EPA/CPSC WORKSHOP ON SUBSTITUTES FOR ASBESTOS

July 14, 1980, Arlington, VA

NON-ASBESTOS FRICTION MATERIALS

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ABSTRACT

Friction materials for automotive brakes are complex composites containing three general types of ingredient materials: reinforcing fibers; modifiers that adjust or maintain friction level, wear rate, and noise properties; and organic resin binders. Historically, the foundation or major constituent of automotive friction materials has been asbestos fiber, so chosen because of thermal stability, friction level, reinforcing properties, availability, and relatively low cost.

Numerous substitutes for asbestos in conventional organic materials have been evaluated, including both naturally occurring and synthetic materials. Direct substitution of these alternative materials in conventional formulations has resulted in poor friction levels, friction instability, roughness, structural failure, increased noise, mating surface deterioration and/or front-to-rear vehicle brake imbalance. Complete reformulation, not simple substitution, is necessary to meet the numerous, complex performance requirements of consumers, manufacturers, and government standards, such as FMVSS 105-75 and FMVSS 121.

In the 1960's, a new class of friction materials, called semimetallics, was developed to meet severe braking requirements, primarily in heavy-duty disc brake and extreme duty truck block applications. Semimetallics operate satisfactorily against the ventilated cast-iron rotors in the smaller brakes of downsized cars, as well as against the solid rotors found in the lighter brakes of new front wheel drive vehicles. Semimetallics rely on steel fiber and powder metallurgy techniques for reinforcement, and do not require asbestos. The improved performance of

semimetallics compensates for their higher costs due to more expensive ingredients, higher specific gravity, and more costly processing requirements. Overall development took more than ten years from introduction to significant customer acceptance.

The characteristics of semimetallics make them extremely difficult and costly to process as a drum lining segment. Consequently, an additional new class of friction materials is under development, specifically for drum lining applications. Additional development effort is necessary, not only to confirm the performance characteristics of these new substitute fiber formulations, but also to develop new processing techniques. These new-type friction materials will be more costly, however, due to the ingredients and new processing techniques.

INTRODUCTION

Automotive brakes can be viewed, quite simply, as energy transformers. During a brake application, the friction material (stator) makes contact with the rotating drum or disc (rotor), creating a friction force resisting the relative motion between the two bodies. The energy of motion is transformed into heat energy, which is dissipated, primarily through the rotating member.

As one might expect, the friction material must operate in a rather hostile environment. Lining soak temperatures in excess of 400°C (750°F) are not unusual, and temperatures at the contact interface can exceed 850°C (1560°F). The nature of the on-the-road operating environment (dust, mud, salt, water, etc.) complicates the problem. The friction material must possess an optimized balance of characteristics, and maintain those characteristics throughout 20,000 to 40,000 miles of vehicle operation.

The fundamental characteristics of friction materials are listed in Table 1. Friction level must be adequate and stable over a wide range of operating speeds, application pressures, and temperatures, regardless of the conditioning and age of the material. Of particular interest are the fade/recovery characteristics, i.e., the ability to resist friction level deterioration when subjected to extreme elevated temperatures (the fade) and then to return to the pre-fade friction level on cooling (the recovery). The friction material must have good wear properties for long life, but it must also not cause excessive wear or grooving on the mating disc or drum. Excessive compressibility, noise and roughness (chatter, vibration, pulsation) must be avoided, and sensitivity to moisture must be minimized. Finally, the friction material must be capable of being manufactured with consistency at a reasonable cost.

Detailed definitions of these characteristics, and their interaction and interdependence, have been discussed at length by Aldrich and Jacko (1). In general, attempting to improve upon one characteristic often results in the deterioration of other characteristics. The development of friction materials is therefore a complex, interactive process seeking an optimized combination of interdependent characteristics.

The existence of numerous brake designs provides another level of complexity in designing friction materials. Linings for drum brakes require a wide range of properties. The duo-servo drum brake (the most popular U.S. design) requires two different types of linings, designated primary and secondary, each of which needs different properties of strength, wear resistance, friction level and friction stability. The non-servo drum brake (used on many sub-compact vehicles) requires a friction material which encompasses the best characteristics of the primary and secondary in a single formulation, with emphasis on low-temperature properties and static friction capability. The large hydraulic and air-operated drum brakes utilized on medium and heavy trucks require, in general, the maximum properties of the smaller vehicle linings but at significantly higher operating temperatures. The arcuate form of drum brake linings places additional restrictions on the formulation, because of processing requirements.

Disc brakes demand a totally different set of operating conditions for the friction materials. Disc brakes generally operate at significantly higher temperatures than equivalent drum brakes, and the front disc brakes run hotter than the rear drum brakes on the same vehicle (Table 2). The friction material for disc brakes must be specifically designed for these higher temperatures, and must possess a higher coefficient of friction and better wear characteristics across the temperature range. Friction-material formulations must also be tailored to the specific needs of the particular vehicle application. Numerous parameters such as vehicle weight, front-to-rear brake balance, actuating system design, and duty cycle affect the capability of a particular lining formulation to perform satisfactorily.

The existence of numerous complex performance standards emanating from consumers, associations, manufacturers, and government agencies provides an additional set of parameters that friction materials must meet. Significant differences can exist between friction materials used as original equipment in new vehicles and friction materials available as replacement parts in the aftermarket. Each vehicle manufacturer has a unique, extensive set of test and acceptance standards to ensure the safety, durability, and performance of its products and the components used therein. Government-instituted requirements exist at the federal, state, and local levels. Federal requirements include those promulgated by the Department of Transportation (vehicle performance), the Occupational Safety and Health Administration (manufacturing work practices), and the Environmental Protection Agency (manufacturing practices and raw materials).

In order to meet the many characteristics outlined thus far, friction materials for automotive brakes have developed as complex composites containing three general types of ingredient materials: reinforcing fibers; modifiers that adjust or maintain friction level; wear rate and noise properties; and organic resin binders. Historically, the type of friction materials used in most automotive applications has been conventional organic friction material. The foundation or major constitutuent of conventional organic friction material has been asbestos fiber, so chosen because of its unique combination of characteristics. Asbestos fibers provide reinforcement, possess a high coefficient of friction, and more importantly, have excellent thermal stability. The openness of the fiber, its adsorptiveness, and its compactibility enhance the processing and uniformity requirements. Finally, asbestos fibers have been available in a variety of grades at a relatively low cost.

Once the friction material has been cured, the asbestos fibers are locked into the matrix. During brake operation, the high temperatures generated at the interface convert more than 99.7% of the asbestos to non-fibrous residues (primarily olivine) in the wear debris (2), and less than 0.02% asbestos becomes airborne (3,4).

The conventional organic formulations and the processes by which they are made have been dependent upon and tailored to the physical and chemical properties of asbestos. Two courses of action are open for elimination of asbestos from automotive friction materials:

1. Develop a new generation of friction materials, designed from the start without asbestos in mind.

2. Attempt to substitute an alternative fiber system for the asbestos in conventional formulations, with subsequent modification of composition and process techniques.

Bendix is aggressively pursuing both courses of action. As Mr. William Agee, our Chairman and Chief Executive Officer has stated, Bendix is committed to being asbestos-free at the earliest possible date within this decade.

SEMIMETALLIC DISC PADS

Properties

In the 1960s, a new generation of friction materials, called semimetallic, was developed to meet severe braking requirements which organics could not meet. Class A organics (typical U.S. materials), which perform well in low and moderate temperature duty, are prone to fade and exhibit compressibility and poor wear resistance at high temperatures. Class B organics (typical European and Japanese materials) provide good high-temperature wear and friction levels, but have poor low-temperature wear resistance, produce rotor scoring and/or wear, and are prone to being noisy. Semimetallics were initially developed for these extreme, high-temperature applications (5).

Semimetallics rely on steel fiber and powder metallurgy techniques for reinforcement. Various property modifiers are added to enhance performance to desired levels, with a resin binder holding the materials in a uniform solid mass. Semimetallics may contain metallic powder, sponge iron particles, ceramic powder, steel fiber, rubber particles, graphite powder, and phenolic resin (6,7). Some manufacturers utilize a backing layer of a different composition which can contain asbestos.

Problems Overcome

Inherent in the uniqueness of the semimetallic formulations and their performance properties were a number of significant problems which required resolution. Concentrated development effort was required to resolve both processing and performance related issues. Processing issues included: the uniformity of the raw materials mixtures, the ability to form and handle the in-process material, and the ability to manufacture high-quality parts consistently. Performance issues included: materials strength, cold friction properties, initial wear resistance, and attachment to the backing plate. The development effort on semimetallic friction material has been continuous, not only to further improve its characteristics and properties, but also to overcome the problems inherent in accomodating new vehicle applications.

Semimetallics gained acceptance because they were able to solve some of the problems that could not be overcome using Class A or Class B organics. The improvements/advantages are listed in Table 3. The key element is the attainment of overall excellent properties at both low and high temperatures. Semimetallics cost more because of more expensive ingredients and a costlier process, but the improved performance capabilities offset these factors. An increased usage of semimetallics has occurred over the past few years. The downsizing of vehicles, with resulting smaller front brakes and higher operating temperatures has given impetus to increased use of semimetallics (8). It is expected that the trend toward asbestos-free semimetallic disc pads will continue.

SEMIMETALLIC DRUM LININGS

An obvious alternative to conventional organic drum brake linings is the use of semimetallic material for drum linings. In fact, one of the first applications for semimetallics was for air brakes on heavy-duty trucks used in the logging industry -- an extremely severe application.

Significant development effort has been expended on semimetallic drum brake linings. However, the basic nature of semimetallics does not lend itself to the arcuate segment configuration required for small drum brakes. The semimetallic mix does not possess the necessary green strength, is difficult to bend into the arcuate shape, and is more brittle in its cured form and therefore subject to cracking. Modifications to the formulation to facilitate processibility generally result in a product that cannot achieve commercially acceptable performance characteristics.

These difficulties present a clear challenge, and development work on semimetallic drum brake linings continues.

ALTERNATE FIBERS/REINFORCERS

Properties

Alternative fiber systems in conventional organic formulations represent the second course of action open to friction-material manufacturers. Table 4 is a summary of the properties of some of the various materials which could be considered as alternate reinforcements. Since conventional organics and semimetallics have traditionally been reinforced with asbestos and steel fiber, respectively, these fibers are also included in the table for comparative purposes. The data in Table 4 were obtained from the material manufacturer's literature and extensive characterization data developed at Bendix. Characterization included scanning electron microscopy and x-ray energy spectroscopy (SEM/XES). The selection of suitable alternate materials must also consider the health and safety implication of the substitute fiber system. After considerable study of existing information, Bendix has chosen substitute materials which, in our judgement, are free from serious health implications.

Processing Conditions

Current organic friction materials have been developed around the unique properties of asbestos. Asbestos fiber bundles open during mixing and entrap the friction modifiers and resin, giving a consistent mix. The compactability of asbestos facilitates forming at room temperature with moderate pressure.

The non-asbestos fibers are much more difficult to handle. Most are very brittle and have little or no surface adsorptivity. High bulking and segregation occur during mixing. Spring back and low tack lead to weak structures. Combinations of additives and new processing techniques are required to overcome these problems and produce the cohesiveness necessary for manufacturing parts.

Performance Characteristics

The characteristics of the fibers can have significant influence on the performance properties of the final composite. Asbestos has a high, stable friction level, good adsorptivity for strength and wear resistance, and does not contribute to noise.

Substitute fibers generally show greater frictional instability, little or no surface adsorptivity, and/or significant contribution to both noise and mating-surface degradation.

NON-ASBESTOS ORGANIC DISC PADS

Failures on Direct Substitution

A commercial Class A organic disc pad formulation, similar to one reported earlier (9) and known to contain phenolic resin, asbestos fiber, organic friction particles (cashew and rubber dusts), zinc chips, and barytes was selected as a baseline composition. In a series of new formulations, the asbestos fiber was replaced with glass fiber, mica, mineral wool, Franklin fiber, a glass fiber/mica mixture, a glass/Fiberfrax/graphite fiber mixture, and a glass/Wollastonite fiber mixture.

The composites were run on an inertial dynamometer equipped with a Bendix-designed Series III disc brake loaded to 1000 lbs. Stops from 50 mph (80 kmph) at 3.66 mpsps (12 fpsps) deceleration were run at different initial brake temperatures up to 315°C (600°F). All fiber substitutions produced roughness followed by poor friction. Generally, the composites were structurally inadequate producing tear-out and poor wear resistance, in addition to roughess (Table 5). All formulations were considered failures. This led to the conclusion that simple direct substitution of alternative fiber systems was not practical.

Alternate Approach

A new baseline was selected with increased reinforcement content to better screen the following characteristics:

- o processing
- o strength
- o performance (friction, wear, drum compatibility, and noise properties)
- o cost

The initial objective was improved structural capability. A number of formulations were made using high fiber concentration. As shown in Table 6, the tensile strength results were very encouraging. The next step, which proved very difficult, was attaining a proper balance of friction and wear to go along with the strength.

Sample Dynamometer Results

A series of combinations of materials with a fixed ratio of glass fiber and the other reinforcements was evaluated on a sample dynamometer (Table 7). The results indicate that all of these reinforcement combinations are poor substitutes for asbestos fibers in that they exhibit poor friction, poor wear resistance, poor friction stability, or poor rotor compatibility. However, some clues were provided and it was possible to combine two of the formulations to produce a new composite M. This material was then reformulated with additional property modifiers in 6 other iterations to produce yet another formulation S, which exhibited a high but stable friction coefficient, equivalent wear resistance, and slightly poorer rotor wear resistance. At this point, the study was transferred to full brake inertial dynamometer testing.

Inertial Dynamometer Results

The inertial dynamometer confirmed that formulation S had a higher friction level, slightly better wear resistance, and slightly poorer rotor compatibility than the baseline (Table 8). Approximately 40 iterations of formulation S led to formulation AA which gave good friction with friction stability and very good wear resistance. Further iterations (~10) led to formulation AL which gave lower friction, poorer wear, and good rotor compatibility. In addition to inertial dynamometer tests, a series of vehicle tests was also initiated.

Vehicle Test Results

Several formulation iterations were coupled with processing improvements. Formulation DA was developed after approximately 50 iterations following Formulation AL. Formulation DN was developed after 13 iterations of a new-concept material which has been patented (10). The vehicle test results (effectiveness, fade, and recovery, in addition to wear data and noise ratings) are given in Table 9 and were run according to a modified SAE J843c schedule. Formulation Bendix D7180 is a Class A organic used as the baseline.

The line pressure data show that the non-asbestos organics have higher preburnish, post-burnish, and final effectiveness than the baseline, based on full-system as well as fronts-only checks. This higher friction level and friction stability are also demonstrated in the fade and recovery portions of the test.

Both non-asbestos organics showed poorer burnish wear resistance, and both showed improved wear resistance during the fade and recovery portions of the test. The rotor compatability of both non-asbestos organics was poorer than that of the asbestos-based baseline.

Formulation DA, which is more typical of Class A organics, showed less loss in rotor wear than did the new-concept DN material. Both materials were prone to be noisy.

Status

Non-asbestos organic disc pads are still in the development stage because several problems have not yet been resolved:

- o rotor compatibility
- o wear durability
- o noise properties
- o processing

Bendix is continuing development efforts to commercialize non-asbestos, organic disc pads.

NON-ASBESTOS ORGANIC DRUM BRAKE LININGS

Process Characteristics

Drum-brake linings require different processing characteristics than do disc pads. When made by a wet process technique, friction materials require a binder-wetted plastic mass with good cold flow properties. When made by a dry process technique, they require good hot flow properties, but must first be capable of being preformed under cold pressure conditions to develop strength for handling purposes. Both wet and dry process types require the capability of ultimate arcuate formation. All currently known alternate fibers result in serious problems in these areas.

As in the case of disc pads, the direct substitution of alternate fiber in existing asbestos formulations has been unsuccessful. Basic processibility has been the first obstacle. The generally stiff, non-absorptive alternate fibers do not result in a wetted, densified mass. This precludes cold-pressure forming into brake-lining strip configurations typical of wet-process methods. In the case of dry-process methods, the fiber stiffness is a deterrent to good physical integrity of preforms and also leads to excessive lining cracking during bending. In general, the alternate fiber materials do not result in a mix character which allows them to be processed effectively by currently known techniques. The solutions to these problems call for radically different approaches to material formulation and processing techniques. The new processing techniques require substantial capital investment.

Testing and Development

With the application of suitable material and process changes, non-asbestos type drum linings have been experimentally fabricated and tested. Hundreds of formulations of duo-servo primary linings and secondary linings, along with those for non-servo type brake linings, have been made. When processed satisfactorily, these materials have been tested on sample dynamometers and inertial dynamometers before selecting the better ones for vehicle testing. The use of different formulations to overcome the process problems has resulted in substantially different frictional and wear characteristics which have had to be modified to duplicate current materials more closely.

Table 10 illustrates the magnitude of some of the early problems and some of the later results. Initial tests using very high friction combinations (A and B) run on Vehicle 1 with a front-brake hold-off valve, resulted in a serious duty shift with front brakes projecting greater than normal mileage, and the rear brakes projecting short life because of their higher work load. However, when Combination A was run on Vehicle 2 (which had no front-brake hold-off valve), the secondary lining (the same as in Combinations A and B) projected almost the minimum requirement of 15,000, although the primary gave only 7900 miles. Subsequent tests of improved combinations, particularly with improved primary lining life, projected over 20,000 miles. Tests on Vehicle 3, again without a front hold-off valve, projected reasonably good life on Combinations E, F, G, and H, with quite acceptable life on the more recently developed Combination H. A comparison of wear projections on Combinations F and G shows the importance of primary-secondary teaming. Both combinations had the same primary, but with different secondaries, the life of the primary decreased from 20,900 to 12,200 miles.

The above data illustrates that basic life and performance are achievable, at least on certain vehicles. However, the materials noted above were prepared by more involved, more expensive processes and are noisier than current asbestos types, and the mating surface condition requires further improvement. Further, the ability of these materials to withstand extended in-service usage must be evaluated in a wide range of vehicle applications and environments.

Status

The first generation of asbestos-free drum linings is being evaluated by some vehicle manufacturers. Bendix is continuing development efforts on further improved materials.

ECONOMIC IMPACT

The economic impact of eliminating asbestos from automotive friction materials is significant, and includes three distinct segments:

1) Research and Development/New Capital Investment: Bendix has committed, and will continue to commit, extensive funding to both research and development efforts and to the new equipment and facilities required to support asbestos-free friction materials. Over the last five years, the number of dynamometers and test vehicles at our Friction Materials Division has doubled, and engineering headcount has been increased by over 60 percent. The total engineering budget has tripled, and the share of the budget devoted to asbestos-free product development has grown from 13 percent in 1976 to over 71 percent for 1981. The corporate research laboratories have also expended significant effort in support of the division. Based on our current plans, Bendix estimates that it will have committed over $25,000,000 to engineering activities on asbestos-free product in the U.S. by 1985.

   Capital expenditures must also be increased significantly. Over the next five years, the average annual expenditure related to asbestos-free products will be triple the historical average annual expenditure for the entire division. Based on our current plans, Bendix estimates that it will invest over $60,000,000 (1980 constant dollars) in new equipment and facilities for asbestos-free products.

2) Product Cost: The basic cost of the product itself is a complex function involving many factors. The amount and types of materials used, and the basic raw materials cost are obvious factors. The fixed and variable costs of manufacturing can differ greatly, based on the type of process and its complexity, production volumes, labor costs, energy cost, and process yield, among other factors. Administrative costs and handling/distribution costs are also significant variables.

   Preliminary cost estimates indicate that asbestos-free drum brake linings may cost 20% to 50% more than current linings. Disc brake pads may cost 20% to 100% more than current materials. These estimates are for products delivered in the original equipment market. We emphasize these are preliminary estimates. Until parts can actually be manufactured on production equipment in significant volumes, costing estimates must be preliminary. The estimates are highly dependent on the raw materials and processing techniques, which can vary significantly. Moreover, research and development continues, and future results can affect product cost.

3) Implementation Costs: As noted earlier, vehicle manufacturers have an extensive series of stringent test requirements. Each different vehicle configuration requires the series of tests to ensure that the product conforms to the requirements. Since asbestos-free materials may have some performance or property differences from current materials, vehicle system redesign may be necessary. We do not have sufficient information to accurately estimate costs associated with the test programs. We would expect that each vehicle manufacturer would expend millions of dollars, and possibly tens of millions, in converting their product lines to asbestos-free materials. A key element is the timing of the test programs. Expenses could be minimized by converting to asbestos-free materials as part of the scheduled new vehicle design programs, where significant brake-system testing is already necessary.

TIMING

Friction materials development is a lengthy process. As mentioned previously, the materials themselves and their properties are the results of optimization procedures, and the necessary testing programs are extensive. These programs include not only testing by the friction material supplier to develop and document the materials' capability, but also extensive testing by the customer to ensure suitability and regulatory conformance in the particular application.

Historical data gives us a sense for program timing. Evolutionary changes generally require eighteen to twenty-four months for supplier development and validation testing, twelve to eighteen months for customer application testing, and six months manufacturing lead-time--that is a total of 3 to 4 years. An example of such a change would be an improved organic disc pad utilizing the same basic components (i.e., asbestos, resin, modifiers). Compared to its predecessor, the new formulation might exhibit 15 percent better wear, improved fade resistance, and the same friction and noise properties. Today's asbestos organic linings are essentially the product of 40 years of evolutionary changes.

Revolutionary changes, which advance the state of the art, are more difficult to come by. It is unrealistic to put a timetable on invention, but establishing the feasibility of a new concept can take 12 to 18 months. Reducing that concept to a product with some or most of the basic characteristics can take 12 to 24 months. Formulation development to obtain a balanced set of characteristics for commercial application, and validation of those properties requires 24 to 36 months. As before, 12 to 18 months for customer application testing, and six months manufacturing lead-time are needed--that is a total of 5 1/2 to 8 1/2 years. The semimetallic discussed previously is a good example.

Semimetallic development began in 1962. The first low volume, special-purpose applications occurred in 1969. General acceptance came in the mid 1970s with the second generation of semimetallic formulations. Today, semimetallic disc pads are utilized on the front brakes of approximately 50 percent of the new vehicles built in the U.S., and projections approach 100 percent utilization by 1985. It has taken continued development and improvement of semimetallic properties to achieve this level of use.

The elimination of asbestos from automotive friction materials must be considered a revolutionary change. There are strong indications that the asbestos-free materials can achieve general acceptance more rapidly than semimetallics did. However, basic development needs demand a minimum time from the start of a program to initial production application. Assuming a 1975 start date, historical data would suggest that initial applications could be expected in the 1982/83 time frame, and we believe that we are close to that timetable. However, this only applies to the first generation of asbestos-free materials. Continued engineering effort (evolutionary changes) will be required to develop both the second generation of materials with improved properties, and the multiplicity of types of formulations necessary for different applications.

As indicated earlier, semimetallic disc brake linings containing no asbestos in either the friction material or the backing layer are in use today. It should be pointed out that the semimetallic friction materials have some characteristics which may preclude their utilization in certain vehicle applications. An orderly transition to significantly increased utilization of semimetallic disc pads on new U.S. vehicles is in process, and will probably approach 100 percent utilization no later than 1985.

Development continues on both asbestos-free organic disc-brake linings and on semimetallic drum brake linings, but the timing for production implementation cannot be accurately predicted.

The initial generation of asbestos-free organic drum-brake linings is in the final development stage at Bendix, and initial evaluations are underway at vehicle manufacturers. Some asbestos-free blocks are available commercially for heavy truck applications. While it is too early to tell whether these formulations will achieve commercial success, the first significant production release would probably be in 1982.

Although this presentation has primarily addressed original equipment considerations, the use of asbestos-free materials in the automotive aftermarket will create additional challenges. As new vehicles are produced with asbestos-free friction materials, they should be serviced with asbestos-free products. However, since the asbestos-free materials may very well have property and performance differences compared to current friction materials, it may not be possible to substitute the asbestos-free materials directly in older vehicles without compromising safety. Hence, significant time and effort will be needed to evaluate the effect of new asbestos-free friction materials in aftermarket applications to ensure safe and efficient braking and adequate lining life prior to the release of these asbestos-free materials for use in the aftermarket.

SUMMARY

Automotive friction materials are complex composites that have developed around the properties of asbestos. There is no simple substitution for asbestos fibers in automotive friction materials. Extensive engineering programs are required to develop new asbestos-free formulations and process techniques, and to conduct testing to ensure the adequacy and safety of the new friction materials.

Semimetallic disc pads, originally developed for heavy duty applications, meet the criteria of being asbestos-free and are in use today. The trend toward significantly increased usage is well established. The first generation of asbestos-free drum linings for passenger cars and light trucks is in the final stages of development at Bendix, and in the initial stages of evaluation by vehicle manufacturers. If these asbestos-free drum linings prove to be commercially acceptable, initial limited production usage could occur as early as 1982. Some asbestos-free friction materials are currently available on the market for heavy truck applications.

Engineering programs continue on improved versions of the materials mentioned above, and also on other types of materials which might prove successful. Bendix is committed to developing asbestos-free alternatives, and an orderly transition to such materials is now taking place. Significant engineering effort and time is needed to accomplish this transition.

As stated in the Bendix Corporation's 1979 annual report, "...Bendix early in the 1980's will offer its automotive customers brakes made with long-wearing high-performance friction materials that are asbestos-free." We intend to meet that committment.

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TABLE 1

CHARACTERISTICS OF FRICTION MATERIALS

FRICTION

- o LEVEL (COEFFICIENT)
- o STABILITY - SPEED
  - PRESSURE
  - TEMPERATURE
  - CONDITIONING
  - AGE
- o FADE/RECOVERY

WEAR

- o FRICTION MATERIAL
- o DRUM OR DISC

NOISE

ROUGHNESS

MOISTURE SENSITIVITY

MANUFACTURABILITY

- o PROCESSIBILITY
- o UNIFORMITY

TABLE 2

BRAKE FADE TEMPERATURES*(°F)

(SUBCOMPACT FRONT WHEEL DRIVE VEHICLE)

	1ST SAE FADE** (10 STOPS)		2ND SAE FADE** (15 STOPS)	
	DISC FRONT	DRUM REAR	DISC FRONT	DRUM REAR
COMBINATION 1	780	300	870	360
COMBINATION 2	985	235	1030	240
COMBINATION 3	760	200	855	235

* TEMPERATURES MEASURED BEFORE THE LAST STOP. ACTUAL TEMPERATURES FOR DISC BRAKES ARE 80-180°F HIGHER, AS MEASURED BELOW THE RUBBING SURFACE. SURFACE TEMPERATURES ARE IN EXCESS OF 1600°F (870°C).

** SAE J843c

TABLE 3

IMPROVEMENTS OFFERED BY

SEMIMETALLIC DISC PADS

- IMPROVED ENERGY ABSORPTION
- FADE RESISTANCE
    - TEMPERATURE INSENSITIVITY
    - IN-STOP FADE /
    - SPEED SPREAD
- FRICTION STABILITY (FMVSS 105-75)
- HIGHER TEMPERATURE CAPABILITIES (LIFE)
- ROTOR COMPATIBILITY
    - SCORING
    - HEAT CHECKING
- REDUCED NOISE
- SMALLER BRAKE SIZING

TABLE 6

CHARACTERISTICS OF REINFORCING AGENTS

TYPE	ASBESTOS [illegible]	FIBERGLAS [illegible]	MINERAL FIBER	SUZORITE MICA	FIBERFRAX (CHOPPED)	WOLLASTONITE	[illegible] FIBER	GRAPHITE WEB	CARBON WEB	SOLKA-FLOC	KEVLAR 29	STEEL FIBER
MANUFACTURER	[illegible]	[illegible]	[illegible]	[illegible]	CARBORUNDUM	[illegible]	[illegible]	UNION CARBIDE	UNION CARBIDE	BROWN CO.	DUPONT	AMERICAN STEEL WOOL
COMPOSITION (WEIGHT PERCENT)	[illegible]	[illegible]	[illegible] Other [illegible]	[illegible] Other [illegible]	[illegible] Other [illegible]	[illegible]	[illegible]	99.96 C	[illegible]	CELLULOSE	AROMATIC POLYAMIDE 100% ORGANIC	SAE 1010 C [illegible] Mn [illegible] S [illegible] Fe [illegible]
COST ($/LB)**	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SHAPE LENGTH (μm) DIAMETER (μm) ASPECT RATIO	FIBER [illegible]	FIBER [illegible]	FIBER [illegible]	FLAKE [illegible]	[illegible]	FIBER [illegible]	FIBER [illegible]	FIBER [illegible]	FIBER [illegible]	FIBROUS [illegible]	FIBER [illegible]	FIBER [illegible]
SPECIFIC GRAVITY	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
TENSILE STRENGTH (PSI)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]	[illegible]		[illegible]	
THERMAL STABILITY [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
HARDNESS (MOH)	[illegible]	[illegible]		[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MISCELLANEOUS INFORMATION		[illegible]	[illegible]			[illegible]	[illegible]			[illegible]	[illegible]	

*[illegible]
**[illegible]

TABLE 6

DIRECT SUBSTITUTIONS AND THEIR FAILURES

FORMULATION	REINFORCEMENT	STRENGTH	PERFORMANCE
BASELINE	ASBESTOS	o STRONG NO DEFECTS	o STABLE FRICTION GOOD WEAR RESISTANCE
b,c,e	GLASS	o PAD SURFACE TEAROUT	o ERRATIC FRICTION, FADE, HIGH PAD WEAR, AND SCORED ROTOR
d	MICA	o PAD SURFACE AND EDGE TEAROUTS	o GOOD FRICTION, SL FADE, HIGH PAD, AND ROTOR WEAR
f	GLASS/MICA	o WEAK	o POOR FRICTION, FADE, AND INNER PAD WEAROUT
g	GLASS/FIBERFRAX/GRAPHITE	o STRONG	o ROUGHNESS, FADE, ACCEPTABLE PAD WEAR, AND SCORED ROTOR
h	GLASS/WOLLASTONITE	o PAD SURFACE TEAROUT	o IN-STOP FADE, ACCEPTABLE PAD WEAR, AND SCORED ROTOR

TABLE 6

TENSILE STRENGTH DATA

FORMULATION	REINFORCER	TENSILE STRENGTH (PSI) MIN	AVG	MAX
BASELINE	ASBESTOS	3100	4000	4600
A	GLASS FIBER	3400	4800	6350
B	MINERAL FIBER	600	1300	1850
C	WOLLASTONITE	850	1500	2350
D	SUZORITE MICA	850	1400	1750
E	GLASS*	2750	3500	3750
B'	SILANIZED MINERAL FIBER	2900	3150	3250

*REDUCED CONTENT

TABLE 7

SAMPLE DYNAMOMETER TEST RESULTS

FORMULATION	REINFORCER(S)	250F		450F		650F		250R+		ROTOR WEAR
		μ	W*	μ	W	μ	W	RF	RW	
BASELINE	ASBESTOS	0.32	0.002	0.28	0.004	0.30	0.022	1.00	2.62	0.0000
A	GLASS FIBER	0.32	0.005	0.23	0.010	0.16	>0.080	1.31	1.70	0.0003
F	WOL/GF	0.33	0.004	0.34	0.009	0.16	>0.040	1.16	1.68	0.0003
G	MICA/GF	0.49	0.004	0.19	0.010	0.22	>0.060	1.08	2.31	0.0001
H	MF/GF	0.32	0.004	0.17	0.012	0.16	>0.080	1.37	-	0.0001
J	FRAX/GF	0.36	0.009	0.45	0.013	0.50	>0.200	-	-	>0.0005
K	FF/GF	0.36	0.003	0.50	0.005	0.32	0.016	1.75	2.07	0.0001
L	SOFL/GF	0.35	0.002	0.18	0.003	0.18	>0.080	-	-	0.0000
M	PROPRIETARY	0.35	0.002	0.22	0.003	0.18	-	1.20	1.12	0.0001
S	PROPRIETARY	0.45	0.002	0.45	0.006	0.46	0.018	1.04	2.27	0.0001

* ALL WEAR FIGURES ARE IN INCHES

\+ RERUN USED TO PROVIDE RELATIVE FRICTION (RF) AND RELATIVE WEAR (RW) TRENDS AFTER HIGH TEMPERATURE OPERATION

TABLE 8

INERTIAL DYNAMOMETER TEST RESULTS

	BURN		300F		450F		600F		300F		ROTOR
	LP*	W**	LP	W	LP	W	LP	W	LP	W	W
BASELINE	380	0.004	660	0.003	700	0.009	490	0.028	470	0.007	.0000
S	400	0.003	400	0.003	300	0.008	280	0.018	-	-	.0007
W	400	0.003	400	0.003	360	0.007	300	0.015	-	-	.0004
AA	400	0.002	370	0.002	340	0.006	390	0.008	440	0.003	.0003
AD	420	0.003	650	0.003	600	0.012	450	0.037	330	0.006	.0002
AL	440	0.003	510	0.002	580	0.008	430	0.034	270	0.004	.0000

* ALL LINE PRESSURES ARE IN PSI

** ALL WEAR FIGURES ARE IN INCHES

(1977 FULL SIZE STATION WA[illegible] [illegible]OADED TO 5540 LBS)

FRONTS*	CLASS A ORGANIC D7180 30 MPH (48 KMPH)	CLASS A ORGANIC D7180 60 MPH (97 KMPH)	NON-ASBESTOS ORGANICS DA 30 MPH (48 KMPH)	NON-ASBESTOS ORGANICS DA 60 MPH (97 KMPH)	NON-ASBESTOS ORGANICS DN 30 MPH (48 KMPH)	NON-ASBESTOS ORGANICS DN 60 MPH (97 KMPH)
PREBURNISH EFFECTIVENESS**						
FULL SYSTEM	500	500	440	460	440	400
POST-BURNISH EFFECTIVENESS**						
FULL SYSTEM	600	600	520	530	500	420
FRONTS ONLY	1180	970	1020	900	620	620
1ST SAE FADE (10 STOPS)** MAX	-	1100 MAX	-	1000 MAX	-	1000
(RECOVERY - 10)	(410)	-	(380)	-	(320)	-
2ND SAE FADE (15 STOPS)** MAX	-	800 MAX	-	800 MAX	-	880
(RECOVERY - 10)	(410)	-	(360)	-	(340)	-
POST-FADE EFFECTIVENESS**						
FULL SYSTEM	600	500	450	460	420	460
FRONTS ONLY	900	670	960	850	700	920
WEAR (MILS)						
BURNISH (F/R)	6/6		11/9		11/6	
FADES (F/R)	42/3		33/3		22/2	
TOTAL PADS (F/R)	48/9		44/12		33/8	
TOTAL ROTOR	0		1.0		1.5	
NOISE RATINGS						
FRONTS	10		8		6-8	
REARS	10		10		10	

* ALL TESTS USED SAME REARS (BX4641A/H3133)

** LINE PRESSURES NEEDED FOR 15 FPSPS DECELERATION PER SAE J843C