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# Heavy Equipment Maintenance Exposure Assessment: Using a Time-Activity Model to Estimate Surrogate Values for Replacement of Missing Data

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*This study on four pieces of heavy construction equipment was conducted to determine the concentration of airborne asbestos fibers during in-frame maintenance and repair activities, which included aggressive techniques that resulted in visible dust from work involving friction products and gaskets. Despite execution of a carefully planned sampling strategy, approximately 10% (47) of the samples collected could not be analyzed due to overloading or filter damage. To include the overloaded samples in the data analysis, surrogate values were estimated following a time-activity model. Twelve long-term personal samples, 2 short-term, 30-min personal samples, and 31 long-term area samples were modeled. Personal and area time-weighted average (TWA) data were analyzed both with and without the estimated surrogate values and compared. A total of 444 samples were collected over 9 days. Four experienced heavy equipment mechanics removed and replaced friction products and gaskets. Samples were analyzed using NIOSH Method 7400 Phase Contrast Microscopy followed by NIOSH Method 7402 Transmission Electron Microscopy. Sample data information including the surrogate values for the full-shift, TWA personal sample results ranged from 0.002 to 0.064 asbestos f/cc. Personal, short-term, 30-min sample results, including the two surrogate values, ranged from 0.038 to 0.561 asbestos f/cc. Full-shift TWA area samples, including the 31 surrogate values, ranged from 0.005 to 0.039 asbestos f/cc. Area air sample results at the end of the project were similar to levels measured before the start of the project. No fiber concentration buildup within the work area was indicated over the 9-day study. All full-shift personal and area TWA sample results were below 0.1 f/cc, and short-term 30-min personal samples were below 1.0 f/cc. Statistical results of the sample data with and without the surrogate values were consistent. Use of the time-activity model reduced the uncertainty associated with this data analysis and provided a consistent logical process for estimating surrogate values to replace missing data.*

**Keywords** asbestos-containing, chrysotile, exposure assessment, friction products, gaskets, time-activity model

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## INTRODUCTION

Asbestos has been used in certain applications of engine gaskets and friction products in high- and low-speed automobiles, trucks, buses, light duty equipment, and heavy construction equipment. Workers involved in repair or replacement of gaskets and friction products used in heavy construction equipment are potentially exposed to asbestos fibers. The authors anticipated and hypothesized that resulting airborne asbestos fiber levels would be below 0.1 f/cc 8-hr time-weighted average (TWA) and 1.0 f/cc 30-min short-term exposure limit (STEL). The hypothesis was based on the previous work experience of the authors and results of published studies discussed herein.

Conducting an assessment for asbestos exposures on mechanics performing maintenance activities on heavy equipment presents a number of challenges to sample collection and analysis. The analytical methods used to determine the concentration of fibers are sensitive to the presence of other particles on the filters. Activities such as welding, cutting using torches, and grinding may render the filter overloaded with particulate matter, the result being that the sample cannot be analyzed. This study experienced a percentage of samples that were affected by these activities and as a result, 10% of the samples could not be analyzed. To overcome problems associated with filter overloading and damage, the authors chose to apply a time-activity model commonly used in historical exposure assessment to estimate surrogate values for replacement of the missing data.[1,2,3]

The study was conducted during June 2003 and performed in a heavy equipment repair facility by independent mechanics with extensive experience working on heavy equipment. The work spanned a period of 9 days and was conducted on four pieces of Caterpillar heavy equipment: A D8 Dozer (D8), a 12E Motor Grader (12E), a 930 Wheel Loader (930), and a 955 Track Loader (955).

Brakes, clutches, and engines determined likely to be original equipment with asbestos-containing components were dismantled, cleaned, and reassembled. The gaskets, brake linings, and clutch linings were removed and replaced.

## METHODS

### Work Layout and Ventilation

The repair facility was constructed of a steel frame and metal skin and was fitted with two, large, sectional steel overhead doors. The interior was unfinished and the dimensions were 17.1 m wide by 18.3 m long with a roof that varied from 3.7 m at the side wall to 8.5 m at the apex. Figure 1 shows the location of the equipment during the work and the location of the overhead doors. The D8 was in Location A throughout the study. Sequentially, the 12E, 930, and 955 were placed in Location B and worked on during the study. Figure 1 shows the layout of the facility and the location of equipment.

The repair facility was not equipped with a mechanical ventilation system. The study was conducted under routine conditions with doors being opened only for entry and exit of personnel. The overhead doors were opened only to move equipment and supplies in and out of the repair facility or for a few minutes following work activities, such as operating the diesel engines, welding, and grinding or other activities that generated dense smoke or fume. A pedestal-mounted fan was used by the mechanics at various times to provide air movement inside the repair facility.

Prior to and following work activities, the effective ventilation rate (reported as the number of air changes per hour) of the facility was determined by using carbon dioxide ($CO_2$) tracer gas. The American Society for Testing and Materials (ASTM) Method E 741-00 Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution was followed as a guideline.[4]

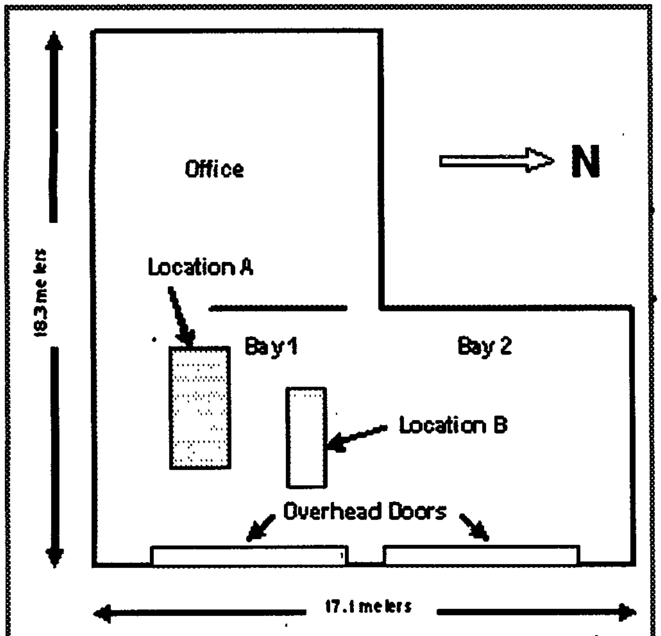


FIGURE 1. Layout of repair facility and location of heavy equipment

## SAMPLING STRATEGY AND ANALYTICAL METHODS

The facility owners removed interfering construction equipment and cardboard boxes from the repair facility.

Ten background air samples were collected for approximately 145 min at 2 L/min on the day prior to the start of repair activities. Five samples were collected inside the facility, and five were collected outside the facility to establish background fiber concentrations.

Personal and area air samples were collected each day with sample pumps started prior to the initiation of work activities and were stopped at the end of the day after completion of work. Consecutive, long-term samples were collected on each mechanic and at each area sampling location. Samples were combined into TWAs over the whole sampling period to achieve full-shift TWA concentrations.

The short-term, personal monitoring periods were for 30 min and were collected during activities when the mechanics were directly impacting the asbestos-containing gasket or friction material. These samples were collected to reflect peak exposure concentrations from activities conducted over a short period of time.

To determine average room fiber concentrations in air, a procedure based on Environmental Protection Agency (EPA) asbestos guidance documents was used.[5–7] The occupied volume of the repair facility was subdivided into 40,320 modules. The volume of each module equaled 0.03 $m^3$. Only areas between the floor and a height of 3.7 m were included in the random generation of area sample locations as this is the zone where the mechanics worked. Eight of the modules were selected using a random number generator. A sample cassette was located in the center of the respective module for the duration of each day of testing. Area samples were collected and analyzed using the same methods as the personal samples.

All background, personal, and area samples were collected and analyzed following National Institute for Occupational Safety and Health (NIOSH) Method 7400 for collection and analysis by PCM.[8] All air samples were collected at a rate of approximately 2 L/min. Samples with results above the limit of detection (LOD) by phase contrast microscopy (PCM) were subsequently analyzed by NIOSH Method 7402 Transmission Electron Microscopy (TEM) to identify fiber type.[9] TEM analysis determines the fraction of asbestos fibers present on the PCM filters. This fraction was then multiplied by the PCM fibers per cubic centimeter (f/cc) result in accordance with NIOSH Method 7402 to obtain a PCM equivalent (PCME) asbestos f/cc. All samples above the PCM LOD in the study were subsequently analyzed by TEM.

For sample results below the LOD, the PCM LOD value was used in the TWA calculation and/or statistical analyses.

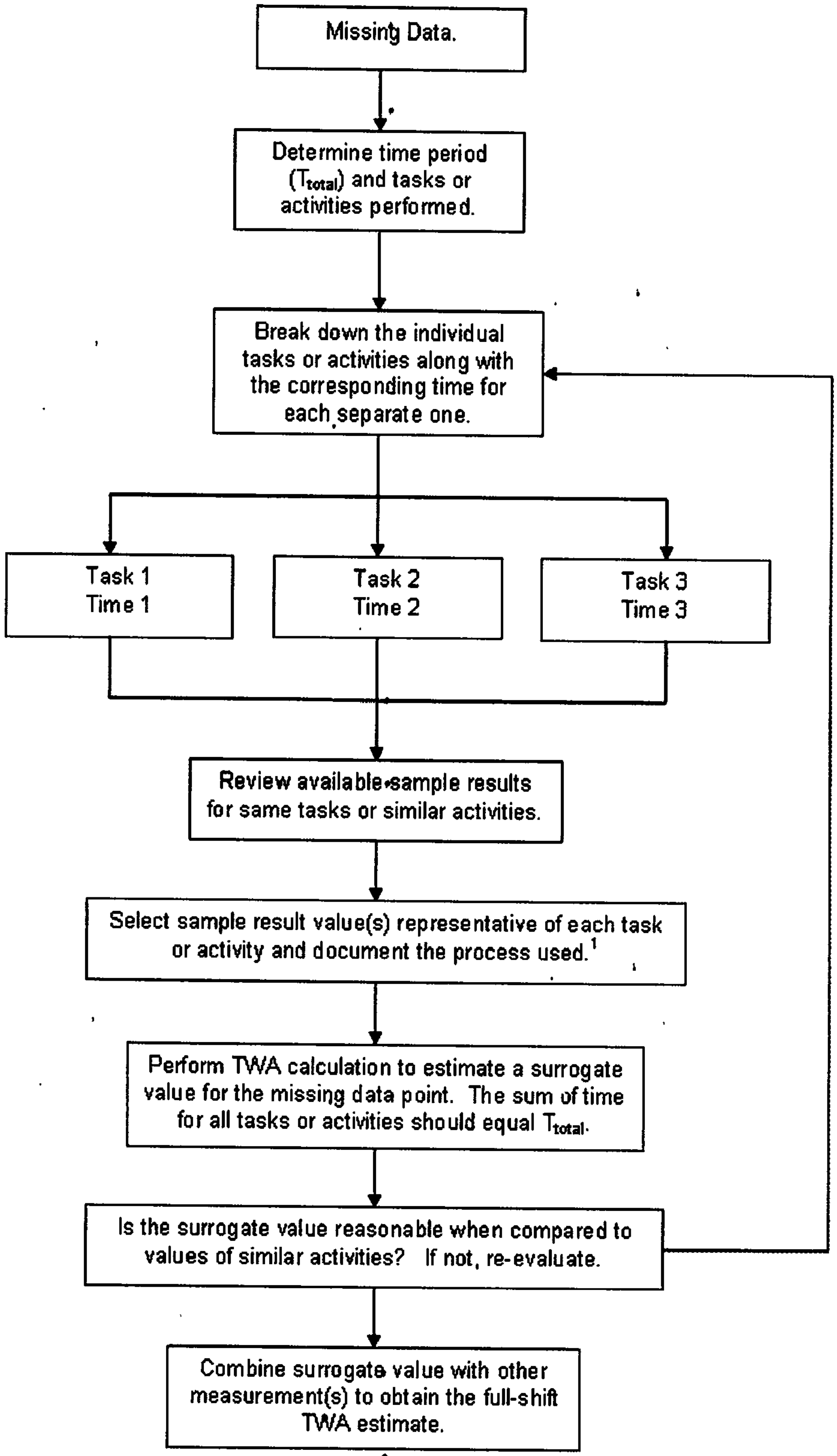


**FIGURE 2.** Process framework for the time-activity model used to determine an estimated surrogate value for missing data. [1] *Note.* This value may be based on an average, mean, maximum, or some other value. Although not used in the model for this paper, commercial software for stochastic modeling is available to assist with selection of a representative value

For example, if a sample was analyzed by PCM and resulted in < 0.045 f/cc, a value of 0.045 f/cc was used as the value for PCM and PCME. For samples analyzed by TEM, and where the result after multiplying the PCM result by the TEM fraction was below the PCM LOD, the PCM LOD was used as the value in the TWA calculation and/or statistical analysis.

Surrogate values for missing (overloaded and damaged filters) samples were estimated by using a time-activity model. This model is consistent with methods described by Leidel et al.[10] and Mulhausen and Damiano,[11] where professional judgment is used to make inferences about exposure concentrations and the use of estimated surrogates in place of missing data. The process used in this study is consistent with the worker time-activity model described by Ramachandran and Vincent[3] and Ramachandran,[1,2] which is used for retrospective exposure assessments. Figure 2 describes the step-by-step process that determined the estimated surrogate value to replace the missing sample data point.

### Bulk Samples

Bulk samples of friction and gasket materials and debris created during the brake and clutch removal process were collected and analyzed for asbestos content and mineral type by polarized light microscopy (PLM) in accordance with guidelines set forth in *EPA Method for Determination of Asbestos in Bulk Building Materials*.[12]

### Statistical Methods

Descriptive statistical functions were performed to summarize personal and area data. Industrial hygiene inferential statistics[10,11,13] of the TWA full-shift, personal sample

**TABLE I. TWA PCME Personal and Area Samples Daily Statistics**

| | | Personal TWA Samples | | | | | Area Samples | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Data Set^A | n | Min | Max | Mean | Std. Dev. | n | Min | Max | Mean | Std. Dev. |
| 1 | AFS | 2 | 0.002 | 0.041 | 0.024 | 0.028 | 0 | — | — | — | — |
| 1 | APS | 1 | — | — | 0.007 | — | 8 | 0.004 | 0.006 | 0.005 | 0.001 |
| 1 | BFS | 3 | 0.002 | 0.033 | 0.016 | 0.017 | 8 | 0.006 | 0.008 | 0.006 | 0.001 |
| 2 | AFS | 3 | 0.005 | 0.007 | 0.006 | 0.001 | 8 | 0.005 | 0.006 | 0.006 | 0.000 |
| 2 | APS | 0 | — | — | — | — | 0 | — | — | — | — |
| 2 | BFS | 3 | 0.005 | 0.007 | 0.006 | 0.001 | 8 | 0.005 | 0.006 | 0.006 | 0.000 |
| 3 | AFS | 2 | 0.020 | 0.028 | 0.024 | 0.006 | 8 | 0.005 | 0.022 | 0.014 | 0.005 |
| 3 | APS | 2 | 0.015 | 0.046 | 0.030 | 0.022 | 0 | — | — | — | — |
| 3 | BFS | 4 | 0.013 | 0.036 | 0.024 | 0.010 | 8 | 0.005 | 0.022 | 0.014 | 0.005 |
| 4 | AFS | 1 | — | — | 0.005 | — | 0 | — | — | — | — |
| 4 | APS | 2 | 0.008 | 0.009 | 0.008 | 0.001 | 8 | 0.013 | 0.018 | 0.014 | 0.002 |
| 4 | BFS | 3 | 0.005 | 0.007 | 0.006 | 0.001 | 8 | 0.007 | 0.007 | 0.007 | 0.000 |
| 5 | AFS | 0 | — | — | — | — | 0 | — | — | — | — |
| 5 | APS | 3 | 0.046 | 0.055 | 0.052 | 0.005 | 4 | 0.03 | 0.04 | 0.036 | 0.004 |
| 5 | BFS | 3 | 0.045 | 0.064 | 0.053 | 0.010 | 8 | 0.034 | 0.039 | 0.036 | 0.001 |
| 6 | AFS | 3 | 0.011 | 0.012 | 0.011 | 0.001 | 5 | 0.007 | 0.010 | 0.008 | 0.001 |
| 6 | APS | 1 | — | — | 0.011 | — | 3 | 0.007 | 0.010 | 0.008 | 0.001 |
| 6 | BFS | 4 | 0.011 | 0.012 | 0.011 | 0.001 | 8 | 0.007 | 0.010 | 0.008 | 0.001 |
| 7 | AFS | 3 | 0.014 | 0.022 | 0.017 | 0.004 | 8 | 0.009 | 0.022 | 0.015 | 0.004 |
| 7 | APS | 0 | — | — | — | — | 0 | — | — | — | — |
| 7 | BFS | 3 | 0.014 | 0.022 | 0.017 | 0.004 | 8 | 0.009 | 0.022 | 0.015 | 0.004 |
| 8 | AFS | 3 | 0.010 | 0.017 | 0.012 | 0.004 | 8 | 0.009 | 0.019 | 0.011 | 0.004 |
| 8 | APS | 0 | — | — | — | — | 0 | — | — | — | — |
| 8 | BFS | 3 | 0.010 | 0.017 | 0.012 | 0.004 | 8 | 0.009 | 0.019 | 0.011 | 0.004 |
| 9 | AFS | 4 | 0.008 | 0.019 | 0.014 | 0.005 | 8 | 0.008 | 0.017 | 0.011 | 0.003 |
| 9 | APS | 0 | — | — | — | — | 0 | — | — | — | — |
| 9 | BFS | 4 | 0.008 | 0.019 | 0.014 | 0.005 | 8 | 0.008 | 0.017 | 0.011 | 0.003 |
| | Total AFS | | 0.002 | 0.041 | 0.014 | 0.009 | | 0.005 | 0.022 | 0.011 | 0.002 |
| | Total APS | | 0.008 | 0.055 | 0.022 | 0.003 | | 0.004 | 0.040 | 0.016 | 0.001 |
| | Total BFS | | 0.002 | 0.064 | 0.018 | 0.005 | | 0.005 | 0.039 | 0.013 | 0.002 |

^A AFS = TWA full-shift analyzed data >390 min; APS = TWA partial-shift analyzed data <390 min; BFS = TWA analyzed plus modeled data.

data and short-term 30-min personal sample data were also determined.

## RESULTS

### Ventilation

The effective ventilation rate with all doors closed was 0.13 air changes per hour (ACH) and averaged 4.7 ACH with both overhead repair facility doors open.

### Background Air Samples

Ten samples were collected (5 inside/5 outside) but only the inside facility samples were analyzed. Results ranged from 0.012–0.025 total fibers/cc by PCM. These samples were further analyzed by TEM and no asbestos fibers were detected (PCME of <0.009 asbestos f/cc) in any of the five samples.

### Bulk Samples

The removed and replaced brake materials from all four pieces of equipment contained from 15% to 95% chrysotile asbestos. Bulk sample analysis for asbestos in brake debris collected from all four machines yielded either nondetectable or less than 1% chrysotile asbestos. Removed and replaced gasket materials positive for asbestos ranged from 3% to 85% chrysotile.

### Personal and Area Samples

A total of 434 personal and area samples were collected during work activities and analyzed: 192 area samples, 101 long-term personal samples, and 138 short-term samples. Forty-seven (approximately 10%) of the 434 samples were overloaded with particulate matter and could not be analyzed. Three samples were excluded from the data compilation and statistical analysis due to pump faults that resulted in sample times less than 30 min or sample time uncertainty.

### *Full-Shift and Short-Term Personal Samples*

Full-shift monitoring periods ranged from 6.5 hr to 9.5 hr, with over half of the samples in the 8-hr time period. Full-shift sample collection ranged from one sample collected over a full shift to collection of five samples averaged to determine the full-shift TWA. From the 101 personal samples, a total of 30 full-shift averaged personal samples were expected. For this study, a minimum sampling time of 390 min defined a full-shift personal sample. Twenty-one averaged personal samples met the full-shift criteria and are described as Data Set AFS (full shift). The remaining nine personal TWAs were less than 390 min due to one or more overloaded samples. The partial-shift samples are described as Data Set APS (partial shift).

Sample filters that overloaded with particulate matter or were damaged resulted in inconclusive data, which then resulted in TWA samples failing to meet the selected full-shift time criteria. To avoid loss of the missing sample data points, a time-activity model (Figure 2) was used to estimate surrogate asbestos fibers/cc values. The estimated surrogate value for each missing data point was then entered into the PCME TWA calculation. The results of including the surrogate values into the PCME TWAs are described as Data Set BFS (full shift).

Personal full-shift TWAs by PCM analysis ranged from 0.005 f/cc to 0.049 f/cc with an arithmetic average value of 0.027 f/cc. Partial-shift TWAs by PCM analysis ranged from

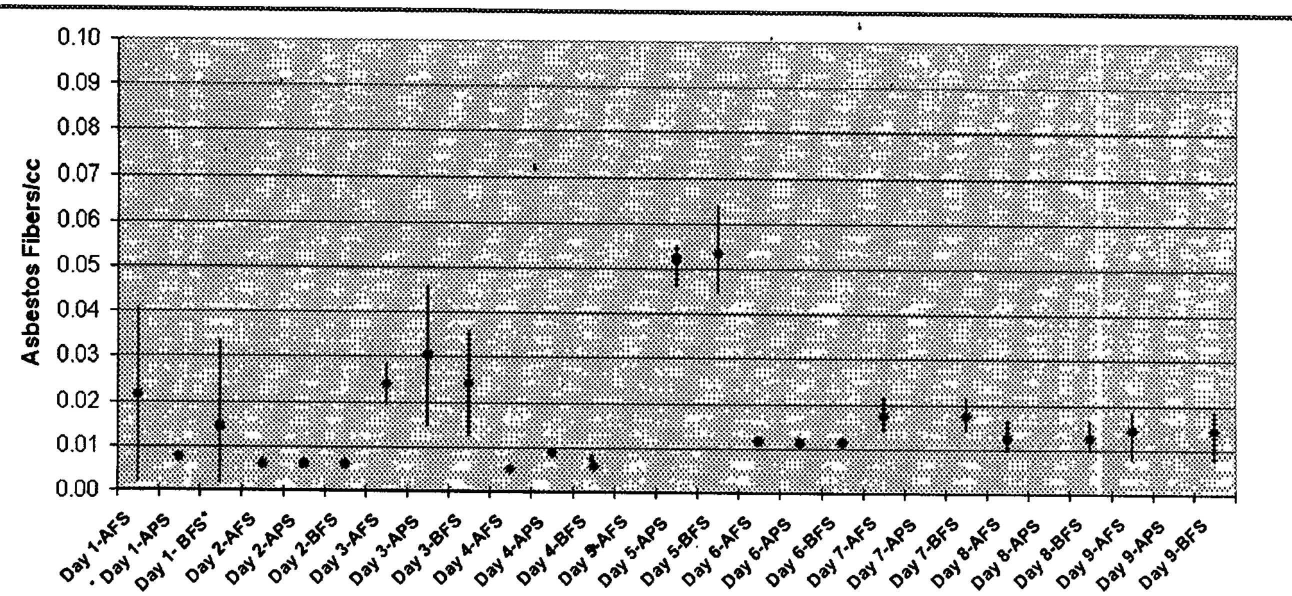


**FIGURE 3.** TWA personal sample results—asbestos fibers/cc by day and data set *Note:* The solid circle on the graph indicates the average value The line extending through the circle indicates the range of the data AFS indicates Data Set A—TWA data >390 minutes. APS indicates Data Set A—TWA partial-shift data <390 minutes. BFS indicates Data Set B—TWA full-shift data including surrogate modeled data. Sample Analysis by NIOSH 7400 followed by NIOSH 7402 *Note:* The maximum value for Data Set BFS is different from AFS because one of the AFS samples included an OL sample that when replaced with the surrogate value, the TWA was lower.

TABLE II. Daily TWA Personal Sample Results with Activity Descriptions (Data Set BFS)

| Sample Information | | | | | | Results |
|---|---|---|---|---|---|---|
| Date | Person Sampled | Activity | Surrogate Estimated Value Time (min)[A] | Total Sample Time (min) | N | PCME TWA (Asbestos Fibers/cc) |
| Day 1 | Mechanic #2 | D8 – Cable control disassembly. 12E—removed wheels and brake | 0 | 490 | 1 | 0.002 |
| Day 1 | Mechanic #3 | D8 – Removed and replaced right cable control brake | 131 | 536 | 4 | 0.033 |
| Day 1 | Mechanic #4 | 12 E – Removed and replaced the air filter, exhaust and intake manifolds, valve cover, and engine head | 123 | 494 | 3 | 0.007 |
| Day 2 | Mechanic #2 | D8 – Removed parts to access the track brakes. Assisted with disconnection of the cable control unit from the body of the dozer. 12E –removed and replaced rear brakes | 0 | 509 | 2 | 0.005 |
| Day 2 | Mechanic #3 | D8 – Removed and replaced left cable control brake, disconnected cable control unit from body of D8 | 0 | 409 | 2 | 0.007 |
| Day 2 | Mechanic #4 | 12E – Removed and replaced rear brakes, cleaned engine head and block, replaced head gasket and engine head, removed radiator connections and gaskets | 0 | 509 | 2 | 0.005 |
| Day 3 | Mechanic #1 | 12E – Removed and replaced rear brakes, cleaned engine head and block, replaced head gasket and engine head, removed radiator connections and gaskets | 0 | 405 | 3 | 0.028 |
| Day 3 | Mechanic #2 | D8 – Removed the left and right track brake bands, replaced left brake band | 162 | 511 | 3 | 0.036 |
| Day 3 | Mechanic #3 | D8 – Removed and replaced clutch and cable puller linkage | 162 | 512 | 3 | 0.013 |
| Day 3 | Mechanic #4 | 12E – Machine fluids replaced, oil filter, crank case breather and air filter parts and gaskets and engine cover replaced. 930 – Removed and replaced the wheels, four brake caliper assemblies, and brake pads | 0 | 504 | 3 | 0.020 |
| Day 4 | Mechanic #2 | D8 – Track band brake replacement and adjustment. Assisted with the removal of clutch using overhead hoist | 350 | 517 | 2 | 0.007 |
| Day 4 | Mechanic #3 | D8 – Removed parts to access the master clutch. Assisted with the removal of clutch using overhead hoist | 223 | 520 | 3 | 0.008 |
| Day 4 | Mechanic #4 | 955 – Removed engine cowling, exhaust manifold, rocker arm assembly, valve cover, engine studs, air intake manifold and air filter, radiator hose connection, water thermostat and the engine head along with associated gaskets | 0 | 493 | 2 | 0.005 |
| Day 5 | Mechanic #1 | 955 – Removed parts to gain access to the rear brake bands. Disassembled and removed the steering clutch linkages and assisted Mechanic #4 | 64 | 422 | 5 | 0.045 |
| Day 5 | Mechanic #3 | D8 – Removed and replaced clutch drive and driven plate friction linings | 155 | 493 | 5 | 0.052 |
| Day 5 | Mechanic #4 | 955 – Removed gaskets from the intake manifold, exhaust manifold, valve cover, radiator hose pipe connection, and the oil cooler/water pump. Replaced ferrules, seals, gaskets and engine head | 279 | 499 | 5 | 0.064 |
| Day 6 | Mechanic #1 | D8 – Assisted with replacement of clutch. 955 – Removed three left side brake band assemblies | 0 | 336[B] | 3 | 0.011 |
| Day 6 | Mechanic #2 | 955 – Removed band brake, D8 Removed and replaced clutch and cable puller linkage | 0 | 438 | 4 | 0.012 |
| Day 6 | Mechanic #3 | D8 – Reinstalled the clutch assembly and clutch linkage | 0 | 574 | 5 | 0.012 |
| Day 6 | Mechanic #4 | 955 – Reassembled with gaskets the valve assembly, air intake manifold, exhaust manifold, thermostat, oil cooler surface, radiator pipe connection surfaces, and air filter assemble | 0 | 576 | 5 | 0.011 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Day 7 | Mechanic #1 | 955 – Removal of left side brake bands, replaced the oil cooler, radiator pipe, gaskets, and radiator fan and fan guard. | 0 | 564 | 4 | 0.016 |
| Day 7 | Mechanic #3 | D8 – Reassembled the clutch linkage and installed the transmission inter-lock assembly with its original gasket. 955 – Assisted mechanic #1 | 0 | 577 | 4 | 0.014 |
| Day 7 | Mechanic #4 | D8 – Removed the "pony" engine exhaust pipe, pony engine supply tube, water manifold pipe, exhaust and air intake manifold, and cylinder heads. Removed gaskets and cleaned engine head and flanged surfaces | 0 | 554 | 4 | 0.022 |
| Day 8 | Mechanic #1 | 955 – Installed right- and left-side brake bands and steering linkages | 0 | 547 | 4 | 0.011 |
| Day 8 | Mechanic #2 | 955 – Installed the brake bands on the right and left side. Reinstalled brake and steering linkages; D8 – Assisted with installation of engine head | 0 | 540 | 4 | 0.010 |
| Day 8 | Mechanic #4 | D8 – Cleaned the exhaust/intake manifolds, front and rear cylinder heads, removed and replaced gaskets | 0 | 482 | 4 | 0.017 |
| Day 9 | Mechanic #1 | 955 – Completed steering clutch and brake linkage installation and adjusted brakes. D8 – Assisted Mechanic #4 | 0 | 489 | 3 | 0.019 |
| Day 9 | Mechanic #2 | 955 – Completed steering clutch and brake linkage installation, adjusted brakes; D8 – Assisted Mechanics #1 and 4 with engine assembly and replaced exhaust stack | 0 | 494 | 3 | 0.013 |
| Day 9 | Mechanic #3 | D8 – Drained and replaced oil, re-installed seats, levers, and steering linkages in cab | 0 | 502 | 3 | 0.008 |
| Day 9 | Mechanic #4 | D8 – Cleaned valve cover surfaces, installed replacement valve cover gaskets. Reinstalled fuel lines, exhaust and water manifold gaskets, and air filter/intake pipe. Cleaned the "pony" engine exhaust pipe flange and replaced gasket. Removed and replaced the fuel filter and gaskets | 0 | 496 | 3 | 0.018 |

[A] The amount of time that the time-activity model was used to estimate a surrogate value for inclusion in the TWA.
[B] The total amount of time this mechanic worked on Day 6.

**TABLE III. Short-Term, 30-Min Personal Sample Daily Statistics**

| Day | Data Set | n | Min[A] | Max |
|---|---|---|---|---|
| 1 | AST | 4 | <0.044 | 0.046 |
| 2 | AST | 6 | <0.044 | 0.045 |
| 3 | AST | 13 | <0.044 | 0.561 |
| 4 | AST | 5 | <0.043 | 0.045 |
| 5 | AST | 18 | <0.043 | 0.413 |
| 5 | BST | 20 | <0.043 | 0.413 |
| 6 | AST | 23 | <0.043 | 0.099 |
| 7 | AST | 30 | <0.043 | 0.170 |
| 8 | AST | 29 | <0.044 | 0.180 |
| 9 | AST | 9 | <0.045 | 0.045 |
| Total AST | | | <0.043 | 0.561 |
| Total BST | | | <0.038 | 0.561 |

*Notes:* AST indicates analyzed data only; BST indicates analyzed plus modeled data.

[A]Minimum values were all less than the limit of detection for the sampling method.

0.011 f/cc to 0.176 f/cc with an arithmetic average value of 0.053 f/cc. The minimum PCME value result for data sets AFS and BFS was 0.002 asbestos f/cc, and 0.008 asbestos f/cc for Data Set APS. The maximum PCME values were 0.041 for Data Set AFS, 0.055 for Data Set APS, and 0.064 asbestos f/cc for Data Set BFS. The means were similar with Data Set AFS at 0.014 asbestos f/cc, Data Set APS at 0.022 asbestos f/cc, and Data Set BFS at 0.018 asbestos f/cc. Table I and Figure 3 present the daily statistics for personal PCME TWA samples and Data Sets AFS, APS, and BFS. A comprehensive list of work activities and sample information for full-shift TWAs representing Data Set BFS values are presented in Table II.

One hundred and thirty-eight short-term samples were collected. Of those, 136 samples were analyzed. Two samples on Day 5 were overloaded with particulate matter and could not be analyzed. The analyzed samples are designated as Data Set AST (short term). The time-activity model was used to estimate surrogate values for the two missing data points and the combination of these values and the analyzed samples are designated as Data Set BST.

All short-term samples were collected for 30 min except for one 34-min sample. Table III and Figure 4 present the sample data grouped and analyzed by day. The range of results of the 30-min short-term samples for Data Set AST by PCM analysis was less than the LOD (< 0.043 f/cc) to 0.561 f/cc. The range of results for Data Sets AST and BST by PCME analysis were less than the detection limits of 0.043 and 0.038 asbestos f/cc to 0.561 asbestos f/cc for both PCME data sets. Mean values were not calculated due to the high fraction of censored data.

Gasket and friction-related excursion limit samples were grouped and analyzed to determine exposure concentrations for the various activities. Data were grouped to evaluate the results by a variable such as perceived aggressive activities, including scraping, hammering, riveting, abrasive cutting, and cleaning surfaces using a die grinder or compressed air. The PCM and PCME results of the sample data grouped by activity are presented in Table IV.

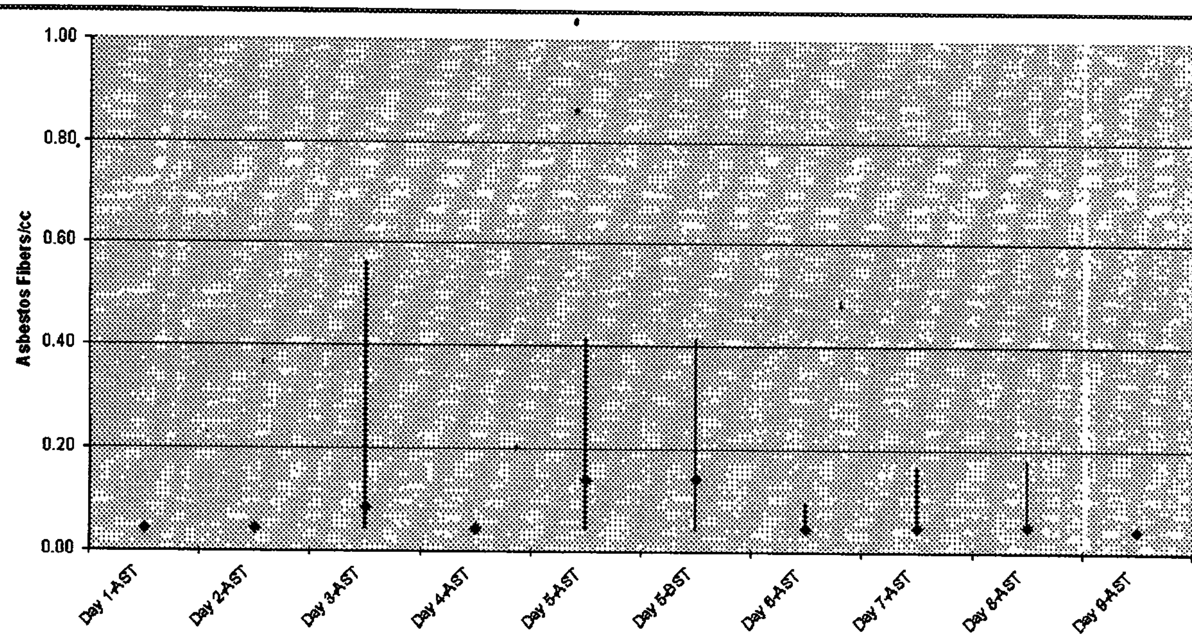


FIGURE 4. Short-term personal sample results by day. *Note:* The solid diamond on the graph indicates the average value. The line extending through the diamond indicates the range of the data. AST indicates Data Set A, BST indicates Data Set B. Sample Analysis by NIOSH 7400 followed by NIOSH 7402

TABLE IV. Short-Term Personal Samples by PCM and TEM

| Sample Information[A] Activity | N[C] | Analysis by NIOSH 7400 Phase Contrast Microscopy (PCM) Min. | Max. | Avg. | Std. Dev. | Analysis by NIOSH 7400 PCM and NIOSH 7402 Transmission Electron Microscopy (TEM)[B] Min. | Max. | Avg. | Std. Dev. |
|---|---|---|---|---|---|---|---|---|---|
| Friction-Related Work | | | | | | | | | |
| Band brake removal | 17 | 0.043 | 0.077 | 0.048 | 0.010 | 0.043 | 0.058 | 0.045 | 0.004 |
| Removal of rivets and friction lining from brake band or brake shoe | 4 | 0.044 | 0.044 | 0.044 | 0.000 | 0.044 | 0.044 | 0.044 | 0.000 |
| Cutting band with abrasive disc | 2 | 0.049 | 0.561 | 0.305 | 0.362 | 0.049 | 0.561 | 0.305 | 0.362 |
| Removal of disc brake assembly | 5 | 0.044 | 0.044 | 0.044 | 0.000 | 0.044 | 0.044 | 0.044 | 0.000 |
| Brake replacement and adjustment | 28 | 0.043 | 0.104 | 0.047 | 0.012 | 0.043 | 0.045 | 0.044 | 0.001 |
| Rivet replacement of friction lining to bands or shoes | 4 | 0.043 | 0.044 | 0.044 | 0.001 | 0.043 | 0.044 | 0.044 | 0.001 |
| Drilling of brake lining | 1 | | | 0.038 | | | | 0.038 | |
| Clutch removal, replacement and adjustment (D8 only) | 28 | 0.043 | 0.201 | 0.079 | 0.050 | 0.043 | 0.099 | 0.048 | 0.013 |
| Rivet removal from drive and driven plates (D8 only) | 2 | 0.190 | 0.230 | 0.210 | 0.028 | 0.150 | 0.184 | 0.167 | 0.024 |
| Cleaning, scraping compressed air cleaning of drive and driven plates (D8 only) | 4 | 0.151 | 0.211 | 0.180 | 0.026 | 0.150 | 0.211 | 0.170 | 0.029 |
| Rivet replacement of friction linings to drive and driven plates (D8 only) | 6 | 0.048 | 0.207 | 0.156 | 0.056 | 0.044 | 0.207 | 0.127 | 0.069 |
| Gasket-Related Work | | | | | | | | | |
| Removal of head/exhaust and intake manifold/water manifold gaskets | 13 | 0.044 | 0.048 | 0.045 | 0.001 | 0.044 | 0.045 | 0.044 | 0.000 |
| Scraping/power cleaning of engine head, engine block, and manifold surfaces | 13 | 0.045 | 0.413 | 0.143 | 0.125 | 0.045 | 0.413 | 0.116 | 0.114 |
| Wiping, cleaning parts | 8 | 0.045 | 0 199 | 0.065 | 0.054 | 0.045 | 0.094 | 0.051 | 0.017 |
| Use of compressed air to clean engine parts | 8 | 0.045 | 0.199 | 0.064 | 0.054 | 0.045 | 0.094 | 0.051 | 0.017 |
| Replacement of engine parts and gaskets | 12 | 0.045 | 0.074 | 0.050 | 0.010 | 0.045 | 0.045 | 0.045 | 0.000 |

[A] All samples were collected for 30 min at approximately 2 L/min except for one 34-min sample during brake drilling.
[B] For all samples less than the PCM LOD, the PCM LOD is the value used in statistical calculations.
[C] Seventeen short-term samples included work under two activities and are included in the analyses for both.

Further inferential statistical analysis of personal full-shift long-term TWA (Data Sets AFS and BFS) and the short-term 30-min data set was conducted. For the short-term 30-min data, 96 of the 138 samples were less than the LOD. Inclusion of data points less than the LOD (censored data) would bias the statistical results toward the low end. To be conservative and avoid the bias associated with analyzing censored data, only samples above the LOD were included in the analysis of the short-term 30-min data. By excluding the censored values from the short-term, 30-min data set analysis, only the upper bound values of the inferential statistics are reported. Each data set was determined to be lognormally distributed. The geometric mean (GM), geometric standard deviation (GSD), percentile value X (95%), upper tolerance limit (95% UTL), 95% exceedance fraction point estimate, and 95% upper confidence limit were calculated. The results of these analyses are presented in Table V.

### *Area Samples*

Seventy-two TWA area samples were calculated from the results of 192 area samples. Of these, 41 area sample results were full-shift TWA samples, with the remainder composed of 31 partial-shift TWA area samples. Sample sets are designated the same as the full-shift personal samples with Data Set AFS representing full-shift TWA samples, Data Set APS representing partial-shift TWA samples, and Data Set BFS, which represented all of the data from the previous two data sets plus the estimated surrogate values for the missing data points.

The range of PCM sample results for Data Set AFS was 0.003 to 0.047 total f/cc with an arithmetic average value of 0.020 f/cc. The range of PCM sample results for Data Set APS was 0.003 to 0.066 f/cc with an arithmetic average value of 0.022 f/cc. The overall statistics for the full-shift PCME data sets AFS and BFS were similar with minimum values of 0.005

**TABLE V. Inferential Statistical Analysis—Personal Samples**

| | Full-Shift Personal TWA PCME Samples (Data Set AFS)[A] | Full-Shift Personal TWA PCME Samples (Data Set BFS)[B] | Short-Term 30-Min PCME Personal Samples[C] |
|---|---|---|---|
| Occupational exposure limit (OEL) f/cc | 0.1 | 0.1 | 1 |
| Number of samples (N) | N = 21 | N = 30 | N = 48 |
| Geometric mean (f/cc) | 0.011 | 0.013 | — |
| Geometric standard deviation (f/cc) | 1.98 | 2.17 | — |
| X(95)% (f/cc) | 0.035 | 0.047 | 0.261 |
| UTL (95% UCL of X(95%)) (f/cc) | 0.057 | 0.074 | 0.359 |
| Exceedance fraction point estimate % | 0.07% | 0.45% | 0.03% |
| Exceedance fraction 95% UCL% | 1.14% | 2.50% | 0.23% |

[A] AFS = TWA full-shift analyzed data >390 min.
[B] BFS = TWA full-shift analyzed plus modeled data.
[C] Analyzed data from Data Set AST—data above the LOD only. Only upper bound statistics reported.

and 0.005 asbestos f/cc; maximum values of 0.022 and 0.039 asbestos f/cc; and arithmetic average values of 0.011 and 0.013 asbestos f/cc for data sets AFS and BFS, respectively. Table I and Figure 5 present the PCME data by day. Figure 5 shows that the arithmetic average asbestos f/cc air level by the end of the study was essentially the same as the beginning asbestos f/cc background level. These results indicated no buildup of asbestos fibers in air from one day to the next.

All TWA samples were below an 8-hr TWA of 0.1 f/cc. All short-term 30-min samples were below 1 f/cc.

## DISCUSSION

The majority of the activities conducted during this study were, according to the mechanics, typical for the servicing required. However, a few unusual practices were also monitored. One unusual practice, the cutting of the brake band, resulted in the highest value for the short-term 30-min samples (0.561 asbestos f/cc). The brake band cutting took approximately 2.5 min and was necessary because the bolts holding the brake band on could not removed. This activity

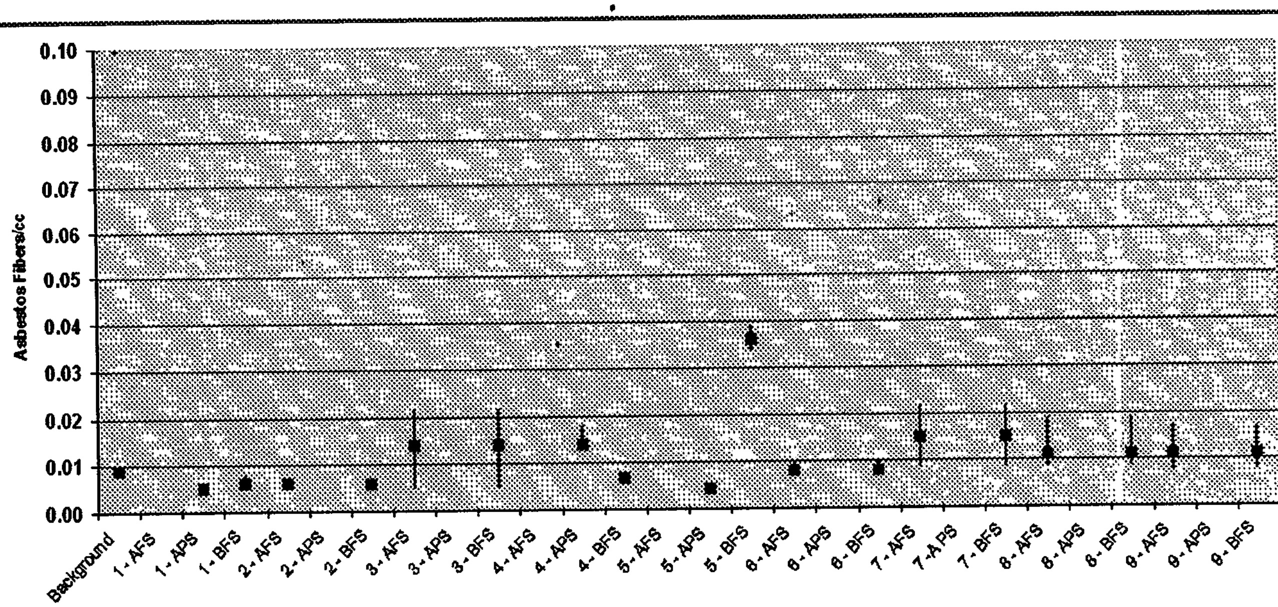


FIGURE 5. TWA area sample results—asbestos fibers/cc by day and data set. *Note.* The solid square on the graph indicates the average value. The line extending through the square indicates the range of the data AFS indicates Data Set A—TWA data >390 minutes APS indicates Data Set A—TWA partial-shift data <390 minutes BFS indicates Data Set B—TWA full-shift data including surrogate modeled values Sample Analysis by NIOSH 7400 followed by NIOSH 7402

| | | | Results | | | |
|---|---|---|---|---|---|---|
| | | | PCM (total f/cc) | PCME (asbestos f/cc) | | |
| **Work Activities, Analyzed Values, and Surrogate Values Personal Sample Information for Mechanic #4 on Day 5** | **Sample Time** | **Duration (min)** | **Value** | **Analyzed Value** | **Surrogate Value** | **Full-shift TWA** |
| Mechanic removed radiator fan, conducted scraping, and used a die grinder and abrasive disc on manifolds and valve cover surfaces. Five short-term samples collected on this mechanic on this day included the same or similar activities described for this time period. An average of the four short-term samples (0.413, 0.270, 0.080, 0.046, and 0.077 asbestos f/cc) was used as the surrogate value (0.172 asbestos f/cc). | 7:42 to 8:46 | 64 | OL[A] | | 0.177 | |
| Mechanic used a die grinder and scrapers/chisels on oil cooler surfaces and air intake pipe flange. Four short-term samples collected on this mechanic on this day included the same or similar activities described for this time period. An average of the four short-term samples (0.413, 0.270, 0.080, 0.046, and 0.077 asbestos f/cc) was used as the surrogate value (0.172 asbestos f/cc). | 8:46 to 9:18 | 33 | OL[A] | | 0.177 | |
| Mechanic used a chisel, hammer, and die grinder on water pump/head flange, radiator head flange, exhaust manifold on engine head, air intake on engine head, valve mechanism assembly, broom cleaned the floor, wiped down work table, and used a solvent to clean and wipe engine head surface. | 9:19 to 10:07 | 48 | 0.26 | 0.16 | | |
| Mechanic used a die grinder and scrapers on the engine block surfaces. Conducted parts inventory. Used a grinder on the equipment frame to allow clearance to install engine head. | 10:07 to 11:48 | 101 | 0.019 | 0.016 | | |
| Mechanic replaced head gasket; assembled ferrules and seals; installed head to engine block; tightened engine head bolts with torque wrench; and helped Mechanic #1 remove brake bands for 5 min. No short-term samples were collected on this mechanic during this time period. To determine the surrogate value we took the air sample result on Mechanic #1 (0.058 asbestos f/cc) for the brake work and used this value for the 5 min Mechanic #4 assisted him. Lunch break was included during this sample and was for 37 min. There was no exposure during lunch. For the remainder of the time (140 min) a value of 0.016 asbestos fibers/cc was the surrogate value. This surrogate value was based on the results of four samples collected on Mechanic #4 on Days 8 and 9 while he performed the same activities during reassembly of the D8, which ranged from <0.008 to 0.016 asbestos f/cc. Using the time-weighted average (TWA) calculation for the above value the result is 0.014 asbestos f/cc for the 182 min. | 11:48 to 14:50 | 182 | OL[A] | | 0.014 | |
| Mechanic completed tightening engine head bolts with a torque wrench, replaced valve mechanisms and engine head gasket. | 14:50 to 16:01 | 71 | 0.043 | 0.040 | | |
| Once the surrogate values were determined for the three OL samples described above, they were averaged with the remainder of the air samples for this mechanic on this day. The total work time was 499 min and the TWA result was 0.064 asbestos f/cc. The activities for this mechanic on this day were similar to his activities on Days 7 and 8. The TWA results for those days were 0.022 and 0.017 asbestos f/cc. Based on comparing the TWA results on Days 7 and 9 to the TWA for this mechanic on Day 4, surrogate values were likely biased on the high side. Because the goal was to compare results with 0.1 f/cc as an 8-hr TWA, the bias was reasonable without being unreasonably conservative. | — | 499 | — | | — | 0.064 |

[A] OL indicates sample was overloaded with particulate matter and could not be analyzed was also conducted a second time on another brake band on the D8 and the sample result was 0.049 asbestos f/cc.

Exposures with the highest numerical values occurred on Days 1, 3, and 5 of the study. Activities on Day 1 included removal of brake bands and removal and replacement of rivets and friction lining on the brake bands. Day 3 activities focused on the brakes and clutch systems on the D8, top-end engine rebuild on the 12E, and brake removal and replacement on the 930. Day 5 activities included D8-rivet removal, cleaning, and replacement on the drive and driven plates; 955-removal and replacement of top-end engine asbestos-containing gaskets.

Days 1, 3, and 5 were also the days when 32 air samples (approximately 70% of all the overloaded samples) were overloaded and could not be analyzed. To overcome the inability to include the overloaded samples and to reduce uncertainty associated with evaluation of the data, a time-activity model to estimate surrogate values for the missing data was applied. There was also a large data set with multiple samples for each task or similar tasks.

As shown in Figure 2, the authors relied on the analyzed data to assist with determination of the surrogate value. Also, for most of the overloaded sample periods, there were one or more short-term 30-min samples collected on the same mechanic during the applicable time frame that were available for use in the model. For each estimate made by following the model described in Figure 2, the authors chose conservative values in recognition that short-term samples, with their higher limits of detection, are likely biased high and are not necessarily good predictors of long-term exposures.[10,14] Therefore, the estimated surrogate results are also likely biased toward higher exposure values.

Because the authors were interested in comparing the results with the maximum likely TWAs, it was determined that conservative but reasonable estimations would be prudent. To determine whether each surrogate TWA value was reasonable, the result was compared with the TWA result of other mechanics performing similar activities. To illustrate the process, Table VI presents the results of using the time-activity model to estimate values for three samples on Mechanic 4 on Day 5 of the project.

The pattern of results of TWA personal samples in Figure 3 is similar to the pattern of the results for TWA area samples in Figure 5. The similarity in patterns was expected and indicates that the area samples, though much lower in concentration, are reflective of the work activities conducted on each day of the study. Results also indicate that the average value of the short-term samples over the 9-day study were consistent as shown in Figure 4.

The PCME mean and range for each data set on each day and demonstrate the consistency of these values throughout the study. However, the authors would caution users of the time-activity model for replacement of missing data that there may not always be this level of consistency for all data sets.

Two published studies provided extensive PCM total fiber data regarding airborne exposures during maintenance and brake lining replacement in automobiles and other types of vehicles.[15,16] Neither of the published studies included analysis to confirm fiber type in the air samples. The PCM total fiber results of our study were within the exposure range of these previously published studies.

In comparison, a number of published studies provided a smaller volume of data regarding exposures to asbestos while removing and replacing gaskets. Although not all of the studies provided TEM analysis results, some did provide 8-hr TWAs. The results of this study were consistent with the previously published studies[5,17–22] where 8-hr TWAs by PCM or fiber identification was included as part of sample analyses using NIOSH method 7402.

## CONCLUSIONS

Repair and maintenance of heavy construction equipment involving asbestos-containing friction products and gaskets resulted in exposure concentrations below 0.1 f/cc as an 8-hr TWA and below 1 f/cc as a 30-min short-term sample.

Average asbestos f/cc air concentrations in the repair facility work environment by the end of the 9-day study were essentially the same as background levels measured before the study, indicating no buildup of asbestos fibers in air from one day to the next.

A time-activity model approach to estimate surrogate values for replacement of missing data is an option to consider for exposure assessments when the ability to resample activities is not possible.

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