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MINUTES OF MEETING

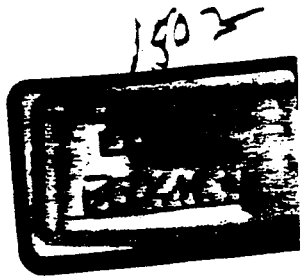
of the

ASBESTOS STUDY COMMITTEE

Thursday, February 10, 1972, at 9:30 A.M.

at the

Institute Office, E-210 Route #4, Paramus, N.J. 07652



MEMBERS PRESENT

I. H. Weaver, Chairman	Raybestos-Manhattan, Inc.
J. C. Henning	Firestone Tire & Rubber Co., World Bestos Division
W. B. Reitze	Johns-Manville Corporation
M.G. Jacko (for W. Spurgeon)	Bendix Corporation Bendix Research Laboratories
J.B. Graham	Carlisle Corporation Molded Materials Division

NOT PRESENT

E. H. Feierabend	Abex Corporation American Brakeblok Division

OTHERS PRESENT

E. W. Drislane	Friction Materials Standards Institute

The meeting was called to order by Mr. Weaver, Chairman, at 9:30 A.M.

MINUTES OF PREVIOUS MEETING

The Secretary read a summary of the minutes of the meeting held September 15, 1971. These minutes had been released, and a motion for their acceptance was entertained.

Upon motion duly made, seconded and unanimously passed, it was

RESOLVED: to accept the minutes of the September 15, 1971 meeting as distributed.

MEETING AT DEPARTMENT OF LABOR, JANUARY 26, 1972

A brief review was read of the activities at the Occupational Safety and Health Administration (OSHA) session held in Washington on January 26, 1972. Mr. Matt Swetonic of J-M attended this session, and the Secretary summarized what Mr. Swetonic had told him as follows: OSHA previously had emphasized safety - now the emphasis is on health - five industrial substances are under attack (asbestos, silica, lead, cotton dust and carbon monoxide). Our immediate

concern is asbestos. OSHA is suggesting voluntary set-up of industry committees working with trade associations. Industry representatives indicated that cooperation should be based on reasonable standards. The proposed standard is 5 fibers/cc (OSHA is apparently considering reducing the standard to 2 fibers/cc).

ASBESTOS EXPOSURE STANDARDS

The proposed standard by OSHA is now 5 fibers per cc. A fiber must have a 3/1 length/diameter ratio, with the length 5 microns or greater to be considered a fiber. This size can be screened with the optical microscope. Dr. Jacko noted that there were studies concerning asbestos fibers in the less than 5 micron length by electron microscopy.

The British Asbestos Regulations of 1969 were discussed. They have a concentration of less than 2 fibers/cc (sampled over a 10 minute period) as being satisfactory, with allowances on 2 to 12 fibers/cc (sampled over a 4 hour period) depending on how much the sample exceeds the 2 fibers/cc limit. See copy of pages 4-5 of Control & Safety Guide 8. At 12 fibers/cc, the plants could be shut down.

For reference:

The Asbestosis Research Council
"Asbestos Based Friction Materials and Asbestos Reinforced Resinous Moulded Compounds," Control and Safety Guide #8.

Environmental Control Committee, Secretary
114 Park Street
London, England W1Y-4AB.

BRITISH FRICTION MATERIALS COUNCIL

The Secretary advised that the British Council had submitted comments to the Illinois Pollution Control Board and had indicated (through Mr. Bob Gibson of Mintex and Mr. Harry Jones of Ferodo at the SAE January meeting) their interest in being informed on the status of asbestos regulations in the U.S.

Upon motion duly made, seconded and unanimously passed, it was

RESOLVED: to inform the British Council of all regulations known to the Friction Materials Standards Institute, and to forward minutes of our meetings to the British Council.

LIAISON WITH ASBESTOS INFORMATION ASSOCIATION OF NORTH AMERICA (AIA/NA)

It was noted that Mr. Matt Swetonic, now with Johns-Manville, will become Executive Secretary of the AIA/NA. It was recommended that the FMSI maintain contact with the AIA/NA concerning any matters [illegible] asbestos in the work-place, etc.

OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION (OSHA)

Mr. Weaver discussed some of the background for the proposed OSHA Standards for Exposure to Asbestos Dust. Proposed rule making for these standards appeared in the Federal Register of December 7, 1971 and January 12, 1972. (Copies were distributed by the Institute by mail to members of the Asbestos Study Committee)

Mr. Weaver is the Industry representative on the Advisory Committee for Asbestos Standards set up under the Occupational Safety and Health Act. He advised that while the proposed standards are for 5 fibers/cc time weighted average airborne concentration of asbestos dust, the others on the Advisory Committee may push for 2 fibers/cc.

OSHA will apparently enforce these regulations and if experience in related safety enforcement is any criteria, fines or plant closings may be used for enforcement purposes. While it is currently too late to present written comments, the hearings are to be held on March 14, 1972 in Washington. In order to be heard, a person must file a notice of intention to appear no later than March 3, 1972. The notice must state name, address, approximate time required for presentation, and a statement must be included indicating the position to be taken by the individual.

The Chairman and Mr. Reitze indicated that these OSHA regulations were now of prime importance to manufacturers of asbestos brake linings and clutch facings, and the Secretary was directed to inform the membership concerning the proposed standards.

ENVIRONMENTAL PROTECTION AGENCY (EPA)

The EPA's emphasis in their proposed emission standards for asbestos did not use numerical limits on airborne asbestos, but concentrated on filters and collectors - control practices. While these are important to all manufacturers of asbestos brake linings, they are practices and standards which, at this time, seem reasonable. The OSHA Standards are the more immediate problem.

ENVIRONMENTAL PROTECTION AGENCY - EMISSIONS FROM ASBESTOS BRAKE LININGS

Dr. Jacko advised that the Bendix Corporation's studies for the EPA on emissions from brake linings may not be complete on schedule, and that Bendix had requested a time extension on this work that would move their final report back into the fall of 1972. Dr. Jacko indicated that the maximum asbestos fiber in brake lining debris is running about 1%.

STUDENT PAPER - BIOLOGICAL EFFECTS OF ASBESTOS ON THE HUMAN ORGANISM

Copies of a term paper by Miss Beth Krull, Chemistry Junior at Mundelein College in Chicago were distributed to the membership. It would appear that this paper may be an interesting source of medical

bibliography concerning asbestos. (The paper was forwarded to the Institute by Mr. J. Greenen, President of F.M.S.I.)

EQUIPMENT FOR MEASURING AIRBORNE ASBESTOS CONCENTRATIONS

Mr. Reitze discussed the equipment necessary for measuring asbestos concentrations. The test is run with a vacuum pump pulling fibers into a filter which is then examined under optical microscopy. (Mr. Reitze discussed the equipment and procedures in more detail in an afternoon session)

Dr. Jacko said that the sub-5 micron asbestos fibers were being examined with electron microscopy. He felt that as far as airborne fibers were concerned, these sub-5 micron fibers might be targets of the regulators in the future.

Mr. Graham asked whether there were any automatic equipment for measuring the asbestos concentrations - either in existence or planned. It was stated that the EPA had made a Request for Proposal for design of equipment for automatic measurement, but apparently they received no response.

As of now, optical microscopy with the membrane filter is the only recognized method.

ASBESTOS STUDY COMMITTEE - FUTURE COURSE

The members indicated that the Committee should exist for screening and passing on information to the members. They do not feel the Committee should be used as a vehicle to comment directly on regulations proposed by the various Federal and State agencies. Further, it is felt that individual company responses to OSHA or EPA or others (such as Illinois Pollution Control Board) are more effective, particularly those from the smaller manufacturers.

Unless directed to prepare responses to government agencies by the general membership, the Committee will not assume this responsibility.

Some members felt that the "Asbestos Study Committee" would have to expand beyond asbestos - such as into silica, resinous by-products, etc. As of now, the prime target is to be asbestos, but other materials, if considered of importance to the members, will be studied.

Another suggestion was that the Committee consider a membership survey on the methods for disposing of brake lining grinding dust.

... and if the

OTHER BUSINESS

Dr. M. Jacko requested that his name be added to the Asbestos Study Committee mailing list, in addition to that of Dr. Sourgeon.

It was suggested that other manufacturers of brake linings, outside the membership, be advised of these proposed standards by OSHA.

Summaries of the afternoon's presentation by Mr. Reitze will be distributed to the membership.

* * * * * * *

Upon motion duly made, seconded and unanimously passed, it was

RESOLVED: to adjourn.

Adjourned at 12:00 noon

E. W. Drislane
Executive Secretary

cc: Committee Members
J. Greenen
L. Stickles
British Council
AIA/NA

EPA No. 3X-167

Ducher

SECTION 1

INTRODUCTION AND BRIEF SUMMARY

The chrysotile form of asbestos is a major constituent in automotive brake linings and disc pads, and in the friction materials used in clutches. These components are expendable. In typical passenger car service, drum linings wear out in about 40,000 miles, disc pads in about 30,000 miles, and clutch facings in about 70,000 miles. There are, of course, wide variations in the service lives of these components, which depend on the nature of the friction materials used, on driver habits, and on driving conditions.

The expendable members of the common automotive friction couples contain not only asbestos, but also various organic and inorganic friction and property modifiers. These constituents are bound together by phenolic resins. Because of their high content of organic substances, such friction materials are classified as "organic." Asbestos-free friction materials with a high content of metallic substances are classified as "semi-metallic." Over 99 percent of the automotive friction materials used today are organics.

The mechanisms by which organic friction materials wear can be classified under five headings: thermal, abrasive, adhesive, macroshear, and fatigue. Thermal, abrasive, and adhesive wear are considered to be the most important mechanisms, thermal wear predominating above 450°F, abrasive and adhesive wear predominating below 450°F (the temperature being measured by a thermocouple in the rotor, about 0.050 inch from the sliding interface). The organic constituents pyrolyze or oxidize, and are emitted to the air as carbonaceous solid particles or gaseous reaction products. The asbestos fibers are pulverized into small particles which are trapped in the brake (or clutch) housing, or fall to the road, or are emitted to the air. Disc brakes do not trap as much as drum brakes. Most of the asbestos is heated to temperatures high enough to cause chemical conversion, and is therefore trapped or emitted as olivine or forsterite particles.

When the large number of existing cars and trucks is considered, each with eight or more pieces of friction material in the brake system, plus more in the clutch mechanism, it becomes apparent that an air pollution problem may exist. Considered in another light, there are perhaps one billion pieces of friction material in vehicles in the United States, gradually being pyrolyzed and ground to dust. The brake systems in the vehicles utilizing these friction materials can thus be considered as chemical reactors, each emitting organic and inorganic compounds, including asbestos and its decomposition products, to the atmosphere. The compositions of the gaseous and solid emissions have not been well known,

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and the particle sizes and shapes of the solid emissions have not been well known. Because of the possible damage which these emissions can produce in human respiratory systems, it is desirable to identify and quantify them, with particular regard to asbestos. That is the purpose of the program described in this report.

The amount of asbestos emitted is a function of many variables:

the number of vehicles on the road,

the number of miles driven per year by each,

vehicle size,

the number of vehicles using manual clutches,

conditions of driving (city, expressway, mountain; driver habits, etc.),

brake system design, and

brake type (drum or disc),

rotor condition (surface roughness, scoring, cracking, pitting, etc.),

rotor design (e.g., solid or ventilated discs, finned drums, etc.),

rotor metallurgy (cast iron or aluminum),

volume percent of asbestos in the friction material, and

inherent wear resistance of the friction material.

In this program a passenger car of medium weight (test weight: 4800 pounds), produced in high volume, was used. It was equipped with a manual transmission and clutch, ventilated cast iron disc brakes on the front, and standard cast iron drum brakes on the rear.

A passenger car was selected for testing because of the following factors:

(1) vehicle braking cannot be simulated realistically on small-scale friction test-machines with the present state of the art;

(2) full-scale brake and clutch dynamometers provide fairly good simulation, and can be used for checking out the emissions collection system; separate tests for brakes and clutches would be required, however, thus increasing program costs, whereas on the vehicle, disc and drum brakes and clutches can be tested simultaneously;

(3) air flow in the dynamometers differs from that in vehicles, and emissions from drum brakes will therefore be different in the two cases.

Three series of tests were run, using friction materials [illegible] below:

Vehicle Test	Simulation	Friction Materials	Remarks
1	Original Equipment	OEM[1] Disc Front OEM Drum Rear	Class A organic disc pads
2	Partial Reline	AM[2] Disc Front Used OEM Drum Rears	No metallic chips; Discs and drums not turned
3	Full Reline	AM Disc Front AM Drum Rear	Disc pads and secondaries contain brass chips Discs and drums turned

This selection has several features. It provides a replication of one test, thus giving an estimate of repeatability. It includes a primary/secondary combination that serves both OEM and aftermarkets. It includes one combination (two materials) of widely used OEM materials. It includes one combination (two materials) from one of the larger aftermarket suppliers. It includes a set of used linings (about 3,000 miles) to give data on the emissions at various stages of lining life. It includes two different disc pad materials from two of the larger aftermarket suppliers. Five different manufacturers were represented in the friction material selections.

The collection of particulate and gaseous emissions from any vehicle friction couple has never before, to the authors' knowledge, been reported in the literature. To define the extent of these emissions, a combination separation and storage collection system was devised. Unique emissions collectors for both disc and drum brakes, and for a clutch, were conceived, designed, and built as the main embodiment of this instrumentation. The collectors separated the wear debris into three different fractions: a sump sample which included the wear debris on the lining surfaces, in the rivet holes, and on the brake drum; a surfaces sample which included the wear debris on the brake and collector shroud surfaces; and an airborne sample collected on membrane filters.

The vehicle was equipped with standard brake test instrumentation. A front disc brake collector and a rear drum brake collector were installed on the right side of the vehicle. The clutch was sealed by closing the

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[1] OEM - Original Equipment Manufacturers
[2] AM - aftermarket

...le, in its casing. The left wheel brakes were left in their normal configuration and were used to monitor the operation of the shrouded brakes. Wear debris was also taken from the left brakes; the amounts of debris collected and its composition were used to demonstrate that the brake shrouding did not significantly affect the operation of the brakes and the emissions collectors.

Although there are many acceptable original equipment manufacturers' brake and friction material tests for measuring a specific collection or combination of collections, no one test adequately matches driving conditions which would be representative of all vehicles. Consequently, it became necessary to devise a rational and meaningful vehicle test. A total of seven schedules were chosen and each was followed by a measurements procedure (take emissions samples, measure wear, inspect systems, and replace worn parts). The first three schedules - Burnish, After Burnish (A.B.) Baseline, and Detroit Traffic - Represented low-temperature testing. The final four schedules - 10-Stop Fade, After Fade (A.F.) Baseline, 15-Stop Fade, and Final Baseline - represented high-temperature and abrasive testing.

The mileage accumulations for each schedule of each vehicle test verified the possible test mileage reproducibility. A critical component of the front disc brake collector was a unique rotating seal. For the 8100 miles of testing, only eight rotating seals were required — an exceptional improvement over the anticipated need at the start of the program.

Prior to vehicle test 1, a Burnish schedule was performed and the temperatures for the right front disc brake were found to be near 400°F. The temperature difference, ΔT, between the right and left front brakes ranged from 200 to 250°F. This was unacceptable. The addition of several thermal control aids reduced the ΔT to a range of 115 to 160°F. Most important was the reduction of the right front brake operating temperature from about 400°F to about 300°F. The brake shrouding did not present any problems on hot days. During the Detroit Traffic Test, the ΔT between the front brakes remained between 100 and 140°F while that for the rear drum brake remained between 10 and 30°F.

The range of asbestos content in the brake emissions for vehicle tests 1 and 2 went from a high of 1.65 percent to a low of 0.03 percent for the 90 analyses; only three were above 1.00 percent. The overall average for vehicle test 1 was 0.40 percent and for vehicle test 2 was 0.25 percent. For vehicle test 3, the range of asbestos content was from a high of 0.51 percent to a low of 0.003 percent. The overall average was 0.07 percent. In this work, all values for heavy-duty (abusive) braking were less than one percent, which is significantly less than the 15 percent asbestos content reported by Lynch of the U.S. Public Health Service.

To provide a systematic, independent check on the asbestos analyses, the EPA Project Officer arranged a second contract for Battelle Columbus Laboratories to analyze twenty-four samples generated by Bendix Research

laboratories. Johns-Manville also provided three analyses. The Johns-Manville and Battelle data agreed very well. In 19 of the 24 analyses, the Bendix results were slightly higher than the corresponding Battelle results. The Bendix average was 0.25 percent, while the Battelle average was 0.17 percent, or 68 percent of the Bendix average. The Bendix data were expected to be higher for the following reasons: all fibers found were assumed to be cylinders of projected diameter and length, and a fiber with an elliptical cross section was actually smaller in volume than reported; and all fibers were assumed to be pure asbestos, (partially degraded asbestos or olivine fibers were mechanically reduced to non-fibrous material by the other analytical techniques, so only the strongest asbestos fibrils that remained were counted).

Analysis of the gaseous emissions was made difficult by the large quantities of water and carbon dioxide which by-passed the gas conditioning trap and entered through the rotating seals. Most samples showed traces of C_1 to C_3 hydrocarbons only as lower concentrations of higher molecular weight gases could not be detected. When the gases were concentrated from the fade tests, C_4 to C_8 compounds such as butanes, benzene, toluene, phenol, and cresols were detected in the gas traps. The corresponding shroud extracts showed C_{12} to C_{30} materials, including cardanol.

To compare the generation of asbestos emissions properly, it was found necessary to calculate the emissions factors for each sample in micrograms/mile (ug/mile). These values were obtained by multiplying the weight of generated brake debris by the appropriate asbestos percent, followed by dividing by the miles per test schedule. Thus, either a high asbestos content or a large sample gave a high factor.

The following observations were made:

- Asbestos emissions were higher for new friction surfaces and decreased with use.
- Initially the drum brake produced more asbestos emissions than the disc brake. The difference decreased as the materials continued to be used.
- Heavy (abusive) duty did not necessarily give a higher percent asbestos, however, the large amount of debris produced gave a significant rise in asbestos emissions.
- The order of decreasing asbestos emissions from brakes was found to be:

  Fade or heavy-duty stops
  Burnish
  Moderate braking

  ↓ Decreased asbestos emissions

- For the disc pads only, there was an increase in asbestos emissions with increased asbestos content in the friction material (there was no such trend for the drum brake materials).
- Both the front disc pads and the drum linings of vehicle test 3 had wear comparable to that of the other two vehicle tests, yet the asbestos emissions were significantly lower. Both pads and linings contained brass chips which may have been in part responsible for the more complete conversion of the asbestos in the brake emissions, possibly because of better heat transfer to the asbestos.
- For both disc and drum brakes, the surfaces sample was the largest of the three (~92 percent), the sump sample was next (~7 percent), and the airborne sample was the smallest (~1 percent).

Two series of weighting factors were developed. The distribution weighting factors were calculated from the material recoveries in the shrouded and unshrouded brakes as indicated earlier. Estimates were made for both disc and drum brakes from the test vehicle for the amounts of the different samples distributed from the brakes. These estimates were made for the Burnish schedule, for the end of a complete vehicle test, and for the end of all three vehicle tests. For the drum brake, estimates were made up to 40,000 miles. The severity weighting factors were calculated from the percentages of different braking modes: for new versus burnished friction materials, for severe (or abusive) versus moderate braking, and for the renewal of friction surfaces (A.F. Baseline).

The total asbestos emissions estimate for the test vehicle was calculated from the asbestos emissions factors and the severity weighting factors. The average asbestos emissions factor for the disc brakes, drum brakes, and clutch were used along with the Burnish (new surfaces), A. B. Baseline (surface preparation), Detroit Traffic (moderate braking), 10-Stop Fade (severe braking) and A. F. Baseline (surface renewal) weighting factors. The value obtained for the test vehicle was 28.51 µg/mile.

The fate of the asbestos emissions was calculated with the use of the distribution weighring factors as follows:

Road Drop-out	81.9%
Airborne:	3.7%
Brake Retention:	14.4%

The annual total asbestos emissions estimate for 96,400,000 passenger vehicles travelling an average of 9,978 miles per year was found to be 60,400 pounds, distributed as follows:

Road Drop-out:	49,470 lbs
Airborne:	2,230 lbs
Brake Retention:	8,700 lbs
	60,400 lbs

The annual total asbestos emissions estimates for light trucks, medium trucks (and buses), and heavy trucks were found to be:

Light trucks	32,300 lbs
Medium trucks (and buses)	16,300 lbs
Heavy trucks	22,900 lbs
	81,500 lbs

The distribution of the total asbestos emissions estimate for trucks calculated to be as follows:

Road Drop-Out:	87.9%
Airborne:	2.9%
Brake Retention:	9.2%

The estimated asbestos emissions for all vehicles in pounds/year is summarized as follows:

	Total Asbestos Emissions (lbs)	Distribution (lbs)		
		Drop-Out	Airborne	Retention
Passenger Cars	60,400	49,470	2,230	8,7[illegible]
Light Trucks	32,300	28,420	940	2,9[illegible]
Medium Trucks (and buses)	16,300	14,330	470	1,5
Heavy-Trucks	32,900	28,920	950	3,0[illegible]
Miscellaneous (motorcycles, trailers, etc.)	16,300	14,330	470	1,5[illegible]
	158,200	135,470	5,060	17,67[illegible]
Distribution by percent:		85.6%	3.2%	11.2%

These estimates are considered to be maximum values

2.2.2 Unpublished Data

At the time of writing of this report, there were three known works which had been completed or were in progress. The amount of brake wear debris and its composition were determined on a full-brake inertial dynamometer using a duo-servo drum brake in 1968-69.(2-2) The determination of the amount of asbestos in airborne brake debris sampled downwind of a disc brake installed on an inertial dynamometer was in progress.(2-3) The determination of asbestos content in airborne brake debris sampled downwind of vehicle-mounted disc and drum brakes was also in progress.(2-4)

2.3 BACKGROUND

2.3.1 Energy Absorption by Friction Materials

2.3.1.1 Brakes

During a stop, the automobile brake converts the kinetic energy of the moving vehicle into heat, absorbs the heat, and gradually dissipates it to the atmosphere. The sliding friction couple in the brake consists of a cast-iron rotor (drum or disc) and a stator on which is mounted a friction material or lining consisting of asbestos fiber, property modifiers, and an organic resin binder. Lining is considered expendable. Over a long period of time and many miles of service, much of it is converted to dust and gases. Smaller amounts of the rotor are also converted to wear debris. Particulate debris is partially retained and partially emitted from the vehicle in normal service.

2.3.1.2 Clutches

The "manual" automobile clutch transfers the kinetic energy of the engines rotating crankshaft smoothly to the transmission and wheels. Any slippage results in generation of heat, which is absorbed and eventually dissipated to the atmosphere by the clutch. Thus the clutch is basically a dry-running static friction couple (which slides momentarily during gear shifts). The mating materials are usually cast-iron or steel and a friction material or lining which is frequently organic-bound. Organic-bound friction materials consist of asbestos fiber reinforcement, property modifiers, and an organic resin binder. The composition is qualitatively similar to that of brake linings. Clutch linings are also expendable, gradually wearing away in use. The wear debris can escape from manual clutches. Wear debris from friction materials in automatic transmissions is retained almost completely in the transmission fluid.

2.3.2 Compositions of Friction Materials

2.3.2.1 Generalized Classifications

Table 2-1 gives typical compositions of drum lining, disc pad,[2-5] and clutch facing friction materials. The foundation, or major constituent, of practically all organic friction materials is asbestos fiber. Asbestos is chosen because of its thermal stability, its relatively high friction level, and its reinforcing properties. Since asbestos alone does not offer all of the desired friction properties, other materials called friction modifiers are added. Modifiers are varied in type and content to provide desired levels of effectiveness, wear, fade, recovery, and noise. A resin binder is also added to hold the other materials together with adequate strength.

2.3.2.2 Asbestos

The asbestos usually used in friction materials is chrysotile from Quebec or Vermont. Chrysotile, the principal mineral of the serpentine group, has the approximate composition formula

$$Mg_3(Si_2O_5)(OH)_4 \quad \text{or} \quad 3MgO \cdot 2SiO_2 \cdot 2H_2O$$

Table 2-1 - Composition of Typical Automotive Friction Materials (Volume Percent)

	Drum Linings		Disc Pads		Woven Clutch Facings	
	Primary	Secondary	Class A Standard	Class B Heavy-Duty	Standard	Heavy-Duty
Resin Binder	20-30	25-35	18-22	15-18	20-30	20-30
Asbestos Reinforcement	Major	Major	Major	Major	Major	Major
Friction Modifiers						
• Organic						
Friction Dust	10-15	5-15	20-25	0-15		
Elastomer		5-15	10-15	0-10		
• Inorganic						
Carbons/Graphites			1-2	2-15		
Zinc Chips			1-2			
Oxides		0-5		2-7	0-5	0-5
Copper/Brass		0-5		5-10	0-5	5-10
Misc. Inorganics		5-10	0-5	5-15	5-10	5-10
Sulfur					2-5	2-5

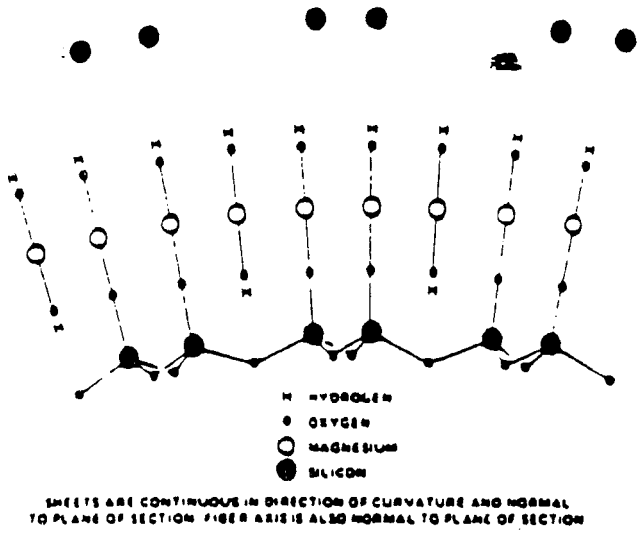


Figure 2-1 - Schematic Structure of Chrysotile Asbestos

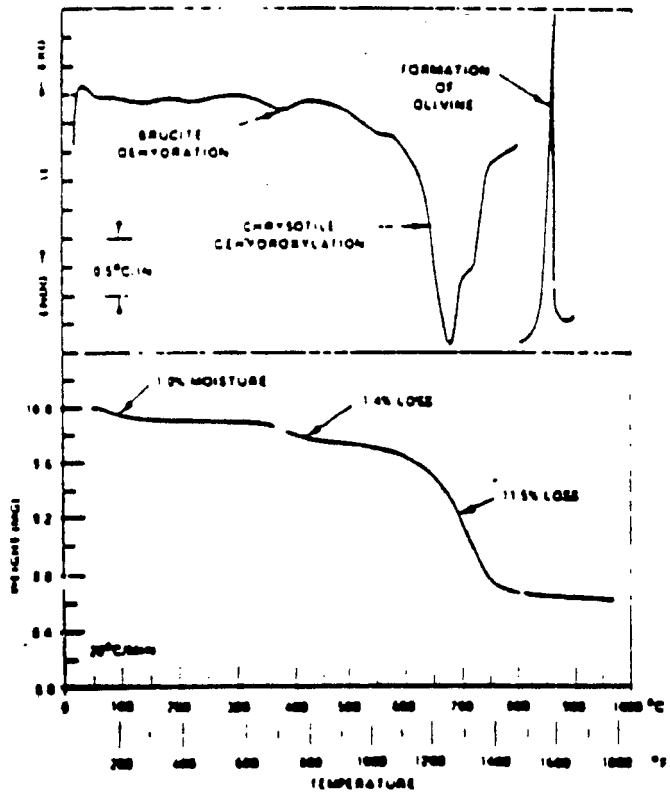


Figure 2-2 - DTA and TGA Thermograms for Chrysotile Asbestos (Bendix Data)

transmission vehicles. Phenolic-bound brake lining compositions containing asbestos serve as one of the best classes of low-cost expendable members of the friction couple for all-around performance. At low energy absorption rates, the temperature of the friction material, approximately 40 mils from the interface, may rise to 300°F; the interface itself is hotter. Most of the heat is removed from the interface by convection and conduction.(2-10) At high energy absorption rates, heat is generated faster than it can be dissipated and the temperature at the sliding interface reaches a point where chemical reactions occur rapidly. Surface temperatures up to 1600°F have been observed or calculated; the presence of olivine in the wear debris confirms that such temperatures have been reached.

2.3.3.2 Physical and Chemical Changes in Linings During Use

Figure 2-4 illustrates the heterogenous nature of a typical friction material composed of the following ingredients: phenolic binder (30 volume percent), asbestos fiber (55 volume percent), and cashew friction modifier (15 volume percent).

As a result of the energy conversion at the stator-rotor interface, the composition of the brake lining surface is altered. At low service temperatures, the phenolic resin and organic friction modifier convert, on the surface, to compositions with slightly higher carbon/oxygen ratios. At somewhat higher use temperatures, the resin and organic friction modifier convert to carbon more readily, and this in turn oxidizes to carbon dioxide. At the same time, the asbestos wears away more rapidly because of the reduced binder strength and volume at the surface. Figure 2-5 is a photomicrograph of typical wear debris collected from Bendix Research Laboratories' dynamometer, operated at 600°F. Asbestos fibers are prevalent in several of the wear debris particles. Figure 2-6 is a photograph of the improved wear debris collector designed and built for friction and wear research.(2-11) At still higher temperatures, the asbestos converts from its fibrous form to an olivine powder with little or no reinforcing value. Figure 2-7 shows the frictional-heat-affected layer of lining which had experienced more than 10 successive stops from 100 mph without sufficient cooling between stops.(2-12) (A large piece of material is about to separate from this sliding interface - an example of macroshear wear, described later.)

When heat is generated at the sliding interface between stator and rotor much faster than it can be dissipated, the temperature rises and may reach a point where the lining or pad components decompose, oxidize, or melt. The stator material then wears rapidly and the friction coefficient, μ, may decrease. This is fade. Fade has been attributed by some to evolution of gas at the sliding interface; on heating, the gas expands and exerts a force on the lining or pad, tending to push it away from the rotor.(2-13) Fade can generally be ascribed to the formation of a gaseous, a liquid, or a low-friction solid phase at the interface, or to some combination of these phenomena. Figure 2-8

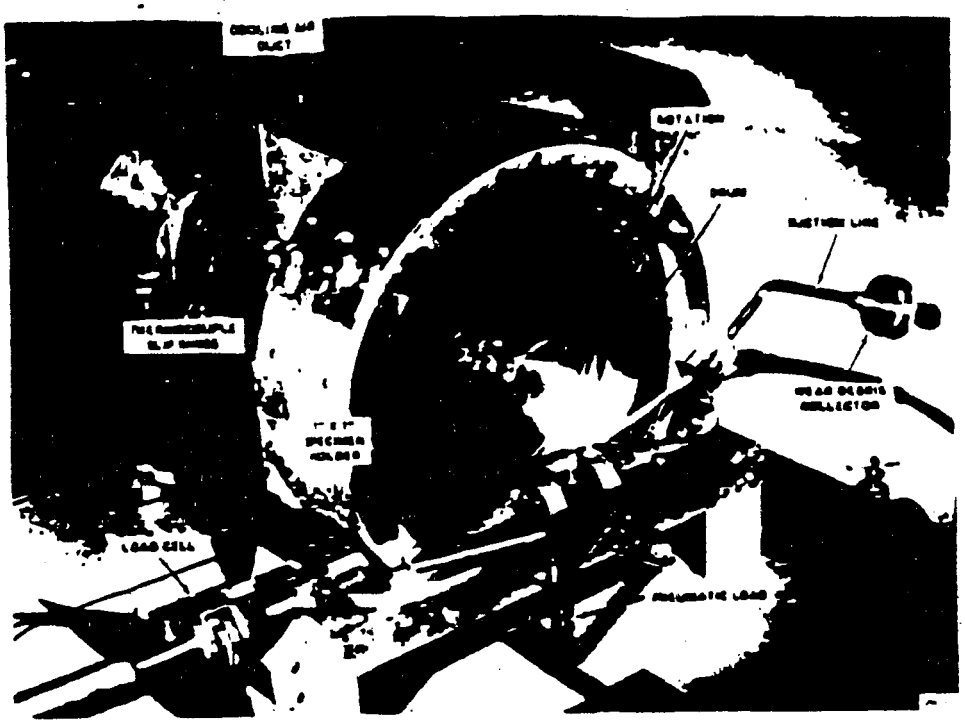


Figure 2-6 - Close-up View of Bendix Drag Dynamometer Showing Wear Debris Collector



Figure 2-7 - Photomicrograph of Cross Section of Friction Material Test Specimen After More Than 10 Successive Stops from 100 mph on Bendix Full-Brake Dynamometer

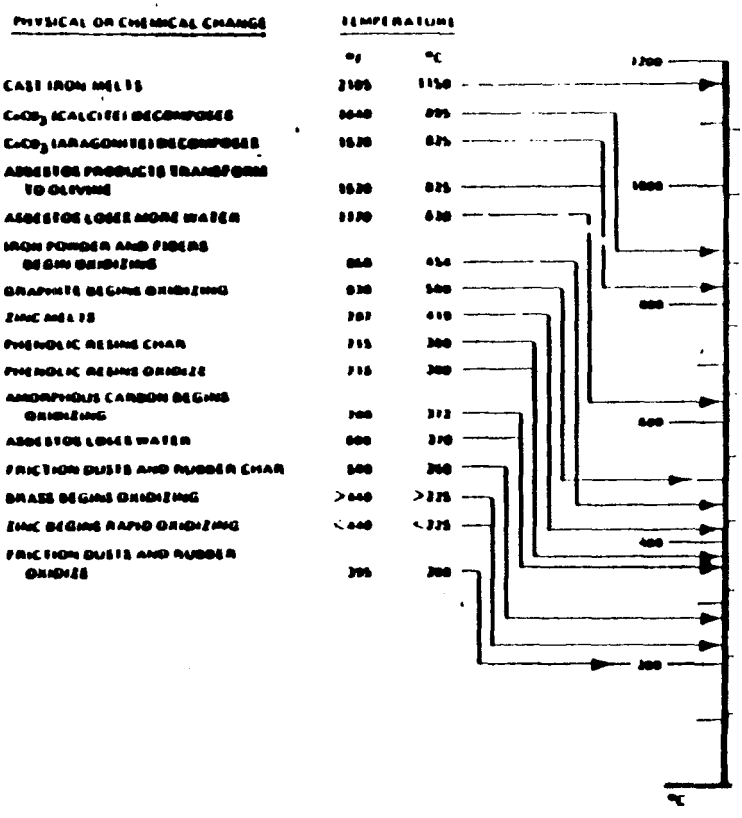


Figure 2-8 – Changes Occurring in the Friction Material as the Temperature Rises

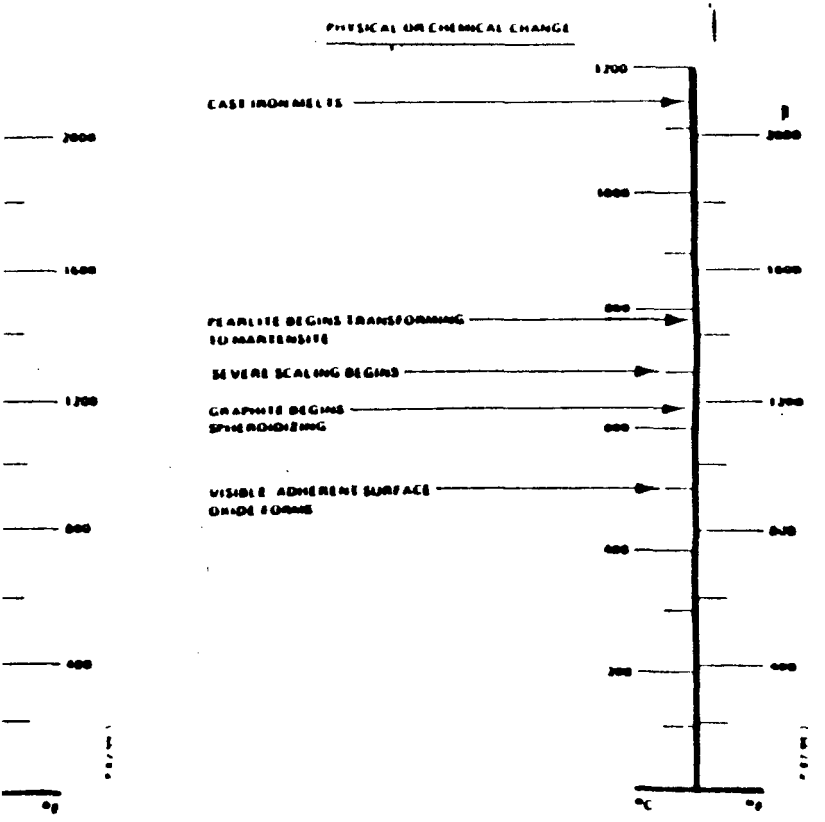


Figure 2-9 - Changes Occurring in the Rotor as the Temperature Rises

summarizes the physical and chemical changes which take place in the friction material as the temperature rises.(2-14) Figure 2-9 summarizes the physical and chemical changes which take place in the cast-iron rotor as the temperature rises.

2.3.4 Brake Lining Wear Mechanisms and Generation of Emissions

2.3.4.1 Types of Wear Mechanisms

Emissions are generated by wear. To the consumer, wear is an economic consideration. To the environmentalist, these emissions are substances to be characterized and, if harmful, to be eliminated.

From the basic friction material engineering standpoint, wear resistance is inversely related to friction level and other desirable performance characteristics. Linings with faster wear rate and more frequent surface renewal generally have greater frictional stability. This circumstance is used to advantage in the development of primary-type linings for duo-servo brakes, where, because of design, the stability of frictional properties is of greater significance to brake performance than is wear resistance; use of primary linings with too much wear resistance results in poor face resistance, less frictional stability, and generally poor overall performance.

Except in the case of primary linings, however, one of the formulator's objectives must be to achieve the highest possible level of wear resistance. Contrary to the opinion of some, maximum life does not require a friction material of maximum physical hardness. What is desirable is a minimum wear rate in normal low-temperature use, a moderately increased rate at elevated temperatures, and a return to the original low-temperature wear rates after being subjected to elevated temperatures.

Total emissions generation may be defined as the sum total of the losses associated with five basic types of wear.(2-15)

- abrasive wear,
- thermal wear,
- adhesive wear,
- fatigue wear, and
- macroshear wear

As shown in Table 2-2, there are several possible mechanisms for each type of wear.

2.3.4.1.1 Thermal Wear

Thermal wear encompasses a group of physical and chemical reactions in the course of which interatomic bonds are broken by thermal energy. These reactions include pyrolysis (thermal decomposition),

Table 2-2 - Wear Mechanisms in Friction Materials

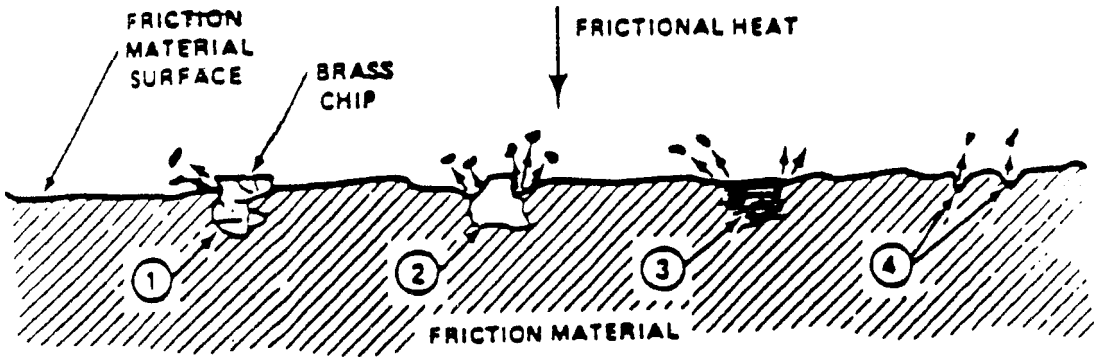
THERMAL WEAR	ADHESIVE WEAR
PYROLYSIS	ORGANIC MATERIAL ADHESION
OXIDATION	BINDER
THERMOPARTICULATION	FRICTION DUST
MELTING	RUBBER
EVAPORATION	INORGANIC MATERIAL ADHESION
SUBLIMATION	METAL PARTICLES
EXPLOSION	ICE
ABRASIVE WEAR	FATIGUE WEAR
TWO-BODY	THERMAL
ASPERITIES	CYCLING
SCORING	SHOCK
CRACK EDGES	MECHANICAL
PIT EDGES	REPEATED BRAKING
THREE-BODY	DRUMS OUT OF ROUND
WEAR DEBRIS	DISCS OUT OF PARALLEL
ROAD DUST	
	MACRO-SHEAR WEAR
	ACROSS THE PAD
	AT CORNERS AND EDGES
	THROUGH HEAT-AFFECTED LAYERS

oxidation, thermoparticulation, explosion, melting, evaporation, and sublimation. Their rates increase exponentially with temperature, and in extreme cases they result in fade.

Pyrolysis probably occurs predominantly at the centers of linings and pads and to a lesser extent at the corners and edges. Oxidation, on the other hand, probably predominates at the corners and edges and is less severe at the center. Explosive reactions occur under highly abusive braking conditions, where the rate of heat input is so high that solids are converted to gases well beneath the surface; because these gases are greater in volume than the solids they displace, they create a pressure that ruptures the lining in an explosive manner. Four such reactions are represented in Figure 2-10.

It might be thought that rapid thermal wear occurs only at high soak temperatures.* In fact, however, thermal wear probably

*Soak temperatures are temperatures measured during dynamometer or vehicle testing, using a thermocouple located in the friction material or in the rotor, generally at a distance of 20 to 50 mils from the sliding interface.



① $CaCO_3$ (s) → CaO (s) + CO_2 (g) *

② CASHEW DUST (s) → CO_2 (g) + H_2O (g) + C (s)

③ ASBESTOS → H_2O (g) + OLIVINE (s) + ASBESTOS FIBRILS (s)

④ PHENOLIC RESIN → CO_2 (g) + H_2O (g) + C (s)

(S): SOLID
(G): GAS

*THE BRASS CHIP CONDUCTS HEAT RAPIDLY INTO THE FRICTION-MATERIAL SURFACE.

Figure 2-10 - Mechanism of Explosive Thermal Wear

occurs at appreciable rates at low soak temperatures as well. It has been shown that the materials in a sliding friction couple contact each other at the tops of asperities on their surfaces. There is considerable evidence to indicate that the temperature increase at these asperities for low sliding speeds is represented by the equation(2-16, 2-17)

$$T - T_o = (guvw/4aJ)[1/(k_1 + k_2)]$$

where

T is the "flash" temperature

T_o is the soak temperature

g is the acceleration due to gravity

u is the coefficient of friction

v is the sliding velocity

w is the load on the asperity

a is the radius of the asperity junction

J is the mechanical equivalent of heat

k_1 is the thermal conductivity of the disc

k_2 is the thermal conductivity of the slider

Modifications of this equation have also been developed for high sliding speeds. Experiments indicate that the flash temperature may be as high as 1400°F (760°C) if the soak temperature is 650°F (343°C). This flash temperature is high enough to cause rapid localized pyrolysis of the organic compounds used in friction materials, as well as conversion of fibrous asbestos to powdery olivine and transformation of pearlite to martensite in the cast-iron mating surface.

2.3.4.1.2 Abrasive Wear

Abrasive wear is of two types: two-body wear (Figure 2-11) and three-body wear (Figure 2-12). Plowing by asperities on the rotor surface and plowing by edges in rough-machined, scored, cracked, or corroded (pitted) rotors are examples of two-body wear. Grinding by wear debris and by foreign particles such as sand, clay, mud, or salt in the sliding interface is three-body wear.

Abrasive wear would be expected to increase with temperature. It increases also with the braking load and with the concentration, size, and hardness of foreign particles. It may be accompanied by negative fade.

Figure 2-13 is a Bendix scanning electron photomicrograph of a dynamometer-tested friction material showing the abrasive wear tracks on the surface. Several adherent wear debris particles are similar in size to the wear track widths.

2.3.4.1.3 Adhesive Wear

Adhesive wear, illustrated in Figure 2-14, involves the adhesion of organic and/or inorganic materials to the rotor and the subsequent tearing or separation of these materials from the lining or pad.

Organic constituents of friction materials include the binder, friction modifiers and elastomeric compounds. Inorganic constituents include zinc powder, brass chips, and asbestos. Little is known about the tendency of these materials to adhere to the cast iron used in today's drums and discs, though experience with hot elastomeric compounds suggests that elastomers are very likely to stick. Experiments at Bendix Research Laboratories indicate that brass chips will alloy with certain nonferrous rotor alloys.[2-18] When this occurs, metal is transferred from the rotor to the lining, scoring the surface of the rotor and in turn subjecting the lining to a high rate of two-body abrasive wear.

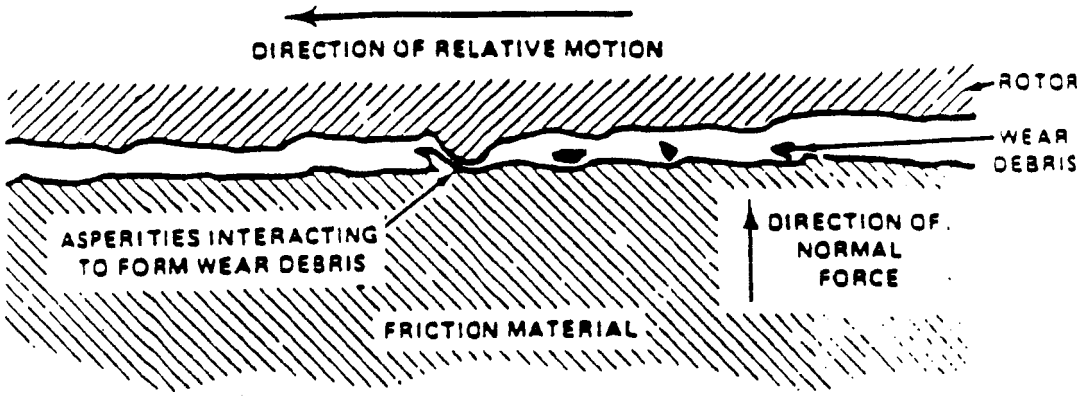


Figure 2-11 - Mechanism of Two-Body Abrasive Wear

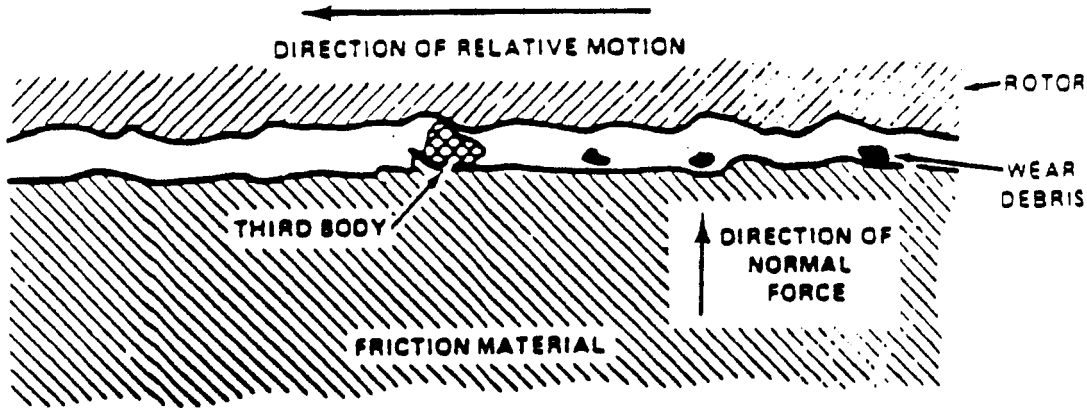


Figure 2-12 - Mechanism of Three-Body Abrasive Wear



Figure 2-13 - Scanning Electron Photomicrograph Showing Abrasive Wear Tracks on Friction Material Surface and Adherent Wear Debris Particles

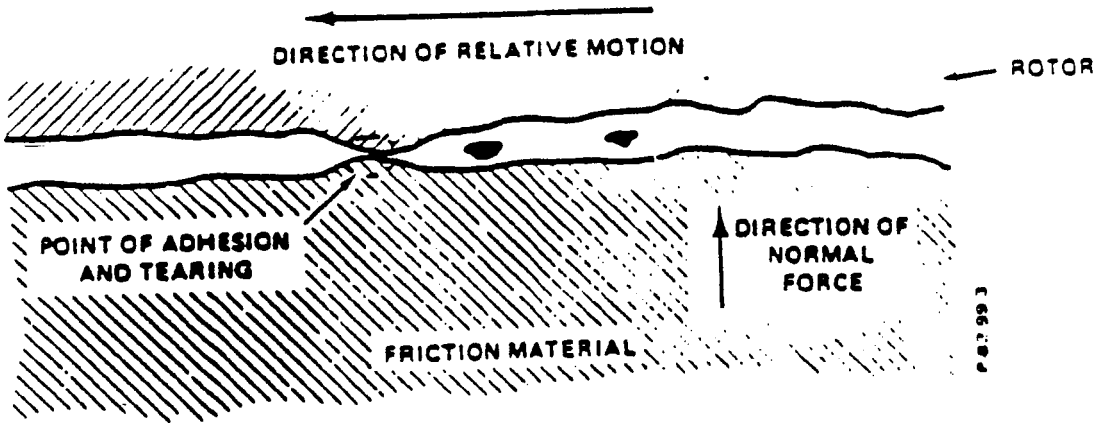


Figure 2-14 - Mechanism of Adhesive Wear

- Adhesive wear probably increases with temperature, braking load, and the concentration of adherent components in the friction material. It is also caused by the presence in the friction material of metal particles capable of solution in or reaction with the rotor alloy, increasing with the size and concentration of such particles. Because this type of wear can cause stick-slip, it may be associated with brake noise.

2.3.4.1.4 Fatigue Wear

Fatigue wear (Figure 2-15) is most commonly observed in metal bearings. However, it may also be experienced by organic friction materials, occurring in two forms, thermal and mechanical.

Thermal fatigue is caused by repeated heating and cooling. Such repeated temperature changes impose cyclic stresses on the surface material, which heats and cools more rapidly than the bulk material and thus expands and contracts to a greater extent. Because of their low thermal conductivities, the thermal gradients and resultant thermal stresses in organic friction materials may be higher than those in metals.

Thermal-shock cracking may be thought of as a special case of thermal fatigue, occurring as a result of a single abusive loading.

Mechanical fatigue is caused by repeated mechanical stressing. Because of the frequency of brake use, friction materials are subjected repeatedly to both compression and shear forces. Additional stresses are also applied repeatedly if drums are out-of-round, if discs are out-of-parallel, or if rotor thickness is not uniform.

Figure 2-13 shows the initiation of fatigue wear around the large cashew particle. This material swells when heated and thus the surface wears. After cooling, the particle contracts, cracks, and pulls away from the edges. When the particle is completely loose, it can fall out.

2.3.4.1.5 Macroshear Wear

Three types of material removal fall in the category of macroshear wear, which is illustrated in Figure 2-16.

A fracture, in shear, may occur across the entire brake pad under extremely heavy loading, especially if the friction material has previously been weakened by heat. This is a sudden rather than a gradual type of wear.

Fracture at the edges and corners of a piece of friction material is another type of macroshear wear. Oxidation of organic components weakens the friction material at these locations.

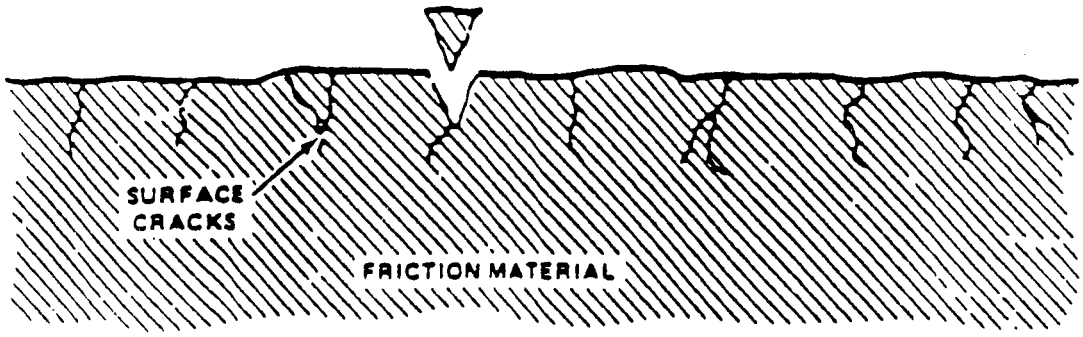


Figure 2-15 - Mechanism of Fatigue Wear

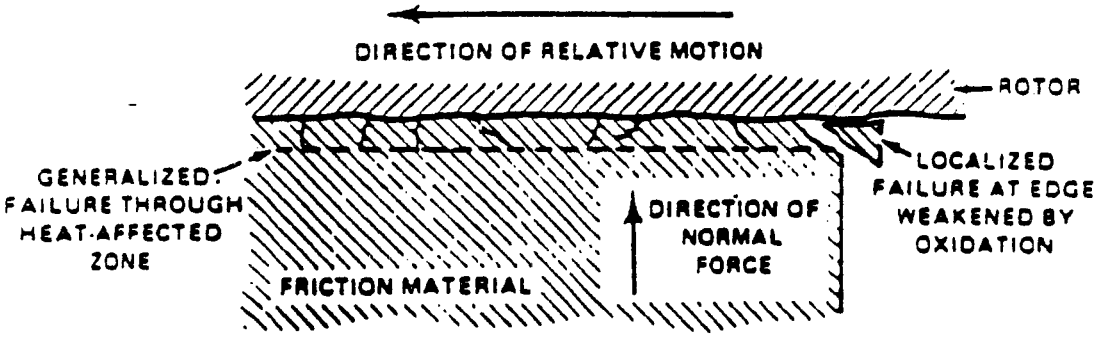


Figure 2-16 - Mechanism of Macroshear Wear

Fracture at the edges and corners of a piece of friction material is another type of macroshear wear. Oxidation of organic components weakens the friction material at these locations.

A third type of macroshear wear can occur when a friction material such as that shown in Figure 2-15 is subjected to heavy loading following thermal abuse. The heat-affected layer in the material pictured is about 100 mils deep, and from this layer organic material has been removed by pyrolysis. If sufficiently weakened, such a layer can be sheared away by a single, heavy brake application.

Whatever the mechanism, macroshear wear is promoted by nonuniform loading and by oxidation and thermal degradation of the binder. It is most likely to occur at elevated temperatures and under severe braking conditions. Its end products are typically large fragments of friction material that leave the surface rough. These fragments subject the remaining friction material to plowing or abrasive wear, and while they are present in the interface, friction behaviour will be erratic.

2.3.4.2 Predominant Wear Mechanisms

The predominant wear or emissions-generation mechanisms may be summarized simply (Figure 2-17):(2-19)

- Below 450°F:
  Abrasive and adhesive wear.
- Above 450°F:
  Thermal wear.

Figure 2-18 illustrates the wear loss of three different kinds of friction materials as a function of temperature, illustrating these predominant wear mechanisms.

2.3.4.3 Wear Equation

Recent work at Bendix Research Laboratories has indicated that each friction material wears according to a universal wear equation.(2-20)

$$\Delta W = k \cdot p^a \cdot v^b \cdot t^c$$

or

$$\log (\Delta W) = \log k + a \log P + b \log V + c \log t$$

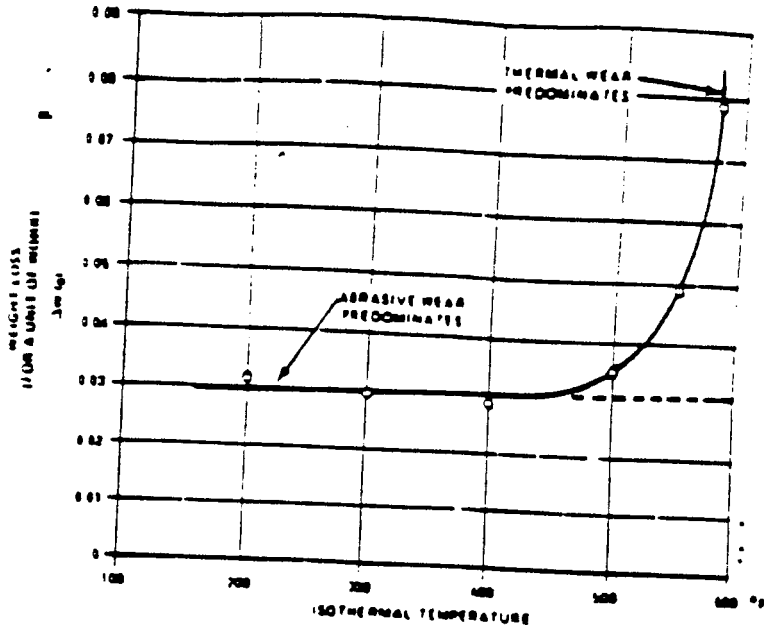


Figure 2-17 - Predominant Wear Mechanisms of Friction Materials

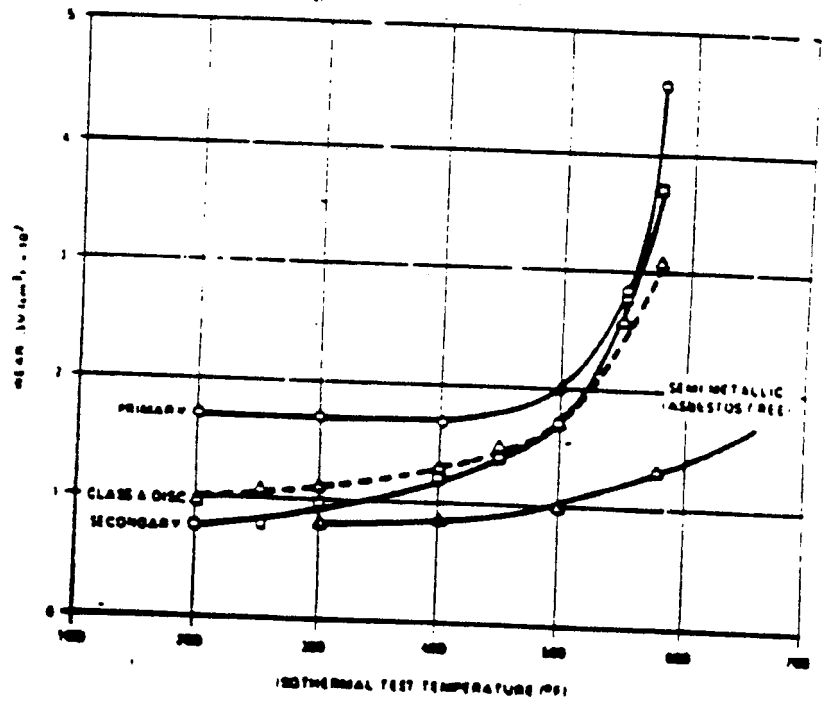


Figure 2-18 - Variation of Friction Material Wear with Temperature

where

ΔW is the weight lost

k is the wear factor

P is the load

V is the sliding velocity

t is the time of sliding, and

a,b,c are constants characteristic of a given friction couple.

When further developed, this equation will be useful for predicting wear (and emissions) under various driving conditions.

2.3.5 Emissions of Particulate and Gaseous Emissions

2.3.5.1 Drum Brakes

Gaseous decomposition products in drum brakes are emitted from two areas:

- The space between the rotating drum and the stationary backing plate.
- The small holes in the backing plate itself (e.g., clearance holes, brake adjusting slot, etc.)

Particulates are emitted from the same two areas, although only small particulates would come through the holes in the backing plate. In drum brakes, some particles are not emitted but remain in the rotating drum. It is expected that some of these particles would eventually be emitted through the space between the rotating drum and stationary backing plate. Also, some large particles would be "ground up" and emitted as a number of smaller particles if they are trapped between the friction material and drum on subsequent braking or if they are trapped between the rotating drum and stationary backing plate. If the brake shoes are of riveted construction, then some particles can be trapped in the rivet holes and thus retained in the brake.

If convective cooling of drum brakes is improved in the future, as is desirable for safer operation and longer driving life, it is likely that fewer particles will remain trapped. The particles emitted, however, will probably be larger, as they will be subjected to grinding action for shorter periods of time.

2.3.5.2 Disc Brakes

As the disc brake is essentially an open braking system, it is expected that all particulate and gaseous decomposition products

will be emitted. However, a small amount of particulates collect in the rivet holes of riveted disc brake pads and on some areas of the caliper.

2.3.5.3 Clutches

In the dry clutches commonly in use on "stick-shift" cars, there are very few openings for gases and particles to escape. The two main areas are:

- The area around the clutch fork, which generally has a rubber boot on it for protection of the clutch from road spray, sand, etc.
- A small opening at the lower front of the clutch to drain any oil, water, etc., which may get into the clutch.

Because of the construction, many particulates remain in the clutch housing.

2.3.6 Distribution and Changes in Brake and Clutch Emissions

Entrapped gases and pyrolysis gases released during braking or clutch slipping will be hot enough to mix rapidly with the surrounding air and become part of the air wake of the car. The higher molecular weight vapors will condense and eventually settle to the ground. The low molecular weight gases will disperse as part of the local atmosphere. Some of the condensible vapors may, of course, settle on small, air-borne dust particles and could be carried into the respiratory system as part of the breathing air.

The particle emissions will disperse in different ways depending on their size, shape, and density. Submicrometer-size particles, regardless of shape, will ordinarily remain air-borne until they are scrubbed out by rainfall or some other separating action. In effect they become a long-time part of the atmosphere.

Spherical particles in the 1.0 um to 10 um diameter range will settle, under gravity and in still air, at velocities from 12 to 1000 cm/hr, according to Stokes' law. Irregularly shaped particles of similar size and in turbulent air will settle at much slower velocities and could remain air-borne for hours or days. These particles cause the greatest aggravation in the human respiratory system because they collect in the tracheo-bronchial regions and, to some extent, in the alveoli.

Particles from 20 um to 100 um in diameter will settle as part of the dust trail left by the car or will collect with any larger particles in mechanical traps in the car. Eventually these larger-size particles will fall or be shaken out of the car and become part of the road dust.

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