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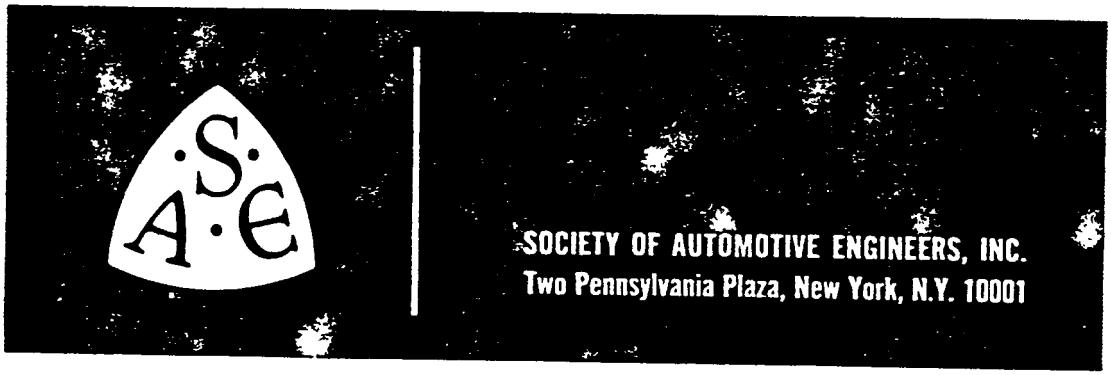

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ASBESTOS HAS BEEN A MAJOR constituent of automotive friction materials for more than 50 years. It is used to impart strength, flexibility, and heat resistance to a brake lining and to enhance friction and wear properties. Most present brake linings use resin or rubber binders and chrysotile asbestos, together with organic and inorganic friction modifiers and fillers. The asbestos content varies with formulation, from a low of 25% to about 65% by weight. Minimum asbestos levels are found in some high performance European disc brake linings which are highly filled with metals and inorganic constituents. Brake linings in the United States average about 50% asbestos content.

Of a total United States annual asbestos consumption of 800,000 tons (730 Mkg), about 28,000 tons (25 Mkg) of chrysotile asbestos are purchased annually for friction materials of all types (1)*. (Ref. 9 suggests 59,000 tons (53 Mkg) is more correct.) Of this, it has been calculated that brake lining wear consumes about 12,000 tons (11 Mkg) of asbestos per year. Roughly an equal amount remains on brake shoes at the time of replacement or is manufacturing wastage.

*Numbers in parentheses designate References at end of paper.

Recent tests have shown that densely populated urban atmospheres often contain significantly higher asbestos concentrations than surrounding areas (2). Background asbestos levels in the atmosphere result from the natural weathering of asbestos-bearing rock and soil, as well as from mining, farming, and excavating. The generally higher urban concentrations suggest commercial and industrial sources. Brake lining and clutch facing wear was suggested by Thomson (3) as a possible source for higher asbestos levels in the urban atmosphere.

Lynch (4), in a study undertaken by the Public Health Service, reported the findings of several brake dynamometer and friction machine tests in which wear debris was trapped on a filter and subsequently examined by means of a transmission electron microscope (TEM). He concluded that "free fibers from brake lining wear seem to be an inconsequential health factor in urban air pollution." Lynch detected no free fiber from an automobile clutch and a bus drum brake, but some free fibers were found in one test of an experimental disc brake.

With mounting concern over air quality in general, and asbestos pollution in particular, this study was initiated in 1970 to provide additional data on the asbestos emissions from disc brakes.

ABSTRACT

Dynamometer tests of a production disc brake provided new information on asbestos fiber emissions during break-in, normal use, and high temperature use conditions. Both ambient air and brake cooling air were sampled isokinetically, using 0.45 μm filters. Examination of test and background filters required a clarification process to maximize fiber detectability, the use of transmission electron microscopy (at 40,000X) for detection, and electron diffraction for positive identification of asbestos fibers. Most of the lining asbestos was found to be converted to a nonfibrous material by the high flash temperatures of the braking surface. Less than 0.02% of the lining wear was released as asbestos fibers. The concentration of asbestos fibers in the urban atmosphere, due to brake usage, was conservatively estimated at less than 0.07×10^{-9} g/m^3. Based on this upper bound, the use of brakes was judged to be not significant as a source of atmospheric asbestos.

OBSERVATIONS OF LINING WEAR

The near absence of free asbestos fiber from lining wear has been reported by Luxon (5) using x-ray diffraction and by Lynch (4) using the TEM. Several authors have suggested that interfacial temperatures during braking could be high enough to decompose the chrysotile asbestos into nonfibrous thermal degradation products. Analytical relationships exist which permit calculation of interfacial temperatures (6). However, several of the significant parameters are difficult to determine accurately for heterogeneous materials such as brake linings. The asbestos crudes (larger fiber bundles) were calculated to reach their rapid decomposition temperature during normal braking at speeds above 56 mph (25 m/s) as an upper bound value and above 18 mph (8 m/s) as a lower bound value. An experimental approach was undertaken to provide closer bounds.

Added insight into the thermal decomposition of asbestos fibers in brake lining wear was attempted by direct visualization of the frictional process. A small laboratory friction test machine was constructed using a thermal shock resistant (Vycor) glass rubbing surface (replacing the conventional cast iron) in which the friction interface was directly viewed with a low power (7-50X) binocular microscope (7). Scaled rubbing velocities were used to compensate for the thermophysical property differences between the glass and cast iron.

Moderate scaled velocities, roughly equivalent to 12 mph (5 m/s), provided a view of intermittently incandescent asbestos crudes. During the initial burnishing operation, resinous material surrounding these asbestos crudes was observed to pyrolize, producing microbeads of condensation products around the crude. These organic products of resin degradation and the apparently powdered asbestos decomposition products were seen to smear into platelets, often of such size as to be discernible to the unaided eye.

At higher rubbing velocities (over 30 mph, or 13 m/s) the platelets formed a surface char layer under the action of more severe thermal and mechanical action. The larger asbestos crudes then could be seen to glow with apparent depth and for greater time durations, often several seconds.

The actual brake lining contact area was only a few percent of the total available surface, with contact spots moving in a random manner with time. From these friction visualization studies it appeared that local flash temperatures and severe mechanical action could be major factors in the breakdown of asbestos fibers for most brake usage. Examination of the lining surfaces revealed the presence of nonfibrous magnesium silicate in both crystalline (Forsterite) and amorphous phases. Magnesium silicate is a thermal degradation product of chrysotile asbestos. Forsterite transformations have been reported to occur at 600°C over a period of hours. Differential thermal analysis (DTA) studies in our laboratory indicated this transformation occurs within seconds at 820°C.

Special brake lining formulations were then prepared and tested on the glass visualization apparatus and a Friction Assessment and Screening Test (FAST) machine. (8). Chemical reactions were found to take place at the friction interface, which would require a flash temperature rise of 740°C to initiate when an equivalent of 35 mph (16 m/s) rubbing speed was used on the FAST machine. At this same speed, melting of inorganic lining additives and metal particles confirmed brake flash temperatures up to 980°C.

Based on these findings, it would not appear surprising for few asbestos fibers to be emitted from brakes in normal usage. However, some mechanical removal of fiber appeared possible during the first several brake applications with new linings. Also, high brake temperatures possibly could weaken the organic binders and cause increased fiber emissions.

TEST PROCEDURES

Complete sample collection and examination procedures, along with sample data calculations are included as Appendixes A-D. Briefly, the tests were performed as follows: a new Pinto disc brake assembly was installed on a single station brake dynamometer in a room which was cleaned of extraneous asbestos sources. Air from within the room was blown through a diffuser screen to provide a velocity distribution over the brake which approximated that of vehicle usage. The air stream in front of and behind the brake was sampled isokinetically, using matched 0.45 μm filters, holders, and air pumps. The system schematic is shown in Fig. 1 and the ac-

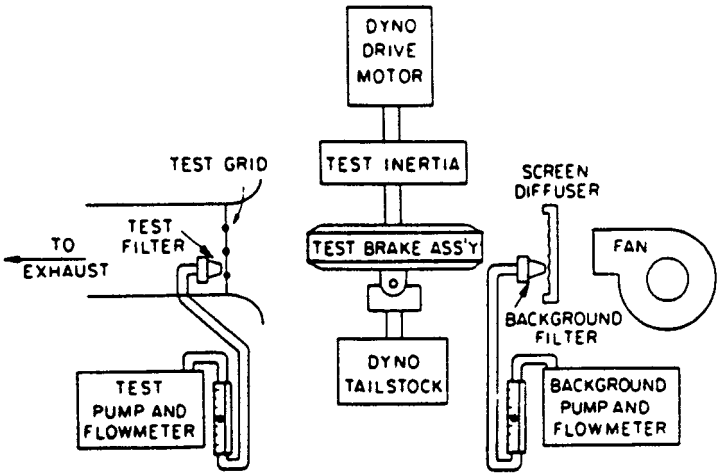

Fig. 1 - Dynamometer test schematic

tual test setup in Fig. 2. The brake exhaust air was discharged out of the building.

The first pair of filters was used during the first 82 burnish stops, to represent "break-in" conditions. After further burnishing, a second pair of filters collected samples during 560 "normal use" brake applications. A third set of filters was then utilized in a "high temperature use" test of 41 brake stops.

All brake applications were made from a 40 mph (18 m/s) equivalent speed. Break-in and normal use tests employed brake torques corresponding to 1/4 "g" (2.45 m/s^2) deceleration. This torque level was doubled for the high temperature tests.

During the normal use procedure, the test filter was located for 20 brake applications at each of 28 grid locations in the exhaust duct throat to insure a representative sampling of the airflow over the brake. This test grid and filter are shown in Fig. 3. A central collection site in the test grid was used for the "break-in test" and the final "high temperature" test.

Samples of the three pairs of filters (break-in, normal use, and high temperature use) were subjected to a clarification process involving low temperature ashing to oxidize all organic material and mechanical action to separate the particles. This assures maximum detectability of asbestos filter (2).

RESULTS AND DISCUSSION

Transmission electron microscopy at 40,000X was used in the search for fibers. At this magnification the ultimate fibrils appear to be above 1 mm (0.040 in) in diameter. Quantity, length, and apparent diameter measurements provided data for calculation of asbestos fiber mass per unit of filter area. Coupled with dimension, mass, and flow determinations from the dynamometer tests, these data were used to calculate the emitted asbestos fiber concentration in the collected wear dust, in the cooling air stream, and from the brake lining worn. The size distribution of collected fibers was not determined by this method, since the clarification process involved sufficient mechanical action to reduce most fiber bundles to the ultimate fibril size.

Additional samples of the "normal use" test filters were examined on the TEM without recourse to the clarification process, in an effort to determine the asbestos fiber size distribution. Roughly 10% of the asbestos fiber was visible on the background sample, based on the results from corresponding samples after clarification. The largest observed fiber bundle was 0.20 μm in diameter and over 1.1μm long. A similar direct TEM search of the "normal use" test filter revealed about 2% of the asbestos fibers observed after clarification. This reduced percentage of visible fiber was attributed to the greater concentration of obscuring matter in the test filter. However, the

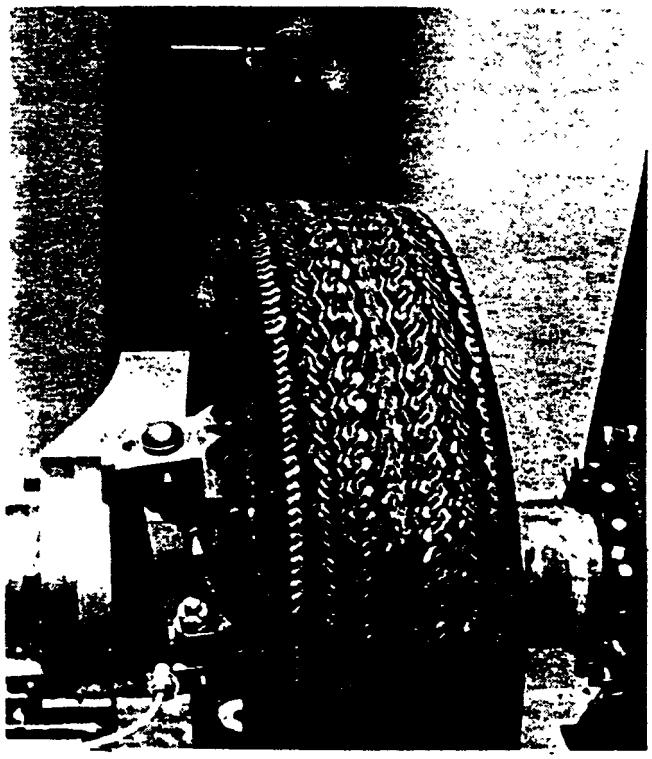

Fig. 3 - View of brake assembly and test grid

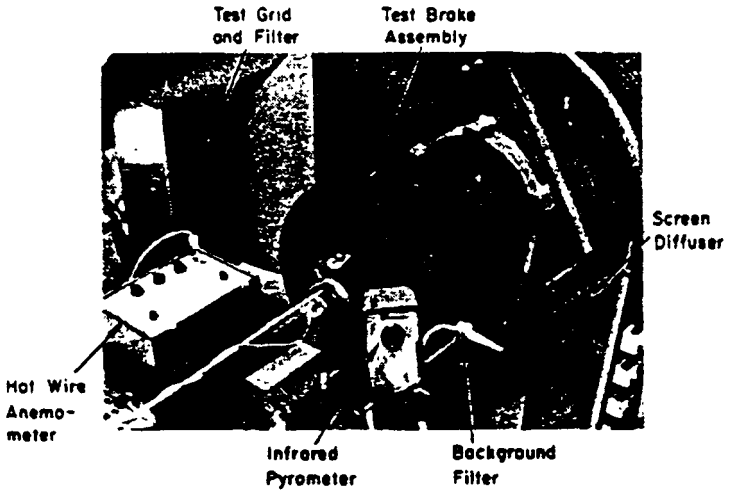

Fig. 2 - Dynamometer test setup

largest observed asbestos fiber in the test filter (0.13 μm in diameter and over 1.2 μm long) was about the same size as was found on the background sample. The similar, low fiber content of both background and test filters precluded a fiber size distribution estimate. However, it appeared that the quantity of the larger asbestos fibers on the test filter was no greater than that of the background filter.

This supports the observation from the lining wear visualization tests that normal brake wear degrades most of the asbestos fibers. A brake lining grade of asbestos appears on the TEM as in Fig. 4. The fiber bundles are composed of strong, but weakly adhering fibrils of about 0.03 μm (roughly 1 μin) diameter. Mechanical action causes the larger fibers to "open" into smaller fibers or even fibrils, as illustrated in Fig. 5. Contrast these "raw material" fibers with one of the larger fibers (Fig. 6) and one of the more typical fibrils (Fig. 7) from the "normal use" test filter.

The similar, low fiber content of both background and test filters required clarification to permit an asbestos fiber count, thus providing more accurate fiber mass determination, but obscuring the actual fiber size distribution. Therefore, the calculations of fiber concentration (Table 1) were expressed as asbestos mass per unit mass of lining wear dust and asbestos mass per unit mass of lining worn. Asbestos fiber concentration in the ambient air (background) and in the brake exhaust air (test) was calculated in units of nanograms (ng = 10^{-9} grams) per cubic meter of air. However, the actual asbestos emissions from brake usage would be diluted substantially through mixing. The asbestos concentration in urban air due to brake usage was estimated based upon existing automotive exhaust lead dilution data. These calculations appear in Appendix C.

All the test results in Table 1 have been reported as ten times the calculated test values to allow for possible losses in

Fig. 4 - TEM image of chrysotile asbestos fibers

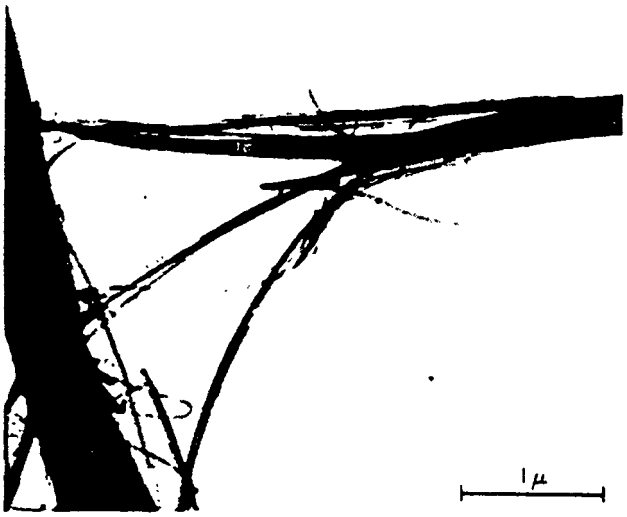

Fig. 5 - TEM image of partially opened fiber bundles

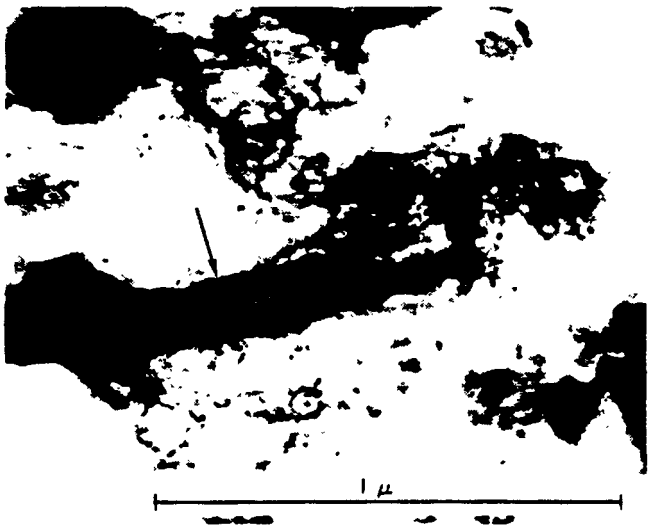

Fig. 6 - TEM image of fiber bundle on "normal use" filter

Fig. 7 - TEM image of fibril on "normal use" filter

Table 1 - Asbestos Emissions from "Normal Use" Braking

Dynamometer Data for Production Disc Brake*

Background asbestos in ambient air	$<19 \times 10^{-9}$ g/m^3
Asbestos fiber from brake in exhaust air	$<13 \times 10^{-9}$ g/m^3
Total asbestos fiber in exhaust air	$<32 \times 10^{-9}$ g/m^3
Estimated brake asbestos fiber in urban air	$<0.07 \times 10^{-9}$ g/m^3
Asbestos fiber from brake in airborn wear dust	<0.05%
Asbestos fiber released from lining wear	<0.02%

*Reported values are 10 times the observed test values to provide upper bounds.

collection, processing, and counting. These values, therefore, should provide upper bounds for asbestos emissions from brake uage. For example, the local (Detroit) atmospheric asbestos concentration ranges 0.5-13.4 ng/m^3. The observed background asbestos value was 1.9 ng/m^3, for the normal use test, but is reported in Table 1 as 19 ng/m^3. The low asbestos emissions from the test disc brake under "normal use" conditions is underscored by the addition of only 13 ng/m^3 (1.3 ng/m^3 observed) in the undiluted exhaust air stream.

The lining wear rate during the first 82 break-in stops was found to be about five times above the "normal use" rate. Asbestos fiber release during break-in was also higher, an average sevenfold increase. However, since the break-in wear is less than 1% of the total lining wear, the increase of emitted asbestos fiber resulting from this temporary sevenfold increase would be about 3%, when averaged over the life of the linings.

High temperature brake usage also increased lining wear rates, in this case by a factor of 11. Asbestos fiber emissions increased by less than a factor of three. Frequent vehicle operation under such high temperature conditions would lower lining life to levels far below present averages. However, even if all brake wear provided the same fiber emission rate as found in the high temperature use test, the percentage fiber release to the atmosphere would still be under 0.06% of the lining wear.

The remaining brake wear was a mixture of nonfibrous organic and inorganic matter. Of the estimated 62-77% collectable wear debris, 47% were accounted for by the test filter on the normal use test. The remaining 15-30% presumably were retained on the lining edges, the caliper, spindle, rotor, wheel, and tire. Accurate measurement of this material was not possible, due to the added retention of dust from the ambient air.

More precise values of brake lining asbestos emissions or the determination of their particle size distributions appear possible, for these low fiber concentrations, only by testing brakes in an asbestos-free atmosphere. This approach was used in an EPA sponsored study (9), where prefiltered air was flowed through sealed brakes at a flow rate greatly reduced from normal.

CONCLUSIONS

1. Automotive brake usage provides a very small emission of asbestos fiber (less than 0.02% of the lining worn).
2. Automotive brake usage provides a very small asbestos fiber input to urban atmospheres (estimated to be below 0.07 ng/m^3).
3. Intense local heating and severe local mechanical action causes the decomposition of most asbestos fiber in brake linings during typical usage.

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APPENDIX A

SAMPLE COLLECTION

DYNAMOMETER ROOM PREPARATION

The normal brake cooling air was found to be more variant and higher in dust concentration than was the room air. Consequently, the supply air duct was removed and sealed. To reduce the background asbestos level to a minimum, the dynamometer room was thoroughly cleaned and vacuumed while maximum exhaust airflow was maintained. All potential sources of fiber emissions were removed from the room and asbestos handling was curtailed in adjacent rooms.

A production Pinto disc brake assembly was installed on the single station brake dynamometer, as shown on the schematic of Fig. 1. The major elements of the test setup may be seen in the photograph of Fig. 2. Cooling air was supplied from the room by means of a fan and diffuser screen. Containment of all possible airborn wear dust was assured by fitting a rectangular collector nozzle to the exhaust air duct, about 2 ft downstream of the brake. Metal panels were installed below and beside the brake to contain the cooling airflow further and to help provide a representative airflow over the brake, compared with vehicle service. System parameters were adjusted until the air velocity distribution matched closely with actual usage and the air flowing over the brake assembly was fully captured by the exhaust duct. This was confirmed using a smoke generator.

The exhaust duct throat was partitioned into a 4 X 7 array of roughly 3 in square grids (Fig. 3). The velocity profile within this grid was measured to provide mean values for each grid square.

SAMPLE FILTER PREPARATION

Microporous membrane filters with 0.45 μm pores were selected to assure high retention of asbestos fibrils and most of the wear dust powders. A matched pair of Gelman sampling pumps and 35 mm diameter holders were used. Thin metal cones of 12 deg included angle were fabricated and sealed to the filter entrance. These cones increased the tip entrance velocity to that of the exhaust air duct so isokinetic sampling could be achieved. The cone tips were carefully matched in size. Flowmeters and differential pressure indicators were installed in the system to monitor the filter airflow during each test and to set the tip entrance velocity before each test.

Tests were performed on the unused filters to determine their weight change with variation of humidity. Filter weights were measured on a microbalance to the nearest 10 μg. Filters were placed in the center of the designated exhaust duct grid and at a fixed position upstream of the brake, but downstream of the diffuser screen. This latter (background) filter was located where the upstream air velocity equalled the average over the test grid. In this way the sampling was isokinetic with essentially equal volume flows through both filters.

TEST PROCEDURE

All brake stops were conducted from the same speed equivalent (40 mph, or 18 m/s) to maintain fixed airflow conditions. Burnish and "normal use" brake applications were at 0.25 "g" (2.45 m/s^2) deceleration and with a 2 min time interval. This provided a peak rotor temperature of 180°C (350°F). The number of brake applications was selected to provide about 1 g of lining wear per test.

Break-in wear was monitored for the first 82 stops. No sampling was performed for about 200 more brake applications, while the linings and rotor developed essentially steady-state conditions.

The "normal use" test was then performed on this burnished brake assembly. Twenty brake applications were made under the same conditions, with the test filter located sequentially at each of the 28 grid locations. The filter cone entrance velocity was adjusted to match the grid velocity at each relocation. Four grids were used to monitor exhaust velocity. Slight

Table A-1 - Test Data

Test	Break-in	Normal Use	High Temperature Use
Brake speed, rpm	535 (40 mph)	535 (40 mph)	535 (40 mph)
Brake decel, "g"	0.25 (2.45 m/s^2)	0.25 (2.45 m/s^2)	0.50 (4.9 m/s^2)
Wheel load, kg	257 (567 lb)	257 (567 lb)	257 (567 lb)
Brake applications	82	560	41
Total energy, kW·h	0.938 (1.25 hp·h)	6.405 (8.54 hp·h)	0.469 (0.625 hp·h)
Maximum apply temperature, °C	115 (240°F)	115 (240°F)	410 (770°F)
Total lining wear, g	1.10	1.60	1.07
Lining wear rate, g/kW·h	1.17 $\left(0.051 \frac{in^3}{hp \cdot h}\right)$	0.25 $\left(0.011 \frac{in^3}{hp \cdot h}\right)$	2.28 $\left(0.100 \frac{in^3}{hp \cdot h}\right)$

adjustments were sometimes required to compensate for drift which appeared to be external wind initiated.

A third test was performed to provide an estimate of the fiber emissions from a hot brake assembly. As in the break-in test, the test filter was positioned in a central location for this procedure. Thirty-one stops were made at 0.5 "g" (4.9 m/s^2) and minimal time interval until the rotor attained 410°C (770°F). This temperature was then maintained by adjusting the application time interval. Ten additional stops were made as the brake was allowed to cool.

All filter weight determinations were performed at equilibrium conditions and then corrected for humidity. After use, the filters were individually stored in covered glass containers. Lining weights were taken after removal of wear debris but before they had cooled completely, to minimize weight changes from water absorption. Between tests the linings were stored in a dry jar.

The relevant test data are included in the Table A-1. A slight pad drag caused the outboard lining to wear above expectations on the "normal use" test. Since this added work was not included in the lining wear rate calculations, the specific wear is above the usual range for this lining. No adverse effect on the test results would be expected to have resulted from this drag. Similar pad drag effects may occur on cars, when smooth road conditions prevent "pad knockback."

APPENDIX B

SAMPLE EXAMINATION

PREPARATION AND EXAMINATION OF ASBESTOS CARRYING SAMPLES FROM TEST FILTERS*

1. All slides, dishes, scalpels, and other utensils used in the following preparations were cleaned in acetone, followed by rinse in 200 proof ethanol.
2. An area of measured dimension was selected at random from the test filter, cut, and placed particle side down on a clean glass slide.
3. Several drops of acetone were placed on the filter segment to dissolve it partially and secure it to the plate.
4. The samples were ashed for a period of 2 h by using a low temperature asher at a chamber pressure of 0.5 torr (70 Pa) oxygen and power of 200 W.
5. Several drops of a 1% solution of nitro-cellulose in amyl acetate were placed on the residue, and a clean watch glass was used to grind the mixture for a period of 5 min.
6. A second clean glass slide was then placed over the mixture of nitro-cellulose and residue, and a "smear" obtained by pressing the two slides together and then sliding them apart.
7. The films thus formed were permitted to dry and then were removed by scoring the edge of the slide with a scalpel and "floating" the film free from the slide in a distilled water bath. It was found that the film was most easily removed from the slide introduced in Step 6.
8. Approximately 10 electron microscope grids (3 mm, finder grids) were placed at random on the floating film, and the film was lifted by putting a clean slide on top of the film and drawing the slide down through the water so as to trap the grids between the slide and the film (which should now cling to the slide).
9. A carbon layer of approximately 0.06 μm was deposited on the film to prevent charging during examination in the TEM.

Direct examination specimens were prepared by depositing a carbon layer on the dust side of the test filter and dissolving the filter in acetone. Electron microscope grids were used, both to support the sample and to provide grid location reference marks.

TEM EXAMINATION AND COUNTING PROCEDURES

Approximately 10 electron microscope grids were prepared for each of the five filter samples analyzed. Four grids were arbitrarily selected from each sample and two grid squares on each grid were scanned for asbestos. The individual grid squares are approximately 90 μm on each side and were examined at a TEM magnification of about 40,000. For each grid area scanned, photographs were taken where possible of the first, last, and one randomly chosen fibril for the purpose of determining an average fibril diameter accurately. Measurements were then made visually, that is, each fibril, fiber, or asbestos bundle was compared to known calibration marks on the electron microscope screen to estimate the lengths. The length could be estimated to within 20%, as determined by the photographic measurements. The marks on the screen are 0.5 cm apart corresponding to 0.125 μm when a magnification of 40,000 is used. This approach was taken because it was impractical to photograph all the fibrils and, furthermore, length measurements were not as critical as diameter measurements in determining fiber volume. Where both measurement methods were used, the values providing the greatest indicated brake asbestos levels were chosen. The results are shown in Table B-1.

From photographic measurements of 120 chrysotile fibrils,

*Sample preparation techniques outlined are similar to those reported by Selikoff, et al. in Ref. 2.

the asbestos fibril average diameter was determined to be 0.0337 μm with distributions similar to that observed by other workers (10). From 45 fibrils of triple jet-milled chrysotile, the average diameter was determined to be 0.0316 μm, with a standard deviation of 0.0063 μm.

ASBESTOS IDENTIFICATION

Asbestos can be identified in the transmission electron microscope in one of two ways. The first and absolute method is by electron diffraction. Such a diffraction pattern is presented as Fig. B-1. Measurement of diameters and correlation of these measurements with a known standard gives the interplanar spacings of the material. Comparison of these spacings with the ASTM file identifies the material as clino-chrysotile (asbestos).

Table B-1 - Asbestos Concentration on Filters

Sample	Sample Identification	Concentration, ng/cm^2 of filter
A	Test–normal stop-new brakes	15.32
B	Background for A	1.06
C	Test–normal stop-burnished brakes	7.98
D	Background for C	4.64
E	Test–high temperature stop-burnished brakes	5.37
F	Background for E–not used, insufficient sample	
–	Blank–unused filter	0.33

The second method of identification is by appearance. Fig. B-2A represents an image of asbestos obtained in the TEM. Fine lamellae are observed within the fibril which are parallel to the long axis. This appearance is characteristic of chrysotile asbestos fibrils. Because of the nature of the electron beam, radiation and heat damage can occur in the material markedly altering the appearance. Such changes in asbestos are represented in Fig. B-2B. The fine linear appearance of the fibril of Fig. B-2A has been changed to a mottled structure.

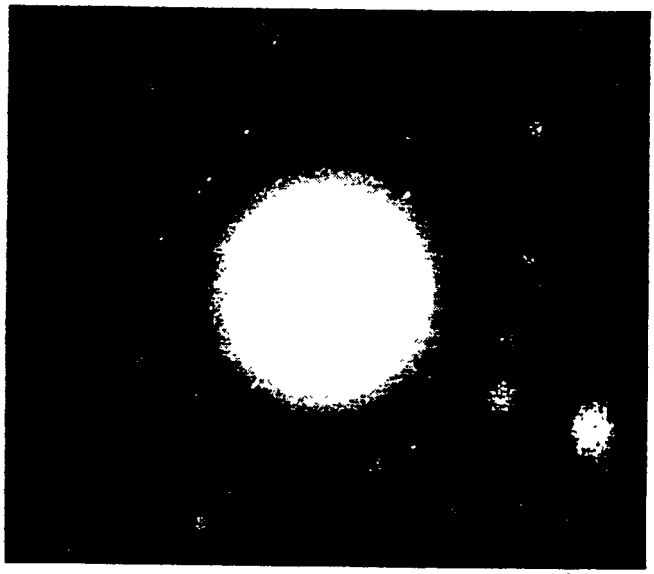

Fig. B-1 - TEM electron diffraction pattern of chrysotile fibril

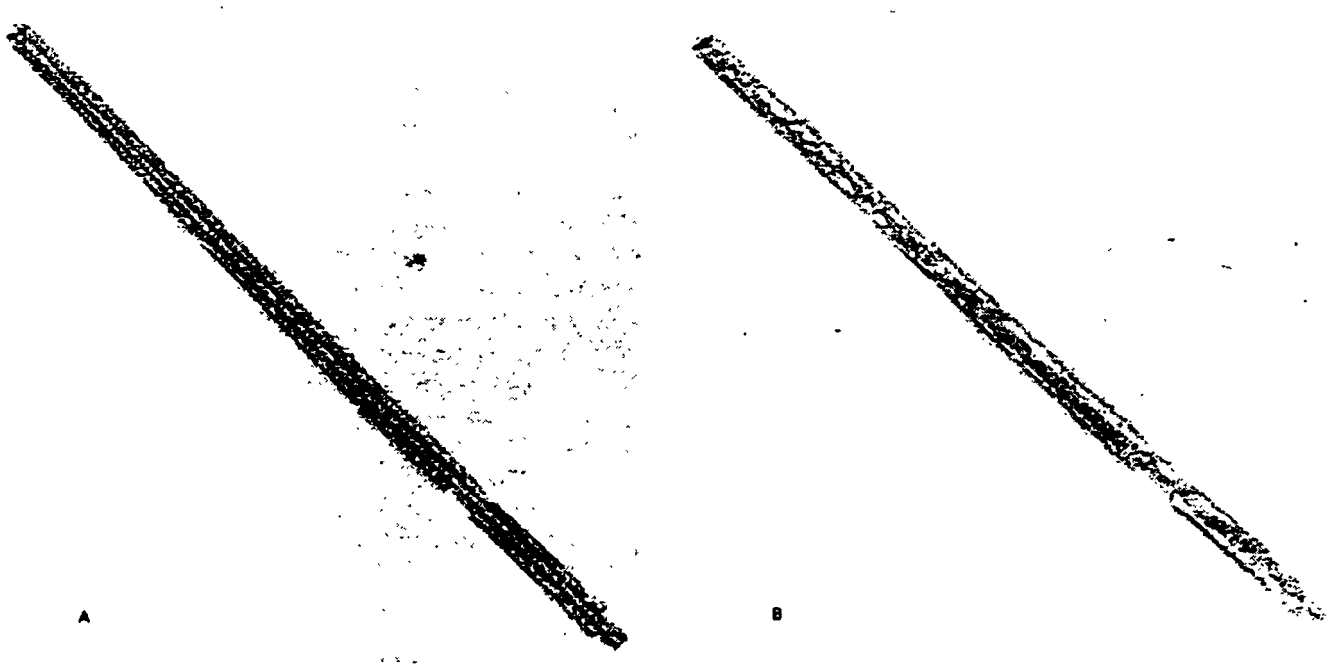

Fig. B-2 - TEM image of fibril; A-before, B-after electron beam damage

APPENDIX C

DATA REDUCTION

Table C-1 contains the pertinent test data and calculated results from the brake dynamometer tests.

ESTIMATION OF BRAKE LINING ASBESTOS DILUTION IN URBAN ATMOSPHERE

The concentration of asbestos fiber from the brake lining wear debris is assumed to be the same as was found in the "normal usage" dynamometer test and to be dispersed and have the same residence times as the lead emitted from the engine. Assume an average mileage of 15 mpg from cars which emit 75% of the lead to the atmosphere.

When gasoline averaged 2.52 g Pb/gal, the typical Pb concentrations in urban atmospheres were about 2 $\mu g/m^3$ (JAPCA, September 1969, Vol. 19, p. 684). Typical United States cars wear 202 g of lining/year and drive 10,000 miles/year. The "normal use" dynamometer tests provided asbestos fiber amounting to 0.0023% (2.3×10^{-5}) of the brake lining worn. Allowing a factor of ten to provide an upper bound in this determination, the asbestos concentration in urban atmospheres from brake wear should be less than

$$10\,(2.3 \times 10^{-5}) \left(\frac{202\ g}{10{,}000\ miles}\right) \left[\frac{2\ \mu g\ Pb/m^3\ (15\ mpg)}{2.52\ \frac{g\ Pb}{gal}\ (0.75)}\right]$$

or 0.07 ng/m^3

Urban atmospheres vary in asbestos fiber concentration from city to city, within a city, and from one time to another. This variation does not correlate with expected automobile brake usage. The concentration has been reported to reach 100 ng/m^3 (2). Thus, it appears that the wear of brake lining produces, at most, a small fraction of the asbestos fiber in urban air. This is not surprising when one considers that brake lining wear involves only 1.5% of United States asbestos usage and that brake usage converts over 99.95% of this to nonfibrous dust.

Table C-1 - Test Data and Calculated Results from Brake Dynamometer Tests

Test Sample	Break-in		Normal Use		High Temp Use		Calculation Basis
	Test	Bkgrd	Test	Bkgrd	Test	Bkgrd	
1. Filter airflow, m^3	2.22	2.22	23.00	21.80	0.564	0.564	Measured
2. Filter pickup, mg	0.36	0.10	1.56	0.90	0.27	0.00	Measured
3. Filter asbestos concentration, ng/cm^2	15.32	1.06	7.98	4.64	5.37	0.12*	Measured
4. "Blank" asbestos concentration, ng/cm^2	0.33	0.33	0.33	0.33	0.33	0.33	Measured
5. Filter area, cm^2	9.62	9.62	9.62	9.62	9.62	9.62	Measured
6. Filter asbestos, ng	144.2	7.02	73.59	41.46	48.48	1.07*	[(3) − (4)] X (5)
7. Asbestos concentration in air, ng/m^3	64.95	3.16	3.19	1.90	85.96	1.90*	(6) ÷ (1)
8. Lining asbestos in exhaust air, ng/m^3	61.8		1.29		84.1		Δ(7)
9. Lining asbestos on filter, ng	137.2		29.7		47.4		(8) X (1)
10. Duct flow/filter flow	1235		1235		1235		From measure
11. Lining asbestos released, mg	0.169		0.0367		0.0586		(9) X (10)
12. Lining worn, mg	1100		1600		1070		Measured
13. Asbestos released as % of wear	0.015		0.0023		0.0055		(11) ÷ (12) X 100
14. Lining dust on filter, mg	0.26**		0.61†		0.27**		Δ(2)
15. Lining dust in air, mg	321		754		333		(10) X (14)
16. % asbestos in wear dust	0.053		0.0049		0.018		(11) ÷ (15) X 100
17. Lining dust as % of wear	29**		47		31**		(15) ÷ (12) X 100

*Value calculated based on "normal use" background, due to insufficient sample.
**Filter in one (central) location, and thus possibly nonrepresentative.
†Corrected for flow volume difference through test and background filters.

APPENDIX D

CALCULATIONS OF COLLECTION EFFICIENCY

Lining composition estimate from laboratory analysis, %

SiO_2	16.3	Chrysotile asbestos 42.4
MgO	17.8	
Fe_2O_3	2.5	
Al_2O_3	0.3	
H_2O	5.5	
$CaCO_3$	15.4	
Zn	3.9	
Organic	38.3	
Total	100.0	

Wear debris estimate, %

Decomposed asbestos	36.9
Decomposed limestone	8.6
Zinc metal	3.9
Inorganic	49.4
Organic	
Volatile	10.5
Uncertain	15.7
Low volatility	12.1
Organic collectable	12.1-27.8
Total collectable	61.5-77.2
Collected on filter	47
Collectable material not trapped by filter	14.5-30.2*

*This material presumably on shoe edges, caliper, rotor, wheel, and tire.

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