAKE WEAR DEBRIS

FINAL WORK PLAN

Submitted to

Association of Bay Area Governments
c/o Marcia Brockbank
San Francisco Estuary Project
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by

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1. INTRODUCTION

Characterization of airborne brake wear debris is one element of the Brake Pad Partnership's (BPP's) investigation of the environmental fate and transport of copper from vehicle brake wear debris. The objective of the environmental transport and fate modeling is to predict how copper released from brake pads travels through the environment and its potential effect on the short-term and long-term concentrations of copper in the Bay.

The primary objective of this task will be to characterize airborne vehicle brake wear debris to provide input data needed to run the air deposition model. The air deposition model will then calculate the transport of the wear debris from the point of origin to the points where the debris falls onto the watershed. Data input requirements for the air deposition model include aerodynamic diameters and particle size distributions for the airborne brake wear debris particles.

This Work Plan describes the set of tasks required to conduct the airborne characterization of brake wear debris from a representative sample of brake pad material. This effort will entail the measurement of the particle size distributions of the airborne brake wear debris particles. Samples of airborne wear debris will be collected during generation of a representative sample of brake wear debris on a brake dynamometer at Link Testing Laboratories in Detroit, using a standard brake wear debris generation protocol developed by the BPP. Some advanced preparation for the sampling effort and post-sampling analyses will be conducted at Clemson University.

2. BACKGROUND

In a recent article, Sanders et al. (2003)[1] reported on work characterizing the size distribution of airborne brake wear debris. They found that the mass mean diameter of the brake wear debris they tested was 6 μm, while essentially all the mass of brake wear debris was contained within the range of 1 to 30 μm. Iron (Fe), copper (Cu), and barium (Ba) were the three predominant elements identified in the brake wear debris, regardless of the material used in the brake lining. The size distributions obtained in this study, however, may have been influenced by the testing protocol used, such that there may well be a significant amount of material with a size of less than 1 μm. For example, in an earlier study by Garg et al. (2000)[2], the mass median diameter of brake wear debris was found to be smaller than that measured by Sanders et al. (2003), and ranged from 0.5 to 2.5 μm.

After discussion with the BPP Steering Committee and air deposition modelers, it was determined that the best approach would be to use a micro-orifice uniform deposition impactor (MOUDI) to determine the aerodynamic diameters and particle size distributions of the airborne brake wear debris particles. These impactors operate at an airflow rate of 30 liters per minute

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[1] P.G. Sanders, N. Xu, T.M. Dalka, and M. Maricq (2003) "Airborne Brake Wear Debris: Size Distributions, Composition, and a Comparison of Dynamometer and Vehicle Tests," *Environ. Sci. Technol.*, **37**,4060-4069.

[2] B.D. Garg, S.H. Cadle, P.A. Mulawa, P.J. Groblicki, C. Laroo, and G.A. Parr (2000) "Brake wear particulate matter emissions," *Environ. Sci. Technol.*, **34**,4463-4469.

(lpm) and typically have ten stages, with aerodynamic diameter cutoffs from 0.056 to 18 µm. A downstream filter collects particles that escape the MOUDI (i.e., particles smaller than 0.056 µm in diameter).

MOUDI analyzers were first described by Marple et al. (1991)[3], and are considered to be very well-characterized instruments. They have been successfully used in many projects since becoming commercially available. For example, Dr. Christoforou has used MOUDI analyzers during his participation in the Southern California Ozone study in 1997.

3. AIRBORNE BRAKE WEAR DEBRIS SAMPLING

3a. Achieving Isokinetic Sampling Conditions

Sampling instruments require isokinetic sampling conditions—i.e., it is necessary that the velocities of the air flow in the duct and in the probe (the inlet to the MOUDI) be close to one another, usually within 10%. The reason for this is to ensure that the sample is fully representative of the particles suspended in air. Particles, because of their inertia, do not necessarily follow bending air streamlines. If the velocity of the duct air is significantly higher than the air velocity in the probe, the streamlines must diverge around the probe. Larger particles, because of their inertia, will tend to go straight, and therefore additional particles will enter the sampling probe, introducing a bias in the measurement. In this case, the measurement will show a higher mass concentration than actual. If the velocity of the duct air is less than the air velocity in the probe, the streamlines must converge into the probe. Particles, because of their inertia, will tend to go straight and therefore miss the sampling probe, again introducing a bias in the measurement. In this case, the measurement will show a lower than actual mass concentration. Perhaps even more importantly for the current project, the measured particle size distributions will not be accurate because larger particles are more likely than smaller particles to cross streamlines when isokinetic sampling conditions are not maintained.

Measurements and information available from a previous test using the same dynamometer protocol[4] indicate that the speed of the air inside the dynamometer duct at the location of the inlet probe is approximately 5 miles per hour (low of 3 mph and high of 8 mph), or approximately 134.4 m/min. Since the inlet to the MOUDI must have an air flow close to 30 lpm, to achieve velocities comparative to 134.4 m/min we need a sample probe area equal to:

$$Area = \frac{flow}{velocity} = \frac{30 \times 10^{-3} m^3 / \min}{134.4 \ \ m / \min} = 2.23 \times 10^{-4} m^2$$

This means that the inlet pipe to the MOUDI must have an inner diameter (ID) of approximately 0.017 m (17 mm).

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[3] Marple, V.A., Rubow, K.L., and Behm, S.M., (1991) "A Microorifice Uniform Deposit Impactor (MOUDI) - Description, Calibration, And Use," *Aerosol Sci. Technol.,* **14 (4)** 434-446.

[4] Brake Manufacturers Council Product Environmental Committee, *Disc Brake Wear Debris Generation and Characterization: A Dynamometer Based Protocol for Generating and Collecting Vehicle Disc Brake Wear Debris*, prepared by James T. Trainor, May 15, 2001.

Currently, a Schedule 40 nominal 2-inch PVC pipe is permanently installed in the dynamometer ductwork, which serves as the inlet to the high volume sample filter. This location is the most convenient inlet for placing any particulate sampling equipment. Therefore, we propose inserting a stainless steel tube that is approximately 17 mm inside diameter through the PVC pipe that will serve as the inlet to (i.e., sampling probe for) the MOUDI. This tube will be held in place at both ends of the existing PVC pipe with rubber stoppers and/or collars fabricated from an appropriate material, such as plexiglass, stainless steel, or Teflon. In addition to holding the inner tube in place, the stoppers/collars will serve to seal the annulus region between the PVC pipe and inner tube. The leading edge of the stainless steel tube will be ground with a shallow conical bevel, such that it provides minimal disruption to the air flow. The rear end of the stainless steel tube will be electrically grounded to the MOUDI frame to dissipate any electrostatic charge. With this proposed sampling scheme, we anticipate that changeovers between the MOUDI device and the normal high volume filter will be accomplished rapidly, thereby requiring only a minimum amount of downtime during any one brake wear debris generation run. This proposed sampling scheme will maintain isokinetic sampling for the MOUDI device and minimize the degree to which the dynamometer is modified from its originally designed specifications.

3b. Coordinating with the Effort to Generate the Representative Sample of Wear Debris

For the purposes of economy, the airborne wear debris sampling will be performed in conjunction with the effort to generate a representative sample of non-airborne brake wear debris, which will require close coordination with Link Testing Laboratory and the industry members of the BPP Steering Committee who are leading the representative sample generation effort. The representative sample of non-airborne wear debris will be developed by compositing wear debris from three different brake pad formulations. 300 to 500 mg of the representative sample is required for planned solubility and leaching tests. An unknown amount of additional representative wear debris may be required for additional tests yet to be determined. The plan below outlines how the airborne wear debris sampling will be conducted in conjunction with the effort to generate a representative sample of non-airborne wear debris. This plan has been selected based on the industry members' workplan to generate the brake wear debris and discussion of such workplan by the BPP Steering Committee members.

Link technicians should be able to generate enough non-airborne brake wear debris for the needs of the solubility and leaching studies by running their standard ~8-hour dynamometer test on each brake pad material following the established protocol.[4] Therefore, the testing of all three brake pad formulations is expected be completed in approximately three to four days, taking into account the actual protocol run time plus the required assembly/disassembly time between materials. This expedited schedule will enable the Clemson team to complete all of their MOUDI measurements in this same time period. Then, after the Clemson team has finished their work and departed, the Link technicians will generate additional wear debris from these same three brake pads as deemed necessary by the industry representatives and BPP Steering Committee.

Conducting the actual MOUDI measurements will proceed as follows. Link technicians will burnish each brake pad prior to installation of the MOUDI sampler. After the burnishing has been completed, the technicians will commence generating brake wear debris following the established protocol.[4] This protocol consists of a 300 brake application cycle that is repeated eight or more times. At an appropriate time within a protocol run (e.g., completion of a full cycle), the Link technicians will stop the run so that the Clemson team can connect the MOUDI sampler as described above. The technicians will then restart the run for a specified number of cycles, at which point they will again stop the run so that the Clemson team can remove the MOUDI device and reconnect the high volume sample filter.

3c. Collecting, Replicate Samples and Blanks

In a previous test using the same dynamometer protocol,[4] 2.38 grams of airborne brake wear debris were generated over the course of 8.5 dynamometer cycles, taking 18 hours. Based on this information, we estimate that one full dynamometer cycle will be sufficient to generate enough material for us to determine the physicochemical characteristics of the airborne brake wear debris. We plan to collect three replicate samples for each brake pad material. For the first brake pad material, the first MOUDI replicate measurement will be conducted on one full dynamometer cycle. To confirm the calculations used to derive our estimate above and to take into account potential differences in generation rates, we will collect the second replicate measurement over two full cycles with the first brake pad material. If the MOUDI flow characteristics are not adversely affected by this extra dynamometer cycle, we will then make one additional two-cycle measurement for our third replicate measurement of the first brake pad material. However, if the two-cycle measurement clogs the MOUDI, we will then make two subsequent replicate measurements using only one full dynamometer cycle each. In the event that one full dynamometer cycle clogs the MOUDI, we will need to resort to selecting a fraction of a full cycle that best represents the full cycle characteristics.

For the second and third brake pad materials, we intend to use our results from the first brake pad material to guide how we will collect the subsequent MOUDI samples. For example, if two full dynamometer cycles are possible with the first material, we will then start off by making a two-cycle dynamometer MOUDI measurement for the second brake pad material. If no clogging occurs, then two additional two-cycle replicates will be made. However, if we observe that only one full dynamometer cycle (or fraction thereof) is possible with the first material, then all subsequent measurements will be done for only one cycle (or fraction thereof).

Prior to the generation test for the first brake pad material, we will install the MOUDI sampler and collect a one-cycle (~ 2 hours) blank sample and a two-cycle (~ 4 hours) blank sample to determine whether the HEPA filter installed on the dynamometer's airflow system is allowing an appreciable mass of particles to pass the filter. Based on the filter's design performance of 99.7% capture efficiency for > 0.3 micron sized particles, we do not expect this to be the case but will verify it nonetheless. If the blank sample results indicate no appreciable background particle concentration in the dynamometer ductwork, then no background corrections will be necessary. However, if the background particle concentrations are appreciable, then the blank sample particle masses associated with each MOUDI size cut will be subtracted from the actual samples.

Upon completion of a particular MOUDI sample/blank run, the device will be disassembled and the filters removed and placed into premarked containers for mass determinations (described below) back at Clemson University. New preweighed filters will then be removed from their marked containers and placed in the MOUDI device, and the device will be reassembled in preparation for its next sample measurement.

4. GRAVIMETRIC ANALYSIS

Gravimetric analysis will be used to determine the total mass of brake wear debris collected on the Teflon filters of the MOUDI analyzer. Each filter will be weighed before and after sampling, and the total mass collected by the filter will be determined by the difference. The mass of brake wear debris collected on each stage/filter will then be used directly to determine the mass-based particle size distribution and overall average aerodynamic diameter. The average particle concentration in the air can be calculated by dividing the total mass collected by the total volume of sampled air for deriving an emission factor, if needed. Alternatively, other parameters such as number of stops, equivalent miles, etc. can be used to normalize the total collected mass if required for estimating emission factors.

Teflon filters will be weighed on a Mettler-Toledo UMT-2 microbalance, which has a maximum capacity of 2.1 mg and a display precision of 0.1 µg. Gravimetric analysis of samples as small as those to be collected is subject to a number of obstacles, such as mechanical vibrations, air currents, static charge on the filters, and temperature and relative humidity variations. The weighing chamber of the UMT-2 microbalance is enclosed to avoid the effects of air currents, and the balance is designed to dampen mechanical vibrations. Throughout the gravimetric analysis procedure, the room will be maintained at 75 ± 5 °F and 45 ± 5% relative humidity.

Since three brake pad materials will be tested, with each test performed in triplicate, we estimate that we will need approximately 200 Teflon filters (including blanks and spares). The gravimetric determination of the Teflon filters will take approximately 1.5 weeks for the pre-measurement weighing and a similar amount of time for the post-measurement weighing.

5. POST-SAMPLING ANALYSIS

As described above, the exposed filters will be weighed to determine the mass size distribution. Additional analysis of the airborne brake wear debris samples will include determination of element/metals content of the material captured on the filters.

The copper and iron contents of the collected airborne brake wear debris will be analyzed after microwave-assisted acid digestion by inductively coupled plasma-atomic emission spectroscopy (ICP/AES), following the procedures developed by Dr. Schlautman's research group[5] to determine the copper and iron contents of non-airborne brake wear debris in support of ongoing BPP activities. For a very limited number of samples, we will demonstrate the effectiveness of the digestion procedure and ICP/AES analysis by performing the copper and iron analyses using an independent technique such as neutron activation analysis or other appropriate technique. This independent analysis for copper and iron will provide an additional QA/QC check on our analytical procedures.

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[5] J. Hur, S. Yim, and M. Schlautman (2003). Copper leaching from brake wear debris in standard extraction solutions. *J. Env. Monit.* **5**, 837-843.

6. CONSULTATIONS, MEETINGS, AND DELIVERABLES

Our major deliverables will be those associated with each of the major tasks on the schedule shown in Table 1. In addition, as required by our contract, brief written monthly progress reports to SFEP/BPP via email on the first of each month will be provided. Also, brief quarterly verbal updates to the BPP Steering Committee will be scheduled as needed. Finally, written quarterly reports will be submitted electronically to ABAG/SFEP by the 5th of the month following the end of the quarter.

If the schedule shown in Table 1 can be maintained, we would then expect to submit a draft final report no later than July 27, 2004. The final version of the report will be submitted within one month of receiving comments from the BPP. The report deliverable will be provided in both Adobe Acrobat and Microsoft Word formats.

Following completion and submission of our final report (tentatively scheduled no later than September 15, 2004; see Table 1), we will continue through the end of the project to provide consultation and/or will participate by teleconference in meetings with the BPP project team, Steering Committee and Scientific Advisory Team on an as-needed basis.

7. ANTICIPATED SCHEDULE

Table 1 below shows the anticipated timeline by task for this Work Plan. Some dates are tentative, and are subject to the scheduling associated with the operators of the dynamometer facility, reviewers of the Work Plan and/or reports, etc.

Table 1. Anticipated subcontract time line.

Task	**Anticipated Completion Date**
Task 1 – Engineering Calculations; Develop Draft Work Plan	April 1, 2004
Task 2 – Finalize Work Plan	May 7, 2004
Task 3 – MOUDI Preparation and Filter Weighing	May 7, 2004
Task 4 – Sampling at the Dynamometer Site	May 7 to June 7, 2004 (1)
Task 5 – Gravimetric and Other Analysis of Samples	One month following completion of sample collection, or at latest June 30, 2004 (2)
Task 6 – Develop and Submit Draft Final Report	Draft report three weeks after completion of sample analyses, or at latest July 27, 2004.
Task 7 – Submit Final report	Final report two weeks after receipt of comments. Target date September 15, 2004.
Task 8 – Consultation & Meetings	January 6, 2004 to October 10, 2005

(1) Dates are tentative. Testing will be done in coordination with dynamometer facility.

(2) Dates shown are based on a sample collection completion date of June 7, 2004. Actual dates will be earlier if sample collection is completed earlier according to the times allocated per task here.

8. BUDGET

Our deliverables and budget by task are listed below in Table 2. Payment is expected to be made to Clemson University upon submission of the task deliverables.

Table 2. Deliverables and Budget per SubcontractTask.

Task	**Budgeted Amount** (1)
Task 1 – *Deliverable: Draft Work Plan*	$4,000
Task 2 – *Deliverable: Final Work Plan*	$3,000
Task 3 – *Deliverable: Raw Data of Filter Masses*	$7,000
Task 4 – *Deliverable: Brief Email message reporting that MOUDI measurements have been completed.*	$8,000
Task 5 – *Deliverable: Raw Data of Filter Masses and Cu/Fe concentrations*	$9,000
Task 6 – *Deliverable: Draft Final Report*	$4,000
Task 7 – *Deliverable: Final Report*	$3,000
Task 8 – *Deliverable: Brief E-mail message reporting that the overall project has been completed*	$2,000

1. Budgeted amounts shown for each task include all direct and indirect (i.e., facilities and administration) costs. The indirect cost used (i.e., 47% of the modified total direct cost) is Clemson University's federally-approved facilities and administration charge for the College of Engineering and Science.