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FABRICATION AND TEST OF EXPERIMENTAL AUTOMOTIVE FRICTION MATERIALS

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Three classes of experimental ingredients having good high temperature stability were substituted, singly and in combination, for corresponding ingredients in a standard friction material. The effects of substitution were evaluated by physical and chemical analysis, and principally by determination of friction and wear properties as a function of temperature on a sample drag dynamometer.

The major finding was the demonstration of the potential of potassium titanate fiber for the improvement of a friction material of the secondary lining type. For example, the maintenance of a mean friction coefficient of 0.35 between 232 and 343°C (450 and 650°F) was achieved in the presence of the titanate fiber, as opposed to a value of 0.30 in its absence. Wear improvement of the order of 30 to 40% also becomes possible by proper adjustment of resin content and potassium titanate fiber-to-asbestos ratio.

An improved formulation based on the standard lining, in which one half of the asbestos has been replaced by potassium titanate fiber and in which the phenolic resin content has been increased by 40%, was fabricated and tested on a full scale inertial dynamometer. Results suggested that this formulation offers the potential for greater friction stability and less speed spread than the standard, and thus has improved properties for meeting the FMVSS 105-75 requirements.

Formulations containing the other two ingredient types showed no improvement relative to the standard lining. p-Polyphenylene substitution for cashew friction particles brought about a large loss in friction without improving wear. Polyimide resin substitution gave friction and wear properties that were comparable to those of friction materials containing the standard phenolic resin.

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FOREWORD

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ABSTRACT

Three classes of experimental ingredients having good high temperature stability were substituted, singly and in combination, for corresponding ingredients in a standard friction material. The effects of substitution were evaluated by physical and chemical analysis, and principally by determination of friction and wear properties as a function of temperature on a sample drag dynamometer.

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SUMMARY

1.1 OBJECTIVE

This Report describes work done under NASA Contract NAS 2-7758, "Fabrication and Test of Experimental Automobile Brakes," in the period August 1973 to March 1976. The objective of the project reported herein was to determine the effect on friction and wear of a commercial friction material formulation modified by substitution of several types of experimental ingredients provided by NASA. The approach taken was to substitute, singly and in combination, the experimental ingredients for the corresponding ones in the standard (commercial) composite. The effects of substitution were evaluated by physical and chemical analysis, and principally by tests of friction and wear as functions of temperature on a sample drag dynamometer. The experimental formulation showing the best improvement over the standard material was subjected to further testing on a full-scale inertial dynamometer. Its performance was compared to that of the standard in two separate tests: a dynamometer simulation of Federal Motor Vehicle Safety Standard (FMVSS 105-75)* and an accelerated wear test.

The experimental ingredients supplied by NASA were:

(1) potassium titanate fiber (substituted for asbestos reinforcement fiber)

(2) three types of polyphenylene (substituted for cashew-type friction particles)

(3) two types of polyimide resin (substituted for phenolic resin binder)

All three ingredient types were more thermally stable than the corresponding standard components, and were thus expected to contribute to

*FMVSS 105-75 specifies requirements for hydraulic service brake and associated parking brake systems to insure safe braking performance under normal and emergency conditions.

greater high-temperature wear resistance of the brake lining. Other material properties were also considered in making the above selections including the lower hardness of the potassium titanate fiber relative to asbestos and its degradation products.

1.2 ACCOMPLISHMENTS

The major finding of this work was the demonstration of the potential of potassium titanate fiber for the improvement of a friction material of the secondary lining type. For example, the maintenance of a mean friction coefficient of 0.35 between 232 and 343°C (450 and 650°F) becomes possible in the presence of the titanate fiber, as opposed to a value of 0.30 in its absence. This becomes even more significant if it is pointed out that the corresponding mean values are 0.33 and 0.25 in the 316 to 343°C (600 to 650°F) range: fade can definitely be improved by incorporation of potassium titanate fiber. Wear improvement of the order of 30 to 40% also becomes possible by proper adjustment of resin content and potassium titanate fiber-to-asbestos ratio. Having been demonstrated, this principle now remains to be exploited for general application in the friction material industry.

Actual development of an improved formulation has also been accomplished, as based on the results of sample drag dynamometer tests and single-wheel full-scale inertial dynamometer tests. This formulation is based on the standard lining, in which one half of the asbestos has been replaced by potassium titanate fiber and in which the resin content has been increased by 40%. A brief exploration within the range of compositions that are possible and that can be fabricated indicated that the cited composition is near an optimum for friction and wear improvement. However, further study is needed to establish whether other composition ranges exist in which friction and wear improvement is possible. Full-scale testing also suggested that this formulation offers the potential for greater friction stability and less speed spread than the standard, and thus is more favorable for meeting the FMVSS 105-75 requirements.

Although only a very limited number of compositions could be studied with each ingredient type, results with the polyphenylenes and the polyimide resins were not considered favorable. Friction of samples containing polyphenylene was very poor, and tended to return to the value for the standard lining, at any given temperature, as the amount of polyphenylene was reduced from 100% replacement of cashew friction modifier. Wear was not improved by the presence of polyphenylene. Replacement of phenolic resin with polyimides gave friction materials with friction and wear similar to, but not better than, the standard.

1.3 RECOMMENDATIONS

Among the questions that still must be examined, should the specific lining formulation based on the standard lining incorporating potassium titanate fiber be a candidate for development in commercial applications, are those concerning its behavior in a vehicle test and its large scale manufacturability. First of all, the vehicle test would establish in actual usage the lining's performance in a FMVSS 105-75 test; it would also establish the wear pattern of the lining in actual usage such as the industry's Detroit or Los Angeles Traffic Tests. In addition it would allow the evaluation of the effect of potassium titanate fiber on drum wear and on the more subjective but crucial requirement of minimal brake noise. The lining will not be considered acceptable before it is established that it satisfactorily meets the above requirements. As for its manufacture, additional development is necessary; either the composition or the processing or both may require adjustment before it can be fabricated on a large scale. This is part of the normal development process, and it is not possible at this time to predict what difficulties may or may not be encountered.

Based on the results of this study, the following recommendations can be made regarding the three experimental materials, insofar as their suitability for inclusion in automotive friction materials is concerned:

(1) Incorporation of potassium titanate fiber, providing the formula contains a sufficient amount of resin binder, allows

the fabrication of formulations with improved high temperature wear, and improved friction properties for meeting FMVSS 105-75 requirements.

We must consider, however, that the present work has only demonstrated the potential for friction material improvement in this fashion. Very few full-scale tests were performed, and none were on a vehicle; improvements in the crucial full-scale tests are real, but questions regarding noise and rotor (or drum) wear still remain to be answered. Vehicle tests are therefore in order to answer some of these pending questions.

(2) p-Polyphenylene contributed undesirable frictional properties without improving wear; its inclusion in conventional automotive friction materials should not be considered further at this time without considerable additional investigation.

(3) The two polyimide resins studied gave friction and wear properties comparable to those of friction materials containing phenolic resin. In some cases, high temperature friction was even increased, although wear resistance tended to deteriorate. It should be recognized, however, that this is a limited study, and that there is a great need for further basic information about composite matrices of the friction material type containing polyimide resin. Results obtained in the present study could form a point of departure for a systematic study of such composites and means of optimizing their desirable high temperature properties.

SECTION 2
INTRODUCTION

2.1 OBJECTIVES AND APPROACH

2.1.1 Objectives

The objectives of this work, as paraphrazed from the Request for Proposal and the Contract were as follows:

(1) General Objective - It was the purpose of this contract to provide a brake lining with improved performance for a particular road vehicle, utilizing specific types of experimental materials.

(2) Specific Objectives - The experimental materials were assessed by measuring the effect of the performance of linings in which the experimental materials were substituted for the corresponding ingredients of a particular lining type designated the standard lining. More extensive lining formulation changes from the standard were tested for the purpose of achieving desired performance characteristics, and one lining was selected for qualification tests.

2.1.2 Technical Approach

Phase I

2.1.2.1 Selection of Standard Linings

The standard linings served as a standard of comparison and served as the matrix from which the experimental linings were constructed. The standard linings were chosen to comply with the manufacturers' specifications of the standard vehicle. The ingredients of the standard linings included, but were not restricted to, the following materials:

Fiber - a chrysotile asbestos of grade suitable to the application.

Binder - phenolic or modified phenolic resin.

Friction Modifier - cardolite.

2.1.2.2 Characterization of Experimental Materials

The experimental materials available for the program are listed in Table 2.1.

Table 2-1 - Experimental Materials

CLASS OF INGREDIENT	EXPERIMENTAL MATERIAL TYPE	NUMBER
Friction Modifier	Polyphenylene	3
Binder	Maleimide Resin	2
Fiber	Potassium Titanate	1

The experimental materials were characterized by the following measurements: thermogravimetric analysis (TGA) in both air and nitrogen, differential thermal analysis (DTA) in both air and nitrogen, specific gravity, and x-ray diffraction for potassium titanate both before and after thermal analysis.

2.1.2.3 Determination of Best Cure Conditions Using Experimental Binders

The effect of cure conditions on properties of composites containing the experimental binders was explored to determine the conditions that provide "optimum" properties for friction material application. Each of the two binder types was cured in an artificial composite at two temperatures for two durations at two pressure levels for a total of eight cure conditions per binder type. Thermal analysis, solvent extraction and density determination were performed on selected samples representing extremes of conditions. Shear strength measurements were made on friction materials containing the experimental binders representing five widely differing conditions of molding temperature, pressure and time. The initial choice of conditions was determined on the basis of data supplied by ARC.

2.1.2.4 Determination of Suitable Processing Techniques for the Experimental Fiber

Mixing and molding techniques for composites containing the experimental fiber with and without the presence of asbestos fibers were explored in an effort to determine techniques that provided suitable fiber distribution.

2.1.2.5 Fabrication and Testing of Experimental Friction Materials

Upon determining suitable cure conditions of experimental binders and processing techniques for the experimental fiber, samples were fabricated and their following properties determined: friction coefficient and wear as functions of temperature using a sample dynamometer, density and porosity. Sixty samples were fabricated initially to explore the effect of inclusion of the experimental ingredients into the standard formulas, including several duplicate formulations. Sixteen additional formulas were prepared and tested to explore further the effects of one of the experimental ingredients. Five of the experimental samples that showed the best friction and wear results as well as the standard secondary sample were tested for shear strength, permeability, and by thermogravimetric and differential thermal analyses. Seven experimental samples and the two standards were tested by x-ray diffraction after TGA in an attempt to identify changes in the fibrous materials.

Full-scale brake linings of the optimum experimental formulation and the standard primary and secondary linings were fabricated for the full-scale inertial dynamometer tests. A quantity of brake lining slabs totaling 4 square feet (0.37 m^2) in area and 3/8 inches (0.95 cm) thick, of the optimum formulation, was also fabricated and delivered to ARC for further testing.

Phase II

2.1.2.6 Testing and Evaluation of Experimental Friction Materials Screened in Phase I on a Full-Scale Inertial Dynamometer

A total of twelve primary and secondary linings were fabricated and tested on a full-scale inertial dynamometer. The standard primary was used in all cases, coupled with either a standard or an experimental secondary lining. The test schedules used were a single-wheel simulation of FMVSS 107-75, and an accelerated wear test in which incremental wear was measured at a number of progressively increasing temperatures.

2.2 BACKGROUND*

2.2.1 Energy Absorption by Friction Materials

2.2.1.1 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.

2.2.1.2 Basic Principle of Operation of the Duo-Servo Brake

The Duo-Servo principle is the basic principle of operation of the majority of passenger car drum brakes in use at present.

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* Much of the material in this Section is adapted from "Brake Emissions: Emission Measurements from Brake and Clutch Linings from Selected Mobile Sources," by M.G. Jacko and R.T. DuCharme, March, 1973, EPA Report 68-04-0020.

The brake shown schematically in Figure 2-1 is representative of a left hand assembly as viewed from the outside of the vehicle. Drum to lining and shoe to anchor clearances are purposely exaggerated so that the movement of the shoes can be easily shown. The operational description applies to either the front or rear brake assembly.

When the brake is in its released position, the shoe return spring holds the primary and secondary shoes against the anchor and clearance is provided between the linings and drum rubbing surface. When hydraulic pressure is applied to the brake system by the master cylinder, the force from the wheel cylinder is applied through the links to the brake shoes and the shoes are moved out to contact the drum. If the drum is rotating counter-clockwise as indicated in Figure 2-1 (corresponding to forward motion of the vehicle), the friction force between the drum and the linings rotates the shoes counter-clockwise. This movement causes the primary shoe to leave the anchor and causes the secondary shoe to move against the anchor. The frictional force between the drum and the primary shoe is transmitted through the pivot screw and adjusting nut assembly to the secondary shoe. This servo action increases the pressure between the secondary shoe and the drum.

When the hydraulic pressure is removed from the wheel cylinder, the shoe return spring moves the shoes away from the drum surface and the shoes return to the anchor.

If the brakes are applied while the vehicle is backing (corresponding to clockwise drum rotation, Figure 2-1), the shoes rotate clockwise with the drum. This causes the secondary shoe to leave the anchor and causes the primary shoe to move against the anchor. In this case the secondary shoe applies the primary shoe against the drum. Action of the brake therefore is the same in reverse as in its forward direction.

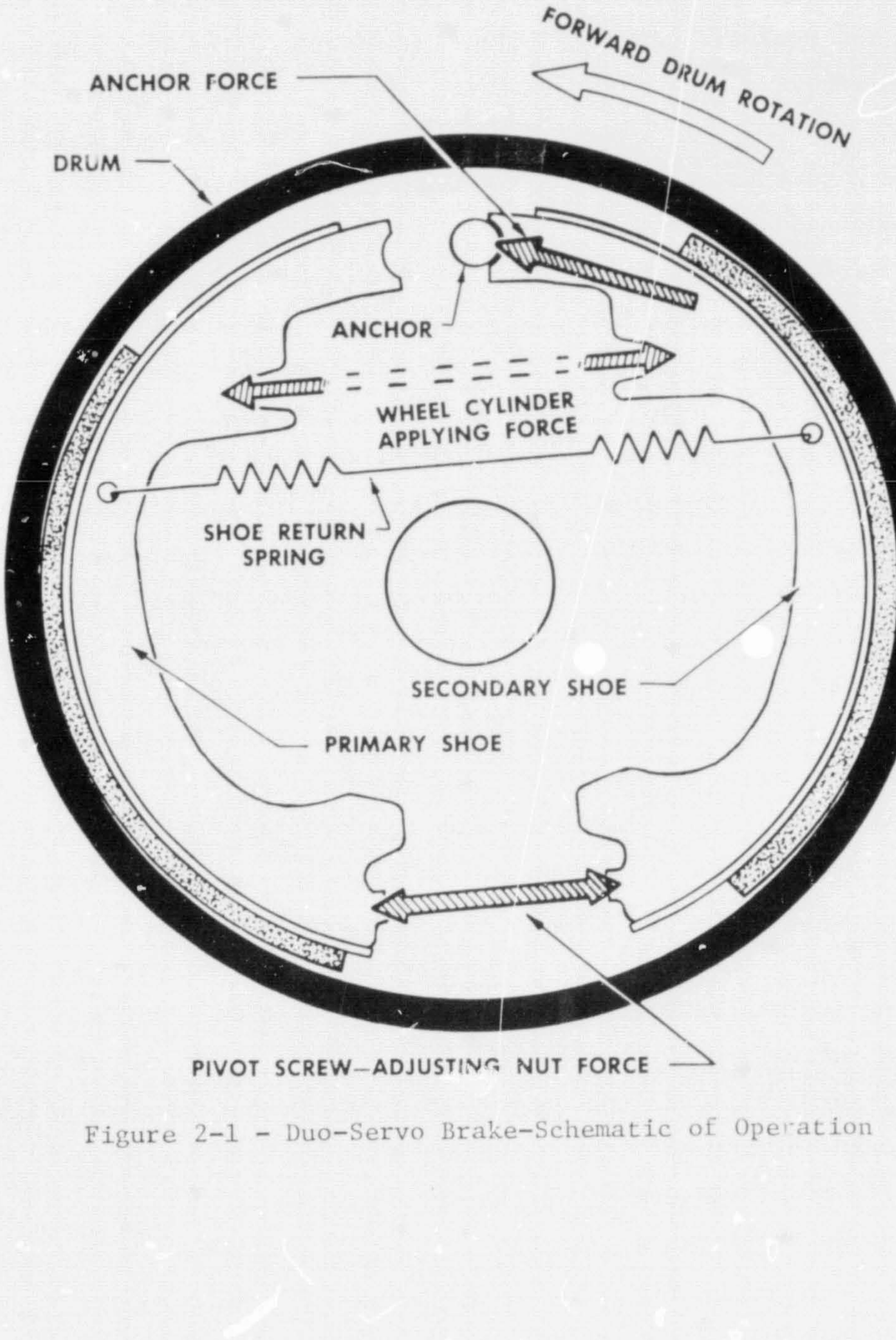

Figure 2-1 - Duo-Servo Brake-Schematic of Operation

2.2.2 Compositions of Friction Materials

2.2.2.1 Generalized Classifications

Table 2-2 gives typical compositions of drum lining and disc pad[(2-1)] 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 and wear 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.

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

	Drum Linings		Disc Pads	
	Primary	Secondary	Class A Standard	Class B Heavy-Duty
Resin Binder	20-30	25-35	18-22	15-18
Asbestos Reinforcement	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
Copper/Brass		0-5		5-10
Misc. Inorganics		5-10	0-5	5-15

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

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

Structurally, it is a pseudohexagonal network of SiO_4 tetrahedra forming a sheet in which all the tetrahedra point one way. A layer of brucite, $Mg(OH)_2$, is joined to the SiO_4 network in such a way that, on one side, two out of every three hydroxyls are replaced by oxygens at the apices of the tetrahedra (Figure 2-2). The macromolecule consists of parallel sheets of brucite-silica layers structured in cylindrical lattices involving closed concentric cylinders, spirals, and sometimes helical arrangements.[2-2]

Bendix Research Laboratories' scientists have been studying asbestos for several years. Figure 2-3 presents the results of differential thermal analysis (DTA) and thermogravimetric analysis (TGA) studies for a common short-fiber grade of chrysotile asbestos.[2-3] The transition at approximately 370°C (700°F), in both the DTA and the TGA thermograms represents the dehydration of the brucite (magnesium hydroxide), the 1.4 percent weight loss corresponding to an approximate concentration of 4.5 percent brucite. The transition at 680°C (1250°F) in both thermograms represents the major dehydroxylation reaction in chrysotile asbestos. At 860°C (1580°F), a sharp exotherm, not associated with any weight change, represents the conversion of the dehydroxylated chrysotile to forsterite ($2\ MgO \cdot SiO_2$) or olivine [$2(Mg_{1.00-x}Fe_x)O \cdot SiO_2$, where x is approximately 0.02 to 0.16]. TGA results for the asbestos were identical in air and in nitrogen.

Asbestos fibers are present in greater concentration (by volume percent) than any other ingredient in friction materials. As a consequence, both the relative concentration and the type of asbestos used (with respect to fiber length and "openness" or absorptiveness) significantly affect the amount of resin binder required and the processing and performance characteristics.

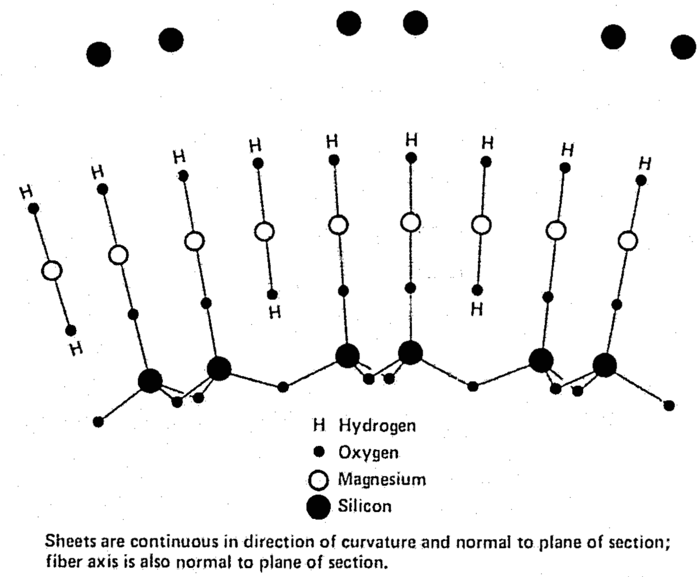

Figure 2-2 - Schematic Structure of Chrysotile Asbestos

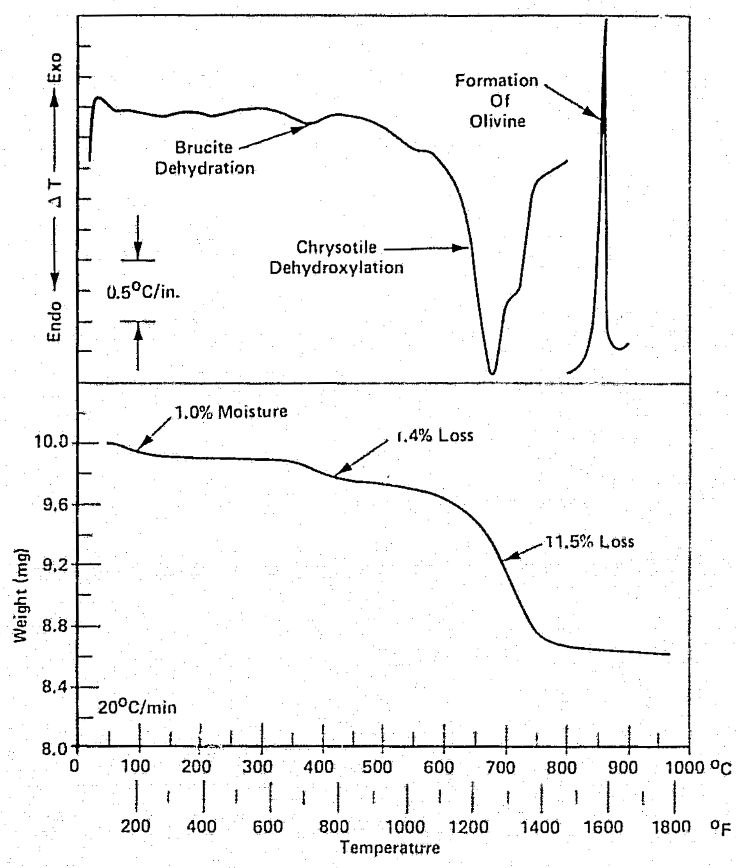

Figure 2-3 - DTA and TGA Thermograms for Chrysotile Asbestos (Bendix Data)

2.2.2.3 Property Modifiers

Friction modifiers can in general, be divided into two classes: non-abrasive and abrasive.(2-4) Organic materials are generally less abrasive than inorganic as described below.

Non-Abrasive Modifiers

Non-abrasive friction modifiers can be classified further as low friction and high friction. The most common and best known of the high-friction materials is friction dust, a cured resinous material. The most frequently used variety is derived from cured or polymerized cashew-nut-shell liquid, chemically a phenolic compound. When heated with hardening agents, such as hexamethylenetetramine or formaldehyde, it becomes sufficiently hard or polymerized to be granulated. Many other cured resinous or polymeric materials, some with fillers, are also used. Certain friction dusts are combinations of these materials and cashew resin. Ground rubber is normally used in particle sizes similar to, or slightly coarser than, those of the cashew friction dusts for noise, wear, and abrasion control.

Carbon black, graphite, petroleum coke flour, or other carbonaceous materials may also be added as friction modifiers to lower the friction coefficient or to reduce noise. These materials are normally used in the form of fine powders or particles, although graphite is sometimes used in coarse particles or pellets. The amount of friction modifier added is dependent upon the properties desired in the final composite.

Abrasive Modifiers

Abrasive modifiers, such as alumina and silica, are usually used in relatively small amounts and only in very fine particle sizes (generally 100 mesh or finer). Particle size is limited by the fact that large particles of such hard materials would groove and wear the mating surfaces. Minerals are generally added to improve wear resistance at minimum cost. Those most commonly used are ground limestone (whiting) and barytes (barium sulfate), though various types of clay, finely divided silica, and other inexpensive or abundant inorganic powders may also perform this function. Such materials are inorganic in nature and tend to detract from noise properties and mating surface compatibility.

Metals or metal oxides may also be added to perform specific functions. Brass chips are frequently found in heavy-duty friction materials where, as scavengers, they break up undesirable surface films. Zinc and aluminum are also used. Zinc chips, in relatively small amounts, can contribute significantly to recovery of normal performance following fade.

2.2.2.4 Resin Binders

Many types of materials, some thermoplastic and some thermosetting, have been used as binders in friction materials. As the heat-resistance and duty requirements of friction materials have increased, the thermoplastic types have become more and more inadequate and the thermosetting types have been called upon for their greater temperature and strength capabilities. In selecting a resin binder or binder system for friction materials, the processing characteristics must be considered along with final frictional and other physical properties.

Two types of resin or resin system are used in practice. In wet processing, the binder is a viscous liquid having characteristics suited to the more fluid or plastic processing techniques. The most critical of these characteristics include viscosity (critical in terms of mix coverage), processing time and temperature requirements (critical in terms of solvent evaporation), solids content (critical for uniformity to ensure that all batches have the same effective resin binder content), and "green" strength (the physical strength to hold together the other raw materials for satisfactory handling in the semi-processed state). In dry processing, the binder is a powdered material that is mixed directly with the other raw materials; it does not become functional until heat and pressure are applied. Its most critical characteristics include particle size (critical for coverage, uniform dispersion, and ultimate part strength), flow properties (critical in terms of dispersion and processing requirements), and cure-rate properties (time requirements for obtaining suitable physical properties at the various chemical stages).

Synthetic resins such as phenolics and oil-modified or otherwise modified phenolics are the most commonly used friction material binders. They are prepared by condensation of the appropriate phenol (sometimes modified) with formaldehyde, in the presence of an acidic catalyst to yield a novolak or in the presence of a basic catalyst to yield a resole. Polymerization at elevated temperatures results in an insoluble, infusible mass.(2-4)

2.2.3 Friction Material Reactions

2.2.3.1 Absorption and Conversion of Energy

The automobile brake converts the kinetic energy of the moving vehicle into heat, absorbs the heat, and eventually dissipates it to the atmosphere. 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, measured at approximately 40 mils (0.10 cm) from the interface, may rise to 149°C (300°F); the interface itself is hotter. Most of the heat is removed from the interface by convection and conduction.(2-5) 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 871°C (1600°F) have been observed or calculated; the presence of olivine in the wear debris confirms that such temperatures have been reached.

2.2.3.2 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).

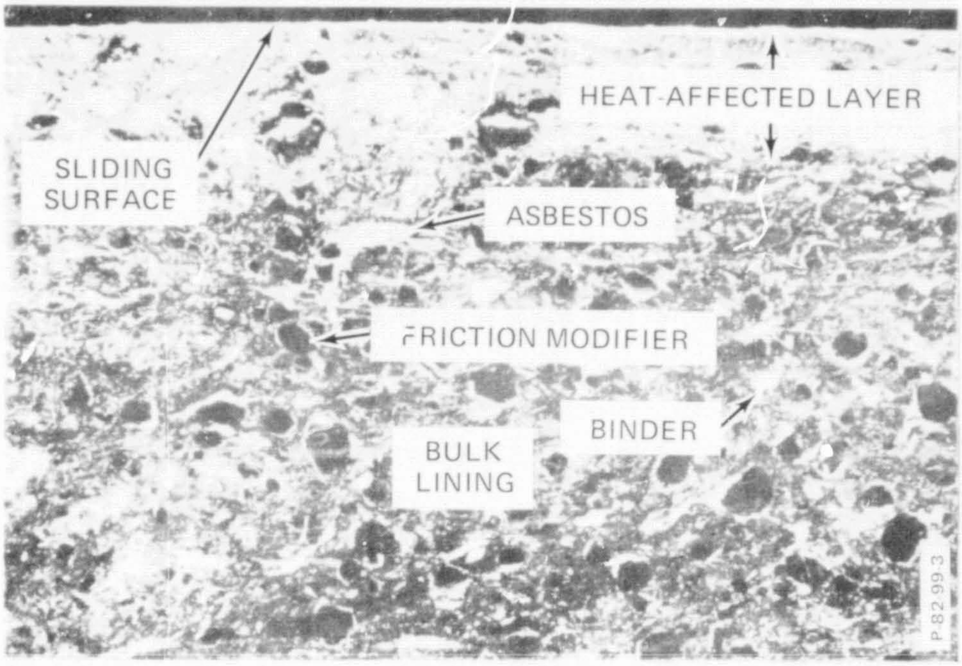

Figure 2-4 - Photomicrograph of Brake Lining Cross Section After 8550 Miles (13,760 Km) of Test-Track Service

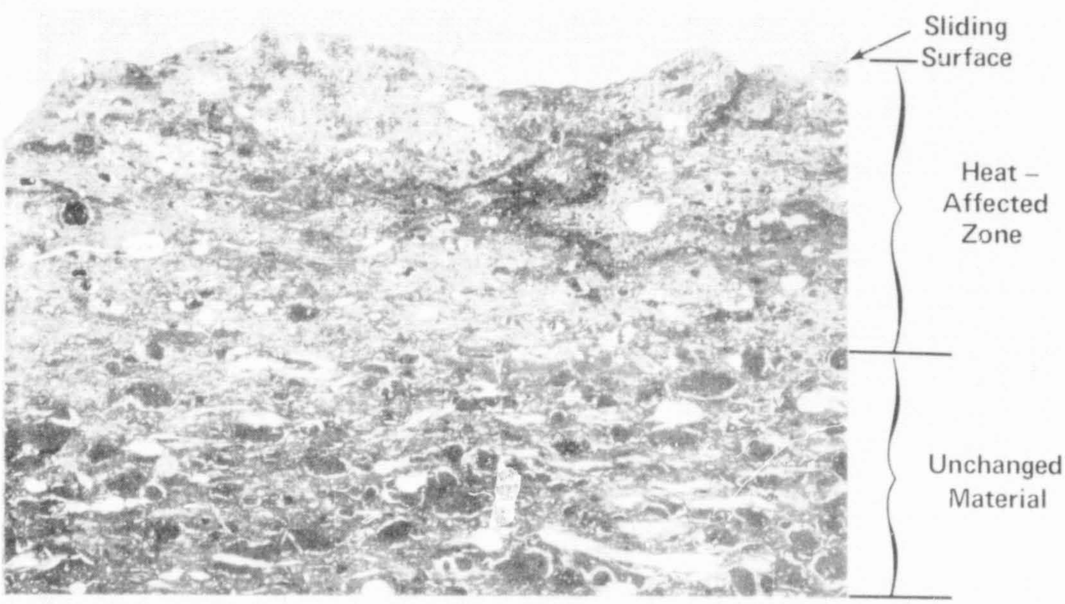

Figure 2-5 - Photomicrograph of Cross Section of Friction Material Test Specimen After More Than 10 Successive Stops from 100 mph (161 Kmph) on Bendix Full-Brake Dynamometer

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. At still higher temperatures, the asbestos converts from its fibrous form to an olivine powder with little or no reinforcing value. Figure 2-5 shows the frictional-heat-affected layer of lining which has experienced more than 10 successive stops from 100 mph (161 Kmph) without sufficient cooling between stops.[2-6]

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 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.[2-7] Fade can generally be ascribed to the formation of a gaseous, liquid, or low-friction solid phase at the interface, or to some combination of these phenomena. Figure 2-6 summarizes the physical and chemical changes which take place in the friction material as the temperature rises.[2-8] Figure 2-7 summarizes the physical and chemical changes which take place in the cast-iron rotor as the temperature rises.

2.2.4 Brake Lining Wear Mechanisms

2.2.4.1 Types of Wear

From the basic friction material engineering standpoint, wear resistance is inversely related to friction level and

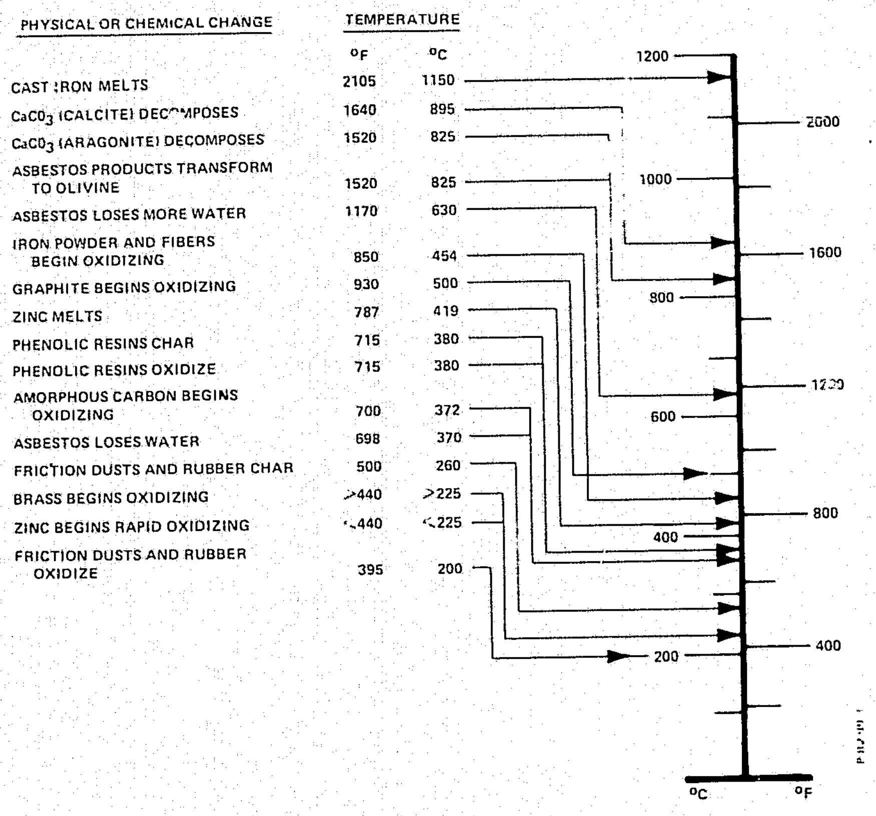

Figure 2-6 - Changes Occurring in the Friction Material as the Temperature Rises

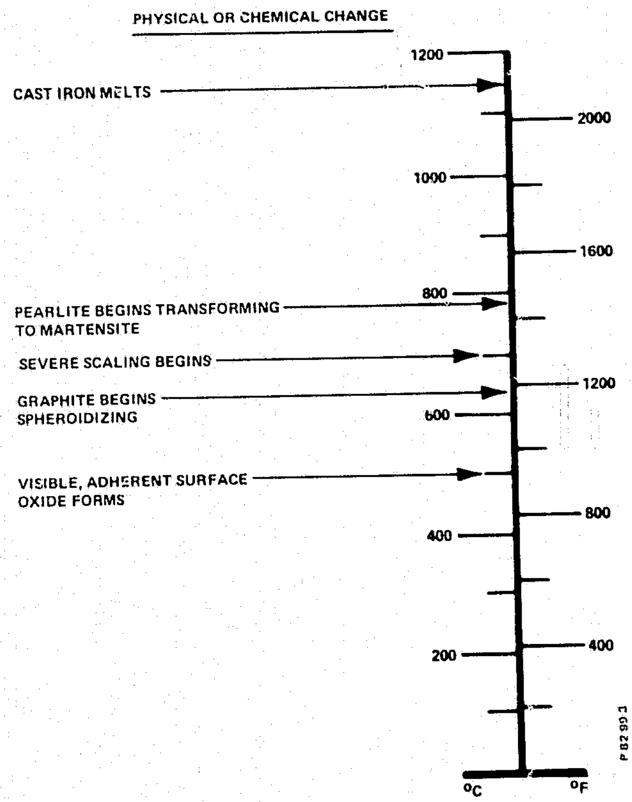

Figure 2-7 - Changes Occurring in the Rotor as the Temperature Rises other desirable performance characterisitics. Linings with faster wear rate and more frequent surface renewal generally have greater frictional stability. This circumstance is used to advantage in the development of primary-type linings 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 fade 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 lining wear may be defined as the sum total of the losses associated with five basic types of wear.[2-9]

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

As shown in Table 2-3, there are several possible mechanisms for each type of wear.

2.2.4.2 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), 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.

Table 2-3 - Wear Mechanisms in Friction Materials

<u>THERMAL WEAR</u>

- PYROLYSIS
- OXIDATION
- THERMOPARTICULATION
- MELTING
- EVAPORATION
- SUBLIMATION
- EXPLOSION

<u>ABRASIVE WEAR</u>

- TWO-BODY
  - ASPERITIES
  - SCORING
  - CRACK EDGES
  - PIT EDGES
- THREE-BODY
  - WEAR DEBRIS
  - ROAD DUST

<u>ADHESIVE WEAR</u>

- ORGANIC MATERIAL ADHESION
  - BINDER
  - FRICTION DUST
  - RUBBER
- INORGANIC MATERIAL ADHESION
  - METAL PARTICLES
  - ICE

<u>FATIGUE WEAR</u>

- THERMAL
  - CYCLING
  - SHOCK
- MECHANICAL
  - REPEATED BRAKING
  - DRUMS OUT OF ROUND
  - DISCS OUT OF PARALLEL

<u>MACRO-SHEAR WEAR</u>

- ACROSS THE PAD
- AT CORNERS AND EDGES
- THROUGH HEAT-AFFECTED LAYERS

It might be thought that rapid thermal wear occurs only at high soak temperatures.* In fact, however, thermal wear probably 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 [2-10, 2-11]

$$T - T_o = (g\mu vw/4aJ)[1/k_1 + k_2)]$$

where

- T is the "flash" temperature
- T_o is the soak temperature
- g is the acceleration due to gravity
- μ 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, and
- 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

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* 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 (0.051 to 0.13 cm) from the sliding interface.

fibrous asbestos to powdery olivine and transformation of pearlite to martensite in the cast-iron mating surface.

2.2.4.3 Abrasive Wear

Abrasive wear is of two types: two-body wear (Figure 2-8) and three-body wear (Figure 2-9). 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 2-10 is a 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.

2.2.4.4 Adhesive Wear

Adhesive wear, illustrated in Figure 2-11, 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.[2-12] 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.

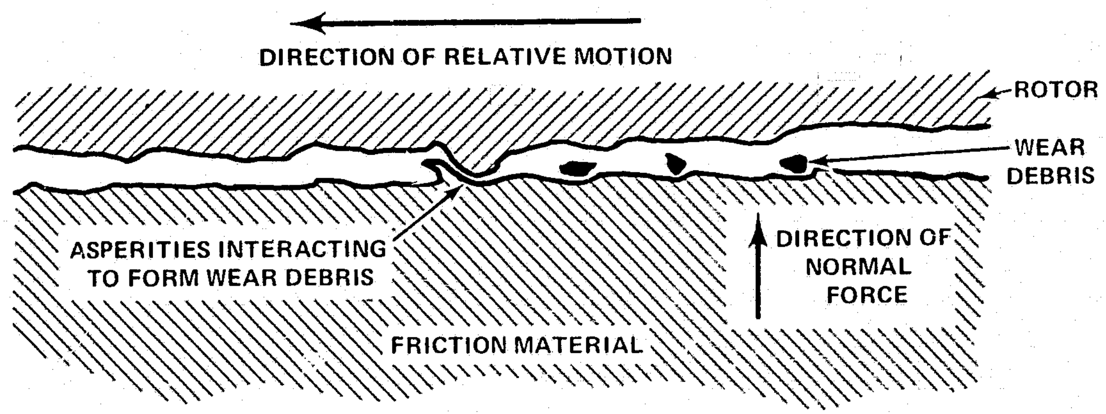

Figure 2-8 - Mechanism of Two-Body Abrasive Wear

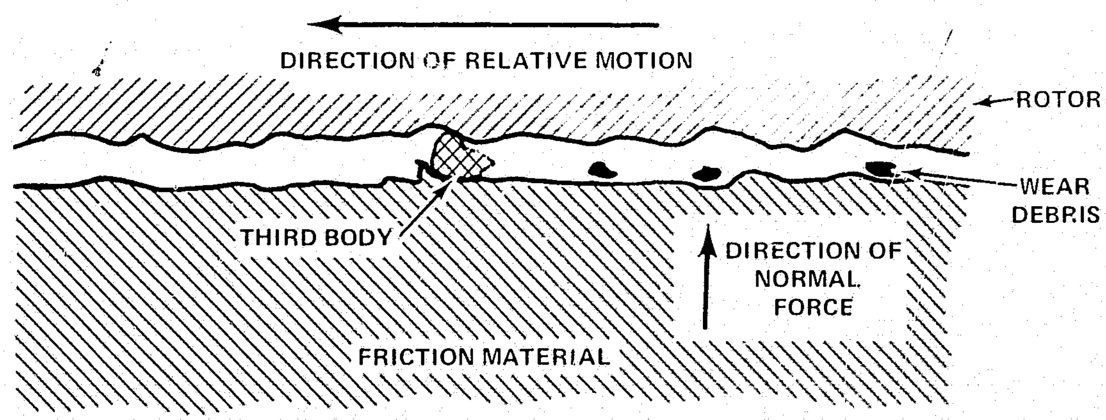

Figure 2-9 - Mechanism of Three-Body Abrasive Wear

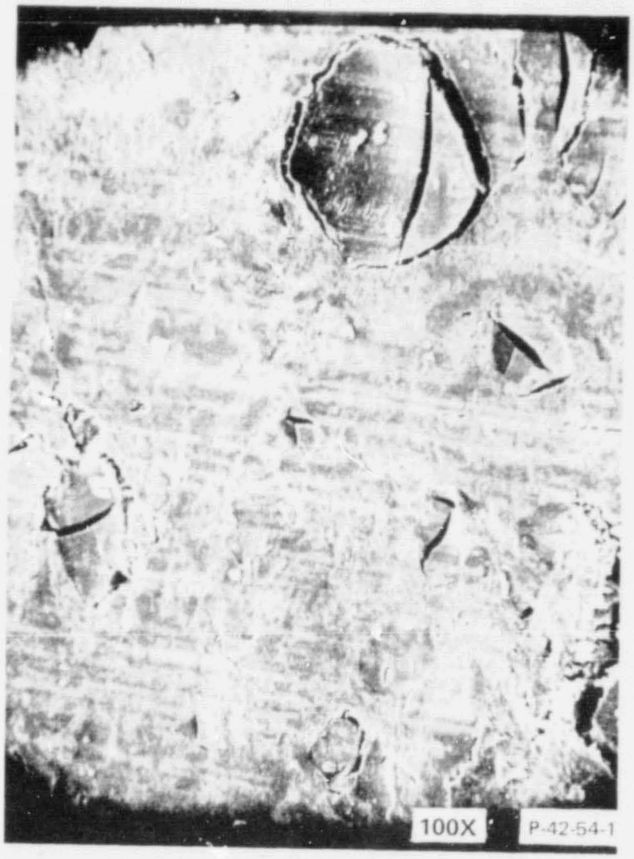

Figure 2-10 - Scanning Electron Photomicrograph Showing Abrasive Wear Tracks on Friction Material Surface and Adherent Wear Debris Particles

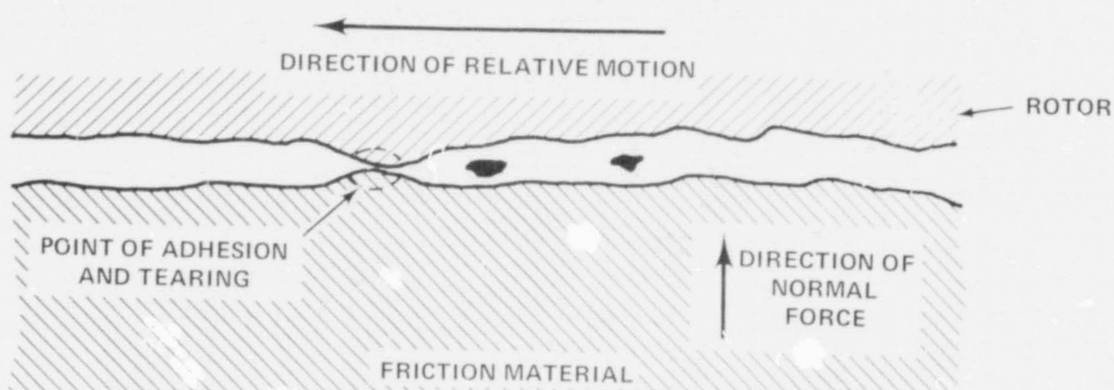

Figure 2-11 - Mechanism of Adhesive Wear

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.

2.2.4.5 Fatigue Wear

Fatigue wear (Figure 2-12) 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 2-10 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.

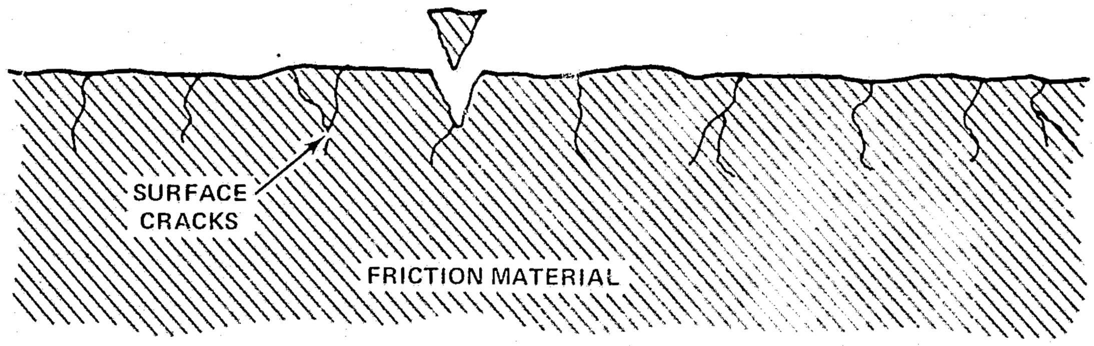

Figure 2-12 - Mechanism of Fatigue Wear

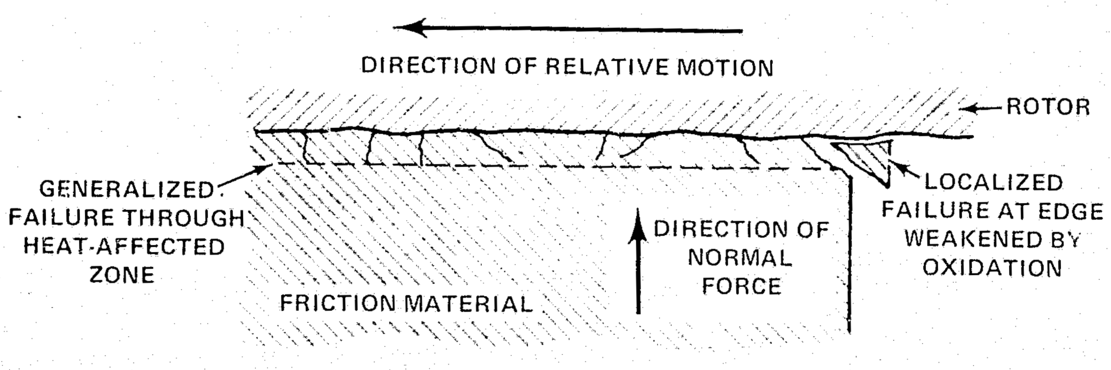

Figure 2-13 - Mechanism of Macroshear Wear

2.2.4.6 Macroshear Wear

Three types of material removal fall in the category of macroshear wear, which is illustrated in Figure 2-13.

A fracture, in shear, may occur accross 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.

A third type of macroshear wear can occur when a friction material such as that shown in Figure 2-12 is subjected to heavy loading following thermal abuse. The heat-affected layer in the material pictured is about 100 mils (0.25 cm) 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.

2.2.4.7 Predominant Wear Mechanisms

The predominant wear generation mechanism may be summarized simply (Figure 2-14):[(2-13)]

- Below 232°C (450°F)

  Abrasive and adhesive wear.

- Above 232°C (450°F)

  Thermal wear.

Figure 2-15 illustrates the wear loss of three different finds of friction materials as a function of temperature, illustrating these predominant wear mechanisms.

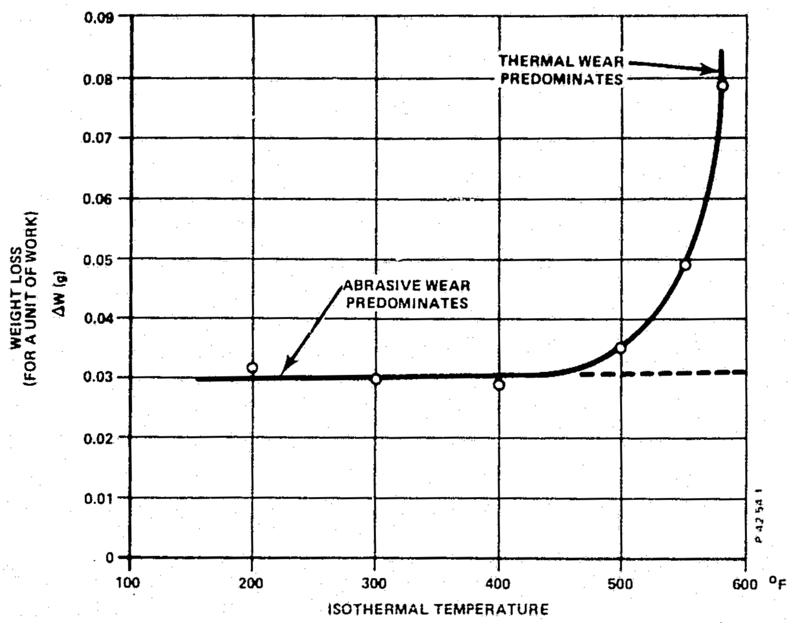

Figure 2-14 - Predominant Wear Mechanisms of Friction Materials

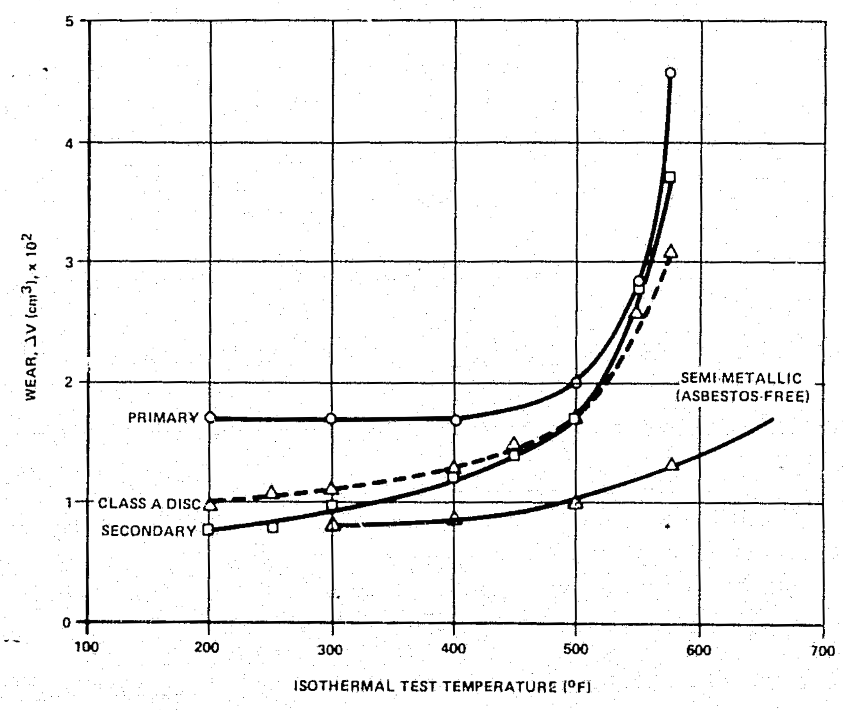

Figure 2-15 - Variation of Friction Material Wear with Temperature

2.2.4.8 Wear Equation

Work at Bendix Research Laboratories has indicated that each friction material wears at a given temperature according to a universal wear equation.(2-14)

$$\Delta W = k \cdot p^{a} \cdot V^{b} \cdot t^{c}$$

or

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

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 characterisitic of a given friction couple.

As development continues, this equation will be useful for predicting wear under various conditions of use.

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(2-13) S. K. Rhee, "Influence of Rotor Metallurgy on the Wear of Friction Materials in Automotive Brakes," SAE Paper 710247, presented at the SAE Automotive Engineering Congress, January 1971.

(2-14) S. K. Rhee, "Wear Equation for Polymers Sliding Against Metal Surfaces," Journal of Wear, 16, p. 431 (1970).

SECTION 3

EXPERIMENTAL

The specific experimental ingredients - potassium titanate fiber, polyphenylene friction modifiers and polyimide resin binders - were evaluated by determining the effect on performance of their substitution for corresponding ingredients in a commercial brake lining. In Phase I, the pure materials and selected experimental formulations were characterized by physical and chemical methods; the friction and wear properties of a large number of composite friction materials were measured with a sample dynamometer (Chase Machine). The most promising formulation resulting from this screening was subjected to full-scale inertial dynamometer tests for evaluation of friction and wear properties in Phase II.

This section will treat

3.1 . the characterization of experimental ingredients,

3.2 . the fabrication and characterization of composite experimental friction materials,

3.3 . procedures for dynamometer testing of friction materials.

Results of friction and wear tests will be presented and discussed in Section 4.

3.1 EXPERIMENTAL INGREDIENTS

3.1.1 <u>Potassium Titanate Fiber</u>

The generic ingredient of automotive friction materials representing the fibrous reinforcing agent is normally included in the form of asbestos, as described in Section 2. An attempt was made in this study to replace part or all of the asbestos with a synthetic potassium titanate fiber having very good thermal stability, but with hardness lower than that of asbestos for potentially lower brake lining and metal rotor wear. General properties of the material are as follows:

Formula: $(K_2O)_x\ (TiO_2)_z$, $z/x \sim 8$

Average fiber length: 8-10 μm

Average fiber diameter: 0.10 - 0.15 μm

Melting point: 2300-2390°F (1260-1310°C)

Moh hardness: 3

Density: ~3.3 g/cm^3

BET (N_2) Surface area: 7-10 m^2/gm

Additional properties are given by Linsen and Regester(3-1)

Thermogravimetric analysis (TGA) of the potassium titanate fiber, Figure 3-1, indicates no weight loss to 1000°C (1832°F), showing the material to be thermally stable. This may be compared to asbestos in Figure 2-3, which undergoes two decompositionssteps below 750°C (1382°F). Differential thermal analysis (DTA) of the potassium titanate fiber also shows a complete absence of distinguishing features, Figure 3-1, once again showing its thermal stability in the range of interest. X-ray diffraction spectra of the fresh material, as well as a sample that had been heated to 1000°C (1832°F) proved extremely complex and could not be analyzed in complete detail. Indications are that a slight modification has taken place as a result to exposure to the high temperature. The heat-treated sample matches quite well a reference spectrum for a compound with the empirical formula $K_2Ti_6O_{13}$.

3.1.2 Polyphenylenes

Preliminary tests at NASA-ARC indicated that, under certain conditions, some highly thermally stable materials of the general class known as polyphenylene exhibited high friction. A detailed account of the synthesis, scaled-up production processing and some properties of the specific type of polyphenylene used in this program may be found in the report by Vincent and Hamermesh.(3-2) A thorough description of its structure and properties have been given recently by Lerner.(3-3)

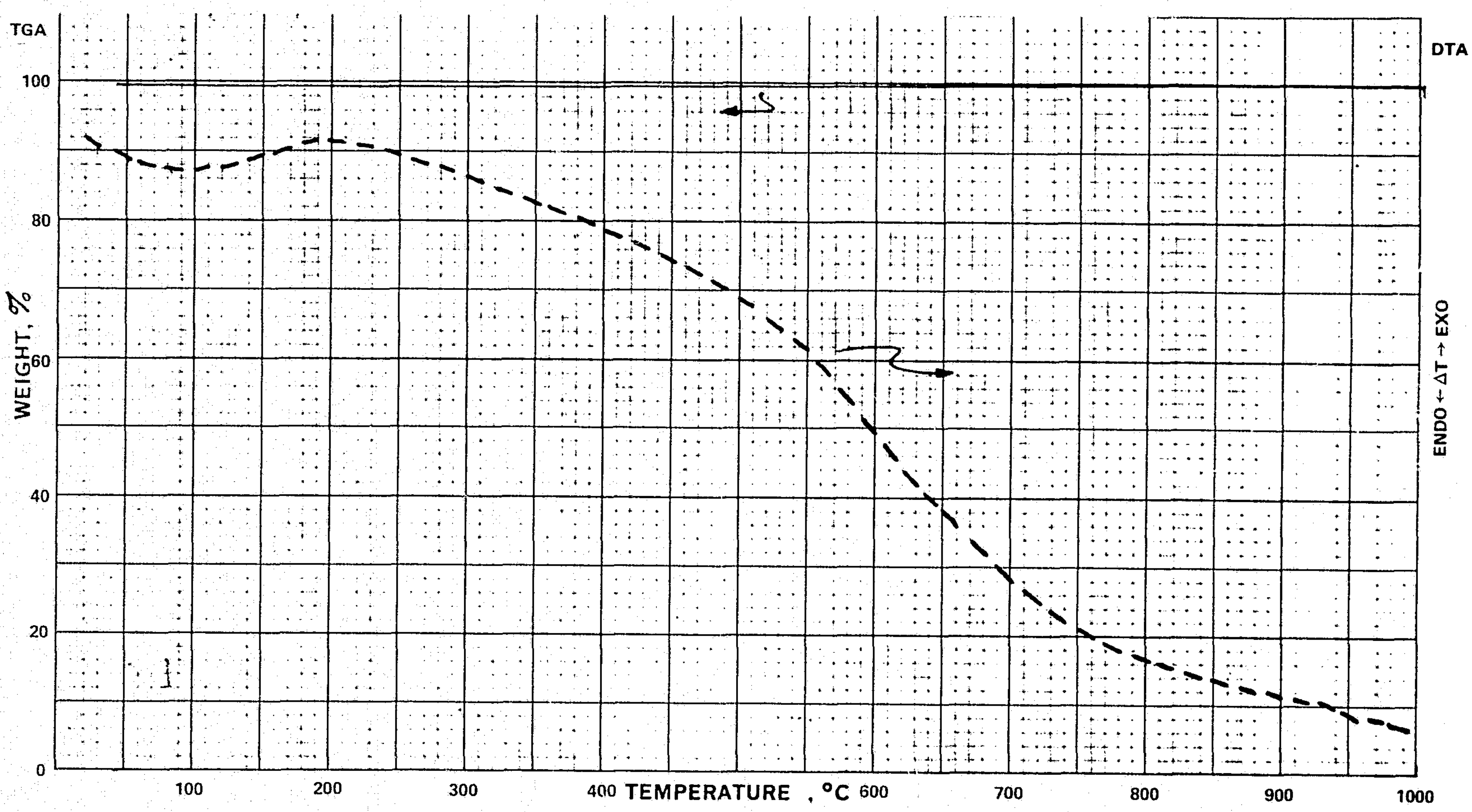

Figure 3-1 - TGA and DTA Thermograms for Potassium Titanate Fiber
Atmosphere: TGA - Flowing Air, 40 cc/min; DTA - Vacuum, 20 Torr

The observed high friction thus led to the evaluation of polyphenylene, treated by several different processes, as friction modifiers in this study. Initially three types were provided by NASA, corresponding to molding at ARC of a pre-polymer under high pressures (20,000 psi = 1.38 x 10^8 N/m^2), and curing in an oxygen-free atmosphere at temperatures of 650, 750 and 1000°C (1202, 1382, and 1832°F), respectively. Early results of friction tests, however, led to the brief examination of several additional types, including uncured pre-polymer that had been extracted with chloroform to remove an impurity, or "washed."

These materials were supplied in the form of small blocks approximately 10 x 10 x 2 mm in dimension. Densities were obtained by careful measurement and weighing of a number of blocks of each type, and are listed in Table 3-1. For incorporation into friction materials these blocks were broken up and ground to size 40 mesh in a Wiley mill. Portions of the ground material were subjected to TGA and DTA to establish their thermal stability.

Table 3-1 - Description and Measured Densities of Polyphenylenes

Material	Abbreviation	Density (g/cm^3)
Uncured pre-polymer[a]	Poly U	0.98
Uncured pre-polymer, washed[b]	Poly UW	1.01
650°C (1202°F) cure for 5 hours	Poly 650	1.21
750°C (1382°F) cure for 3 hours	Poly 750	1.32
1000°C (1832°F) cure for 1 hour	Poly 1000	1.23
650°C (1202°F) cured, washed[b]	Poly 650W	0.90

Notes: (a) Every sample was pressed at 20,000 psi (1.38 x 10^8 N/m^2).

(b) Pre-polymer extracted with chloroform before pressing and curing.

Thermograms for all the polyphenylenes thus examined are given in Figures 3-2 to 3-6, and can generally be interpreted as indicating that they are indeed highly stable organic materials. Comparing first the Poly 650 to Poly 750, the major features are essentially identical, indicating little advantage for the higher temperature cure. TGA under nitrogen (Figure 3-2 and Figure 3-4) shows no weight loss up to 650°C (1202°F). In air, a slow oxidative degradation sets in above 550 to 590°C (1022 or 1094°F), and continues until the material is totally consumed at 840 or 850°C (1544 or 1562°F). Decomposition rates above 720°C (1328°F) are identical. There are not significant features in the DTA's (Figures 3-3 and 3-5); a possible very broad and shallow endotherm above 500°C (932°F) may correspond to the onset of oxidative degradation in the case of air purge. TGA of the Poly 1000, Figure 3-6, shows it to be very similar to the others. The curves for both nitrogen and air purge are not distinguishable from those for Poly 750. The only differences that can be observed between the two is their oxidative decomposition rate above 680°C (1256°F), and the temperature at which oxidation is complete:

Polyphenylene Cure Temperature	Decomposition Rate	Temperature of Total Consumption
750°C (1382°F)	0.096 mg/°C	850°C (1562°F)
1000°C (1832°F)	0.081 mg/°C	885°C (1625°F)

The other polyphenylenes used were not characterized further.

3.1.3 Polyimide Resins

3.1.3.1 Thermal Analysis

The inclusion of a highly stable friction modifier such as polyphenylene was more likely to be successful in producing an improved friction material if it were accompanied by replacement of the commonly used phenolic resin binder by a more thermally stable binder. To that end, two types of polyimide resin were supplied for this study, identified as Maleimide 061 and Maleimide 074 and which

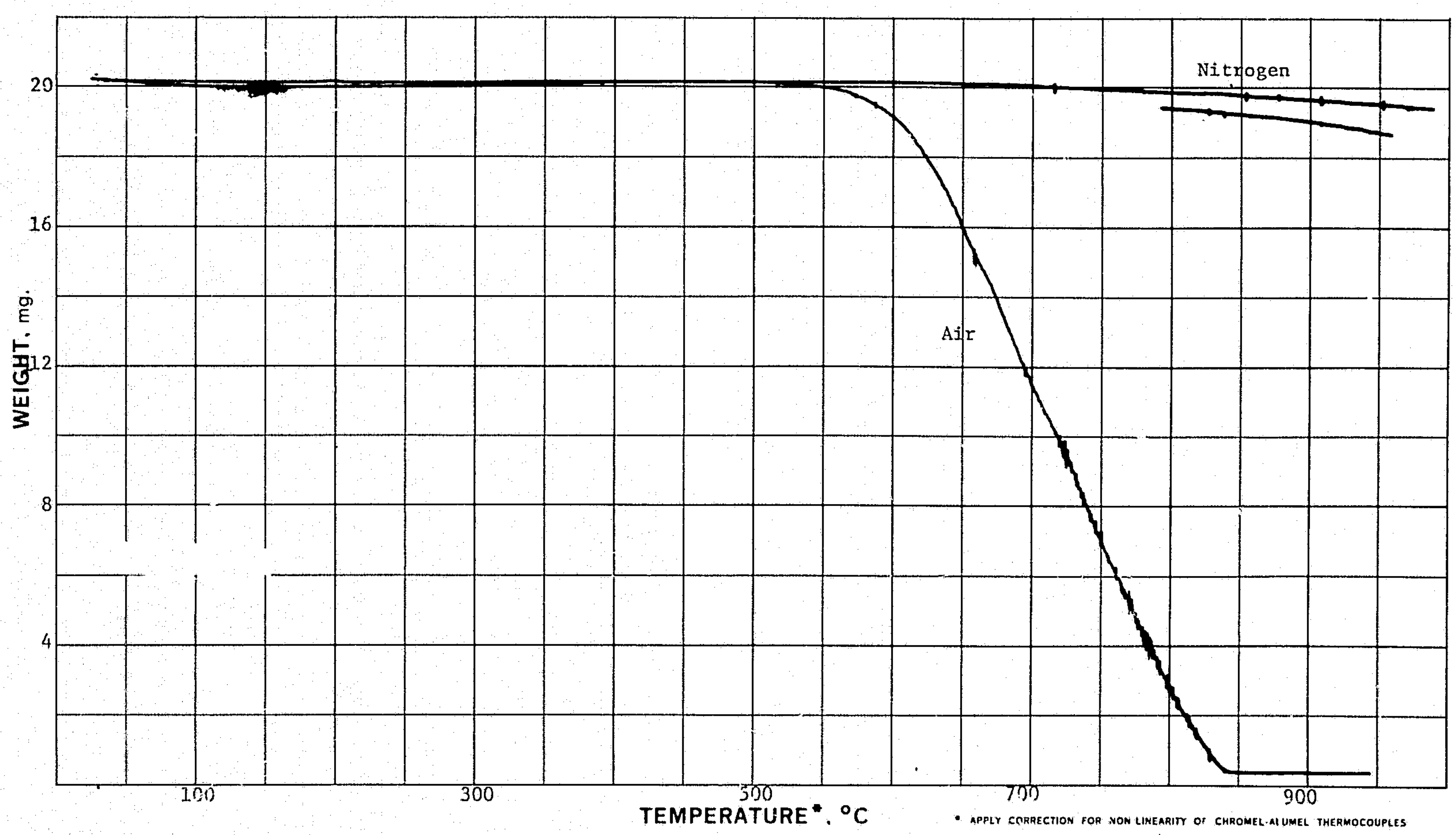

Figure 3-2 - TGA Thermogram of Polyphenylene Cured at 650°C (1202°F)

Atmosphere: Flowing Air or Flowing Nitrogen, 40 cc/min

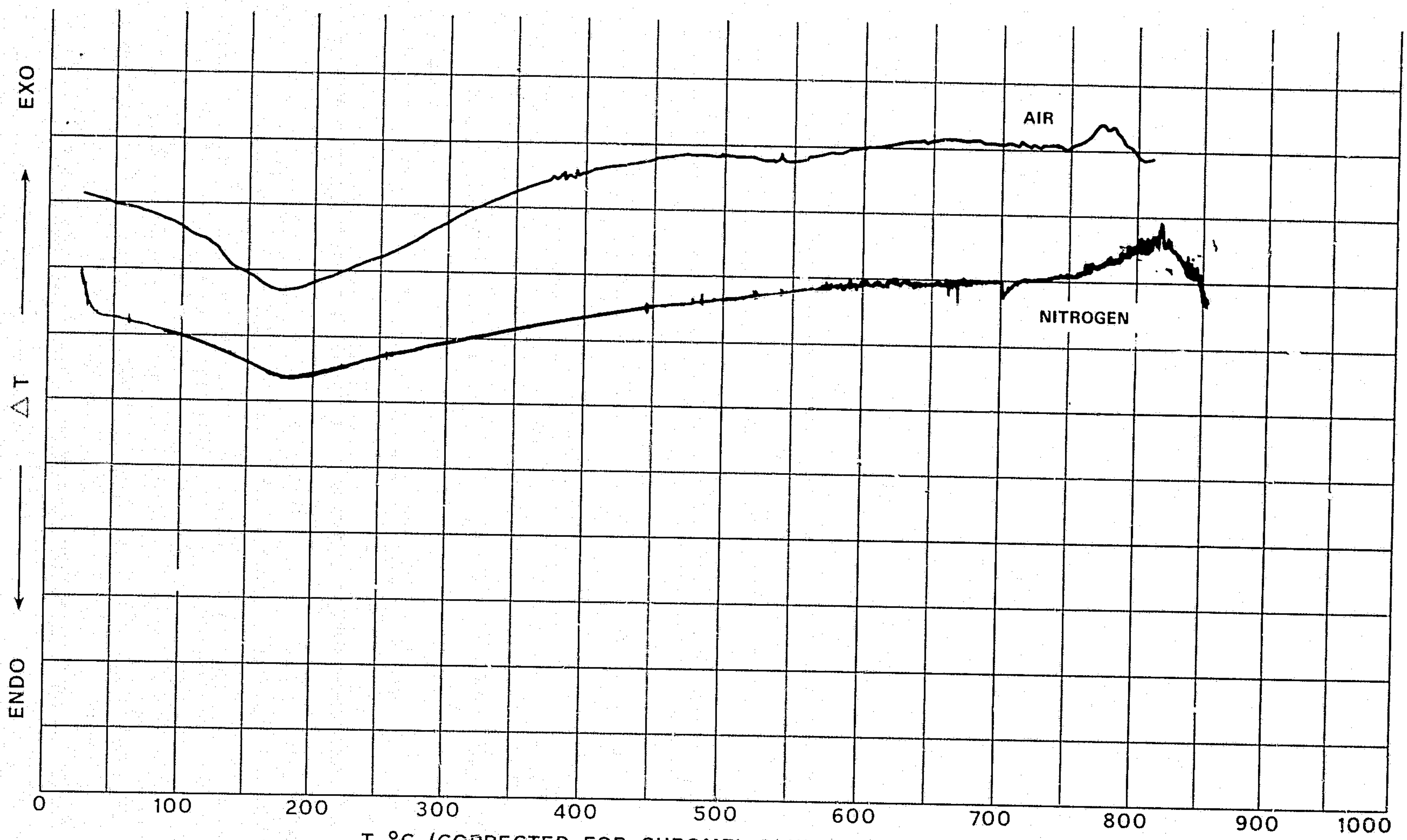

Figure 3-3 - DTA Thermogram of Polyphenylene Cured at 650°C (1202°F)

Atmosphere: Flowing Air or Flowing Nitrogen, 40 cc/min

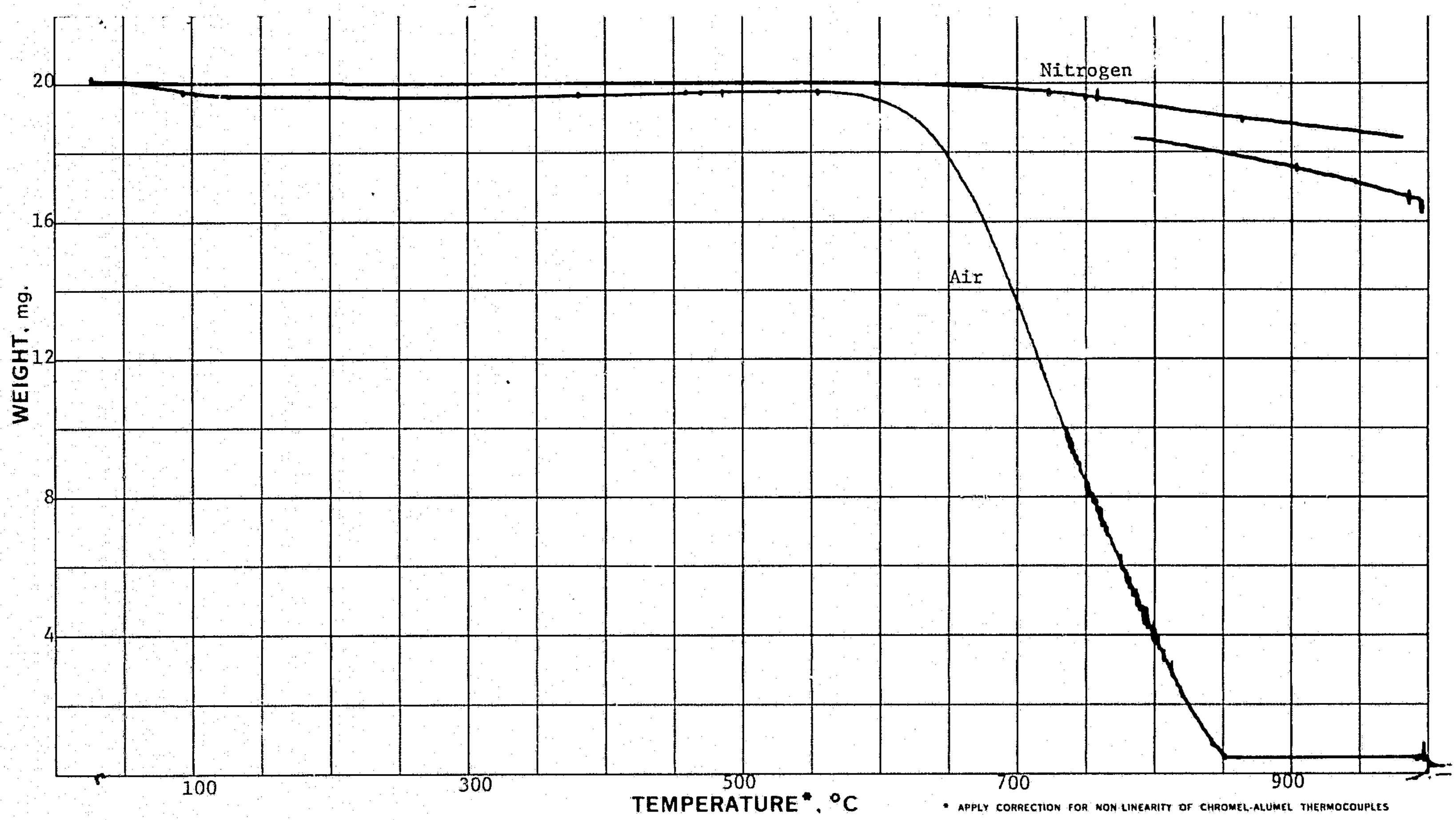

Figure 3-4 - TGA Thermogram of Polyphenylene Cured at 750°C (1382°F)

Atmosphere: Flowing Air or Flowing Nitrogen, 40 cc/min

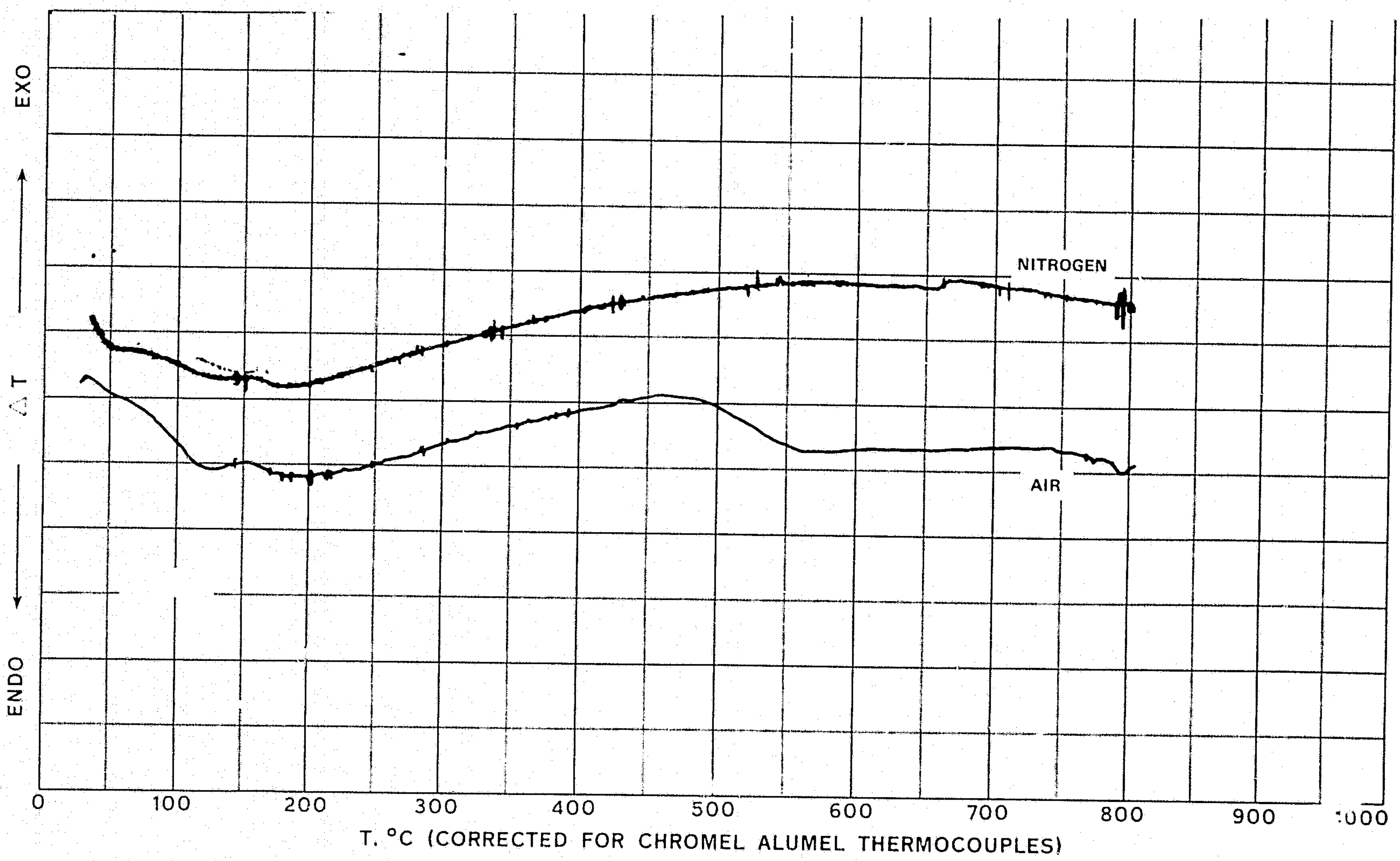

Figure 3-5 – DTA Thermogram of Polyphenylene Cured at 750°C (1382°F)
Atmosphere: Flowing Air or Flowing Nitrogen, 40 cc/min

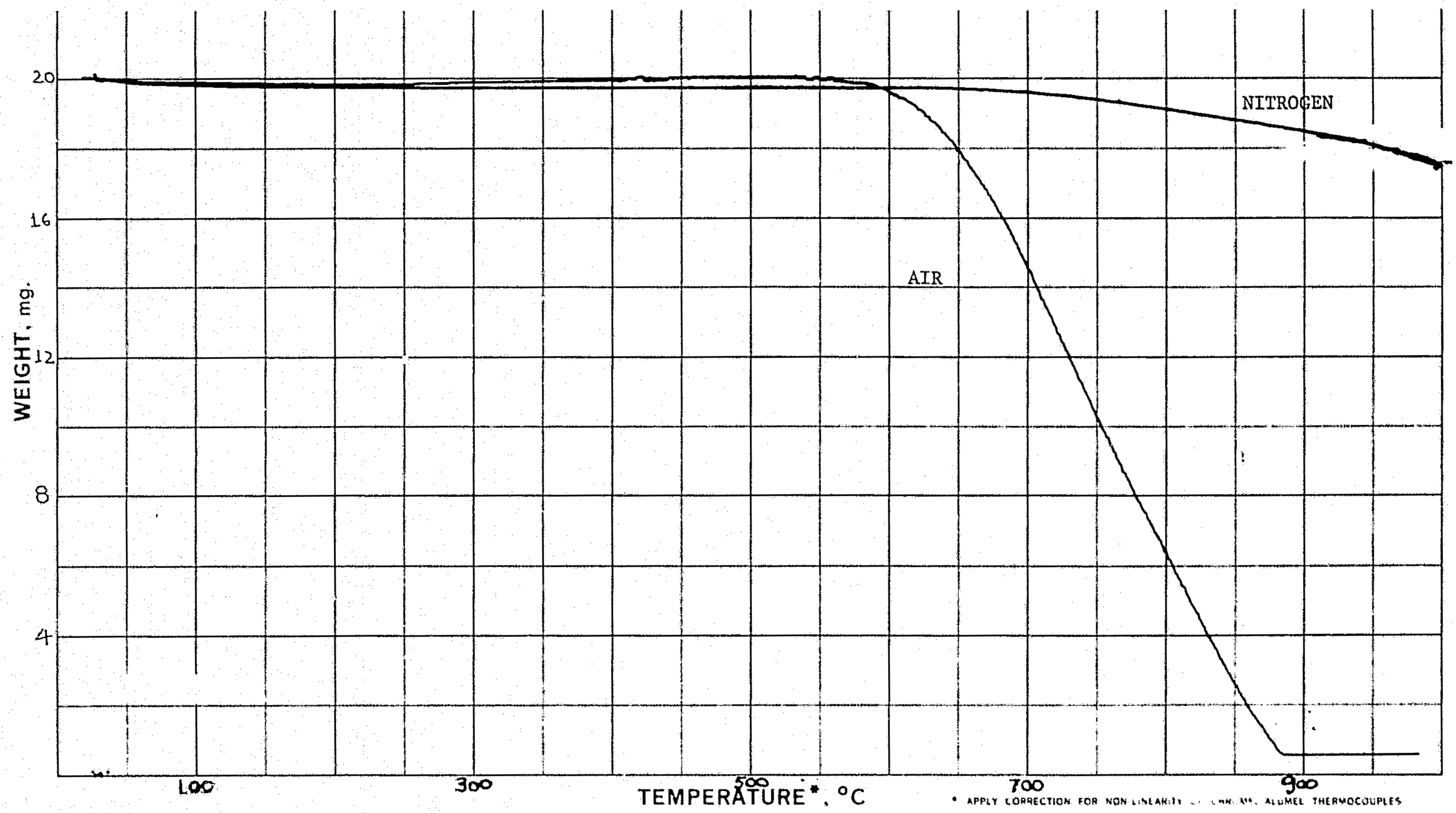

Figure 3-6 - TGA Thermogram of Polyphenylene Cured at 1000°C (1832°F)
Atmosphere: Flowing Air or Flowing Nitrogen, 40 cc/min

will be abbreviated hereafter as M061 and M074, respectively. M061 is a commercial resin of a class that has been amply described in the literature.(3-4,3-5) The M074 is the resin whose synthesis and properties are described in the paper by Gilwee, Rosser and Parker.(3-6) They were characterized in this study by thermal analysis, the results of which are shown in Figures 3-7 to 3-13. Sample 1018A was M074, pan-cured for 16 hours ar 440°F (227°C), and 1018C was M061 exposed to the same treatment. Sample 1018B was M061 that had been press-cured for 6 minutes at 440°F (227°C), followed by a 16 hour post-cure in an open pan at the same temperature.

The only major conclusion that can be drawn from the thermal analysis of the resins is that the M074 is considerably more stable than the M061, toward both thermal and oxidative degradation. In a nitrogen atmosphere, the M074 (1018A) thermogram (Figure 3-7) shows the onset of thermal degradation at 450°C (842°F), with a sharp increase between 500°C (932°F) and 550°C (1022°F) and a subsequent slow decomposition leading to a 40% loss of material at 900°C (1652°F). With air, oxidative degradation begins at 430°C (806°F) and proceeds steadily until all the material is consumed at 830°C (1526°F). The DTA's (Figures 3-8 and 3-9) show a sharp endotherm at 510°C (950°F), indicating a rapid degradation that is apparently independent of the presence of oxygen; it corresponds to the thermal decomposition observed in the TGA, especially in the case of nitrogen purge.

Two samples of M061 were tested: one was molded, press-cured and pan-cured (1018B), while the other was only pan-cured (1018C). The thermograms for both (Figures 3-10 to 3-13) are very similar, though 1018C shows somewhat more rapid oxidative degradation above 580°C (1076°F). The two clear steps in the TGA analyses can be explained as a thermal degradation beginning at 370°C (698°F), augmented by a second, oxidative, degradation at 550°C (1022°F). The DTA curves all show an exotherm at 360-380°C (680-716°F), followed by an endotherm at 440-460°C (824-860°F). This may indicate a delayed cure of the M061; further investigation into the processing of this material for optimal curing was carried out and will be described below.

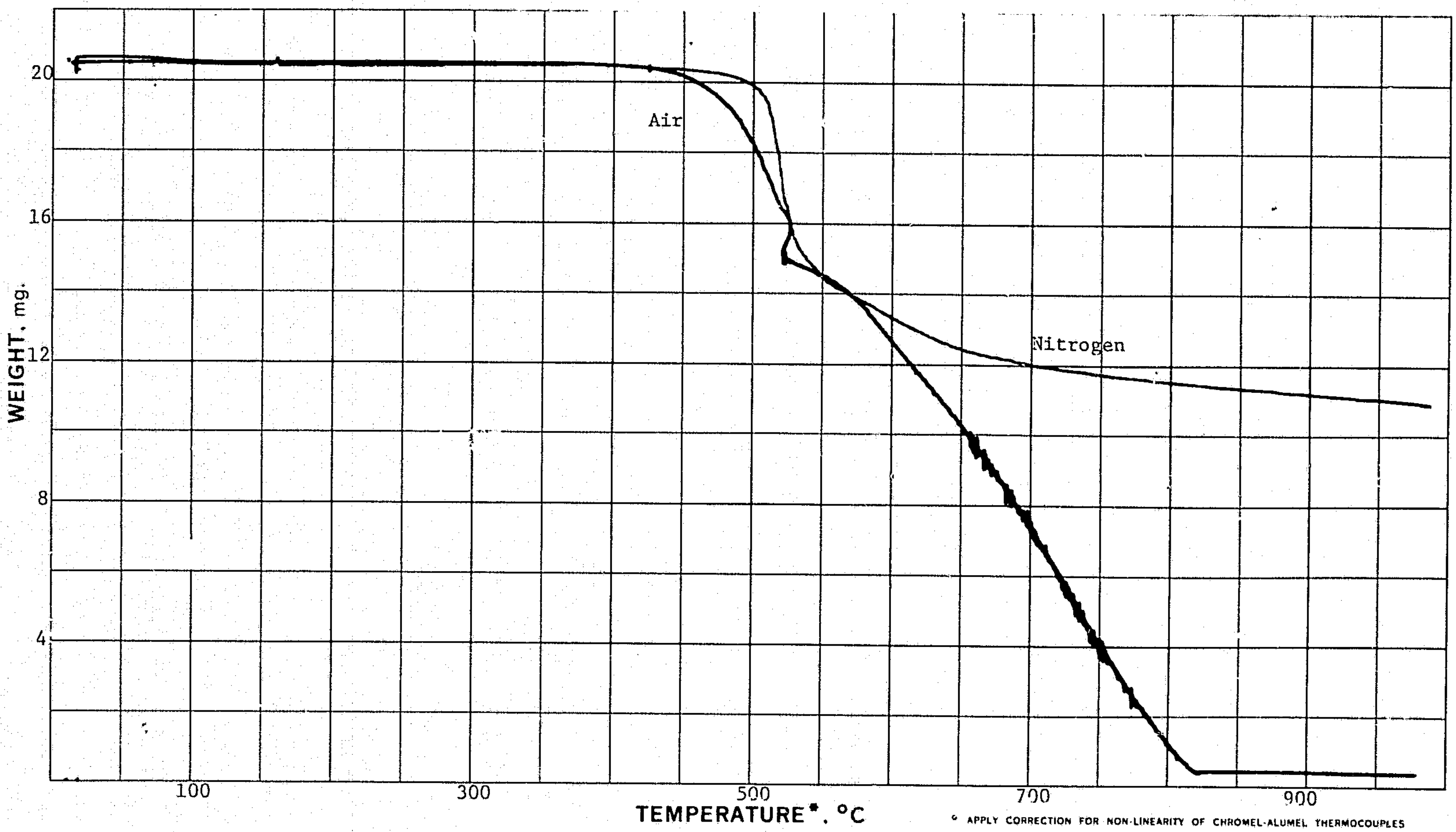

Figure 3-7 - TGA Thermogram of Maleimide 074 Pan Cured at 227°C (440°F) for 16 Hours
Atmosphere: Flowing Air or Flowing Nitrogen, 40 cc/min

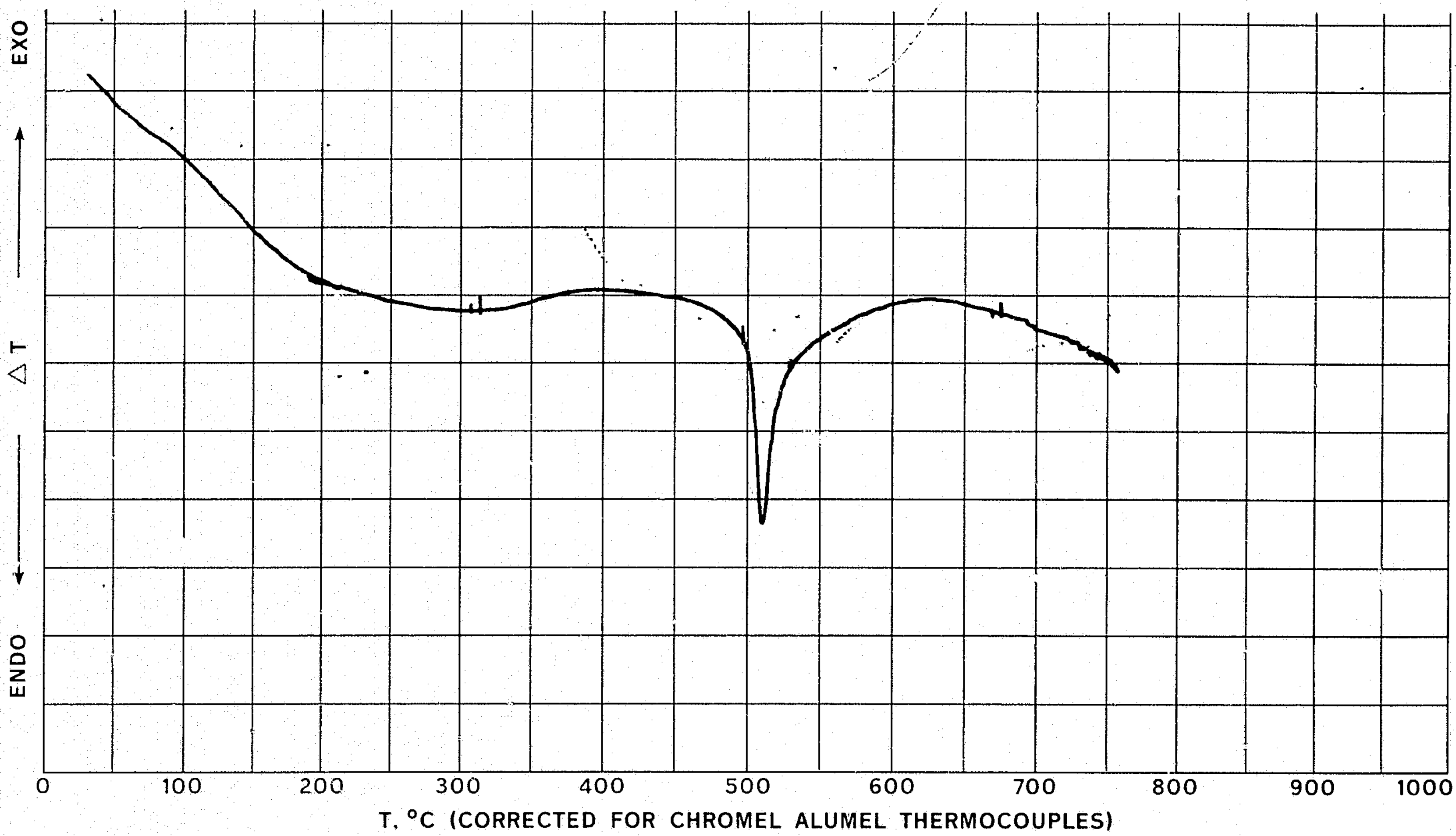

Figure 3-8 - DTA Thermogram of Maleimide 074 Pan Cured at 227°C (440°F) for 16 Hours

Atmosphere: Flowing Nitrogen, 40 cc/min

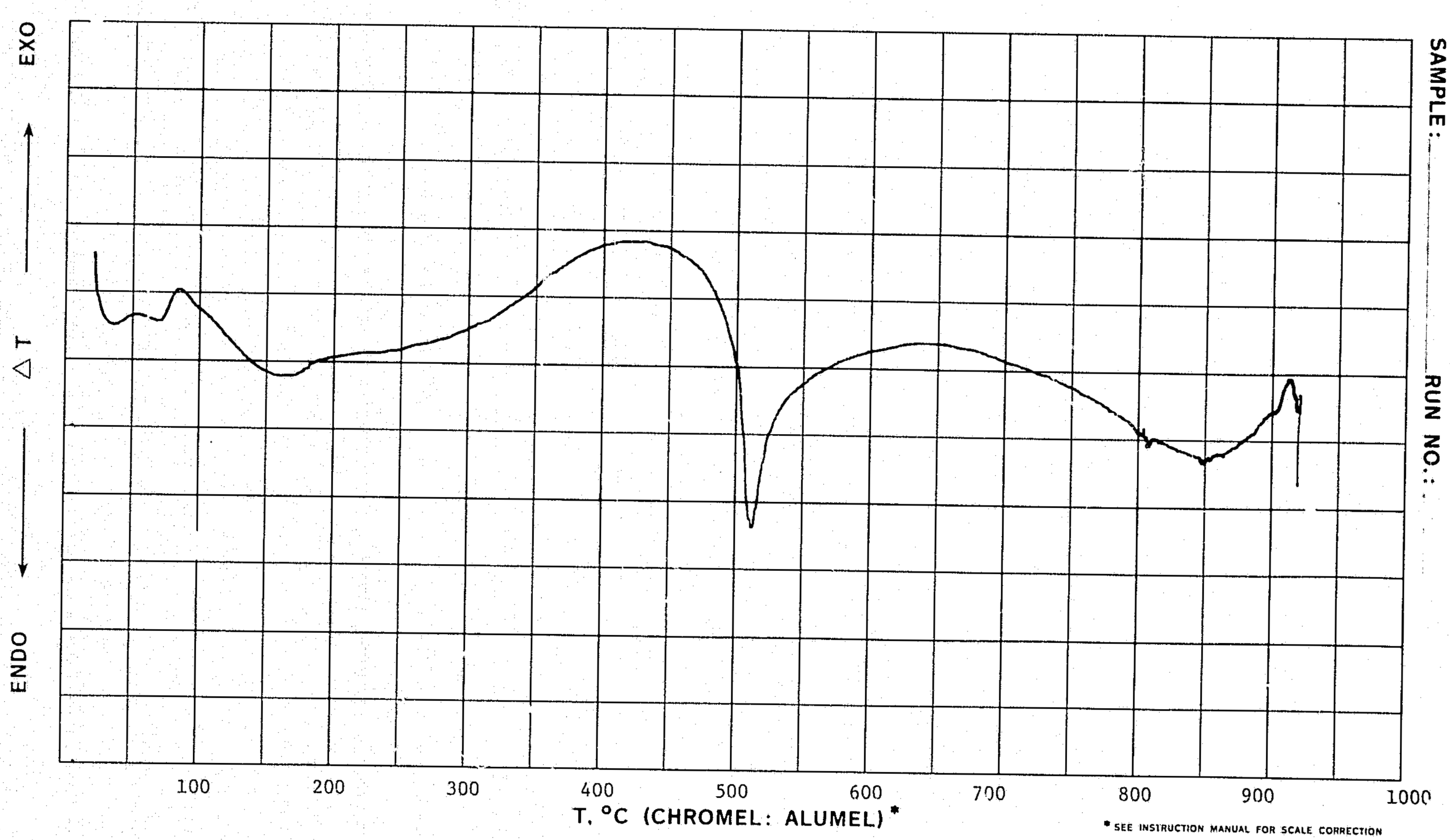

Figure 3-9 – DTA Thermogram of Maleimide 074 Pan Cured at 227°C (440°F) for 16 Hours
Atmosphere: Flowing Air, 40 cc/min

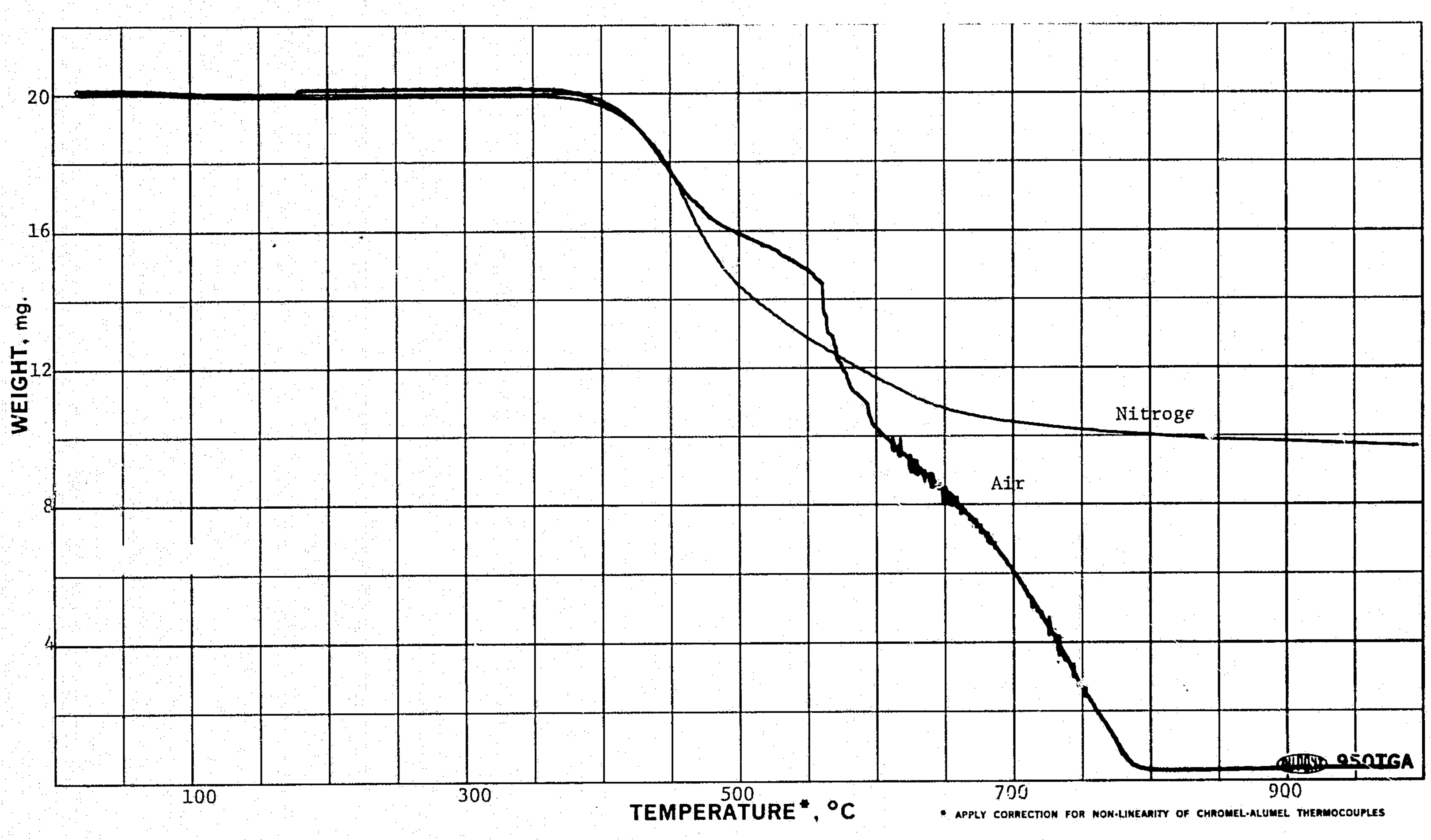

Figure 3-10 - TGA Thermogram of Maleimide 061 Press Cured for 6 Minutes and Pan Cured for 16 Hours at 227°C (440°F)

Atmosphere: Flowing Air or Flowing Nitrogen, 40 cc/min

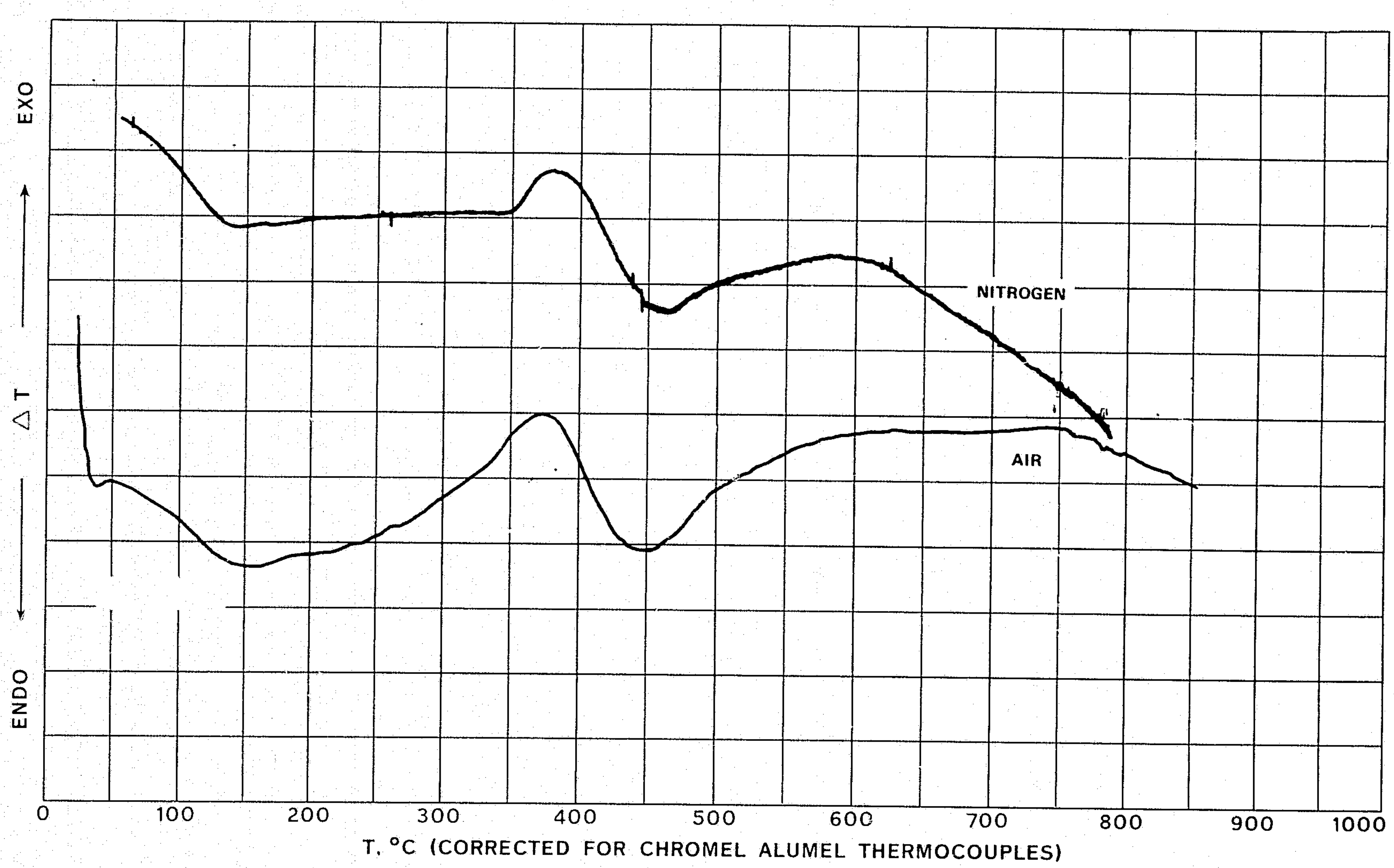

Figure 3-11 - DTA Thermogram of Maleimide 061 Press Cured for 6 Minutes and Pan Cured for 16 Hours at 227°C (440°F)

Atmosphere: Flowing Air or Flowing Nitrogen, 40 cc/min

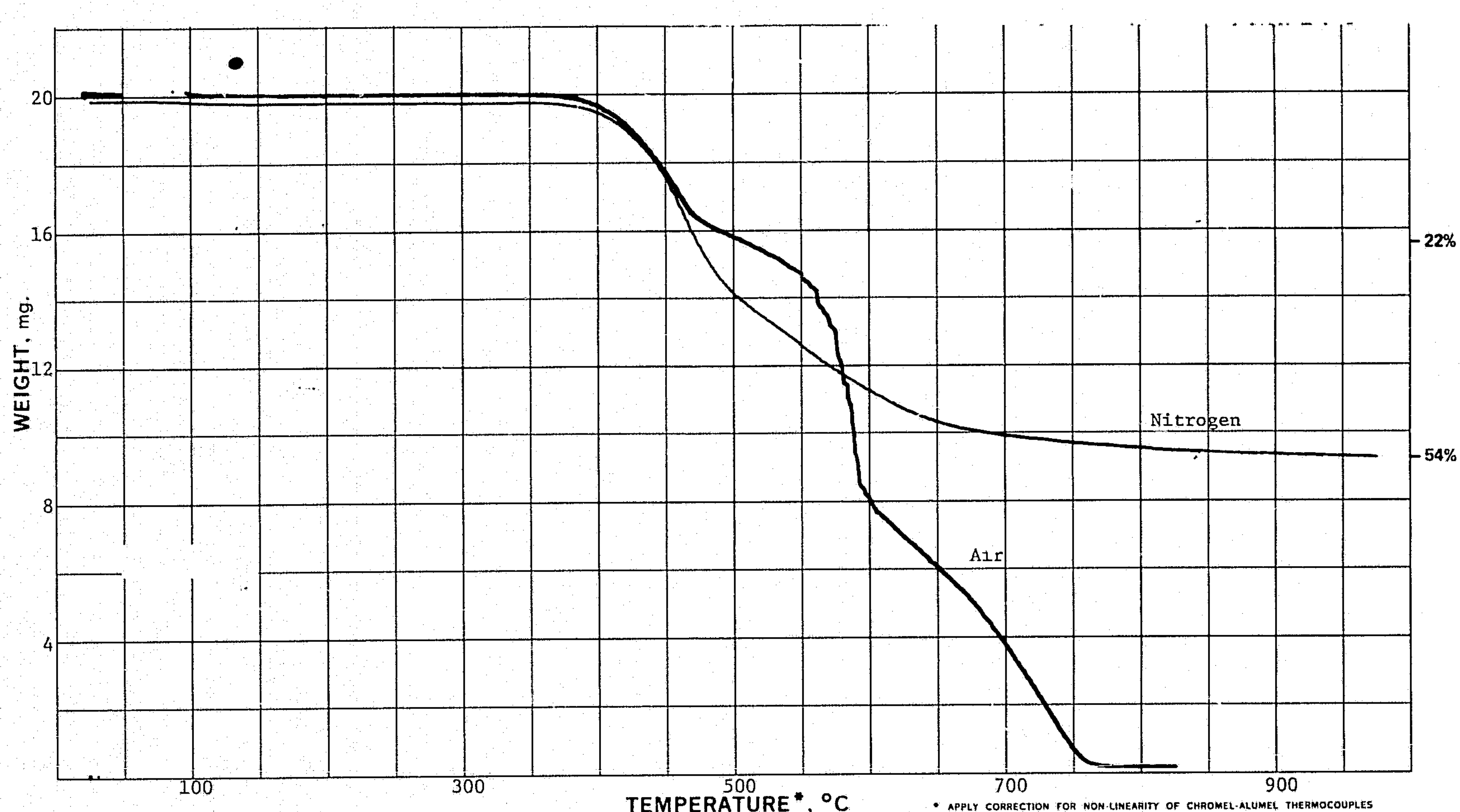

Figure 3-12 - TGA Thermogram of Maleimide 061 Pan Cured at 227°C (440°F) for 16 Hours

Atmosphere: Flowing Air or Flowing Nitorgen, 40 cc/min

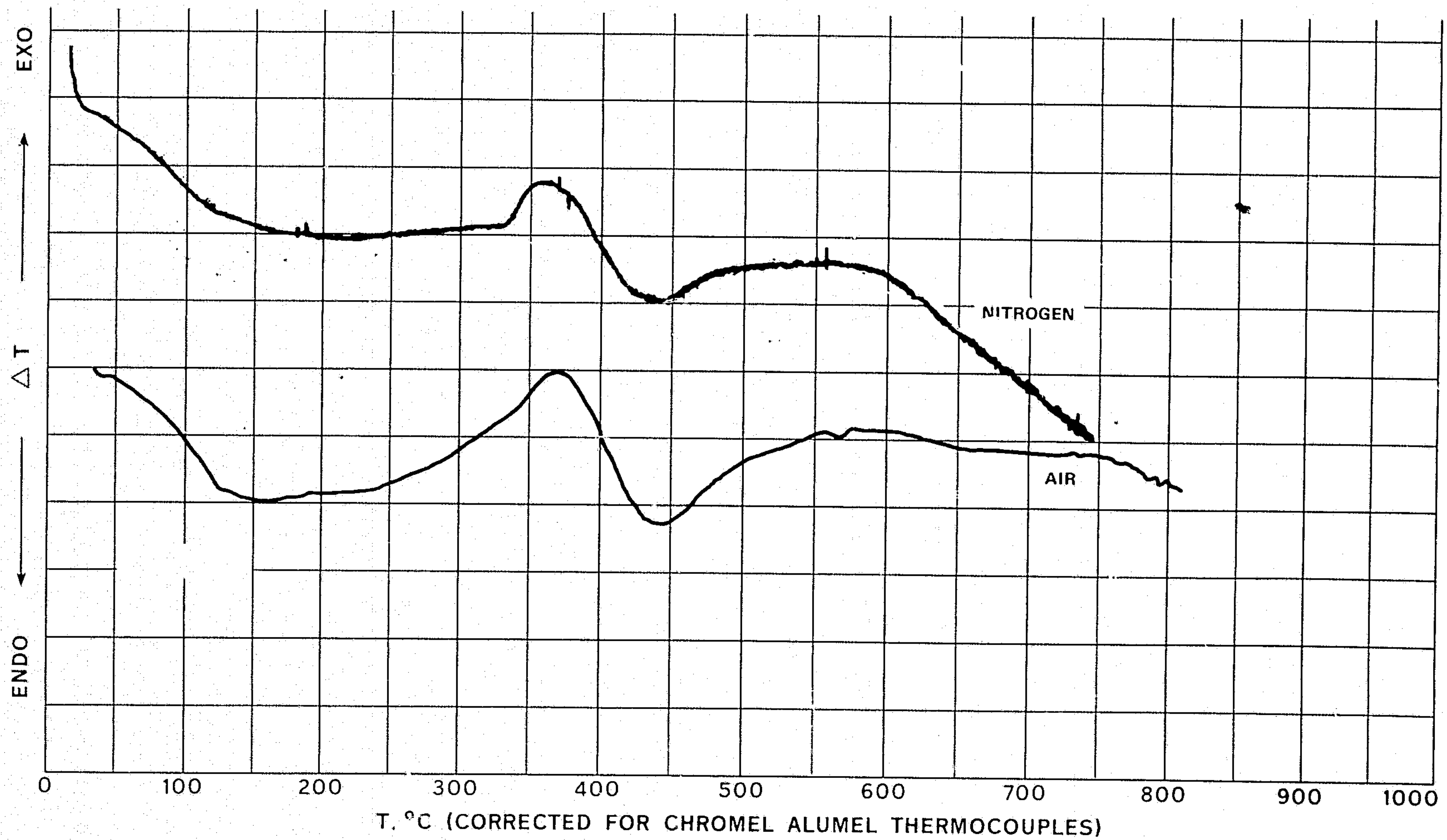

Figure 3-13 - DTA Thermogram of Maleimide 061 Pan Cured at 227°C (440°F) for 16 Hours
Atmosphere: Flowing Air or Flowing Nitrogen, 40 cc/min

Thermograms for a typical phenolic resin are included in Figure 3-14 for purposes of comparison.

3.1.3.2 Determination of Best Cure Conditions for Composites

To determine the best cure conditions for each of the two polyimide resin binders sixteen composite samples were prepared, eight with the M061 and eight with M074. The composition of the composite was:

Potassium Titanate Fiber	50% (by wt.)
Polyimide Resin	25% (by wt.)
Graphite Powder	25% (by wt.)

The graphite was used in place of the polyphenylene to conserve materails, since neither graphite nor polyphenylene was expected toaaffect the polyimide cure.

The composite samples were prepared by first dry-blending the ingredients in a Patterson-Kelly Four-Quart Cantilevered Twin Shell Laboratory Blender with intensifier bar and then compression-molding the samples into 1.25 inch diameter x 0.25 inch (3.2 x 0.6 cm) discs using the time duration, temperatures and pressures indicated in Table 3-2.

The P-K Cantilever Twin Shell Laboratory Blender with intensifier bar proved to be an efficient method of blending potassium titanate fiber with solid resin. A two-minute mix period was sufficient to produce homogeneous blends. The use of the intensifier bar was found necessary to produce good blends. Whenever asbestos is mixed into a blend, however, a 12 to 15 minute period is employed to obtain a homogeneous mix. This longer peiod was used in the preparation of all friction material composites in this study.

3.1.3.2.1 Density

The density of each sample was determined. As expected, the samples molded at higher pressures were somewhat denser than the others, although none achieved the theoretical density of 2.37 g/cm^3. Values are shown in Table 3-3.

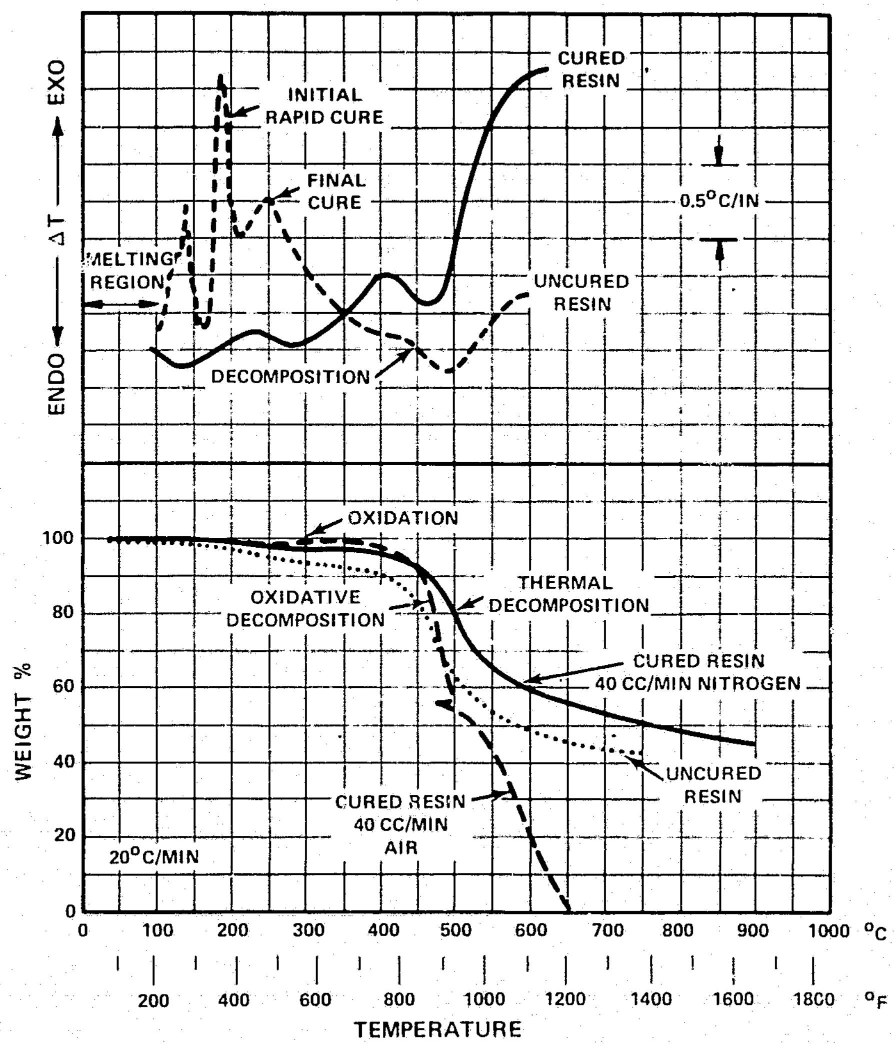

Figure 3-14 - DTA and TGA Thermograms of a Modified Phenolic Resin

Table 3-2 - Summary of Samples Prepared for Determination of Best Molding Conditions

Sample No.	Resin[a,b]	Mold Cure Conditions: Temperature (°C)	Temperature (°F)	Pressure (N/m^2)	Pressure (psi)	Time (Min)
1	Maleimide 061	227	440	1.38×10^7	2000	6
2	Maleimide 061	227	440	1.38×10^7	2000	24
3	Maleimide 061	227	440	2.76×10^7	4000	6
4	Maleimide 061	227	440	2.76×10^7	4000	24
5	Maleimide 061	249	480	1.38×10^7	2000	6
6	Maleimide 061	249	480	1.38×10^7	2000	24
7	Maleimide 061	249	480	2.76×10^7	4000	6
8	Maleimide 061	249	480	2.76×10^7	4000	24
9	Maleimide 074	227	440	1.38×10^7	2000	6
10	Maleimide 074	227	440	1.38×10^7	2000	24
11	Maleimide 074	227	440	2.76×10^7	4000	6
12	Maleimide 074	227	440	2.76×10^7	4000	24
13	Maleimide 074	249	480	1.38×10^7	2000	6
14	Maleimide 074	249	480	1.38×10^7	2000	24
15	Maleimide 074	249	480	2.76×10^7	4000	6
16	Maleimide 074	249	480	2.76×10^7	4000	24

Notes: (a) Composite samples contained:

Potassium titanate fiber	50% by weight
Graphite powder (substitute for polyphenylene)	25% by weight
Resin	25% by weight

(b) Composites were compression molded into discs 1.25-inch diameter x 0.25 inch (32 x 6 mm), under the above conditions. Each disc was cut in half; one half was analyzed as is, and the other half was cured for 16 hours at 249°C (480°F) and 1 atm. pressure before analysis.

Table 3-3 - Results of Density Determinations and Extractions for Various Molding Conditions for Samples Prepared with Two Polyimide Resins

			Molding Pressure = 2000 psi (1.38 x 10^7 N/m^2)				Molding Pressure = 6000 psi (4.14 x 10^7 N/m^2)			
			6 Min.		24 Min.		6 Min.		24 Min.	
	Molding Temp.		Density g/cm^3	Percent Extract.	Density g/cm^3	Percent Extract.	Density g/cm^3	Percent Extract.	Density g/cm^3	Percent Extract.
Maleimide 061			1*		2		3		4	
	227°F	A	2.11	0.35	2.19	---	2.22	---	2.22	---
	(440°F)	B	---	0.35	---	---	---	---	---	---
			5		6		7		8	
	249°C	A	2.18	0.0	2.18	---	2.22	---	2.21	0.20
	(480°F)	B	---	0.32	---	---	---	---	---	0.32
Maleimide 074			9		10		11		12	
	227°C	A	2.06	0.19	2.02	0.0	2.25	---	2.21	---
	(440°F)	B	---	0.22	---	0.0	---	---	---	---
			13		14		15		16	
	249°C	A	2.14	---	2.23	---	2.23	---	2.23	0.17
	(480°F)	B	---	---	---	---	---	---	---	0.25

A = as molded; B = cured for 16 hours at 249°C (480°F) and 1 atm. (1.01 x 10^5 N/m^2) pressure.

NOTE: Samples numbered as in Table 3-2. Format is as in No. 1 for all samples.

3.1.3.2.2 Extraction

To determine if there were any uncured resin in the composites, several of them were subjected to a solvent extraction procedure. Preliminary experiments served to establish that methyl ethyl ketone is a suitable solvent for the quantities of resin in question. Control experiments established that 97% or more of the resin can be recovered from an unmolded, uncured mixture of resin, fiber and graphite. Results are shown in Table 3-3 for the amount of resin extracted from a number of selected samples. (Note that the numbers shown should be multiplied by four to give percentages relative to the original amount of resin in the samples.) The notable results of this sereies of experiments are that: (a) the fraction of resin extracted is very low in all cases, and (b) it is essentially the same for the extremes of molding conditions studied. In other words, it is not possible to make a choice of molding conditions on the basis of this test. As a consequence of the observed results, extraction of the remaining samples was discontinued.

3.1.3.2.3 Thermal Analysis

Portions of the samples on which extractions were run were also subjected to thermogravimetric analysis. Results of these analyses are shown in Appendix A. Only a few runs were made with nitrogen purge, to establish the pattern for thermal degradation of the composites, and to establish that there is no observable difference in the TGA behavior of the cured and uncured samples. Most runs were made with an air purge. Once again, a remarkable similarity is found in all the samples studied, and no clear-cut choice can be made of molding conditions on the basis of these results.

As in the case with the pure resins, samples containing M074 show somewhat greater resistance to the onset of thermal and oxidative degradation than those with M061. The high-temperature degradation, in the range 450-550°C (842-1022°F), shows a somewhat greater stability for the M061 containing samples. An equivalent weight loss is found at a temperature that is about 20°C (36°F) higher for the M061 containing samples than for those with the M074. Above 550°C (1022°F), however, oxidation of the M061 samples is faster, so that complete oxidation of both types of resin is observed at 580-590°C (1076-1094°F), corresponding to 25-27% loss of material from the composites. Slow oxidation of graphite continues until all the carbon has been burned off at about 1000°C (1832°F), corresponding to 44-46% loss of the original composite. Departure from the theoretical 50% can be attributed to uncertainties in weighing and to the presence of a small amount of ash in the graphite. One additional interesting observation can be made. The degradation of material containing M074 - particularly in the present of air - began at a temperature lower than the degradation temperature observed when the pure bulk resin was analyzed (370 versus 430°C) (698 versus 806°F). This is probably due to the presence of the resin as a thin film in the composite, as opposed to the fairly coarse bulk material in the pure resin. The state of subdivision is known to affect the features of a thermogram quite dramatically, finer material appearing to be more reactive.

3.1.3.2.4 Shear Strength

Since the chemical tests were unable to distinguish between the samples prepared under the molding conditions chosen, it was hoped that a decision could be made on the basis of a mechanical test. Toward this end a number of samples were prepared for a shear strength test that was performed at Bendix Friction Materials Division, Troy, New York. Tests of this nature usually show large amounts of scatter between identically prepared friction materials and tested in shear. It was during this fabrication procedure that the most valuable information on molding conditions was obtained. Instead of preparing artificial composites, it was decided to take the actual formulations for the secondary standard lining, and substitute the experimental resins for the commercial one. The original intention was to prepare these friction materials under the extreme of molding conditions listed in

Table 3-2, namely: 225°C (437°F), 2000 psi (1.38×10^7 N/m^2), 6 minutes and 250°C (482°F), 6000 psi (4.14×10^7 N/m^2), 24 minutes. However, it proved unfeasible to hot-press the samples at 250°C (482°F) since large amounts of gases were evolved; this caused the samples to break apart as the pressure was released. These gases are probably evolved due to the decomposition of several components of the commercial formulation, which is normally molded at a considerably lower temperature. This difficulty in fabrication of the friction material essentially eliminates 250°C (482°F) as a practical molding temperature. Even at 225°C (437°F), large quantities of gases are evolved during pressing, but periodic relief of the pressure, allowing the gases to escape, permitted the fabrication of samples that were deemed satisfactory. Based on previous experience, another set of molding conditions was also tried, which it was thought would give a pad with the desired properties. The conditions under which the pads that were shear tested were formulated are shown in Table 3-4. The physical form of the samples prepared was in a standard disc pad configuration, as shown in Figure 3-15. This figure also shows how the pad was machined for the shear tests.

Results of the shear tests are shown in Table 3-5. For the sake of comparison, results obtained for two typical production disc pads are shown in the adjacent Table 3-6. It may be seen that large variations occur in the commercial materials, and that a very large number of samples must be run to obtain an adequate statistical distribution. All four of the experimental samples are well within the acceptable range for commercial disc pads, but the error limits on the failure loads for the experimental samples are sufficiently large that, once again, a clear-cut choice of the molding conditions cannot be made. Perhaps the one exception is in the case of the samples with the M061, in which the formulation molded at 205°C (399°F) appears somewhat stronger than that molded at 225°C (437°F).

On the basis of all the above experiments and analyses, and on the basis of previous experience, the choice of molding and curing conditions was made as follows:

Molding temperature 215°C (420°F)

Pressure	6000 psi (4.14×10^7 N/m^2)
Time	12 minutes

Cure temperature 250°C (482°F)

Pressure	1 atm. (1.01×10^5 N/m^2)
Time	8 hours

Table 3-4 - Fabrication Conditions of Samples for Shear Testing

		Mold Conditions					
		Temperature		Pressure		Time	
Designation	Resin	(°C)	(°F)	psi	(N/m^2)	(min)	Notes
748524	Maleimide 061	250	482	5000	3.45×10^7	24	1,2
744206	Maleimide 061	225	437	2000	1.38×10^7	6	3,4
740512	Maleimide 061	205	399	5000	3.45×10^7	12	2,3,4
844206	Maleimide 074	225	437	2000	1.38×10^7	6	3,4
840512	Maleimide 074	205	399	5000	3.45×10^7	12	2,3,4

NOTES: (1) Samples molded at 250°C (482°F) blew apart when pressure was released; molding at that temperature discontinued.

(2) A pressure of 5000 psi (3.45×10^7 N/m^2) was used instead of 6000 psi (4.14×10^7 N/m^2) because of a malfunction in the large heated press.

(3) Four disc pads were fabricated and tested.

(4) Samples cured for 8 hours at 250°C (482°F) and 1 atm. (1.01×10^5 N/m^2).

Table 3-5 - Shear Strength Measurements on Experimental Friction Materials

	Failure Load (Average of four tests)	
Designation	psi	N/m^2
744206	1238 ± 175	$(8.54 \pm 1.21) \times 10^6$
740512	1450 ± 175	$(1.00 \pm 0.12) \times 10^7$
844206	1306 ± 144	$(9.00 \pm 0.99) \times 10^6$
840512	1325 ± 125	$(8.52 \pm 0.86) \times 10^6$

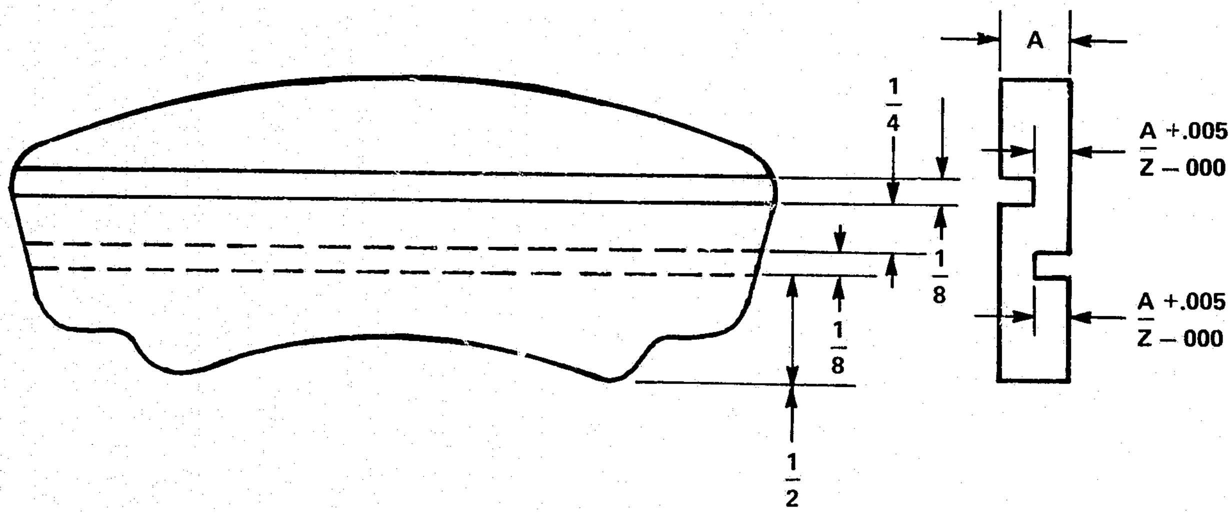

Figure 3-15 - Configuration of Disc Pad Used for Shear Strength Tests

Table 3-6 - Typical Results of Shear Strength Measurements on Commercial Friction Materials

	Failure Loads			
	Friction Material No. 1		Friction Material No. 2	
	psi	N/m^2	psi	N/m^2
Low	680	4.69×10^6	1150	7.93×10^6
Mean (of 30 tests)	1050	7.24×10^6	2020	1.39×10^7
High	1400	9.65×10^6	2580	1.78×10^7

3.2 FRICTION MATERIALS

3.2.1 Standard Linings

To provide a basis for comparison, and to serve as a point of departure for the evaluation of possible improvements, a set of primary and secondary linings was selected. They were composed of chrysotile asbestos, modified phenolic resin binder, and property modifiers of which the principal organic was cashew friction dust (see Section 2). Not only did these serve as bases for the comparison of friction and wear properties, but they also provided the formulations in which substitutions were made for evaluation of the experimental ingredients. They are commercial linings, fabricated at The Bendix Corporation, Friction Materials Division, Troy, New York; they meet the specification for certain 1973 U.S. Government commercial vehicles.

Friction materials were also fabricated for this study using the standard formulas and ingredients, but with slightly different processing techniques, as described below.

3.2.2 Fabrication of Friction Materials

3.2.2.1 General Procedures

All the experimental samples were fabricated by a compression-molding technique commonly used at Bendix Research Laboratories. Rather than fabricating the friction material into an arced drum lining, each material was pressed and cured in a disc pad configuration of the dimensions shown in Figure 3-15. One half of this pad provided the sample for dynamometer testing, while the other half was submitted to NASA-ARC as the quality control sample.

Some of the experimental ingredients provided by NASA had to undergo some preliminary processing before they could be used for fabrication. The polyphenylene blocks were crushed and then ground in a Wiley mill to a size of 40 mesh. Of the resins, M061 was used as received. M074 was subjected to a preliminary cure at 150°C (302°F) for two hours ("B-staged"), after which it was reground into a fine powder for dry mixing. The potassium titanate fiber was used as received.

A typical fabrication procedure was as follows:

(1) Weigh out required quantity of each ingredient. (A sample formulation sheet, showing how these quantities are calculated from a desired formula in percent volume and densities, is given in Appendix B).

(2) Transfer ingredients to P-K blender and blend for 15 minutes with intensifier bar in operation.

(3) Remove mix from blender and transfer to mold for briquetting. This involves pressing at ambient temperature and low pressure for the sole purpose of compacting the mix and giving it the proper shape in preparation for hot pressing.

(4) Place briquette into mold in pre-heated press. Press for 12 minutes at 6000 psi (4.14×10^7 N/m^2) and 215°C (420°F). Relieve pressure for 5 seconds after one, two and three minutes to allow initially formed gases to escape.

(5) Remove pressed pad from mold and place in curing oven for 8 hours at 250°C (482°F). This is usually done by containing the pad between two flat plates at 10-20 psi (6.9-13.8×10^4 N/m^2) to maintain dimensional stability during the final cure.

3.2.2.2 Fabrication of Experimental Friction Materials

Initial fabrication involved the substitution of the six experimental components singly for the corresponding ones in the standard primary and secondary linings. The twelve compositions generated in this fashion are listed in Table 3-7. Of these specified unique samples, however, two were not processable; these were the two samples calling for total replacement of asbestos with potassium titanate fiber, identified as numbers 3 and 9. The very small particle size - and consequent large surface area - of the experimental fiber creates such a large demand for resin binder that not enough resin is present in the standard formulation to bind the composite. A trial in which solvent was added to the mix to assiste in dispersion of the resin to coat the fiber was unsuccessful. This increased resin demand by the addition of the potassium titanate fiber led to the investigation of a number of compositions in which both reduction in fiber and increase in resin was explored.

Table 3-7 - Formulations in Which Experimental Materials are Substituted Singly for Standard Materials

		Primary							Secondary						
		STD	1	2	3	4	5	6	STD	7	8	9	10	11	12
Binder	Standard	X			X	X	X	X	X			X	X	X	X
	Maleimide 061		X							X					
	Maleimide 074			X							X				
Fiber	Standard	X	X	X		X	X	X	X	X	X		X	X	X
	Potassium Titanate				X							X			
Modifier	Standard	X	X	X	X				X	X	X	X			
	Polyphenylene 650					X							X		
	Polyphenylene 750						X							X	
	Polyphenylene 1000							X							X

It was found that there was evidence of hairline surface cracking after dynamometer testing for samples with titanate replacing 60% of the asbestos, even with 40% added resin. Cracking was not evident for this quantity of titanate fiber, or less, when 50 or 60% additional resin was present. Evidence of low strength for low resin-high titanate fiber composites is also provided by the shear strength measurements described in Section 3.2.3.2 below. Further work is required to quantify the apparent practical limit of titanate fiber addition, especially if large-scale processing were to be considered.

Although it was originally intended to simultaneously explore experimental formulations of both the primary and secondary type, it was decided on the basis of the results obtained with the initial formulations (Table 3-7) not to explore the primary lining further. As described in Section 2, the brunt of the work load is carried by the secondary lining, while the primary must have high friction but can tolerate moderately high wear. It was felt that, if an improved secondary could be formulated, a compatible primary could probably be found from among existing formulas. The rest of the experimental formulations prepared and tested were thus based on the secondary lining. They are described in Table 3-8, in which all experimental formulas are listed in numerical order. A summary of the formulations categorized according to the experimental ingredients which they contain is given in Table 3-9.

Full-scale dynamometer tests were conducted for the single experimental friction material which provided the greatest overall improvement in friction and wear. It will be seen in Section 4, which describes the results of dynamometer tests, that the most improved experimental lining contained the experimental ingredient of potassium titanate fiber.

To insure that the full-scale tests were conducted with friction materials which were identical with those used in the small scale dynamometer tests, the full-scale experimental linings were fabricated by the following procedure. First, a number of disc pads of the experimental formula were fabricated by the procedure

Table 3-8 - List of Samples Prepared for This Program

Sample No.	Lining Type	Description
1[a]	Primary	Maleimide 061 for phenolic resin.
2	Primary	Maleimide 074 for phenolic resin.
3	Primary	Potassium titanate for asbestos fiber; not processable.
4	Primary	650°C cure polyphenylene for cashew friction dust.
5	Primary	750°C cure polyphenylene for cashew friction dust.
6	Primary	1000°C cure polyphenylene for cashew friction dust.
7	Secondary*	Maleimide 061 for phenolic resin.
8		Maleimide 074 for phenolic resin.
9		Potassium titanate for asbestos fiber; not processable.
10		650°C cure polyphenylene for cashew friction dust.
11		750°C cure polyphenylene for cashew friction dust.
12		1000°C cure polyphenylene for cashew friction dust.
13		Uncured polyphenylene for asbestos, 5% substitution.
14		Uncured polyphenylene for asbestos, 15% substitution.
15		Potassium titanate fiber for asbestos, 25% substitution.
16		Potassium titanate fiber for asbestos, 50% substitution.
17		Mixture of 75% Maleimide 061 + 25% Maleimide 074 for phenolic resin, 100% substitution.
18		Mixture of 25% Maleimide 061 + 75% Maleimide 074 for phenolic resin, 100% substitution.

*All subsequent samples are of the secondary type.

Table 3-8 - List of Samples Prepared for This Program (Continued)

Sample No.	Description
19	Uncured polyphenylene for Organix X, 30% substitution.
20	Uncured polyphenylene for Organic Y, 100% substitution.
21	650°C polyphenylene, washed, for cashew friction dust, 50% substitution.
22	650°C polyphenylene for cashew friction dust, 50% substitution.
23	750°C polyphenylene for cashew friction dust, 50% substitution.
24	1000°C polyphenylene for cashew friction dust, 50% substitution.
25	Potassium titanate for asbestos, 50% substitution; phenolic resin raised to 120%.
26	Potassium titanate for asbestos, 50% substitution; phenolic resin raised to 140%.
27	Potassium titanate for cashew friction dust, 50% substitution.
28	650°C polyphenylene for cashew friction dust, 10% substitution.
29	Potassium titanate for cashew friction dust, 50% substitution; phenolic resin raised to 120%.
30	550°C polyphenylene for cashew friction dust, 100% substitution.
31	Duplicate of 26 and 52.
32	Maleimide 061 for phenolic resin, 70% substitution.
33	Maleimide 074 for phenolic resin, 70% substitution.
34	Potassium titanate for asbestos, 50% substitution; phenolic resin raised to 140%; modifier-to-fiber ratio increased by 10%.
35	Mixture of (15% Maleimide 061 + 85% Maleimide 074) for phenolic resin. 100% replacement.
36	Potassium titanate for asbestos, 50% substitution; phenolic resin raised to 140%; modifier-to-fiber ratio decreased by 10%.

Table 3-8 - List of Samples Prepared for this Program (Continued)

Sample No.	Description
37(b)	Potassium titanate for asbestos, 50% substitution; potassium titanate for Organic X and for Organic Y, 100% substitution; unstaged Maleimide 074 replacing all of phenolic resin; resin level raised to 140%; Maleimide 074, unstaged, for cashew friction dust, 100% substitution. Special processing: Blend; cold press into briquettes for handling; hot mold at 150°C (302°F) for 1 hour and 50 minutes at atmospheric pressure, or as low a pressure as possible; increase temperature to 250°C (482°F) and pressure to 6000 psi and hold for two hours; do not post-cure.
38(b)	Same composition and processing as 37, with the following change: instead of pure Maleimide 074, use a mixture of (25% Maleimide 061 + 75% Maleimide 074, unstaged) as the resin.
39(b)	Same composition and processing as 37, with the following change: Maleimide 074, staged, for cashew friction dust, 100% substitution.
40(b)	Same composition and processing as 38, with the following change: post-cure for 4 hours at 250°C (482°F).
41	Potassium titanate for asbestos, 50% substitution; phenolic resin raised to 147%.
42	Potassium titanate for asbestos, 50% substitution; phenolic resin raised to 133%.
43	Potassium titanate for asbestos, 40% substitution; phenolic resin raised to 140%.
44	Potassium titanate for asbestos, 50% substitution; phenolic resin raised to 140%; cashew friction dust for Organic Y, 100% substitution.
45	Potassium titanate for asbestos, 50% substitution; phenolic resin raised to 140%; all of Organic Y and 30% of Organic X replaced by fully cured and ground Maleimide 074 (used as modifier instead of binder).

Table 3-8 - List of Samples Prepared for This Program (Continued)

Sample No.	Description
47	Uncured polyphenylene, washed, for cashew friction dust, 100% substitution.
49	Uncured polyphenylene for cashew friction dust, 100% substitution.
50	Uncured polyphenylene for cashew friction dust, 50% substitution.
51	Uncured polyphenylene for cashew friction dust, 10% substitution.
52	Duplicate of 26.
53	Potassium titanate for asbestos, 50% substitution, phenolic resin raised to 160%.
54	Potassium titanate for asbestos, 50% substitution; mixture of (25% Maleimide 061 + 75% Maleimide 074) for phenolic resin, 100% substitution.
55	Potassium titanate for asbestos, 50% substitution; mixture of (25% Maleimide 061 + 75% Maleimide 074) replacing all of phenolic resin; resin raided to 140%.
56	Potassium titanate for asbestos, 50% substitution; mixture of (70% Maleimide 061 + 30% phenolic) replacing all of phenolic resin; resin raised to 140%.
57	Duplicate of 18.
58	Duplicate of 14.
59	Duplicate dynamometer test of 49.
60	Duplicate dynamometer test of 50.
121[c]	New secondary base material for subsequent samples.
122	Potassium titanate for asbestos, 50% substitution; resin raised to 140%.
123	Potassium titanate for asbestos, 40% substitution; resin raised to 140%.
124	Potassium titanate for asbestos, 60% substitution; resin raised to 140%.

Table 3-8 - List of Samples Prepared for This Program (Concluded)

Sample No.	Description
125	Potassium titanate for asbestos, 50% substitution; resin raised to 120%.
126	Potassium titanate for asbestos, 50% substitution; resin raised to 135%.
127	Potassium titanate for asbestos, 50% substitution; resin raised to 160%.
128	Potassium titanate for asbestos, 50% substitution; resin raised to 145%.
129	Potassium titanate for asbestos, 20% substitution; resin raised to 120%.
130	Duplicate of 121.
133	Phenolic resin raised to 140% (adjusted baseline).
134	Phenolic resin raised to 160% (adjusted baseline).
135	Potassium titanate for asbestos, 60% substitution; resin raised to 160%.
136	Potassium titanate for asbestos, 60% substitution; resin raised to 150%.
137	Phenolic resin raised to 120% (adjusted baseline).
138	Potassium titanate for asbestos, 60% substitution; resin raised to 140%.

NOTES: (a) Formulas 1 to 12 represent 100% substitution for the corresponding standard ingredient.

(b) Samples 37 to 40 were subjected to special processing, as described under each individual item.

(c) Sample 121 and subsequent ones were prepared specifically to explore the region in the vicinity of the "best" formula, No. 26.

Table 3-9 - Summary of Samples Fabricated and Tested

A. Total substitution of experimental materials for corresponding ingredients in standard linings -
   Samples 1 through 12

B. Polyphenylene substitution
   Samples 13, 14, 19, 20, 21, 22, 23, 24, 28, 30, 47, 49, 50, 51, 58, 59, 60

C. Resin substitution
   Samples 17, 18, 32, 33, 35, 57

D. Potassium titanate fiber substitution
   Samples 15, 16, 25, 26, 27, 29, 31, 34, 36, 41, 42, 43, 44, 52, 53, 121 through 130, 133 through 138

E. Resin and potassium titanate substitution
   Samples 37, 38, 39, 40, 45, 54, 55, 56

described in Section 3.2.2.1, cut into rectangular pieces of the correct width for the shoe (2 inches = 5.1 cm), and machined to the curvature of the shoe. They were then bonded to the shoe to give a "segmented" lining which was handled in conventional fashion for testing. A photograph of such a lining is shown in Figure 3-16, together with the standard commercial primary lining with which it was paired for testing. A wear test and a friction performance test were carried out on two separate pairs of the segmented experimental-standard primary combination. A standard primary-standard secondary combination was also subjected to each of these full-scale tests.

Development of techniques for full-scale fabrication was not a part of this program. Attempts to manufacture secondary linings of the best experimental composition by normal large scale processing indicated that further refinement of procedures for this composition is necessary. A brief account of the problems encountered can be found in Appendix C.

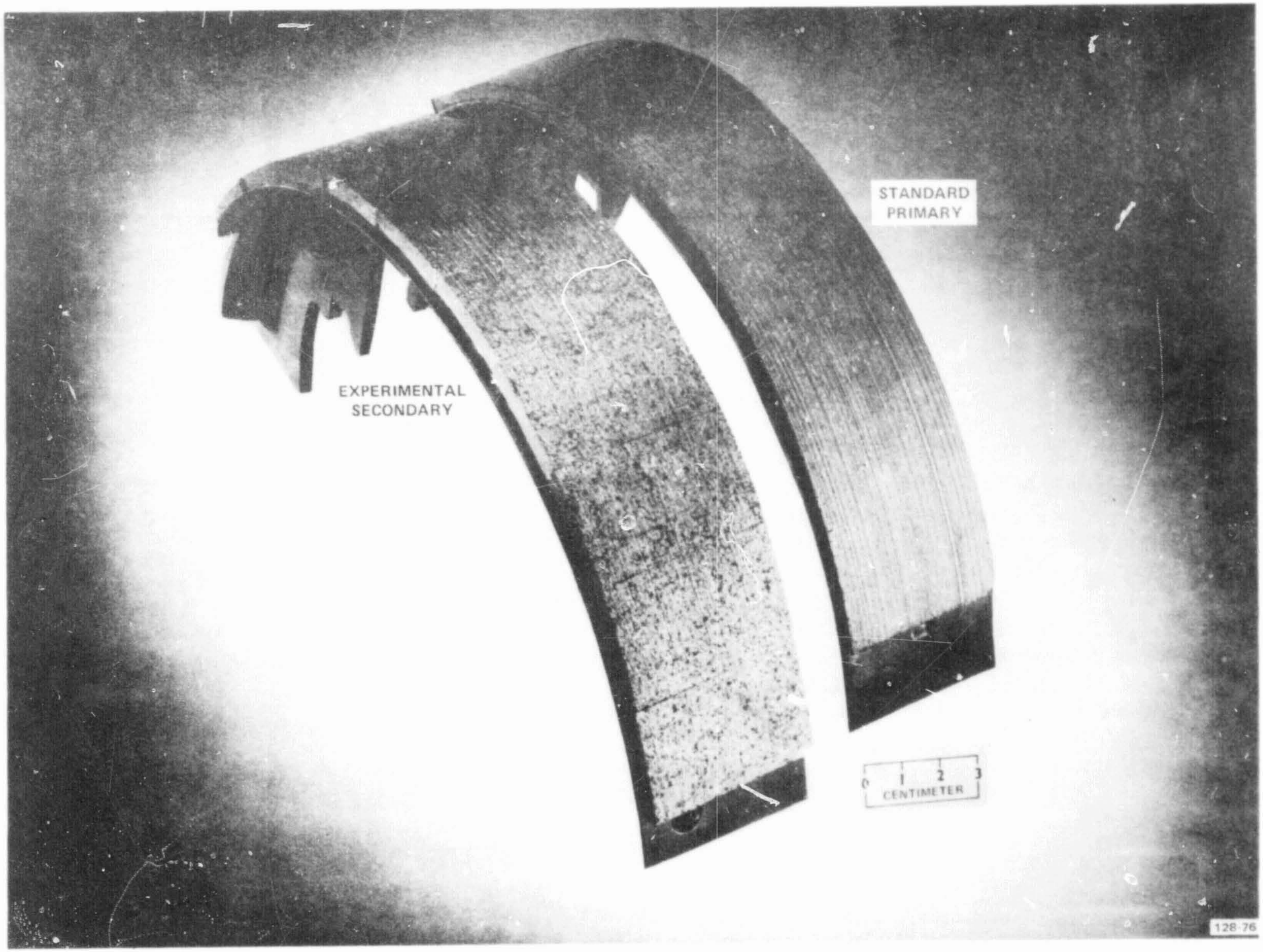

Figure 3-16 - Segmented Experimental Secondary Lining and Standard Primary Lining With Which it was Paired for Testing

We now proceed to describe the results of the characterization studies on the experimental friction materials, with the exception of friction and wear tests, which will be discussed in Section 4.

3.2.3 Characterization of Friction Materials

It is evident from previous discussion that automotive friction materials are extremely complex composites, whose properties of most immediate interest - friction and wear - are usually not the cumulative properties of their components. For this reason it is extremely difficult to correlate their friction and wear properties to physical and chemical characteristics, or to predict the effect of adding an ingredient or substituting one for another.

3.2.3.1 Density and Porosity

One of the most useful properties to monitor is the density of the pressed and cured composite, which should be within a few percent of the theoretical density. If the measured density is more than 10-15% below theory, a processing error may be indicated, such as low molding pressure, inadequate venting during pressing or accidental substitution of one ingredient for another. This naturally calls for refabrication. In other cases, an ingredient may have properties that make it difficult or impossible to process into a mix, such as a fiber that is not sufficiently compressible; fabrication of such a formula cannot be carried out without extensive and detailed investigation.

Densities for the experimental secondary lining samples fabricated for this study are listed in Table 3-10. Porosities have been calculated from the difference between theoretical and achieved densities and are also listed in Table 3-10. It can be seen that the majority of the samples have achieved densities that fall within acceptable limits. Those with exceptionally high porosites all contain large quantities of the potassium titanate fiber, although not all samples containing large amounts of fiber had high porosities. The one sample with a porosity greater than 20% is that in which all the asbestos was replaced by potassium titanate in the standard, and which could not be fabricated into a coherent lining. Its density was measured on a piece of lining that broke apart.

Table 3-10 - Densities and Porosities of Experimental Linings

Sample Number	Theoretical Density (g/cm^3)	Measured Density (g/cm^3)	Percent Density Achieved	Percent Porosity
Std.	1.94	1.72	88.7	11.3
7	1.94	1.83	94.4	5.6
8	1.94	1.76	90.8	9.2
9	2.20	1.74	79.1	20.9
10	1.96	1.77	90.3	9.7
11	1.98	1.85	93.5	6.5
12	1.96	1.86	94.9	5.1
13	1.91	1.76	92.2	7.8
14	1.85	1.69	91.4	8.6
15	2.01	1.87	93.0	7.0
16	2.08	1.89	90.9	9.1
17	1.92	1.80	93.8	6.2
18	1.92	1.85	96.4	3.6
19	1.94	1.78	91.8	8.2
20	1.93	1.78	92.2	7.8
21	1.92	1.74	90.6	9.4
22	1.95	1.79	91.8	8.2
23	1.96	1.78	90.8	9.2
24	1.95	1.78	91.3	8.7
25	2.07	1.87	90.3	9.7
26	2.03	1.87	92.1	7.9
27	2.14	1.95	91.1	8.9
28	1.94	1.77	91.2	8.8
29	2.12	1.97	92.9	7.1
30	1.94	1.76	90.7	9.3

Table 3-10 - Densities and Porosities of Experimental Linings (Continued)

Sample Number	Theoretical Density (g/cm^3)	Measured Density (g/cm^3)	Percent Density Achieved	Percent Porosity
31	2.03	1.84	90.6	9.4
32	1.94	1.81	93.3	6.7
33	1.94	1.82	93.8	6.2
34	2.00	1.78	89.0	11.0
35	1.92	1.80	93.8	6.2
36	2.05	1.84	89.8	10.2
37	2.35	2.26	96.2	3.8
38	2.37	2.14	90.3	9.7
39	2.37	2.08	87.8	12.2
40	2.38	2.14	89.9	10.1
41	2.02	1.77	87.6	12.4
42	2.03	1.76	86.7	13.3
43	2.00	1.75	87.5	12.5
44	2.03	1.73	85.2	14.8
45	2.04	1.69	82.8	17.2
46	Not fabricated			
47	1.95	1.77	90.8	9.2
48	1.92	1.79	93.2	6.8
49	1.92	1.83	95.3	4.7
50	1.93	1.77	91.7	8.3
51	1.94	1.75	90.2	9.8
52	2.03	1.82	89.7	10.3
53	2.01	1.78	88.6	11.4
54	2.06	1.91	92.7	7.3
55	2.01	1.85	92.0	8.0

Table 3-10 - Densities and Porosities of Experimental Linings (Concluded)

Sample Number	Theoretical Density (g/cm^3)	Measured Density (g/cm^3)	Percent Density Achieved	Percent Porosity
56	2.01	1.89	94.0	6.0
57	1.92	1.78	92.7	7.3
58	1.85	1.70	92.0	8.0
59	1.92	1.89	95.3	4.7
60	1.93	1.77	91.7	8.3
121	1.94	1.64	84.5	15.5
122	2.03	1.76	86.7	13.3
123	2.00	1.76	88.0	12.0
124	2.05	1.75	85.4	14.6
125	2.06	1.81	87.9	12.1
126	2.03	1.80	88.7	11.3
127	2.00	1.86	93.0	7.0
128	2.03	1.80	88.7	11.3
129	1.98	1.79	90.4	9.6
130	1.94	1.73	89.2	10.8
133	1.90	1.68	88.4	11.6
134	1.88	1.66	88.3	11.7
135	2.03	1.82	90.1	9.9
136	2.04	1.83	89.7	10.3
137	1.92	1.67	87.0	13.0
138	2.05	1.83	89.3	10.7

3.2.3.2 Permeability and Shear Strength

A further attempt to correlate properties and composition was made by measuring the permeability of several samples in a series with varying quantities of resin and potassium titanate fiber. This property was measured as follows:

(1) A disc one inch (2.54 cm) in diameter was cut from a piece of friction material and machined to a thickness of 0.367 inch (0.93 cm).

(2) The disc was mounted in the center of a steel holder with epoxy resin, care being taken to avoid getting epoxy on the surface.

(3) One side of the disc was pressurized with an inert gas, such as nitrogen, and the rate of flow of the gas through the disc, at various driving pressures measured with a soap bubble flow meter.

The results can be presented in the form of plots of observed flow rate through the material as a function of driving pressure. Such plots for samples 15, 16, 25, 26, 53 and the standard secondary are shown in Figures 3-17 and 3-18. (Refer to Table 3-11 below for clarification of the systematic variation in resin and fiber represented by these samples.) Note that the ordinates vary by an order of magnitude for the two plots. One is at first tempted to try to relate the porosities as listed in Table 3-10 to these permeabilities. The magnitudes of these two properties, in descending order, are:

Porosity: Formula 53 $\approx$ Std > 25 > 16 > 26 > 15

Permeability: Formula 16 >> 25 > 15 > 26 > Std > 53

It is apparent that no direct correlation exists, and that, whatever the reason may be for not achieving theoretical density, the "excess volume" of the composite is not in the form of channels that would allow the flow of gas through the disc. Although the technique is a crude one, it should have allowed us to detect such channeling if it existed.

A more detailed look at the composition of the samples, however, does allow us to make an interesting observation. Listing them in order of increasing resin content: Std = 15 = 16 < 25 < 26 < 53; and listing them in order of increasing potassium titanate fiber content: Std < 15 < 16 = 25 = 26 = 53. Of the samples containing potassium titanate fiber, those with the lowest permeability are those with the highest resin content, numbers 53 and 26. Sample 16, which has had 50% of the asbestos replaced by the titanate fiber without any resin increase, has by far the highest permeability. This sample was also difficult to fabricate, and obviously suffered from resin starvation.

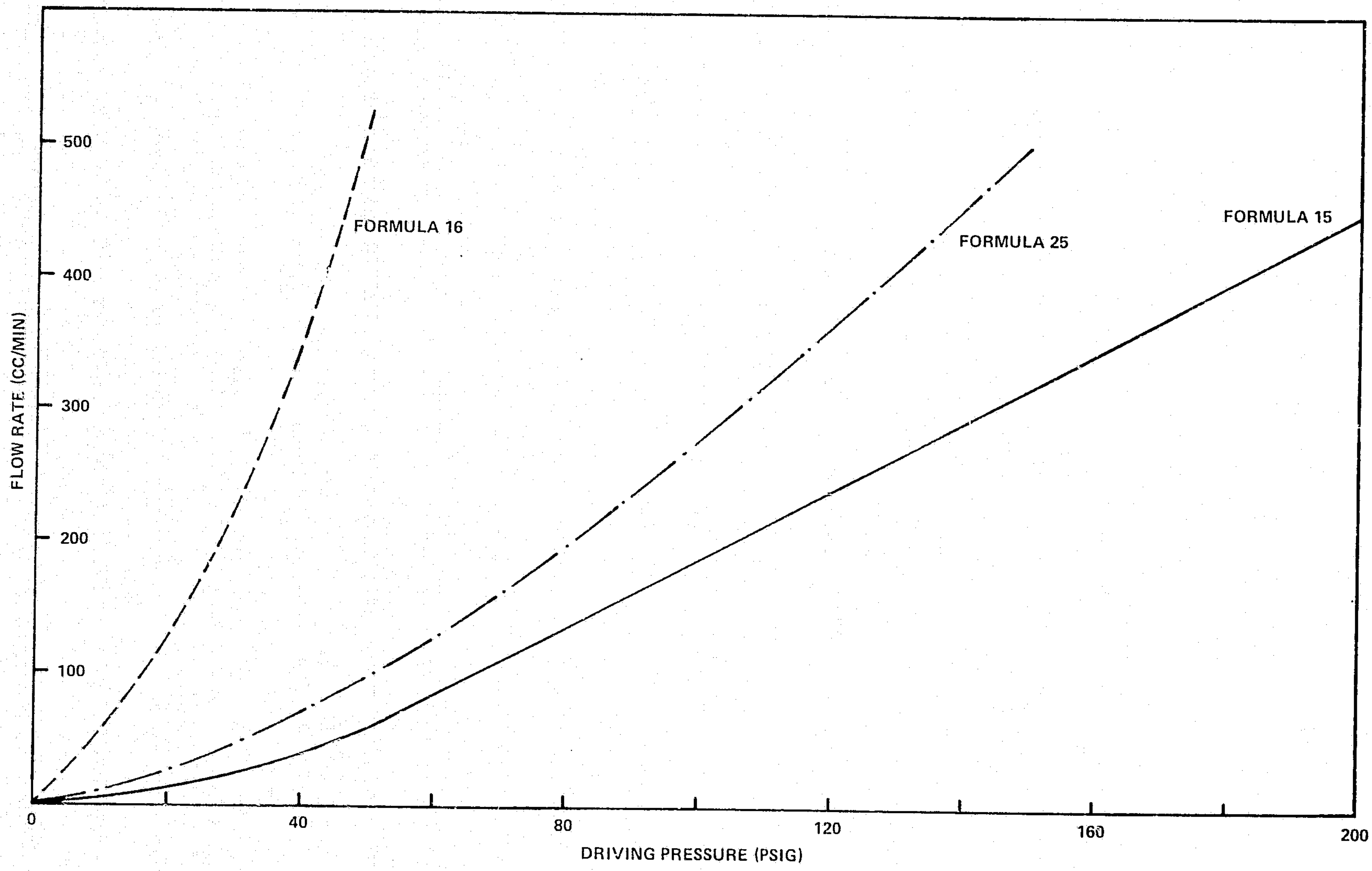

Figure 3-17 - Permeability of Several Formulations With High Flow Rate Through Samples

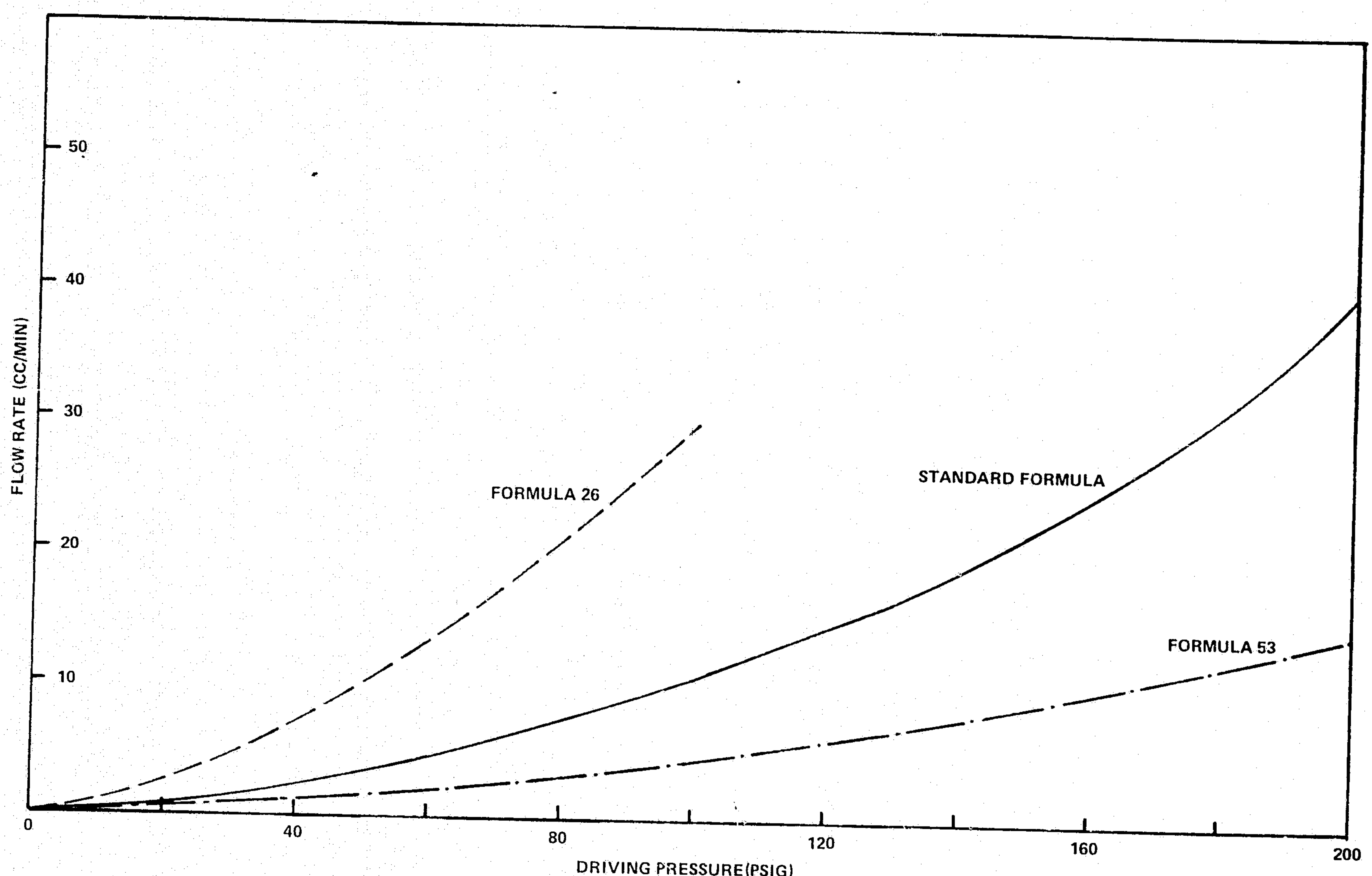

Figure 3-18 - Permeability of Several Formulations With Lower Flow Rate Through Samples

Table 3-11 - Results of Shear Tests on Several Experimental Formulations in Which Resin and Potassium Titanate Fiber were Varied

Sample Number	Percent Resin[a]	Percent Substitution For Asbestos	Shear Strength psi	Shear Strength N/m^2
Standard	100	0	1334 $\pm$ 100	$(9.20 \pm 0.69) \times 10^6$
15	100	25	959 $\pm$ 26	$(6.61 \pm 0.18) \times 10^6$
16	100	50	760 $\pm$ 143	$(4.87 \pm 0.99) \times 10^6$
25	120	50	1266 $\pm$ 122	$(8.73 \pm 0.84) \times 10^6$
26	140	50	960 $\pm$ 64	$(6.62 \pm 0.44) \times 10^6$
53	160	50	1355 $\pm$ 254	$(9.34 \pm 1.75) \times 10^6$

[a] Relative to Standard.

As resin is increased, first by 20%, a marked decrease in flow rate is seen (sample 25), but this is still more permeable than sample 15, in which only 25% of the asbestos has been replaced by titanate fiber. The next resin increase, to 40% over standard, causes an order of magnitude decrease in the permeability, e.g., from 280 cm^3/min at 100 psi (6.9×10^5 N/m^2) for sample 25 to 30 cm^3/min for sample 26. While these results are not startling, they are reassuring and serve to support the observations and conclusions that have been made throughout this study regarding increased resin demand by the potassium titanate fiber.

At the same time that samples were prepared for permeability measurements, several additional pads were fabricated and submitted for shear testing. These tests were run in the same configuration as those described earlier, Figure 3-15. Results are shown in Table 3-11, which gives averages and average deviations for five tests for each composition. Once again the scatter is large and the number of samples too small to establish a good statistical distinction. Certain trends can be identified, however. Figure 3-19 illustrates the expected decrease in strength with addition of potassium titanate fiber

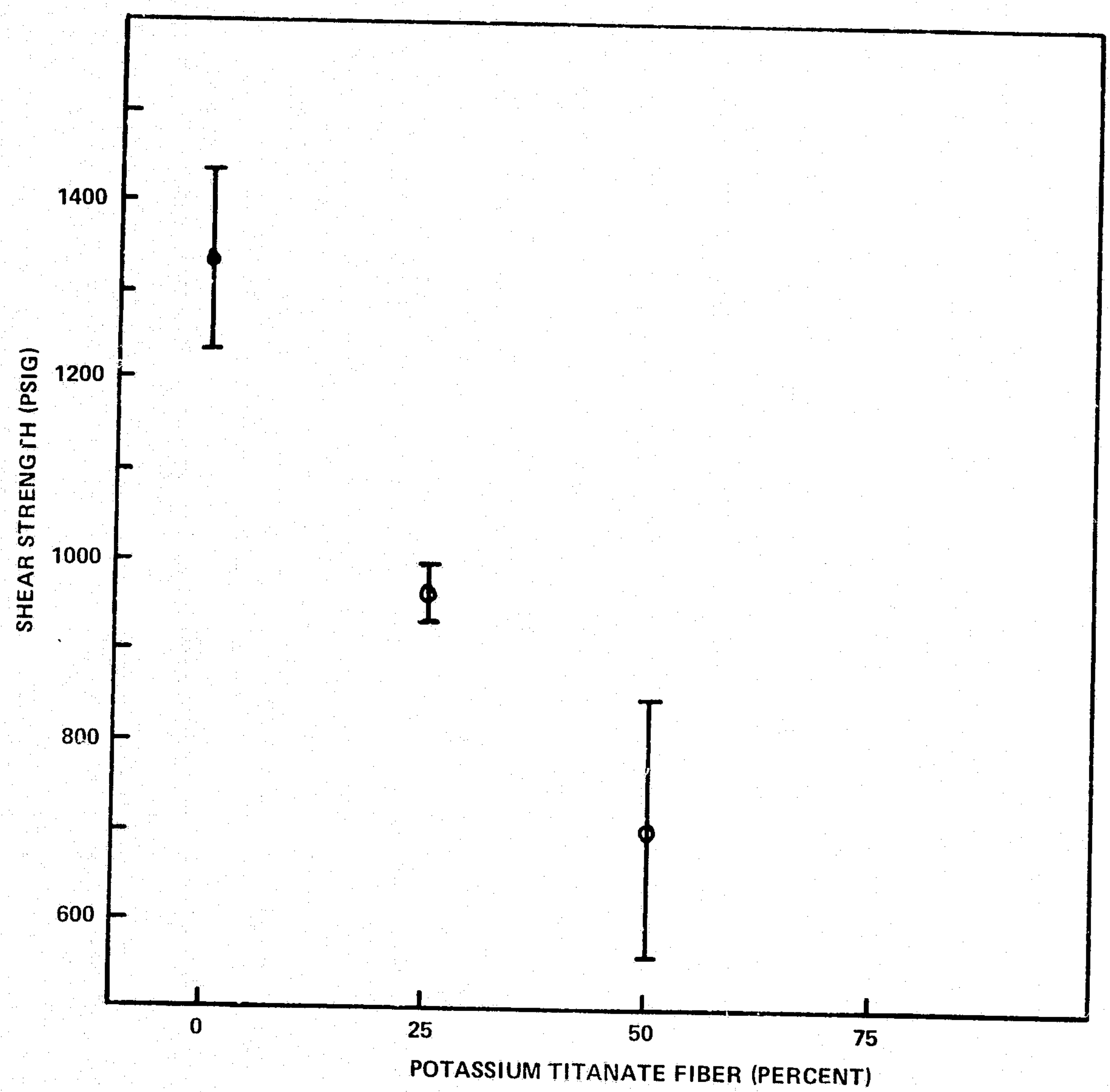

Figure 3-19 - Shear Strength of Experimental Samples as a Function of Increasing Potassium Titanate Fiber Content at constant resin level. Conversely, Figure 3-20 demonstrates the increase in shear strength as resin is increased at a constant level of potassium titanate substitution (50%). It seems that the value for 20% additional resin is anomalously high but this anomaly would be expected to disappear if the number of samples tested were increased to allow a more reliable statistical analysis. No other explanation can be offered for an unusually high value of shear strength for this particular composition.

3.2.3.3 Thermal Analysis and X-Ray

Small portions of the samples characterized above were also subjected to thermal analysis, as was a sample of the standard primary lining. Results are included as Figures 3-21 to 3-23 for thermogravimetric analysis (TGA), and Figures 3-24 and 3-25 for differential thermal analysis (DTA). These curves are quite complex and defy a complete detailed analysis; some of the features can only be explained in a general sense to avoid disclosing some proprietary features of the standard linings.

Figure 3-21 shows the somewhat lower thermal stability of the standard primary lining, as compared to the standard secondary. Above 500°C (932°F), however, the higher inorganic content of the primary causes the curves to cross and a larger residue is obtained than for the secondary. The onset of oxidation of the organic components at 250 to 300°C (482 to 572°F) is typical of friction materials containing organic binders and modifiers, and is observed in all the curves presented here. The details of the slopes of the decomposition regions are functions of the nature and quantity of each modifier, among other factors, e.g., heating rate.

Figure 3-22 shows the difference between oxidative and pyrolitic degradation for sample 26. As expected, the presence of oxygen accelerates the decomposition of organic components. Nevertheless, at sufficiently high temperatures, equivalent quantities of residue are obtained - though their composition is expected to be somewhat different. The actual environment experienced by the lining during

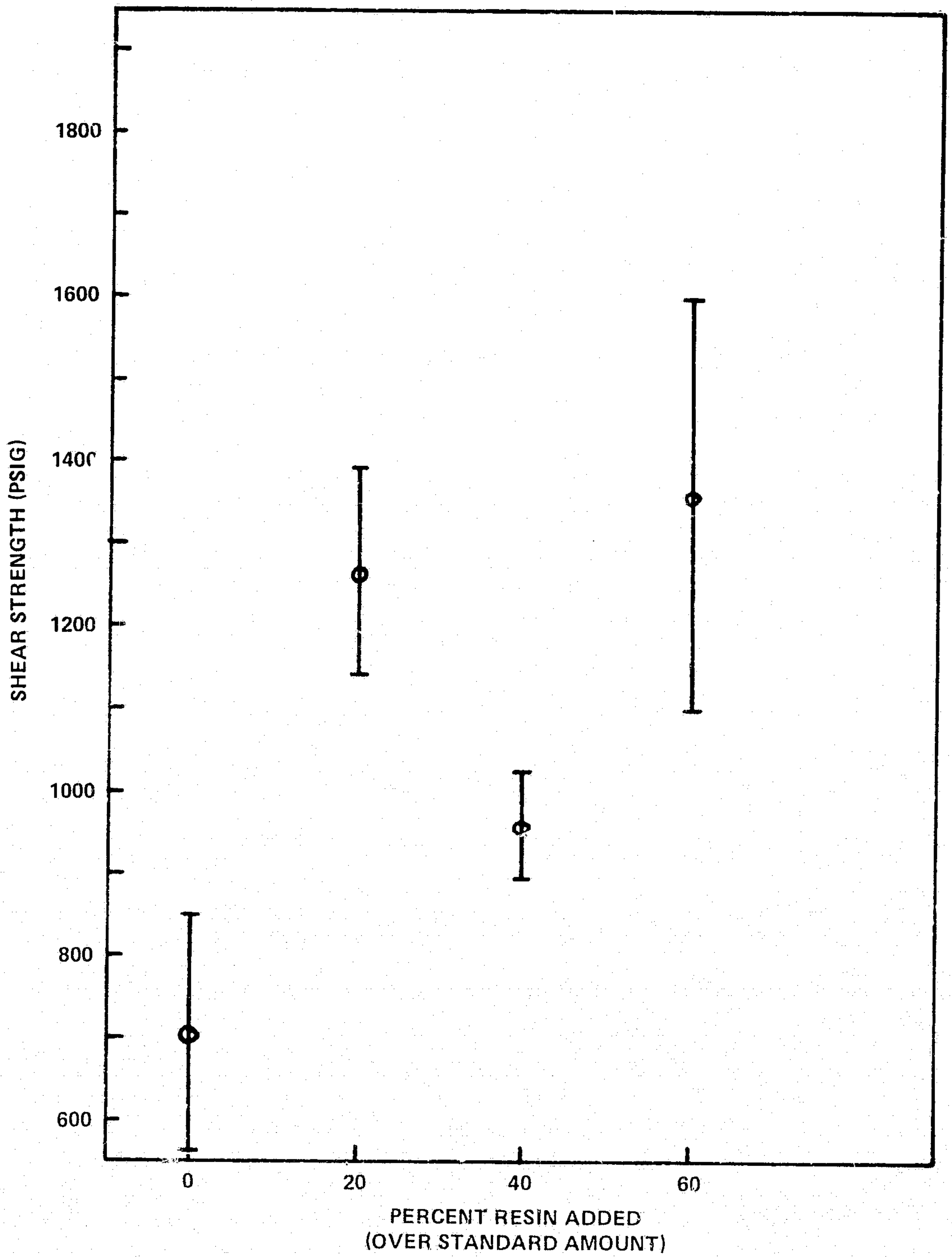

Figure 3-20 - Shear Strength of Experimental Samples as a Function of Increasing Resin Content

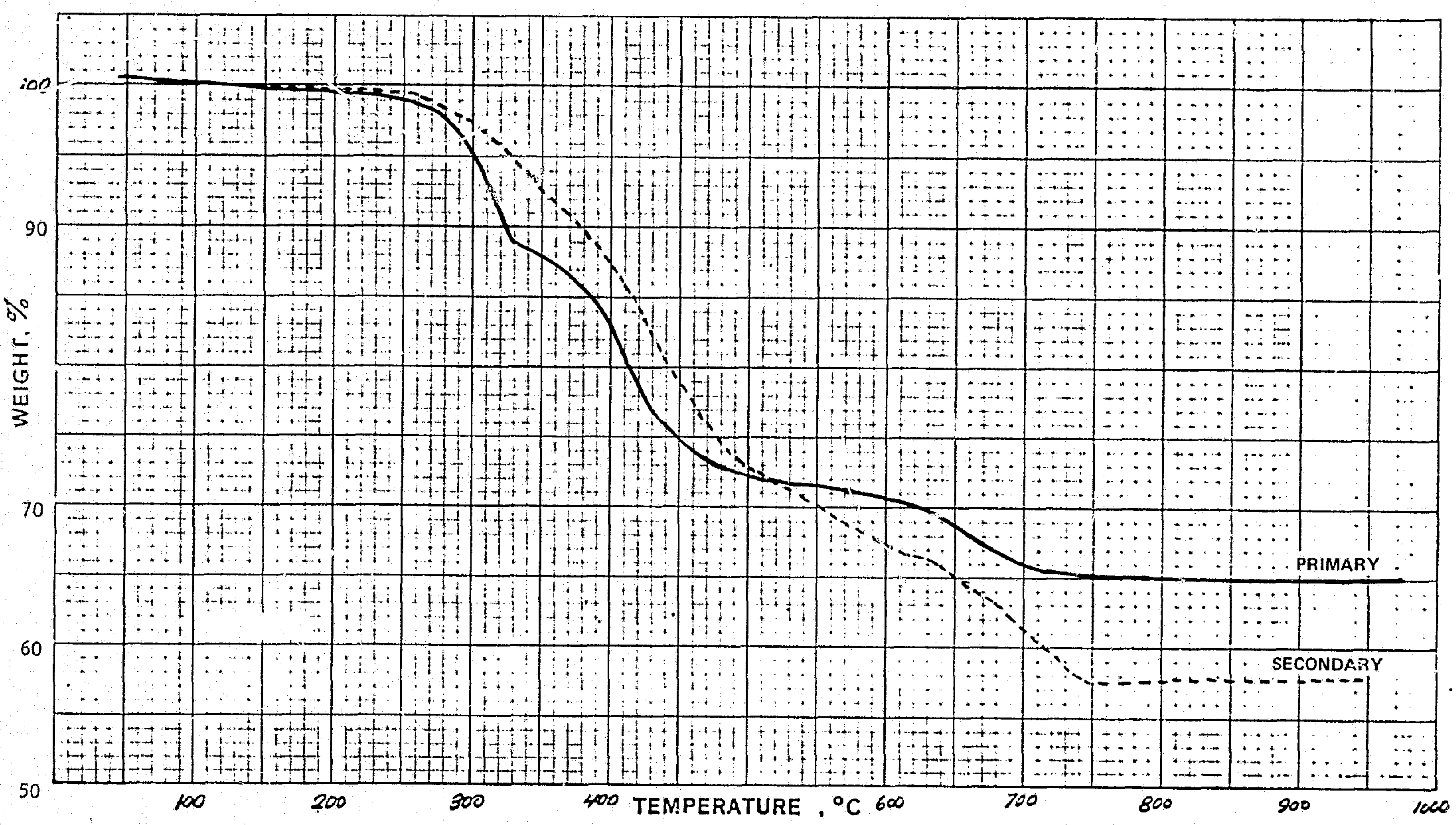

Figure 3-21 - TGA Thermograms of Primary and Secondary Standard Linings
Atmosphere: Flowing Air, 40 cc/min

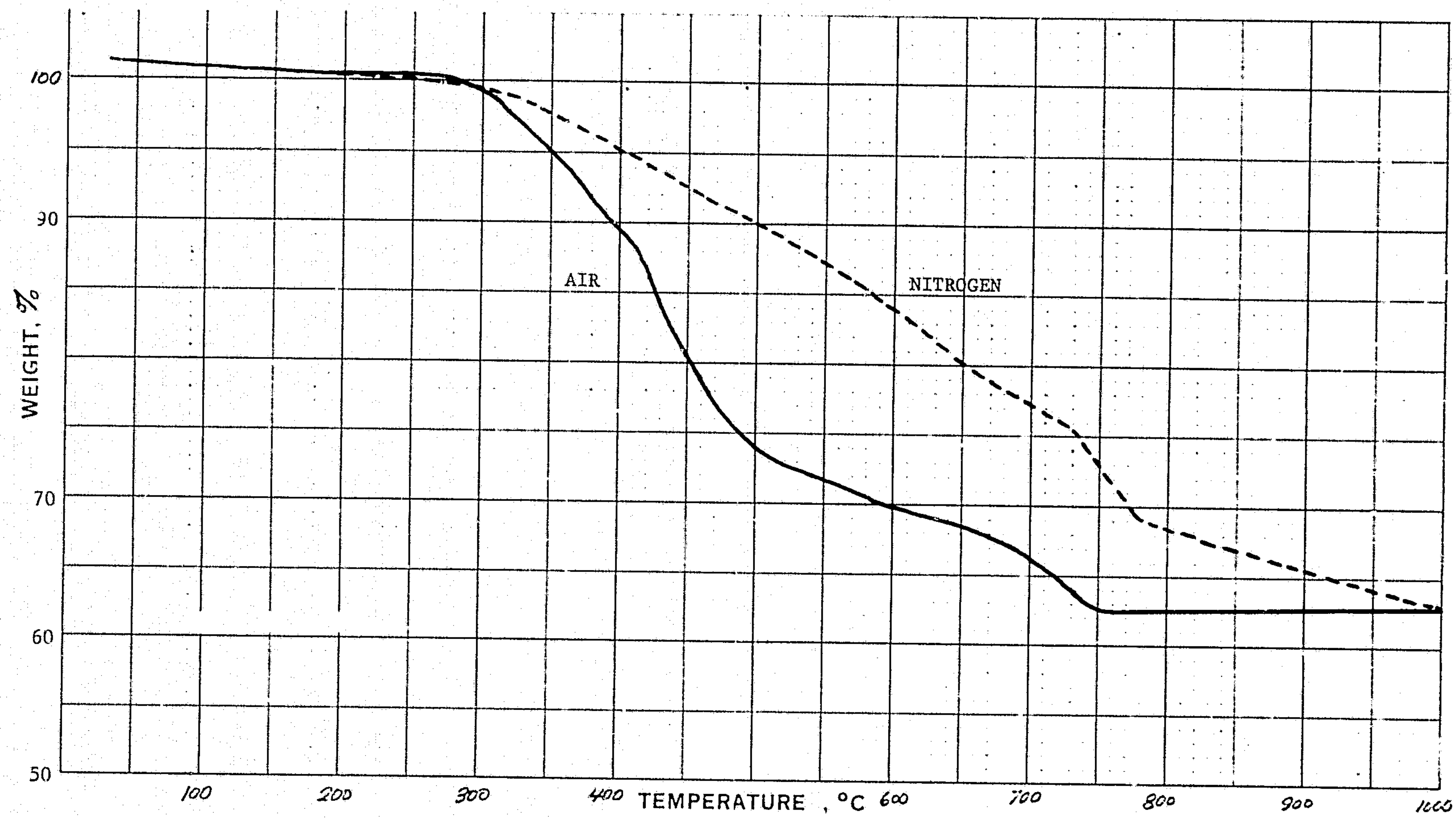

Figure 3-22 - TGA Thermograms of Experimental Formula No. 26
Atmosphere: Flowing Air or Flowing Nitrogen, 40 cc/min

an application is probably such that the decomposition will be somewhere between the two curves shown.

Figure 3-23 satisfies us that the linings with increasing resin content behave similarly in every way, in their oxidative decomposition, except for reflecting the trend in organic to inorganic material content.

Very little information of a quantitative nature can be gleaned from the DTA curves, Figures 3-24 and 3-25. They are presented here for the sake of completeness, and they show that the resin has been completely cured, by comparison with Figure 3-14. The endotherm at 375-400°C (707-752°F) is due to asbestos, as is the endotherm beginning just below 600°C (1112°F). The other features are due to other ingredients and they offer no additional insight to the behavior of the composites. The obvious difference between primary and secondary linings is once again apparent in Figure 3-24. All the thermograms for the secondary lining and its variants are very similar, within the limitations of the technique, consistent with other information already discussed. Three are shown for compositions with increasing quantities of resin at 50% potassium titanate substitution in Figure 3-25.

For the sake of comparison, thermograms are shown for two formulations containing polyimide rather than phenolic resin in Figures 3-26 and 3-27. The TGA's are very similar although they show the onset of oxidation somewhat earlier for the polyimide-containing formulas, 200°C vs. 270°C (392 vs. 518°F). In the 400-500°C (752-932°F) range, however, the polyimide formulas show somewhat greater stability. The DTA's are quite similar to those discussed above. X-ray diffraction spectra were recorded and analyzed for the residues of the samples whose TGA's were just described. These were the most complex of any spectra yet taken, and could not be analyzed completely. A major portion of the spectra were, as expected, due to the major inorganic constituents, asbestos and potassium titanate fiber, and to their respective high temperature transformation products, olivine and $K_2Ti_6O_{13}$.

C-2

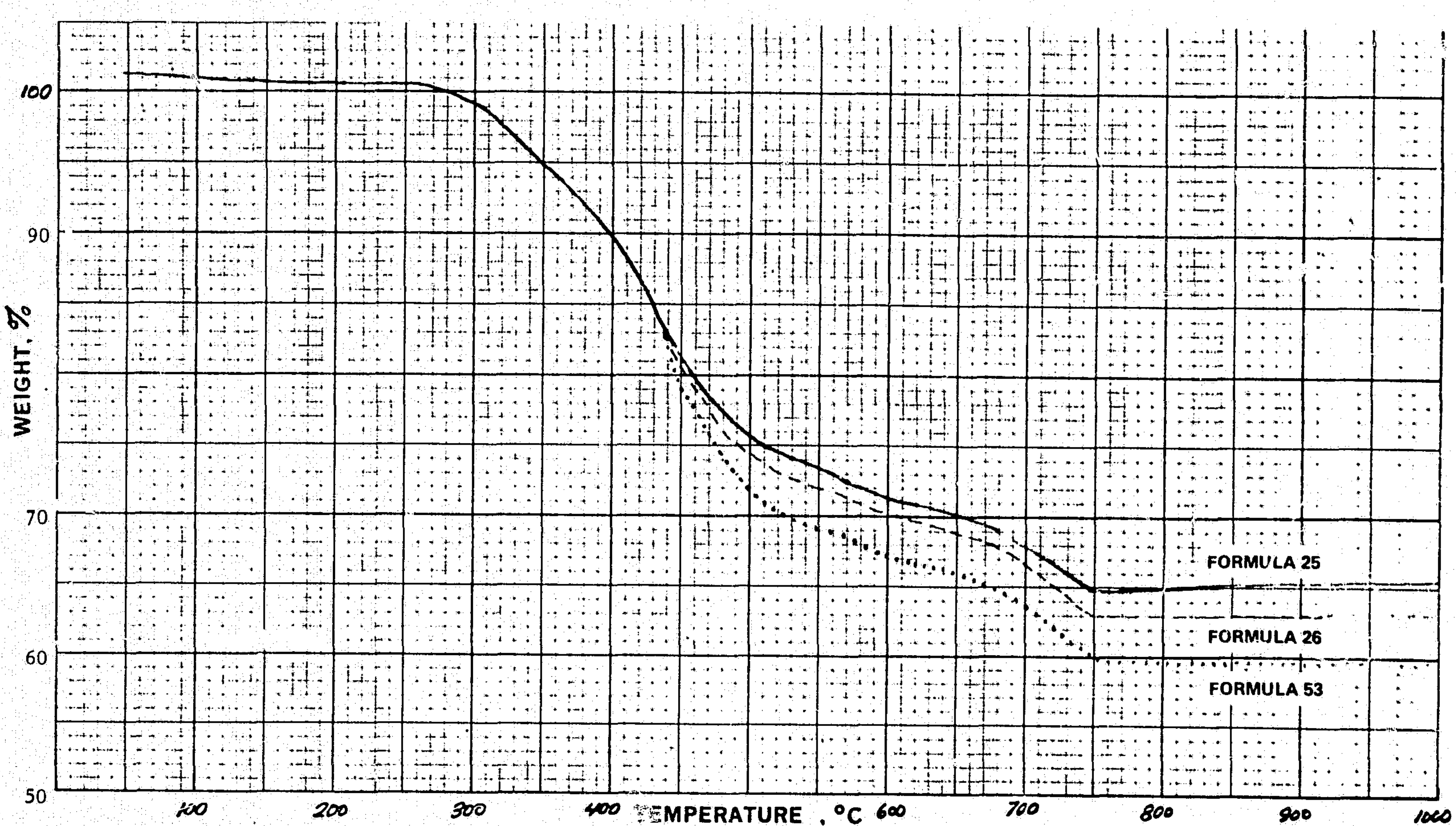

Figure 3-23 - Comparison of TGA Thermograms for Experimental Formulas Nos. 25, 26 and 53
Atmosphere: Flowing Air, 40 cc/min

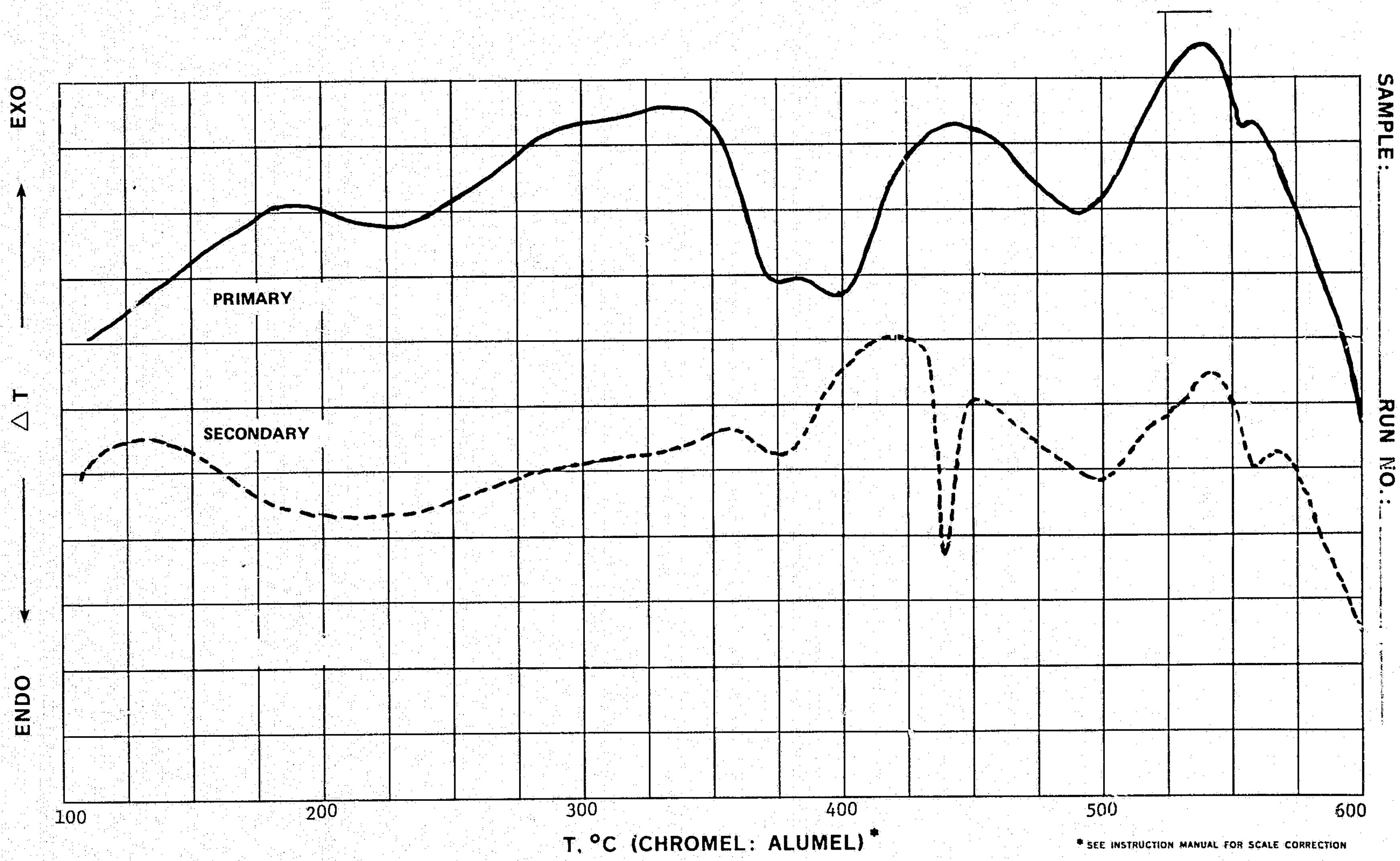

Figure 3-24 - DTA Thermograms for Primary and Secondary Standard Linings
Atmosphere: Vacuum, 20 Torr

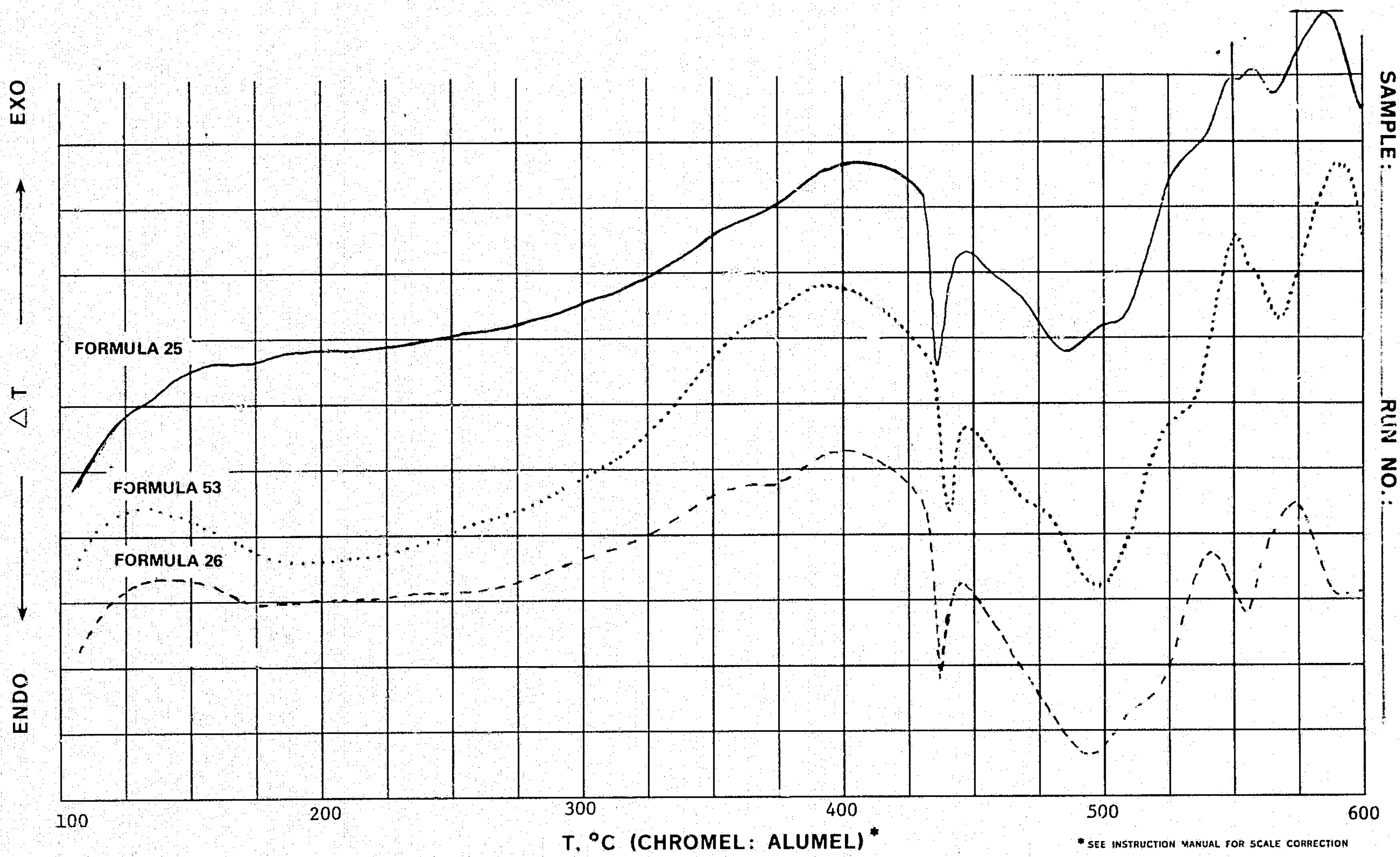

Figure 3-25 - Comparison of DTA Thermograms for Experimental Formulas Nos. 25, 26 and 53

Atmosphere: Vacuum, 20 Torr

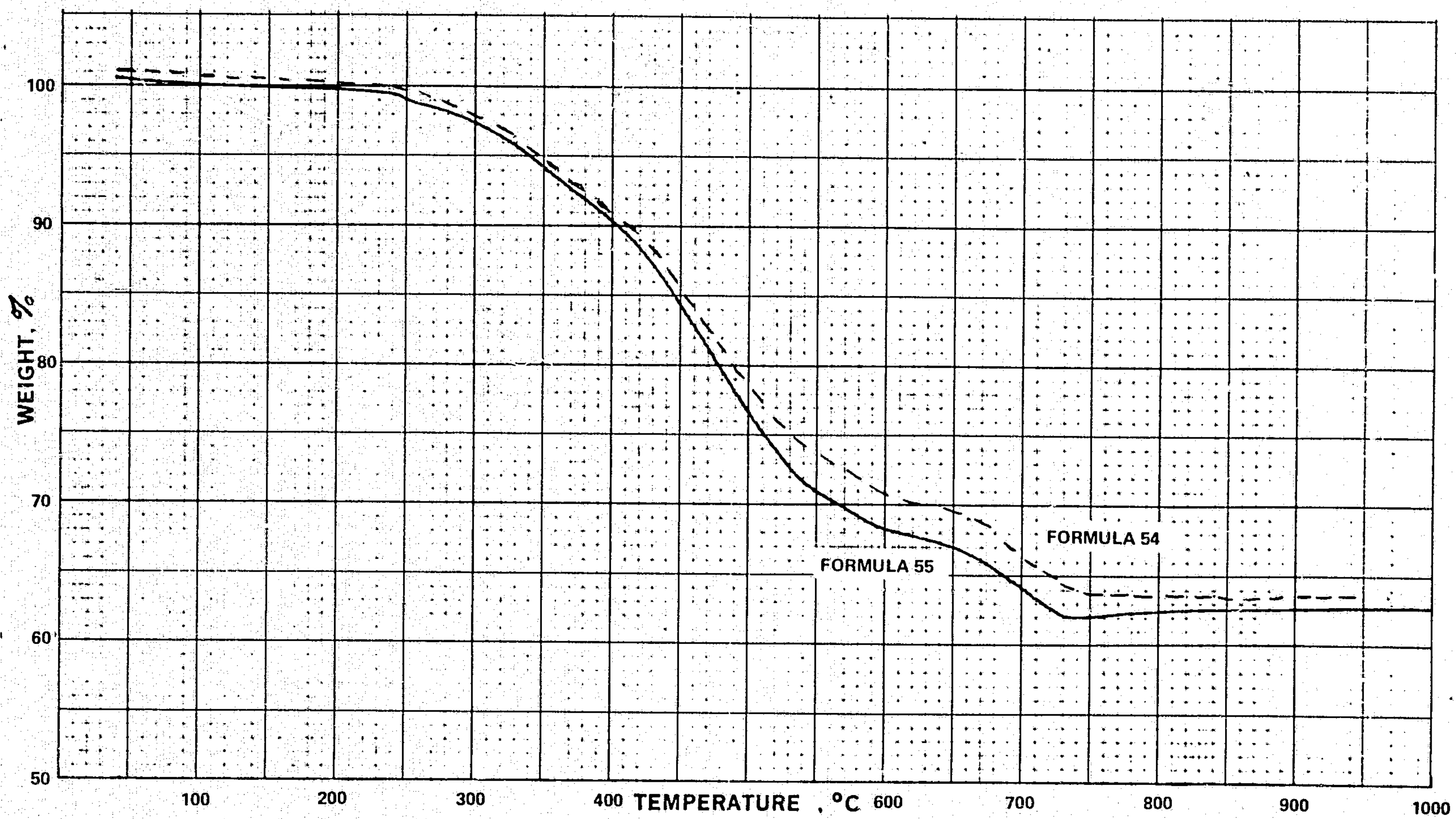

Figure 3-26 – TGA Thermograms for Experimental Formulations Containing Polyimide Resins
Atmosphere: Flowing Air, 40 cc/min

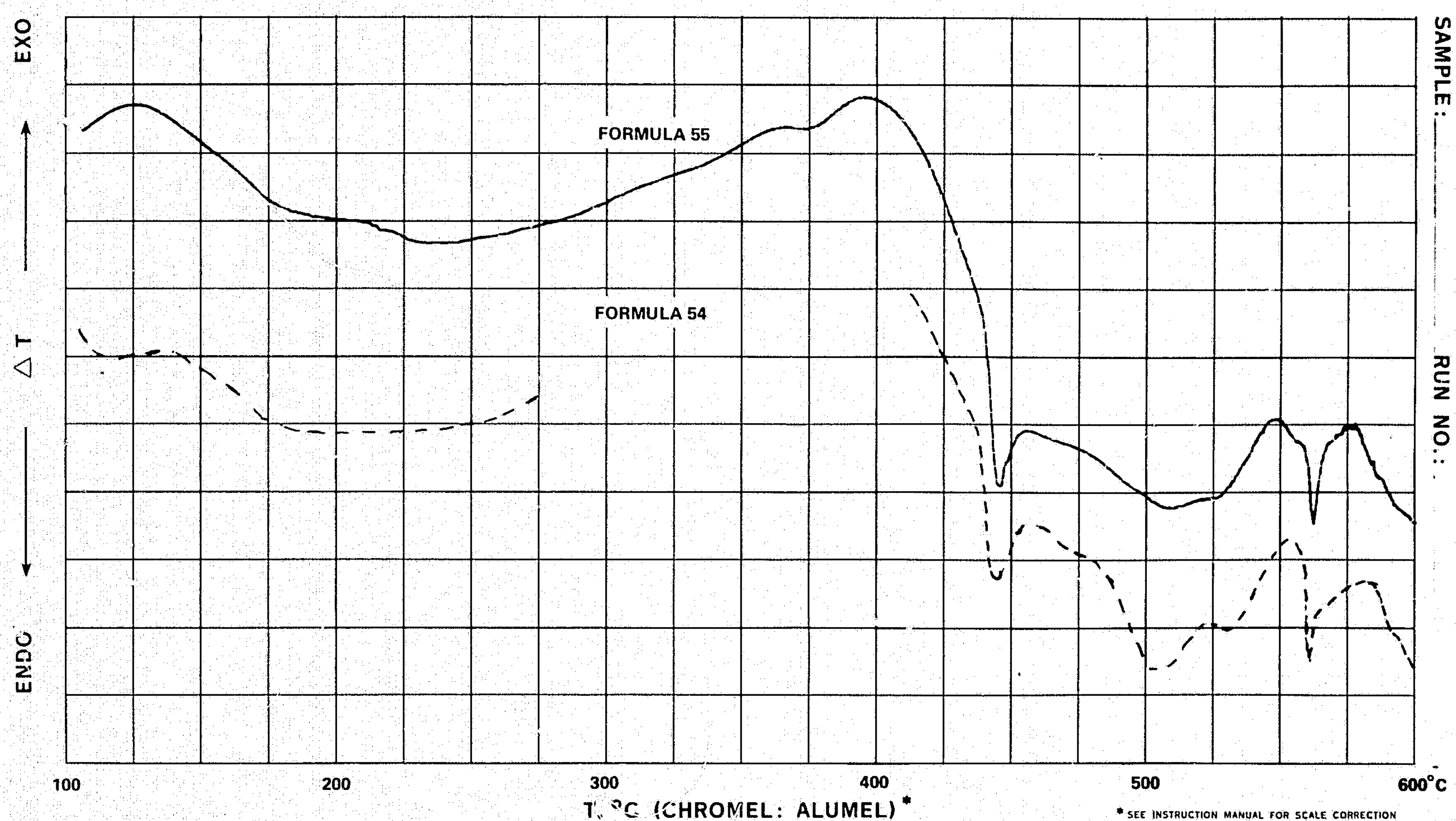

Figure 3-27 - DTA Thermograms for Experimental Formulations Containing Polyimide Resins
Atmosphere: Vacuum, 20 Torr

This concludes the section describing the characterization of experimental friction materials. The next section describes the experimental techniques whereby friction and wear properties were determined.

3.3 DESCRIPTION OF DYNAMOMETER TESTS OF FRICTION MATERIALS

All the initial screening of the experimental friction materials was performed on a sample dynamometer, on which a small portion of a brake lining can be tested in a relatively fast and inexpensive test for friction and wear properties. The most promising of the materials thus screened was tested further on a full-scale inertial dynamometer, on which a full size brake assembly with the experimental linings installed is tested separately for wear and friction performance behavior. The next logical step, a vehicle test, was not performed in this study.

3.3.1 Sample Dynamometer Testing

Friction and wear measurements were conducted with a drag (Chase) dynamometer that was designed and constructed at Bendix Research Laboratories. It has been described in the literature[(3-7)] and is shown in Figure 3-28.

Temperatures of the tests ranged from 122 to 343°C (250 to 650°F) with applications usually being made at 28°C (50°F) intervals. A series of forty applications of the composite sample against a rotating cast iron drum was conducted at each temperature, with the sample-drum sliding speed maintained at 25 ft/sec (7.6 m/sec). The output torque was held constant at 350 in-lb (4.0 Kg-m), and the normal load necessary to maintain the torque averaged over forty applications provided the measure of friction coefficient. Sample wear at each temperature was determined by measuring the cumulative dimensional and weight loss resulting from the forty applications. The drum had an 11-inch (28-cm) ID, and its composition corresponded to the specifications given in SAE Standard J661a.[(3-8)] The drum temperature was measured through a slip-ring assembly with a chromel-alumel thermocouple located at the center of the wear track, 0.050-inch (0.13-cm) below the friction surface. An

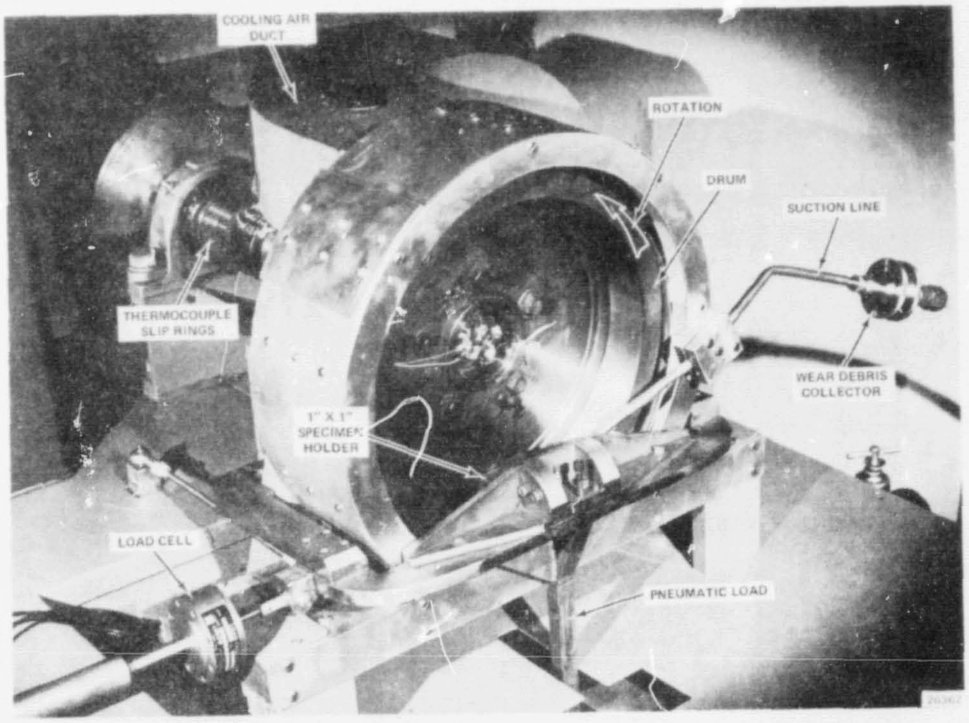

Figure 3-28 - Close-Up View of Drum Portion of Drag Dynamometer. Note Added Feature of Wear Debris Collector (Not Used in this Study)

auxiliary heater-blower system was available for use in maintaining the desired temperature.

Upon receiving the experimental sample in form of a disc pad, the operator cut a piece of the desired dimensions and measured its density. He then arced the friction surface to conform with the drum curvature, always maintaining the same relative orientation for every sample tested. Naturally this orientation is noted and marked during fabrication. Before beginning the initial series of applications at 122°C (250°F), the sample was "broken in" by dragging it against the drum at a sliding speed of 15.6 ft/sec (4.75 m/sec) and a constant load of 100 psi (6.9×10^5 N/m^2). This serves to create a wear track on the drum, which is cleaned and ground before each new sample is tested, and assures that the entire surface of the sample is in proper contact with the drum. The sample is weighed and measured, repositioned, and the 40 applications at 122°C (250°F) are begun.

Results of these tests will be discussed in Section 4.

3.3.2 Inertial Dynamometer Tests

These tests were conducted at The Bendix Corporation Automotive Control Systems Group (ACSG) facilities in South Bend, Indiana. Arrangements for the tests were made through the Bendix Automotive Test Center, New Carlisle, Indiana.

Either a Gilmore or a Link full-scale inertial brake dynamometer was used for the tests, whichever became available when the tests were scheduled to be run. The basic brake information used for the tests was as follows:

Type of Brake:	D.S.S.A. (Duo-Servo)
Size:	11 x 2 inches (27.9 x 5.1 cm)
Rolling Radius:	12.25 inches (31.12 cm)
Wheel Cylinder Size:	1-1/8 inches (2.86 cm)
Wheel Load:	980 pounds (445 Kg)

Two separate tests were conducted, one to give an indication of lining wear, and one to test lining performance in terms of friction.

3.3.2.1 Wear Test

This test is actually similar in concept to the sample dynamometer test described in Section 3.3.1 above. Under controlled laboratory conditions it enables relative comparisons to be made of the durability of brake linings under increasingly severe conditions of usage. This means, of course, that both the experimental lining as well as the standard were tested so that a comparison could be made.

In this test, 300 stops are made from 50 mph (22.4 m/s) at each of a series of temperatures, at a constant deceleration rate of 12 ft/sec^2 (3.66 m/s^2). Line pressure and lining and drum temperatures are recorded, the latter service as control temperature. Weight and thickness are measured for both primary and secondary linings, initially and after each series at a temperature. The standard primary lining was used in combination with both the standard and experimental secondaries. The detailed test procedure will not be given here, but may be found in Appendix D.

3.3.2.2 Performance Test

Rather than measuring wear, this test is designed to test the frictional properties of a brake system, and is usually only defined for a vehicle, in which interactions between front and rear brakes are important. Those aspects of a lining's performance that are emphasized in this test are effectiveness, that is the ability to stop a vehicle within a given distance, and fade, the loss in friction with repeated short interval high torque stops.

The actual test performed in this study was a single wheel dynamometer simulation of FMVSS 105-75.[3-9] Here, also, both standard and experimental secondaries were tested with the standard primary, in order that a comparison could be made. A step-by-step listing of the procedure used can be found in Appendix E.

Results of both types of inertial dynamometer tests will be discussed in Section 4.

3.4 REFERENCES

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(3-8) 1973 SAE Handbook, Society of Automotive Engineers, Inc., New York, New York, 1973, p. 1018.

(3-9) Federal Motor Vehicle Safety Standard 5715 105-75-1, effective date 1 September 1975.

SECTION 4
RESULTS AND DISCUSSION

This section will present the results of the friction and wear tests on the sample and inertial dynamometers. Each of the types of experimental ingredient will be treated separately, with the potassium titanate fiber discussed first, followed by polyphenylene and polyimide resin. Preceding those sections will be a presentation of the results of tests on the standard linings and the initial experimental linings. These tests were made by a 1 to 1 by volume substitution of the experimental ingredients for their standard counterparts into the standard linings, as listed in Table 3-7.

All results of sample drag dynamometer tests will be shown as dual plots of wear and corresponding average friction as functions of temperature. Such plots are commonly used in the industry, since they allow the observer to quickly discern the general behavior of a sample of friction material. While absolute judgements about the same friction material when used on a vehicle cannot be made on the basis of such tests, they provide a valuable screening tool; this is especially true if the tests are used to compare an experimental material to one whose behavior on a vehicle is known, i.e., a "standard." It has been found at Bendix Research Laboratories that such a sample screening procedure is more applicable to drum linings than to disc pads, as long as the sample drag machine is fitted with a drum.

It should be noted that a large amount of scatter is normally encountered in duplicate tests of friction materials on sample machines. The complexities of the materials, the test equipment and the test procedures all constitute sources of variability. Even two samples cut from the same piece of friction material may thus, sometime, show differences in wear and/or friction. In the results presented herein, the reader is cautioned to keep the above in mind, and to be aware of trends in friction and wear behavior, rather than in absolute differences between the friction and wear of any two samples.

4.1 STANDARD LININGS

The general approach adopted in this program was to seek improvements in a commercial secondary lining called the "standard secondary lining." The primary lining required for full-scale testing was selected from available commercial primary linings to appropriately match the secondary lining, either standard or experimental, being tested. It turned out that a single primary lining was a suitable match for testing both the standard and experimental secondary linings; that primary lining is designated the "standard primary lining." This section describes the friction and wear properties of both the standard secondary lining - in which experimental ingredients were substituted - and the standard primary lining.

(Early in the program, a few exploratory samples were fabricated in which experimental materials were substituted into the standard primary lining. The data from these samples are presented and discussed in Appendix F, since they do not add to the general conclusions of the report.)

Figures 4-1 and 4-2* are plots of the results of sample dynamometer tests on the standard primary and secondary linings, respectively. Samples cut from production linings as well as some fabricated at Bendix Research Laboratories (BRL) are included. The scatter is obvious on both graphs. The higher wear shown by the primary as compared to the secondary (note different scales) is typical of linings designed for Duo-Servo brakes. The use of a primary with too much wear resistance would result in less friction stability, poor fade resistance, and generally poor overall performance. Because of this high wear, however, some of the sample dynamometer tests had to be terminated early because the sample had worn too thin and there was a danger of scoring the drum with the sample holder.

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*Note that, in Figures 4-1 and 4-2 and in the following figures, for sample dynamometer tests, the dimensions of wear are not given; the wear represents a normalized weight loss. All of the plots in this report are consistent (they may be compared directly) with a few exceptions that are cited in the text.

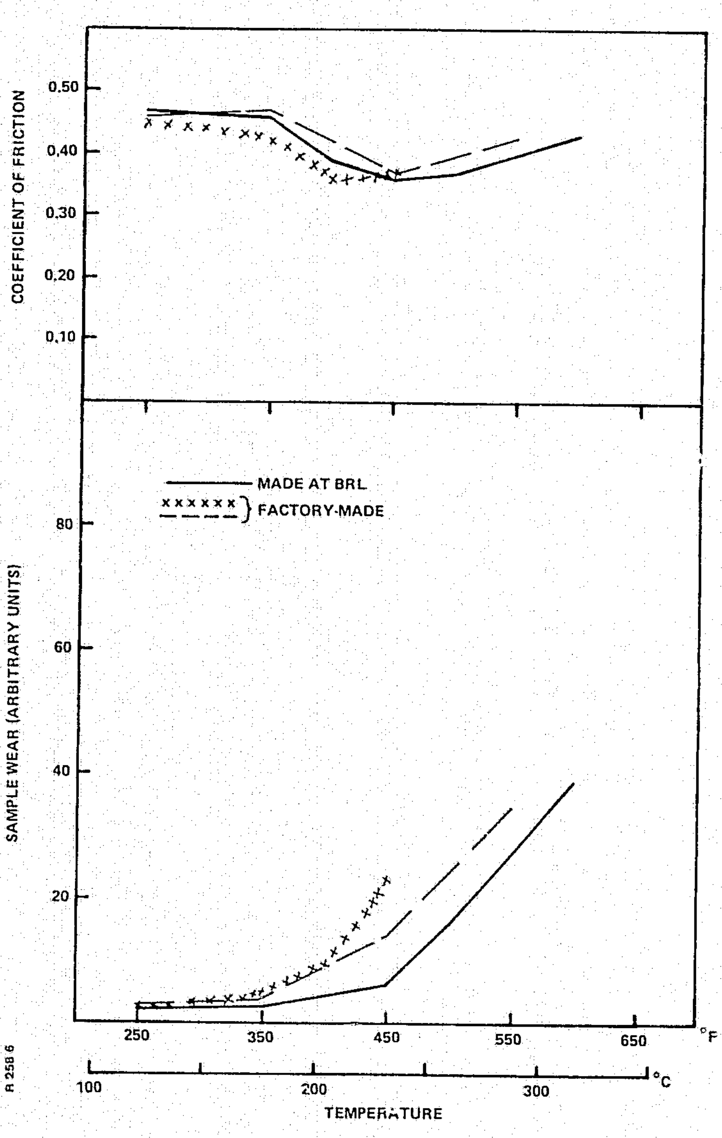

Figure 4-1 - Friction and Wear of Standard Primary Lining as Functions of Temperature

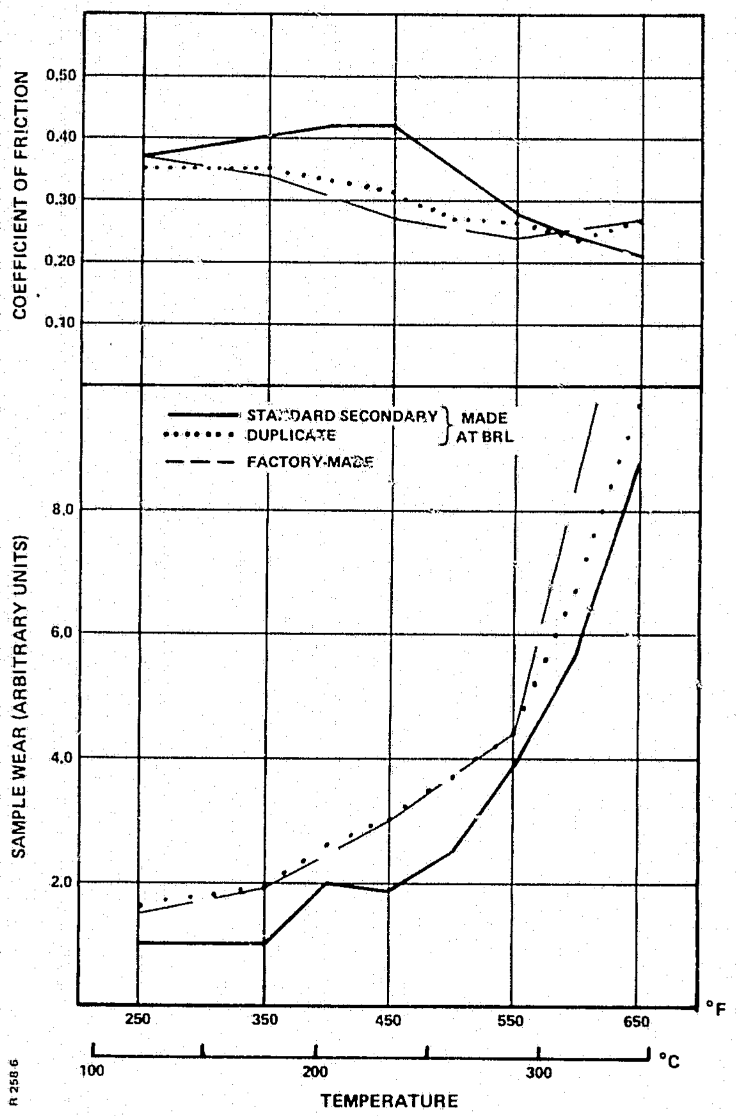

Figure 4-2 - Friction and Wear of Standard Secondary Lining as Functions of Temperature

For the secondary lining it may be noted that one of the BRL samples tracked the production lining very closely in both friction and wear, while the other showed both higher friction and lower wear. Friction and wear regions are thus defined, upon which we would like to make improvements. In initial subsequent graphs, the experimental lining friction and wear will be compared to the best BRL curves, so that we may tell at a glance whether a significant improvement has been made. Subsequently a comparison will also be made with an average curve.

4.2 POTASSIUM TITANATE FIBER SUBSTITUTION

The fabrication problems encountered when all of the asbestos was replaced with potassium titanate fiber (Section 3.2.2.2) suggested two alternate approaches:

(a) partial substitution of asbestos with titanate fiber, and

(b) increase of resin in samples containing this fiber.

Both these avenues were explored, leading to the most extensive investigations and most fruitful results of this program. These studies are the subject of the present section.

A series of tests was first conducted on the sample dynamometer using the standard secondary lining as the matrix for substitution. This series resulted in the maximum friction and wear improvements that were achieved with the standard commercial lining. These experiments are discussed in Sections 4.2.1 and 4.2.2. The effects of variation in potassium titanate fiber level and binder level were then examined further, using as a matrix for substitution a lining that was similar, but not identical to the secondary standard lining. This study provided certain information not obtained in work with the standard secondary, and results are given in Section 4.2.3. Use of potassium titanate fiber as a friction modifier is described in the brief Section 4.2.4. Finally, the composition which represented the largest improvement on the standard formula, as described in Section 4.2.2, was subjected to full-scale dynamometer testing. Results of the full-scale tests are discussed in Sections 4.2.5 and 4.2.6.

4.2.1 Partial Substitution for Asbestos at the Standard Phenolic Resin and Modifier Levels

A summary of the experimental formulas that were fabricated and tested in an attempt to find an optimized combination of potassium titanate substitution and phenolic resin quantity is given in Table 4-1.

Table 4-1 - Summary of Samples Containing Potassium Titanate Fiber and Phenolic Resin

Sample No.	Asbestos Replacement by Potassium Titanate Fiber	Phenolic Resin (Percentage of Standard Amount)	Other
15	25%	100	
16	50	100	
25	50	120	
26	50	140	
27	0	100	50% Titanate for Cashew
29	0	120	50% Titanate for Cashew
31	50	140	
34	50	140	Modifier/Fiber up 10%
36	50	140	Modifier/Fiber down 10%
41	50	147	
42	50	133	
43	40	140	
44	50	140	Cashew for other organic
45	50	140	M074 for non-cashew organics
52	50	140	
53	50	160	

Whereas the total substitution of potassium titanate for asbestos fiber made it impossible to process the friction material sample, due to the increased resin demand, partial substitution of potassium titanate had some dramatic effects, especially in the improvement of high temperature friction. Variation in the ratio of potassium titanate to asbestos from 1:3 to 1:1 are shown in Figure 4-3, in which the 1:1 mixture is superior in wear characteristics to the 1:3 composition. Further, the 1:1 mixture exhibits a flatter friction curve than the standard lining. However, it was found that processing is still difficult with the standard quantity of resin, a portion of the pad breaking off during fabrication. For this reason, the substitution for even larger quantities of asbestos was not explored at this stage. Since the sample with the 50% asbestos replacement showed somewhat more favorable wear, this composition was chosen to study the effect of increasing the resin content.

4.2.2 Partial Substitution for Asbestos Over Ranges of Phenolic Resin and Modifier Level

Increasing the phenolic resin, over the quantity used in the standard formula, in 20%* stages up to 60% indicated that the best combined friction and wear properties result from a 40% increase, as shown in Figure 4-4. In particular, preparation of a sample in which high-temperature wear appeared to be improved over that of the standard was sufficiently encouraging that additional samples of this composition were fabricated and tested. Results of these duplications, shown in Figure 4-5, confirmed the initial findings and led to a more detailed investigation of compositions in this region. A discussion of the potential merits and faults of this formulation will be found below in Section 4.2.3. However, it seems that the quantity of 40% excess resin is near an optimum because even a small departure on either side of this value degraded the wear improvement. This is shown in Figure 4-6, which gives friction and wear plots for composites with 47 and 33% added resin at 50% potassium titanate fiber substitution for asbestos. Alternatively, a similar result was found when the titanate substitution was lowered from 50 to 40% at the 140% resin level, as also shown in Figure 4-6. It was stated in Section 3.2.2.2 that increase of potassium titanate fiber to 60% at 140% resin level did not allow fabrication of samples with adequate strength; this composition was therefore not studied further.

*Percentage changes here are referenced to the amount of resin in the standard formula; i.e., amount of resin in standard = 100%.

It appears, therefore, that an improved formula has been found, based on the standard secondary lining, with 50% of the asbestos replaced by potassium titanate fiber and with the resin increased by 40% (with other ingredients being adjusted to maintain their relative amounts constant). Among the questions that arise, however, and to which an answer was sought, are the following:

(1) Are the improvements really due to the presence of potassium titanate fiber, or is the increase in resin responsible?

(2) How will this friction material behave when used as a full-scale lining?

(3) How will this material behave on a vehicle, and will it have acceptable noise properties and drum or rotor compatibility?

(4) Can it be manufactured easily and safely?

The answer to the first question is treated below in Section 4.2.3. A discussion of the results of inertial dynamometer tests will be presented in Section 4.2.5 and 4.2.6. The last two questions cannot be answered at this time, but will also be discussed later in this report.

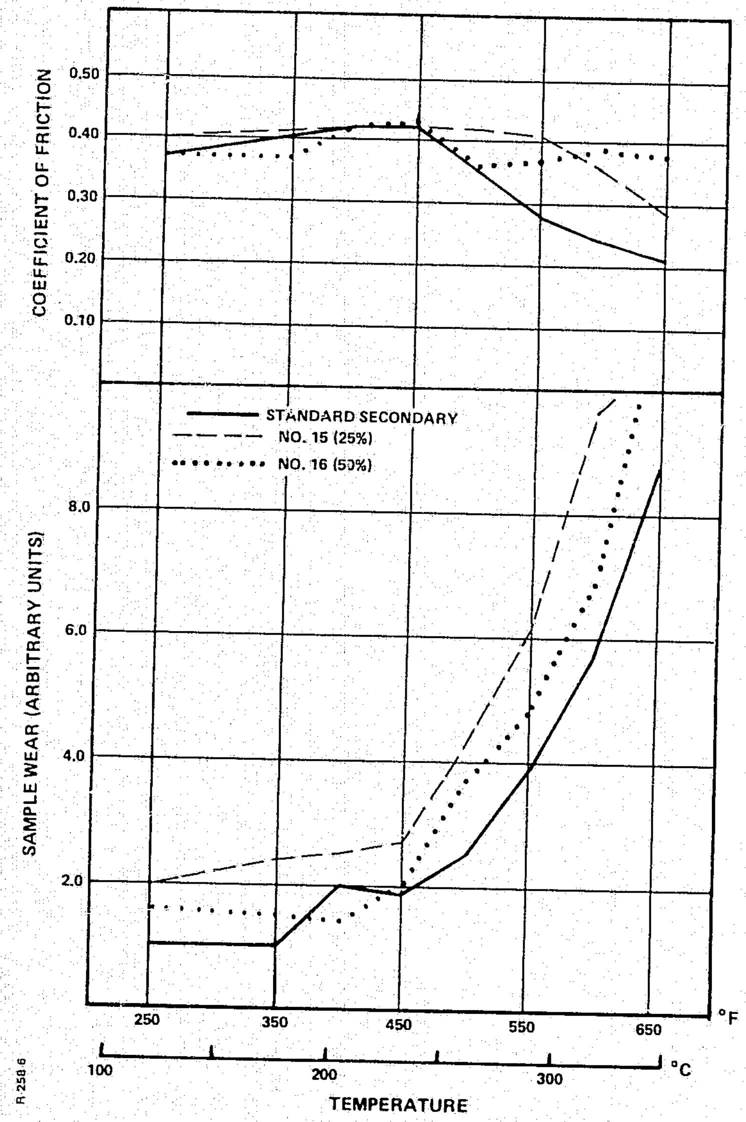

Figure 4-3 - Friction and Wear of Experimental Samples With 25 and 50 Percent Potassium Titanate Fiber Substitution for Asbestos

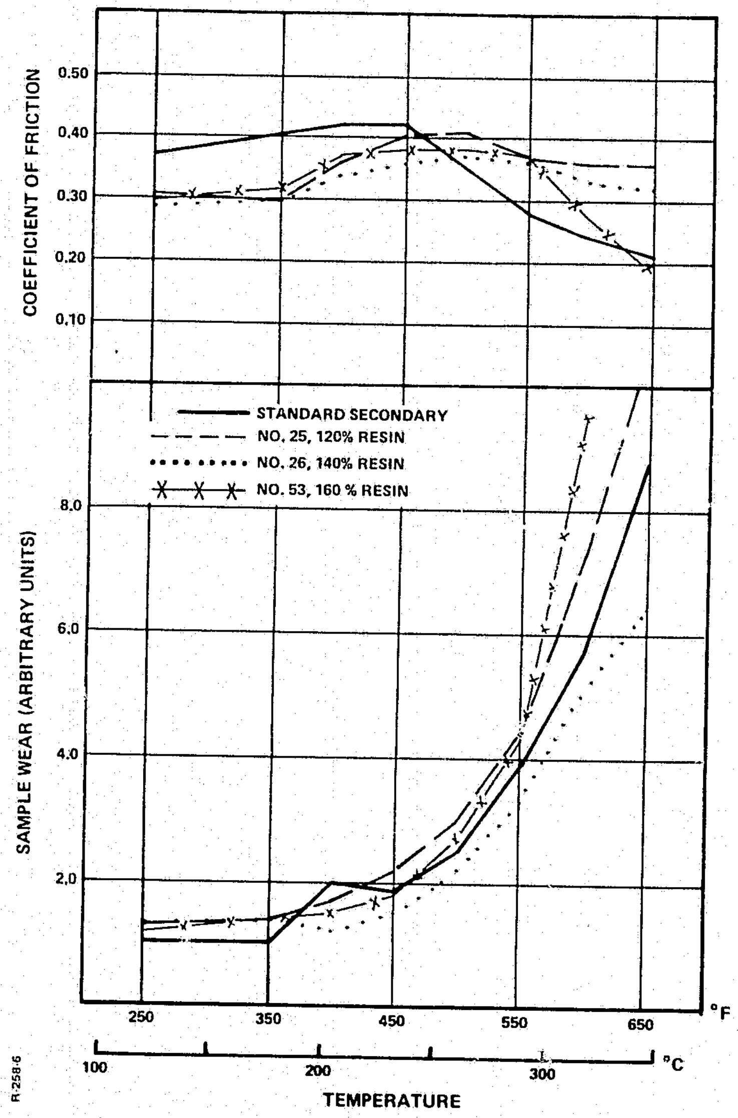

Figure 4-4 - Friction and Wear of Experimental Samples With 50 Percent Substitution of Potassium Titanate Fiber for Asbestos and Three Resin Levels

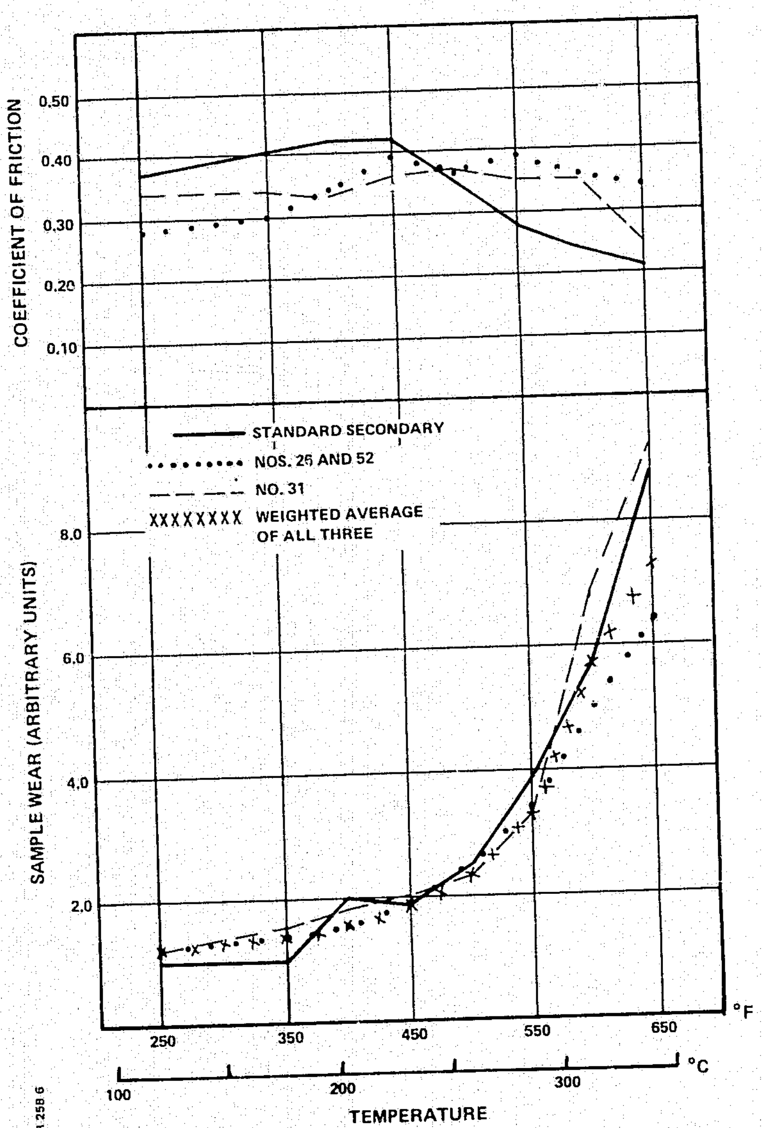

Figure 4-5 – Friction and Wear of Experimental Samples With 50 Percent Potassium Titanate Fiber Substitution for Asbestos and 140 Percent Resin, Triplicate Samples

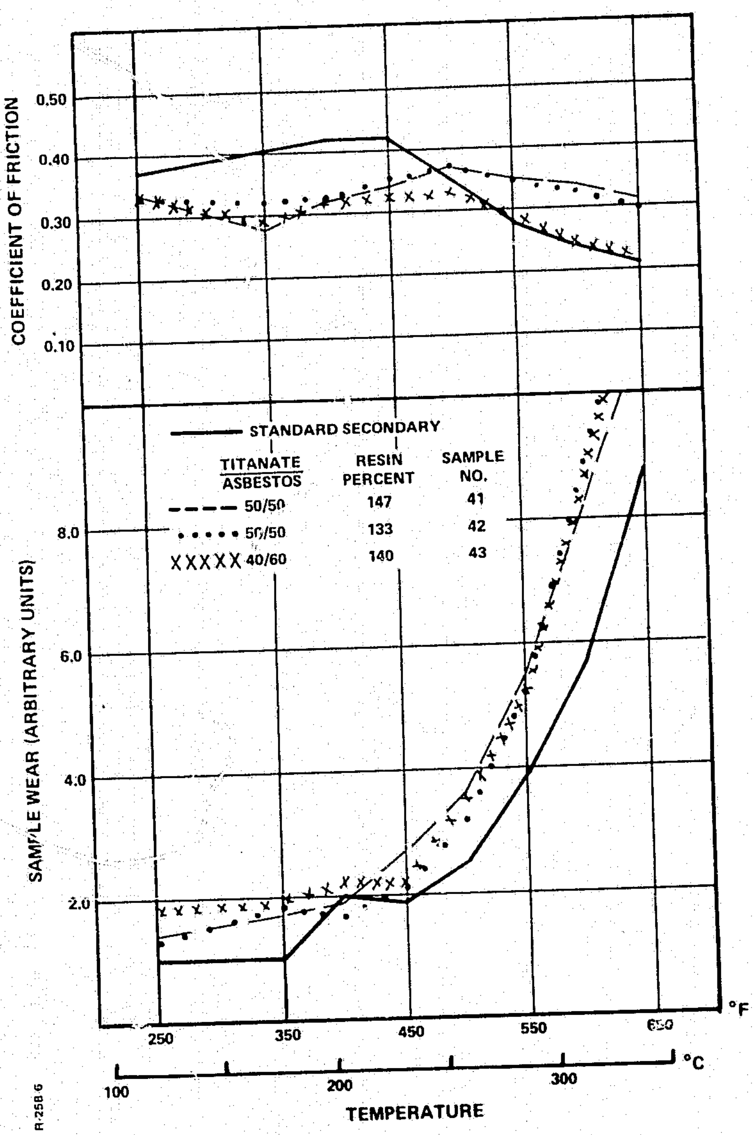

Figure 4-6 – Friction and Wear of Experimental Samples in Which Potassium Titanate Fiber and Phenolic Resin Content Were Varied Slightly From the Optimum

4.2.3 Study of the Effects of Potassium Titanate Fiber in Friction and Wear Improvement

To investigate in greater detail whether the observed improvements in friction and wear were due to the presence of the potassium titanate fiber or to the presence of additional resin, a new series of experimental friction materials was fabricated and tested. The baseline for these was similar to the standard commercial lining described earlier, but some of the ingredients were not the same. This was done to avoid the limitations imposed by the proprietary nature of the commercial lining and thus to facilitate communication. The relevant details of this lining's composition are given in Table 4-2, together with the compositions obtained when the resin is increased by 20, 40 and 60%. A summary of the experimental friction materials which were fabricated, emphasizing resin and titanate fiber variations, is given in Table 4-3. It can be seen that both resin and potassium titanate fiber content were increased in a systematic fashion so that their individual and interactive effects could be determined.

Table 4-2 - Composition of New Baseline Formulation and its Variations (Volume Percent)

Ingredient	Baseline	Resin Added 20%	Resin Added 40%	Resin Added 60%
Phenolic Resin	15.0	18.0	20.0	24.0
Chrysotile Asbestos	37.5	36.2	34.8	33.6
Organic Modifiers (Principally Cashew Friction Particle)	36.5	35.3	34.0	32.6
Inorganic Modifiers	11.0	10.5	10.2	9.8

Sample dynamometer tests were performed, and friction and wear as functions of temperature were plotted in the conventional fashion. Since the majority of these plots do not contribute to the clarity of the following discussion they will not be shown here, but are included in Appendix G. A detailed analysis of the results now follows.

Table 4-3 - Summary of Samples Fabricated With New Base Formulation

Sample No.	Phenolic Resin (Percentage of Standard Amount)	Asbestos Replacement by Potassium Titanate Fiber (Percent)	Comments
121	100	0	Base material
130	100	0	Duplicate of base
137	120	0	Adjusted base
129	120	20	
125	120	50	
126	135	50	
133	140	0	Adjusted base
123	140	40	
122	140	50	
124	140	60	
138	140	60	Duplicate of 124
128	145	50	
136	150	60	
134	160	0	Adjusted base
127	160	50	
135	160	60	

For clarity of presentation in this discussion it has been found convenient to alter some of the terms used heretofore with respect to quantities of resin and potassium titanate fiber. We will be referring to the actual volume percent of resin in the composite, e.g., 20% excess resin means 18% resin by volume, and we will be referring to the potassium titanate fiber-to-asbestos ratio rather than the amount of asbestos replaced, e.g., 60% asbestos replaced means that the titanate fiber-to-asbestos ratio is 60/40 = 1.5. For assistance to the reader, these corresponding terms are listed in Table 4-4.

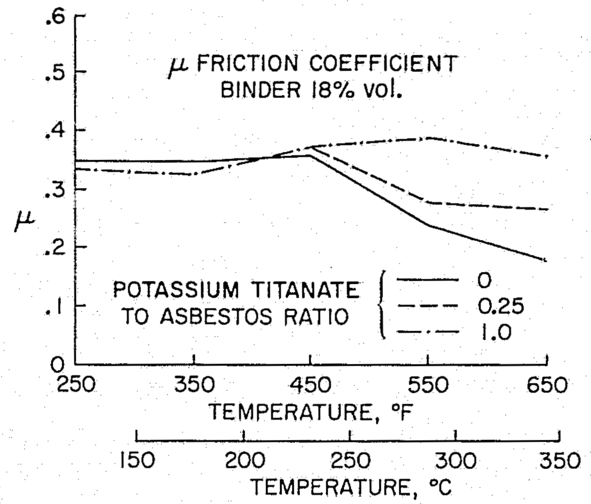

Figure 4-7 - Friction as a Function of Temperature for New Baseline With 18 Percent Resin by Volume at Three Values of Titanate Fiber-to-Asbestos Ratio

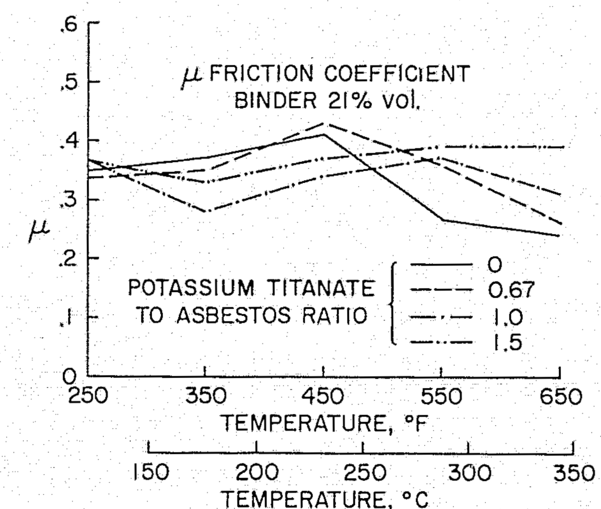

Figure 4-8 - Friction as a Function of Temperature for New Baseline With 21 Percent Resin by Volume at Four Values of Titanate Fiber-to-Asbestos Ratio

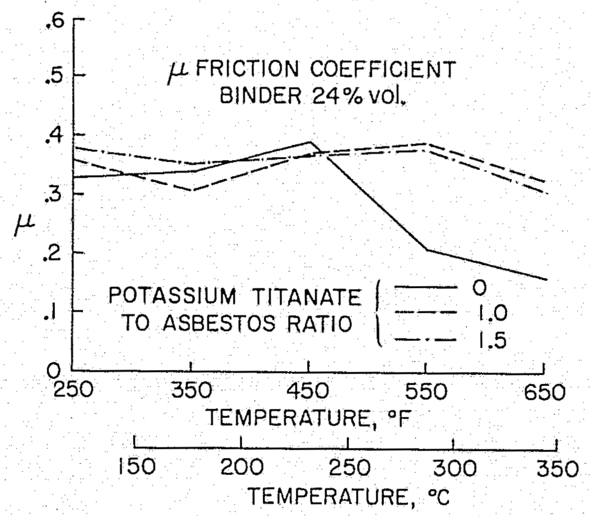

Figure 4-9 - Friction as a Function of Temperature for New Baseline With 24 Percent Resin by Volume at Three Values of Titanate Fiber-to-Asbestos Ratio

Table 4-4 - Definition of Terms Relating Quantities of Materials

A.

Resin Added (% Over Base)	Resin Present (Volume %)
0	15
20	18
35	20.3
40	21
45	21.8
50	22.5
60	24

B.

Asbestos Replaced (%)	Titanate/Asbestos Fiber
0	0
20	20.80 = 0.25
40	40/60 = 0.67
50	50/50 = 1.0
60	60/40 = 1.5

4.2.3.1 Friction and Wear Effects Due to Adjustment of Resin Content and Potassium Titanate Fiber-to-Asbestos Ratio

The friction and wear for materials which contain asbestos as the only fiber are compared in this section to composites which are identical except that part of the asbestos has been replaced by an equal volume of potassium titanate fiber. The comparison is at binder contents of 18, 21 and 24%, and the titanate fiber-to-asbestos ratios range from 0.25 to 1.5.

Friction Improvement - Comparisons in friction level, presented as curves of coefficient of friction as a function of temperature, are given in Figures 4-7 to 4-9. The partial replacement of asbestos with titanate fiber has provided higher friction at the high temperatures of 550 and 650°F (288 and 343°C) in all cases; the increase is substantial in most cases. It appears from Figures 4-7 and 4-8 that the high temperature friction is an increasing function of

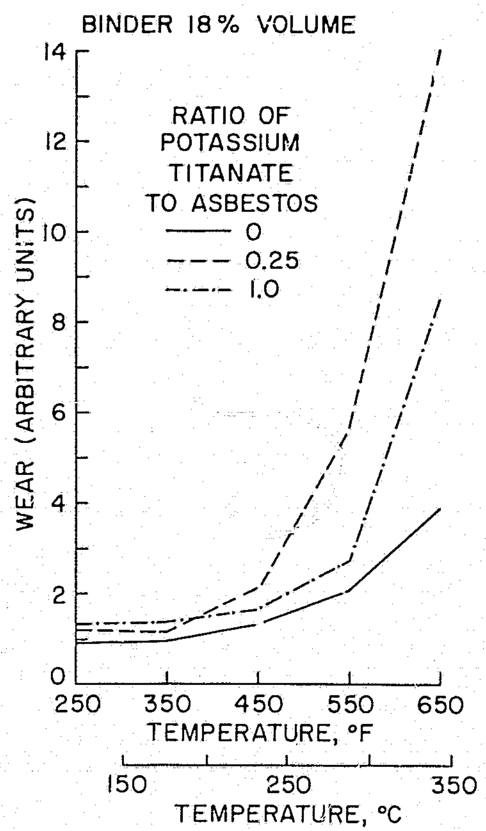

Figure 4-10 - Wear as a Function of Temperature for New Baseline With 18 Percent Resin by Volume

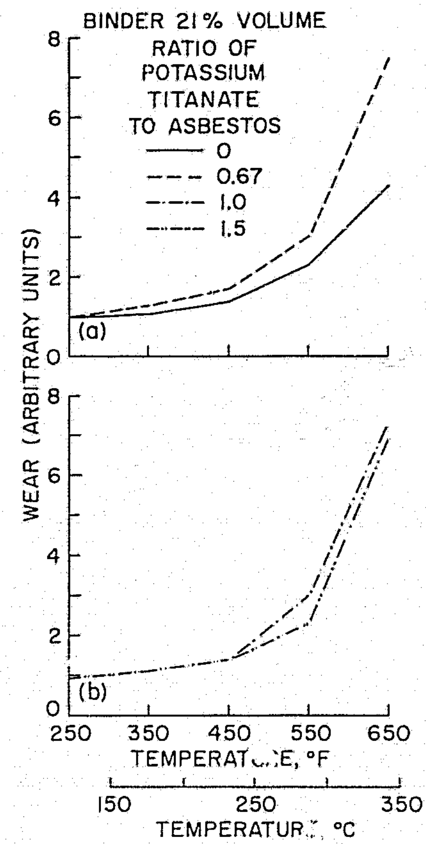

Figure 4-11 - Wear as a Function of Temperature for New Baseline With 21 Percent Resin by Volume

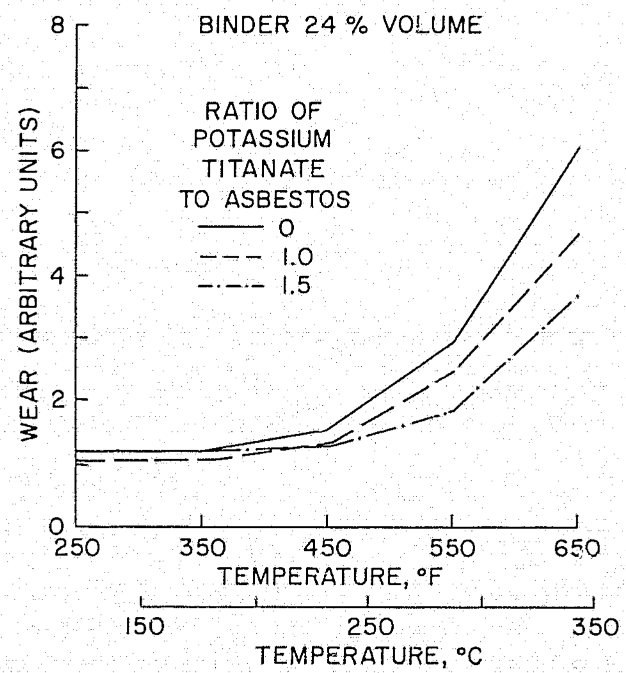

Figure 4-12 - Wear as a Function of Temperature for New Baseline With 24 Percent Resin by Volume the titanate fiber-to-asbestos ratio, for 18 and 21% binder. The apparent exception at 24% binder, Figure 4-9, may be a consequence of statistical variation. The effects of the asbestos replacement on low temperature friction, below 450°F (232°C), tend to be less pronounced, the friction, falling slightly and somewhat irregularly above and below that for the corresponding standard. A possible trend can be seen at 350°F (177°C) on Figures 4-8 and 4-9, the friction first decreasing and then increasing with increasing titanate fiber-to-asbestos ratio. Considering the friction curves over the entire temperature range, the friction is comparatively constant with temperature for potassium titanate fiber-to-asbestos ratios of 1.5. For example, the friction range is 0.33 to 0.39 and 0.32 to 0.38 for binder contents of 21 and 24%, respectively.

With thermal stability as an important controlling factor, we would have expected increased high temperature friction as the titanate fiber-to-asbestos ratio is increased in an otherwise fixed composition. Alternately, at fixed titanate fiber-to-asbestos ratios, increasing the binder content would probably result in a decrease of high temperature friction. Keeping these considerations in mind, and knowing that the potassium titanate fiber may require an unusually large binder content, it was necessary to clarify whether the probable friction-increasing effect of the titanate would be suppressed by the detrimental effect on friction to be expected from the increased binder content. It was also desirable to know how broad a composition range is available over which significant friction enhancement occurs. From the preceding results, it is established that significant high-temperature friction stability can be achieved by the addition of potassium titanate fiber over a broad range of composition.

Wear Improvement - The effect on wear as a function of temperature of the partial replacement of asbestos by potassium titanate fiber, at various resin contents of the composite, is shown in Figures 4-10 to 4-12. The four curves in Figure 4-11 are shown on two plots for clarity of presentation only. (Note that the scales on the ordinates have been changed slightly from those shown in Appendix G.)

It is clear, first of all, that at temperatures below 450°F (232°C), wear is comparatively low and wear differences between the baseline and experimental composites are small. This relatively low wear, showing little temperature dependence, is typical of that found in the abrasion/adhesion wear region,[4-1,4-2] and does not allow us to positively differentiate between the various friction materials. At temperatures above 450°F (232°C), however, increased wear and wear differences become apparent as the binder and other organic components pass into the thermal decomposition region.[4-3] Not only is it easy now to differentiate between the various composites, but trends can be discerned as functions of the titanate fiber-to-asbestos ratio and of the resin content. The former will be discussed in greater detail below, while the latter has already been alluded to by reference to the high binder content required by the titanate fiber.

Whereas the standard composites at all three resin levels have quantitatively similar wear vs temperature curves, the introduction of potassium titanate fiber causes dramatic changes in their behavior. For the case of 18 and 21% resin, a significant increase in wear is observed, the largest change coming about with the lowest resin content. When the resin content is raised to 24%, a reversal takes place and an improvement in the wear of the material is brought about by the replacement of some of the asbestos by the potassium titanate fiber.

The effect of variation in titanate fiber-to-asbestos ratio on high temperature wear can be seen more clearly in Figure 4-13. The data in this figure have been averaged from measurements at 450, 550 and 650°F (222, 288 and 343°C). Wear improvement on this figure and subsequent analogous figures represents the comparative life of the composites with and without potassium titanate fiber. For example, a wear improvement of plus 50% indicates that the life of the experimental composite would be 50% longer than that of the baseline composite (i.e., $\Delta W/W$ = (W baseline - W experimental)/W experimental). A negative value of 50% indicates that the lifetime of the baseline

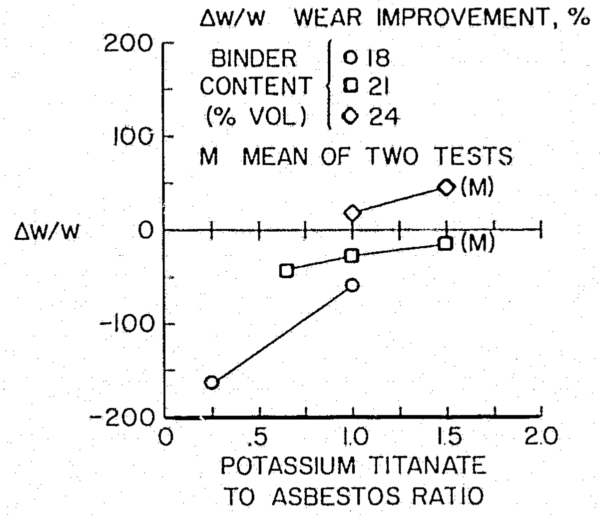

Figure 4-13 - The Effect on Wear at High Temperature ($\geq$450°F or 232°C) of the Partial Replacement of Asbestos With Potassium Titanate Fiber

would be 50% larger than that of the experimental (i.e., ΔW/W = (W baseline - W experimental)/W baseline).

It can be seen from the positive slopes and relative position of the three curves in Figure 4-13 that high temperature wear improvement is an increasing function of titanate fiber-to-asbestos ratio as well as binder content. The upper limit of the titanate fiber-to-asbestos ratio is evidently about 1.5 for binder contents of 21% as discussed in Section 3.2.2 above. Therefore, the trends of Figure 4-13 indicate again that the replacement of asbestos with titanate fiber has a deleterious effect on high temperature wear at binder contents near or below 21%, since the "improvement" is negative. For 24% binder, however, the replacement has a beneficial effect, to values as high as 55% improvement for the titanate fiber-to-asbestos ratio of 1.0 and 1.5.

Within certain limitations, the wear of composite systems of this type without titanate fiber tends to decrease with increasing binder content, with the accompanying tendency toward increased fade. Since the introduction of potassium titanate fiber tends to reduce fade significantly, its introduction permits higher binder content without fade. In that manner, potassium titanate fiber may be viewed as a wear reducing agent. If that were to describe the sole mechanism of wear improvement for composites containing titanate, no wear improvements above zero on Figure 4-13 would be obtained! The positive wear improvements obtained at 24% binder suggests that the potassium titanate fiber replacement of asbestos has resulted in wear reduction above that due to the greater resin content. We may conclude that a difference between one or more of the properties of asbestos and potassium titanate fiber, including their manner of interacting with other ingredients, has contributed to wear improvement.

For low temperature wear, the data differences are comparatively small (in most cases less than the estimated uncertainty), and trends cannot be established. The data presented in Figure 4-14 are averaged over measurements at temperatures of 250, 350 and 450°F (122, 177 and 222°C); data averaged over the lower of these two temperatures are negligibly different.

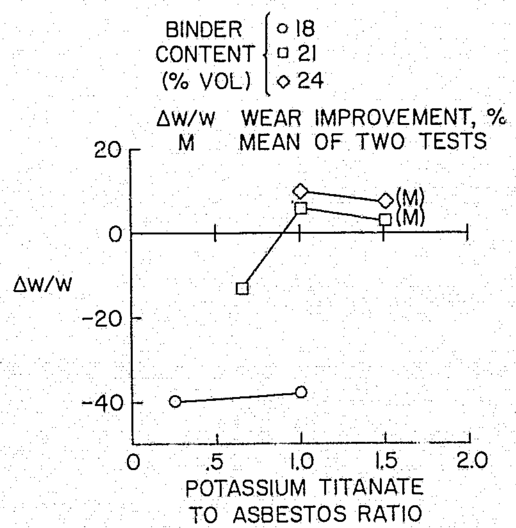

Figure 4-14 - The Effect on Wear at Low Temperature (≤450°F or 232°C) of the Partial Replacement of Asbestos With Potassium Titanate Fiber

4.2.3.2 Friction and Wear Compared to "Best" Adjusted Baseline

Comparisons given in the preceding section do not reveal the maximum simultaneous friction and wear improvements that the addition of a new ingredient can produce, compared to any of a large possible number of "best-compromise" compositions for that set of ingredients. Since a survey of friction and wear properties over the complete composition range of composites was not possible, simultaneous improvement magnitudes cannot be established. However, to obtain an indication of the possible improvements, comparisons are made here to the "best adjusted baseline", which had the lowest wear rate among the adjusted baselines whose friction at high temperature remained above 0.2. It is the composite with 21% binder (140% resin, composition given in Table 4-3). It was clearly the "best" baseline in that its high temperature friction was not exceeded by any other standard, and its wear was only negligibly higher than one other baseline which exhibited extreme fade (as shown in Figure G-2 of Appendix G in a direct comparison).

Friction and wear improvements compared to the best adjusted base are given in Figure 4-15. The friction values are based on measurements at 550 and 650°F (288 and 343°C) and the wear from measurements at 450, 550 and 650°F (222, 288 and 343°C). It can be seen from Figure 4-15(b) that relative to the best adjusted base, high temperature wear improvements would require binder contents near or above 24% and potassium titanate to asbestos ratios near or above unity. Fade would not be significant at those compositions, but the potential wear improvements are small, on the order of 20%.

The indications of maximum improvement in this comparison are subject to an interpretation problem which will be described. First, composition changes that reduce fade tend to increase wear, as was established for composites of this general type by M. Jacko and co-workers.[4-4] It was shown that, in varying compositions from those that exhibit extreme fade to those that exhibit no fade, wear rate increased by a factor of over 2.5. On the basis of its composition and

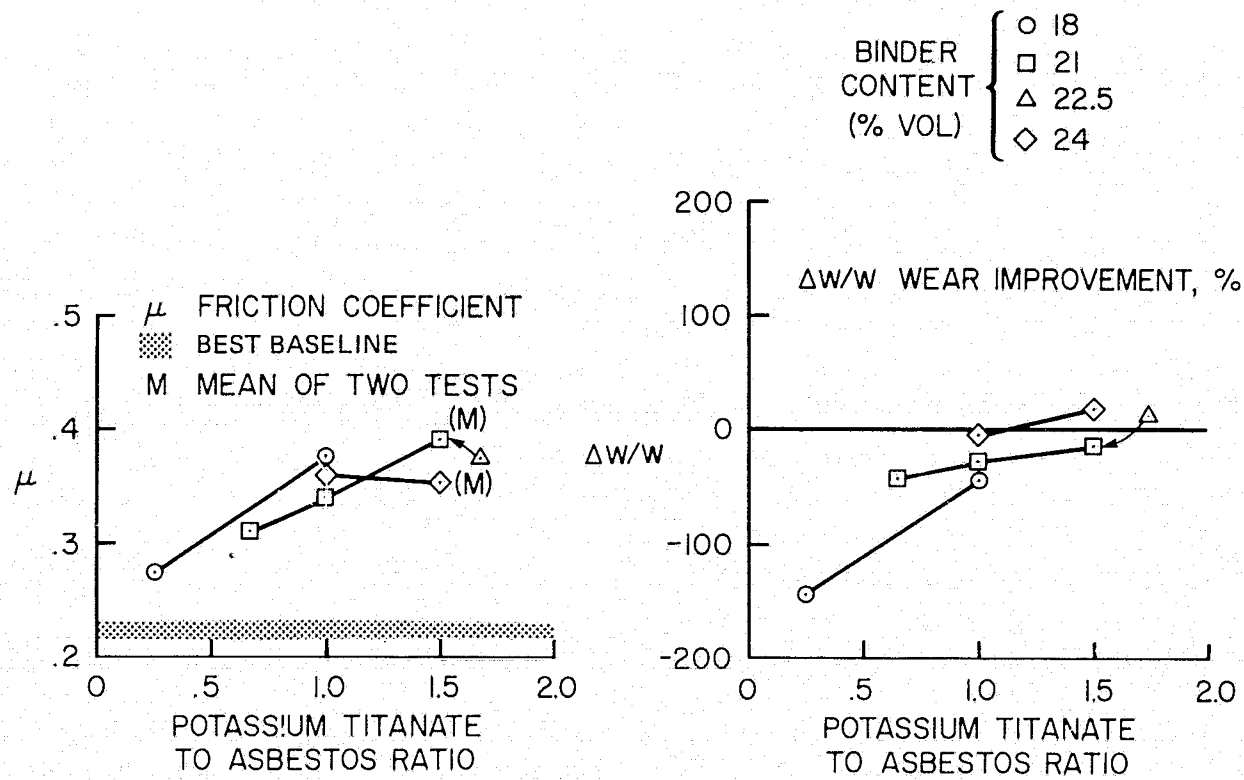

Figure 4-15 - Friction at High Temperature (≥550°F or 288°C) and Wear Improvement at High Temperature (≥450°F or 232°C) Relative to Best Adjusted Baseline

comparative fade and wear characteristics, the best adjusted base used in the above comparisons would tend to be classed as a high fade-low wear composite. The ability of potassium titanate fiber to eliminate the fade in such a composition without impairing the wear has the following consequences: If, in a particular application, relatively high fade is acceptable, but wear improvements are desired, potassium titanate fiber can be of limited benefit; it could be used to reduce the fade, a factor of little concern, and to provide small wear improvements, as shown in Figure 4-15. However, if a particular application demands low fade, and comparatively high wear has been accepted but is not desired, potassium titanate fiber can provide significant benefit. The titanate fiber can be added to a high fade-low wear composition to provide a composite with essentially no fade, and a wear substantially lower than that of the previously accepted low fade composite.

Extrapolation of the trends in wear in Figure 4-15, to higher values of binder content and higher titanate to asbestos ratios, suggests that higher positive improvements in high temperature wear than are shown may be attained. This has not been explored, but it must be recalled that an increasing difficulty of fabricating uniform and coherent samples was experienced with increasing titanate fiber-to-asbestos ratios. This was found even as binder content was increased to accommodate the titanate fiber, and the higher binder-titanate fiber levels shown may be approaching a practical limit.

Wear improvement at low temperatures is shown in Figure 4-16; the values given are averaged over measurements at 250, 350 and 450°F (122, 177 and 222°C). Values and data trends for values based on 250°F, or on the average over 250 and 350°F, closely approximate those given. As in the preceding section, the small differences in wear improvement at low-temperature will not permit trends to be established, and wear is approximately equal to that of the baseline except for wear impairment at low binder content.

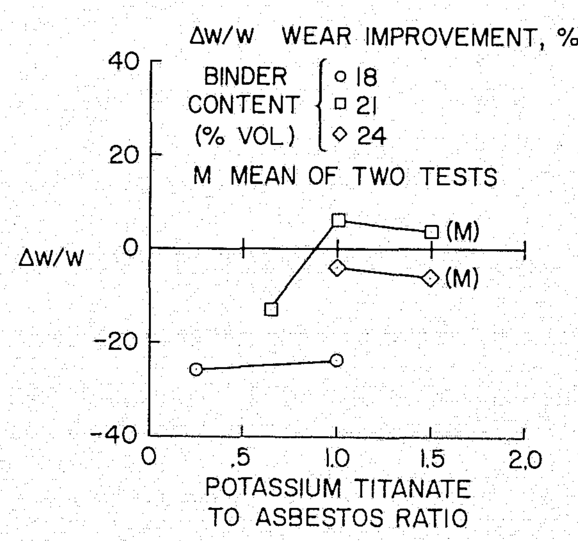

Figure 4-16 - Wear Improvement at Low Temperature ($\leq$450°F or 232°C) Relative to the Best Adjusted Baseline

4.2.3.3 Summary of Improvements Achieved by Incorporation of Potassium Titanate Fiber and Resin Adjustment

Let us now return and consider the improvements made in the standard commercial secondary lining. The friction and wear as functions of temperature for the standard are replotted in Figure 4-17. Brackets in the figure represent the data scatter from multiple tests; note particularly the large scatter in wear measurements at temperatures above 550°F (288°C). In Figure 4-18, the friction and wear of the optimum experimental composite (based on the standard commercial secondary lining) are compared to those for the standard lining. The data points pertaining to the experimental composite are based on the mean from two tests, the brackets represent the combined uncertainty from the individual uncertainties of the data for the standard and experimental composites.

Significant improvements are noted in fade reduction and high temperature wear. The wear improvement averaged over 400 to 650°F (204 to 343°C) is 46%; for temperatures below 400°F (204°C) the wear of the optimum experimental composite is the same as that of the standard. The low temperature friction of the experimental composite is substantially lower than that of the standard.

The improvements relative to the standard commercial lining are thus quite similar to the maximum improvements described in the preceding sections (4.2.3.1 and 4.2.3.2), although the two composite systems are not the same. It has been established that, when 50% of the asbestos is replaced with potassium titanate fiber and the resin increased by 40%, some improvement in wear is due to the added resin. However, some additional wear improvement and the increased high temperature friction can be attributed directly to the substitution of the potassium titanate fiber.

4.2.4 Effects of Friction Modifier Changes

Since the potassium titanate fiber exhibited such obvious potential for friction improvement it was tried, early in the program,

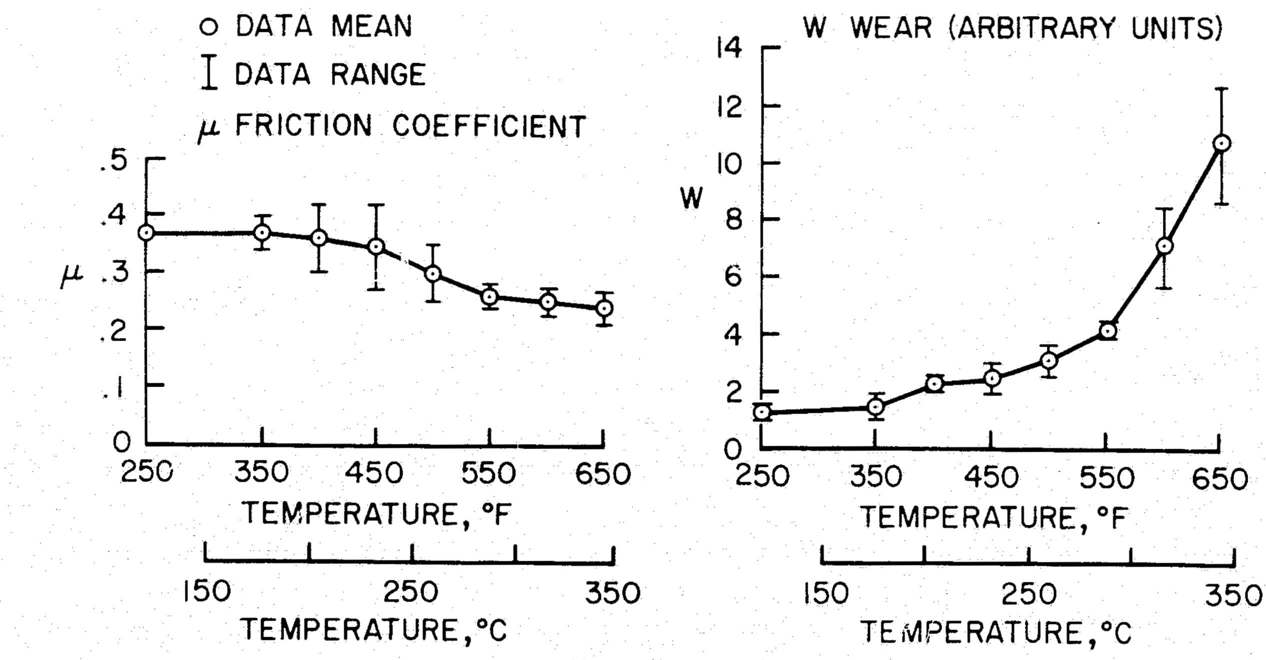

Figure 4-17 - Friction and Wear Characteristics of the Standard Commercial Brake Lining

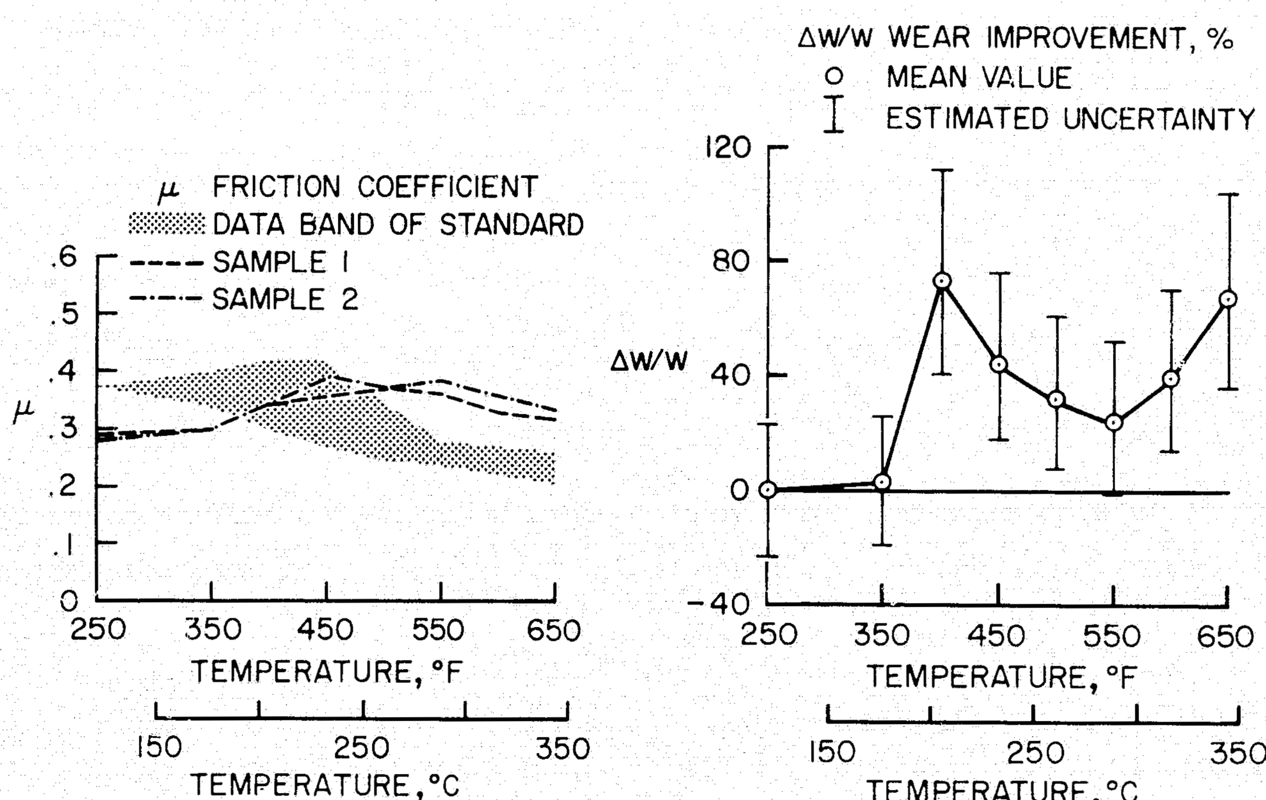

Figure 4-18 - Friction and Wear Improvement of the Optimized Experimental Composite Relative to the Standard Commercial Lining as a partial replacement for cashew friction particle at two resin levels, 100 and 120%. While the friction is indeed quite good, the wear is unacceptably high, Figure 4-19, and this substitution was not explored further.

Other variations in friction modifiers included the following attempts:

(1) Increase or decrease of the modifier to fiber ratio by 10% from the "optimum" formula gave no clear further improvement in friction or wear, as shown in Figure 4-20.

(2) Replacement of a minor organic constituent in the "optimum" formula with cashew friction particle in an attempt to raise its low temperature friction caused a large increase in wear without improving friction.

(3) Replacement of minor organic constituents with fully cured granular M074, used here strictly as a friction modifier, did not improve either friction or wear. Plots for the latter two tests are shown in Figure 4-21.

4.2.5 Full-Scale Evaluation of Friction Material Performance

Since today's vehicles must comply with a government standard for hydraulic brake system requirements (FMVSS No. 105-75),[4-5] the potential of the "best" experimental composite (based on the commercial secondary) for allowing a brake system to meet these requirements was evaluated on a full-scale inertial dynamometer. The vehicle test described in the Safety Standard[4-5] was adapted as a single-wheel dynamometer simulation procedure which is listed in detail in Appendix E. This procedure naturally does not allow the measurement of system parameters, so that a direct determination of whether the lining lets the system comply with the Safety Standard was not possible. However, an indication of factors affecting compliance with the standard could be obtained. In addition, by testing the standard lining and experimental lining separately with identical procedures, the potential of the experimental lining relative to the standard lining could be evaluated.

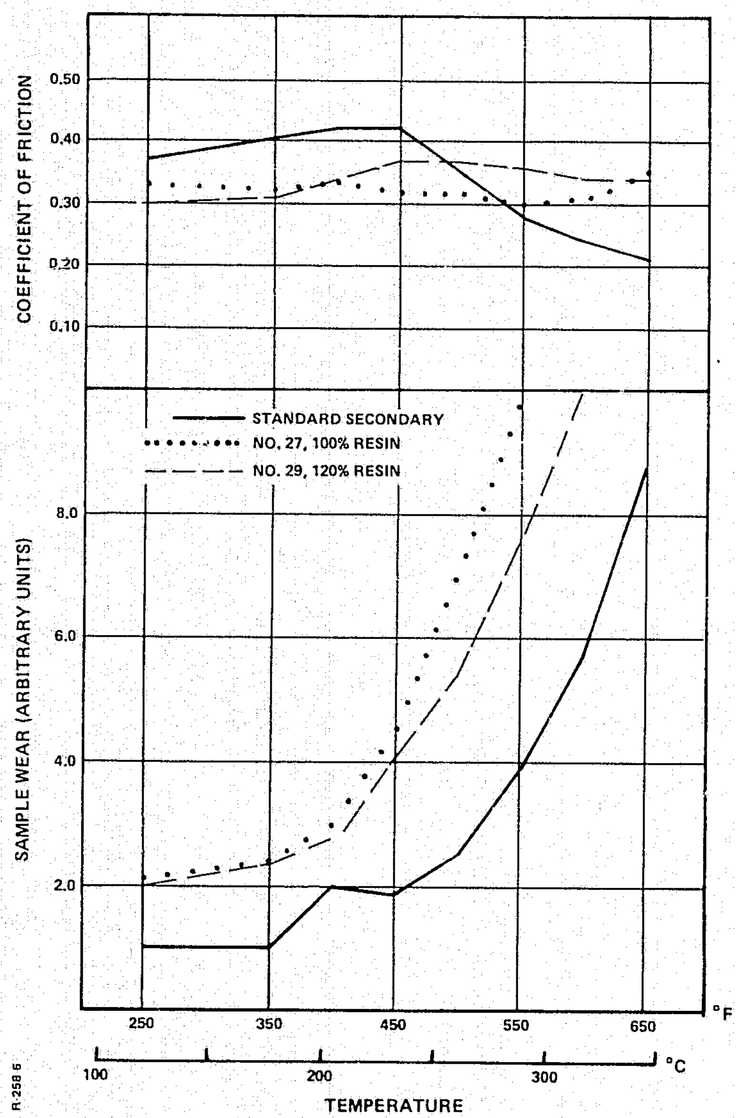

Figure 4-19 - Friction and Wear of Experimental Samples in Which Potassium Titanate Fiber Was Substituted for 50 Percent of the Cashew Friction Particles

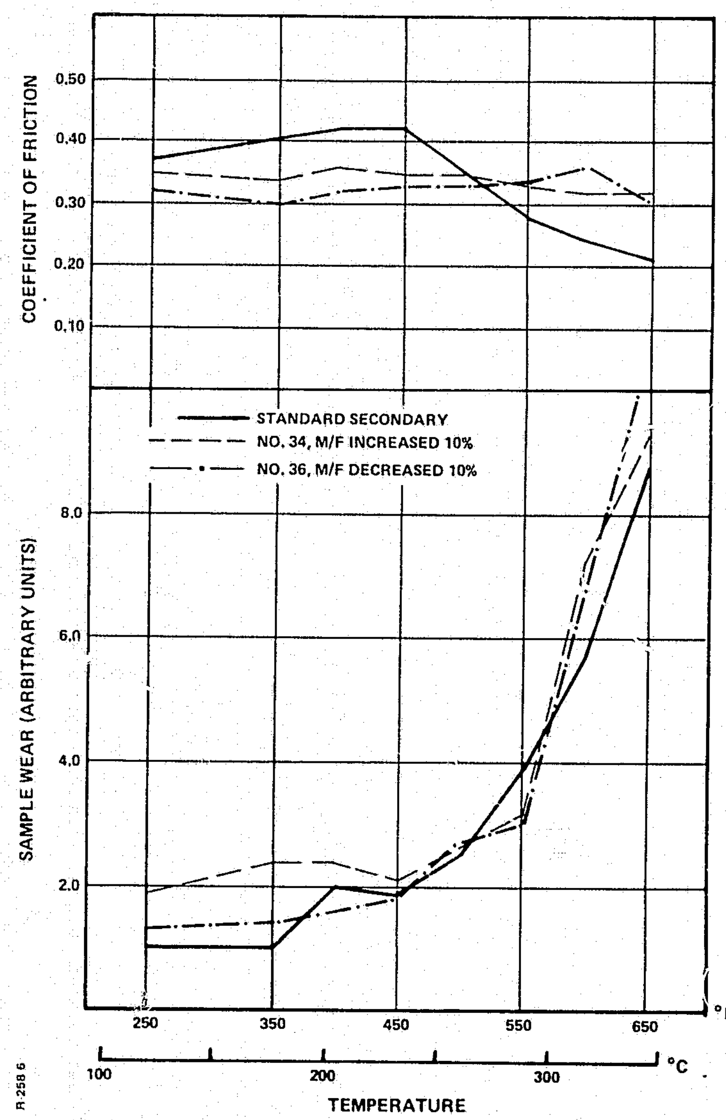

Figure 4-20 - Effect of Variation in Modifier to Fiber Ratio on Friction and Wear of Optimal Experimental Formula

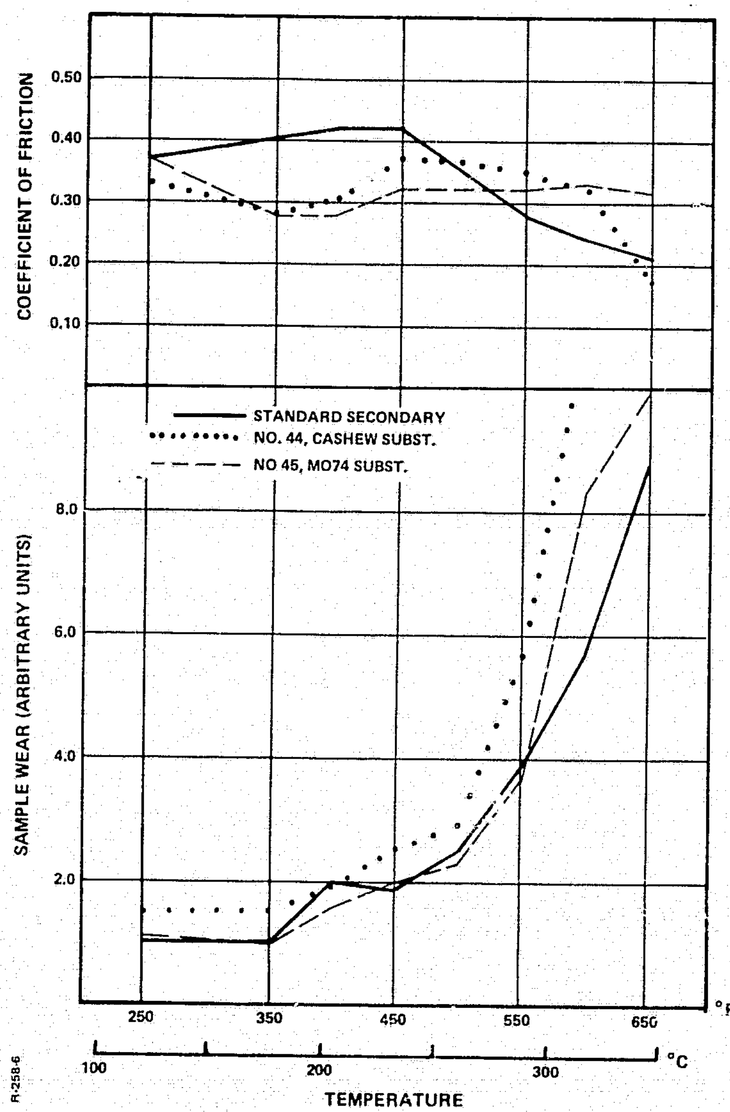

Figure 4-21 - Effect of Replacement of Minor Organic Constituents on Friction and Wear of Optimal Experimental Formula

4.2.6 Lining Performance: FMVSS 105-75 Simulation

The test described in Appendix E may be outlined as follows:

(1) Instrumentation Check
(2) First Effectiveness (Pre-Burnish)
(3) Burnish
(4) Second Effectiveness
(5) Reburnish
(6) Third Effectiveness, Partial System Failure and Inoperative Power Effectiveness
(7) First Fade and Recovery
(8) Reburnish
(9) Second Fade and Recovery
(10) Reburnish
(11) Fourth Effectiveness
(12) Spike Stops
(13) Spike Effectiveness Check

The reader is referred to the Safety Standard(4-5) for a detailed description of the vehicle test, the requirements, and definitions of terms. As performed in this simulation, an effectiveness test consists of several stops from a given speed at constant (pre-set) torque, each stop at a progressively higher deceleration rate. The line pressure required to maintain the torque is recorded for each stop. Plots can be made of torque vs. line pressure at each speed: these are called "effectiveness plots." Ideally effectiveness plots would be superimposable for all speeds and all effectiveness tests in a series (e.g., first, second and fourth effectiveness in above sequence). This would indicate constancy of behavior - hence predictability - of the friction material under all conditions of use. In practice this is not observed, but certain aspects of a series of effectiveness tests can be analyzed for their desirable or unfavorable features. We will return to this shortly.

In addition to effectiveness tests, the above sequence includes a series of "burnishes" which serve to condition the surface of the linings by removing the gross surface features in a series of relatively mild applications following any severe applications. There are also two "fade tests", in which a series of high torque stops are made at closely spaced time intervals, causing a large temperature rise and a loss in friction. The "recovery" stops check the ability of lining to regain its initial friction value immediately after the severe abuse of a fade test. Finally, the "spike" stops to verify the ability of a lining to survive a series of stops at very high rates of pressure rise.

With this introduction, we are ready to discuss the results of the FMVSS 105-75 simulation tests. Plots have been drawn for all effectiveness tests and are shown in Appendix H; the effectiveness curves for the second effectivenss test are also shown in Figure 4-22. These curves usually are approximately linear, with a positive slope indicating a steady increase in torque with increase in line pressure. Note, however, that some of the curves in this plot have abrupt changes in slope, indicating an increase in torque developed at constant or even decreased line pressure; i.e., the linings have gained in effectiveness after a certain number of stops. These curves are not very suitable for further analysis, and it is convenient to define another term,

$$\text{Gain} = \frac{\text{Torque}}{\text{Line Pressure}},$$

and to make a series of plots of "Gain" as a function of "Stop Number" for all the effectiveness tests. Note that the gain plots for an ideal lining would be a set of superimposed horizontal lines. Calculated values of the gain are tabulated in Table 4-5. Several cross-plots of the gain are presented in Figures 4-23 through 4-29.

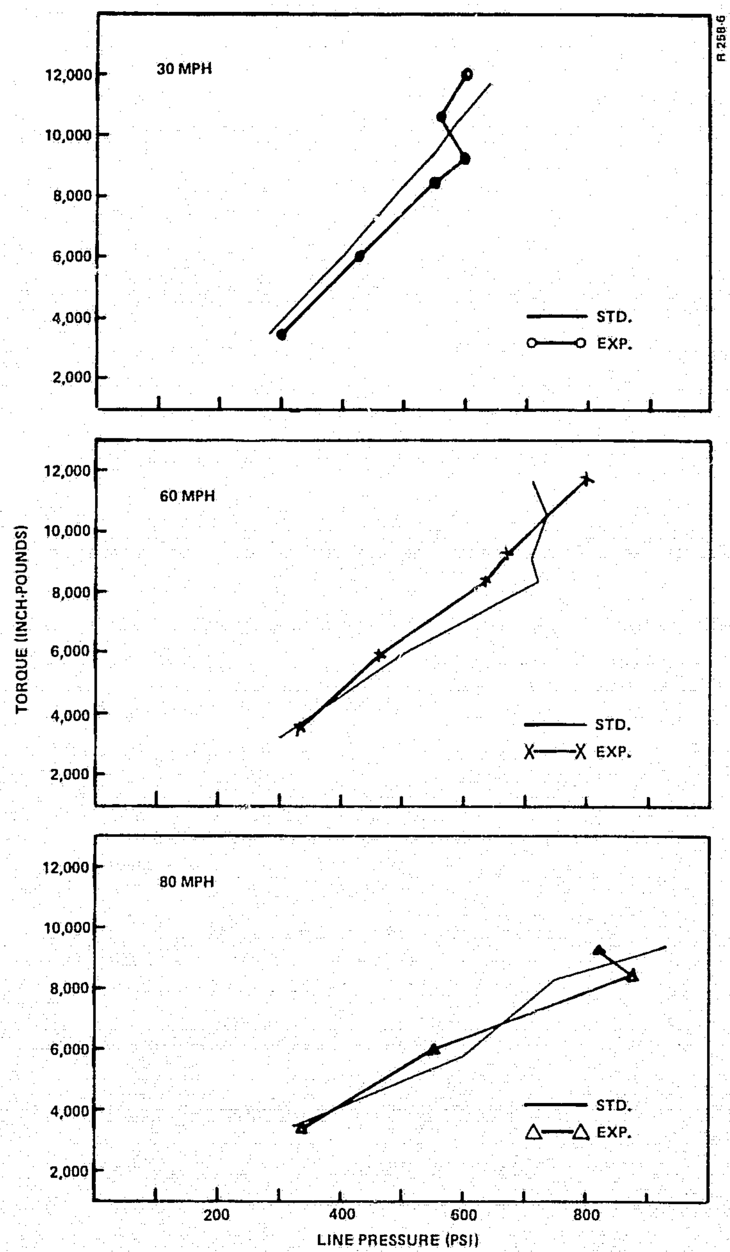

Figure 4-22 - Effectiveness Curves for Second Effectiveness Test

Table 4-5 - Calculated Values of Gain for FMVSS 105-75
Simulation Test Results

A. STANDARD LINING GAIN = TORQUE/LINE PRESSURE

1ST EFF.	2ND EFF.	3RD EFF.	4TH EFF.	SPIKE EFF.
30 MPH	30 MPH	755#	30 MPH	60 MPH
1. 16.0	1. 12.5	1. 9.2	1. 11.7	1. 8.3
2. 23.1	2. 15.0	2. 10.4	2. 12.9	2. 10.9
3. 32.7	3. 16.8	3. 12.2	3. 15.1	3. 12.9
4. 31.7	4. 17.1	4. 12.1	4. 13.2	4. 12.6
5. 32.9	5. 17.8	5. 12.7	5. 16.2	5. 12.7
6. 45.0	6. 18.4	6. 12.7	6. 21.8	6. 13.0
60 MPH	60 MPH	1443#	60 MPH	
1. 13.1	1. 10.8	1. 6.7	1. 9.1	
2. 17.4	2. 12.0	2. 10.0	2. 11.6	
3. 27.4	3. 11.7	3. 10.9	3. 11.6	
4. 24.8	4. 12.8	4. 11.3	4. 11.8	
5. 30.3	5. 14.4		5. 12.3	
6. 27.8	6. 16.5		6. 12.1	
	80 MPH	1643#	80 MPH	
	1. 10.8	1. 7.0	1. 9.1	
	2. 9.7	2. 10.6	2. 10.0	
	3. 11.2	3. 10.7	3. 8.9	
	4. 10.1	4. 10.9	4. 10.0	
		980#		
		1. 6.3		
		2. 8.8		
		3. 10.4		
		4. 11.1		

Table 4-5 - Calculated Values of Gain for FMVSS 105-75
Simulation Test Results (Concluded)

B. EXPERIMENTAL LINING GAIN = TORQUE/LINE PRESSURE

1ST EFF.	2ND EFF.	3RD EFF.	4TH EFF.	SPIKE EFF.
30 MPH	30 MPH	755#	30 MPH	60 MPH
1. 13.8	1. 11.7	1. 9.7	1. 11.1	1. 10.0
2. 17.0	2. 14.1	2. 11.2	2. 13.6	2. 12.0
3. 20.0	3. 15.5	3. 12.7	3. 15.5	3. 12.4
4. 27.8	4. 15.5	4. 12.9	4. 16.0	4. 13.1
5. 24.7	5. 19.0	5. 13.4	5. 17.5	5. 13.4
6. 26.0	6. 20.0	6. 13.9	6. 17.9	6. 13.8
60 MPH	60 MPH	1433#	60 MPH	
1. 12.7	1. 10.6	1. 8.8	1. 10.0	
2. 16.1	2. 12.9	2. 9.7	2. 13.0	
3. 18.3	3. 13.2	3. 11.3	3. 13.3	
4. 19.9	4. 13.9	4. 11.6	4. 14.2	
5. 21.4	5. 14.4		5. 14.4	
6. 24.9	6. 14.8		6, 13.8	
	80 MPH	1643#	80 MPH	
	1. 10.0	1. 7.9	1. 9.6	
	2. 10.9	2. 10.9	2. 11.6	
	3. 9.7	3. 10.7	3. 11.1	
	4. 11.3	4. 11.3	4. 11.3	
		980#		
		1. 6.0		
		2. 8.7		
		3. 9.6		
		4. 10.0		

When analyzing the Gain vs. Stop Number plots, three factors should be kept in mind:

(1) General gain level.

The initial level should not be overly high in a drum brake that is to be used in a disc front/drum rear (abbreviated disc/drum) combination system, in order that the proper balance between the disc and drum be maintained. The latter is a major problem in the design of modern brake systems. For a drum/drum system the absolute gain level is not as important, since we do not have to concern ourselves about balance problems; changes in level will presumably be in the same direction for both front and rear drums, i.e., balance will be maintained automatically.

(2) Change in gain.

The less change in gain, the better the lining, as a general rule.

(3) Speed spread.

The less change in gain with change in speed, the better the lining.

Let us kow examine the gain plots for the first, second and fourth effectiveness tests. First effectiveness - here we would like to see a fairly low level (as close as possible to the level on the fourth effectiveness), and a fairly horizontal curve. Figures 4-23(a) and 4-24(a) show the experimental lining to be clearly superior in these two factors. It also has a slight advantage in speed spread. Second effectiveness - Figures 4-23(b) and 4-24(b) show neither lining to have an advantage over the other. Fourth effectiveness - A first glance at Figures 4-23(c) and 4-24(c) would again seem to indicate very little difference between the two. However, the level at 60 MPH (a very important part of the speed range) is now higher for the experimental than for the standard; this is now considered good. It means that there has been the least change in gain level in going from the first to the fourth effectiveness tests for the experimental lining. The experimental lining can thus be said to have better friction stability than the standard. This is perhaps the most significant advantage it can have because it means that it offers a better stopping distance capability in a disc/drum system. The stability advantage is shown more clearly in Figure 4-25, and especially in Figure 4-26 for 60 MPH; there is no advantage at 80 MPH, Figure 4-27.

Light load, partial system failure, inoperative power, and spike effectiveness tests, Figures 4-28 and 4-29, show no significant differences betweeen the linings. Both seem to be quite acceptable.

Results of both fade tests, Figures 4-30 and 4-31, show quite acceptable behavior; no significant difference can be found between the linings. The experimental may have slightly more fade due to the higher resin content, and it may have a slight tendency toward over-recovery. But the differences between the two linings are probably within the range of variation that would be seen if duplicate tests were run.

In summary then, for use in a disc/drum combination, the experimental lining shows advantages relative to the standard lining by having better friction stability and less speed spread; these factors enhance the ability of a disc/drum system to meet the requirements of FMVSS 105-75. For use in a drum/drum system, the greater friction stability of the experimental lining is not necessarily an advantage for FMVSS 105-75; the lesser speed spread remains advantageous however, because it allows a greater safety margin in pedal effort on the higher speed stops.

We now proceed to describe the results of the accelerated wear test on a full scale inertial dynamometer.

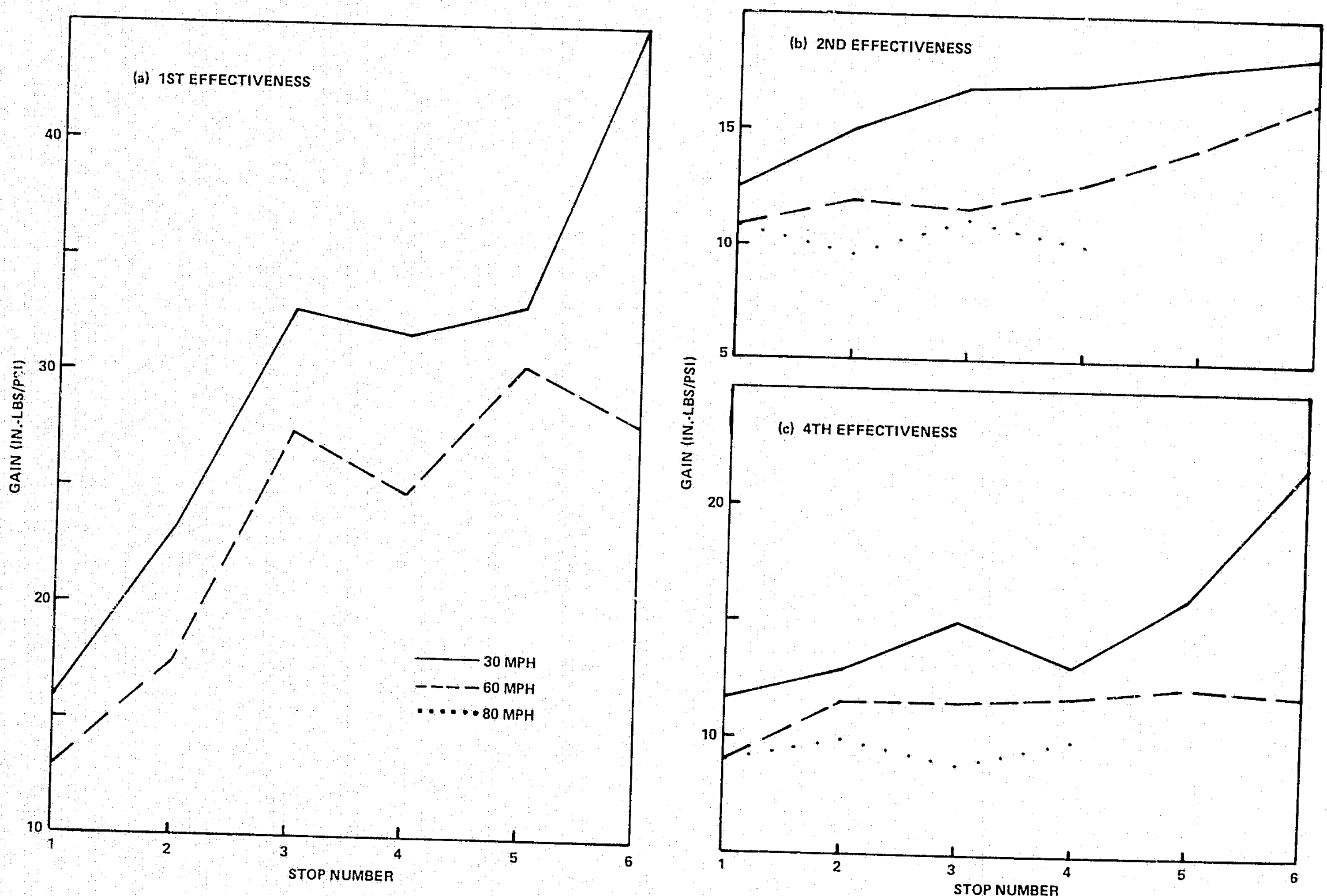

Figure 4-23 - Gain as a Function of Stop Number for Standard Lining Combination

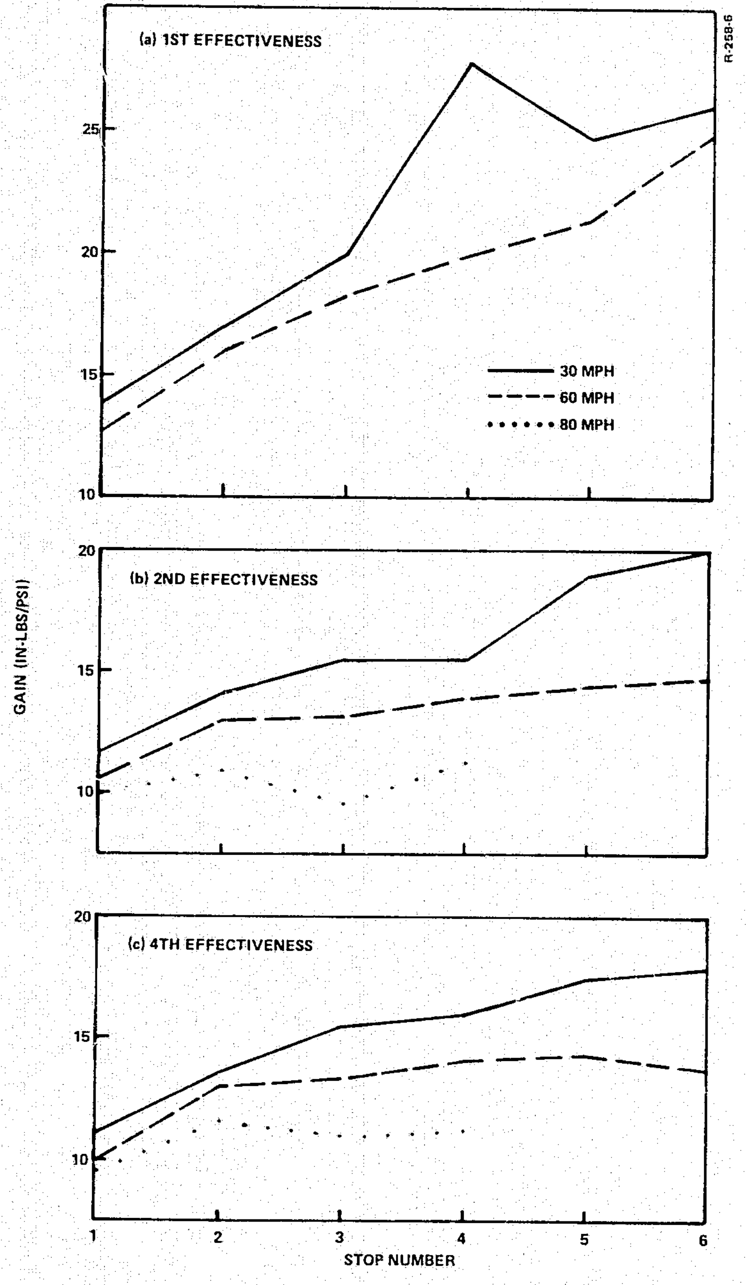

Figure 4-24 -- Gain as a Function of Stop Number for Experimental Lining Combination

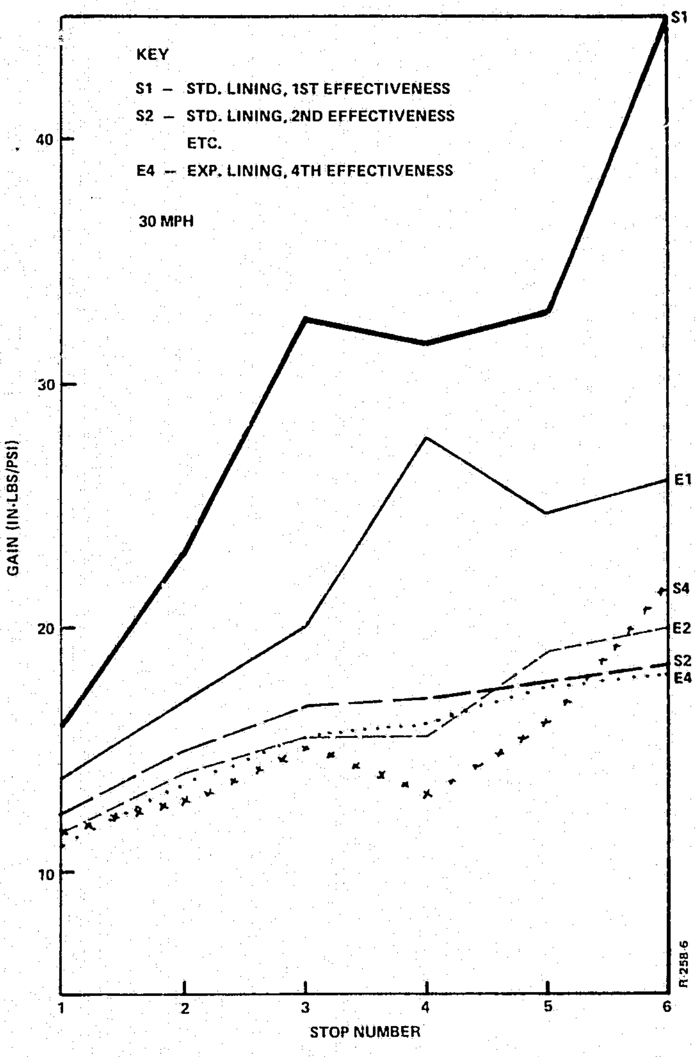

Figure 4-25 - Gain as a Function of Stop Number Stops From 30 mph, Standard and Experimental Linings

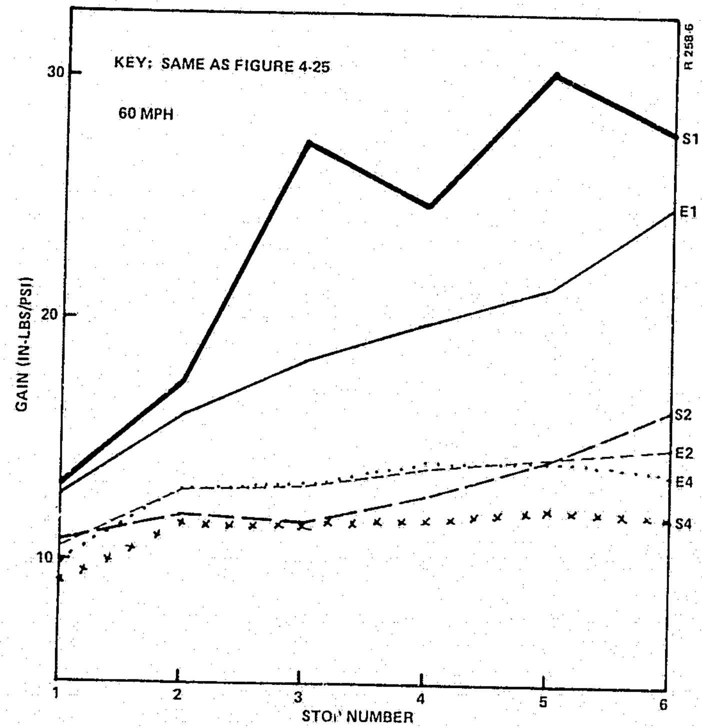

Figure 4-26 - Gain as a Function of Stop Number, Stops From 60 mph

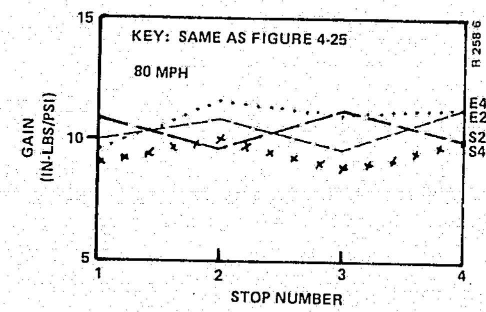

Figure 4-27 - Gain as a Function of Stop Number, Stops From 80 mph

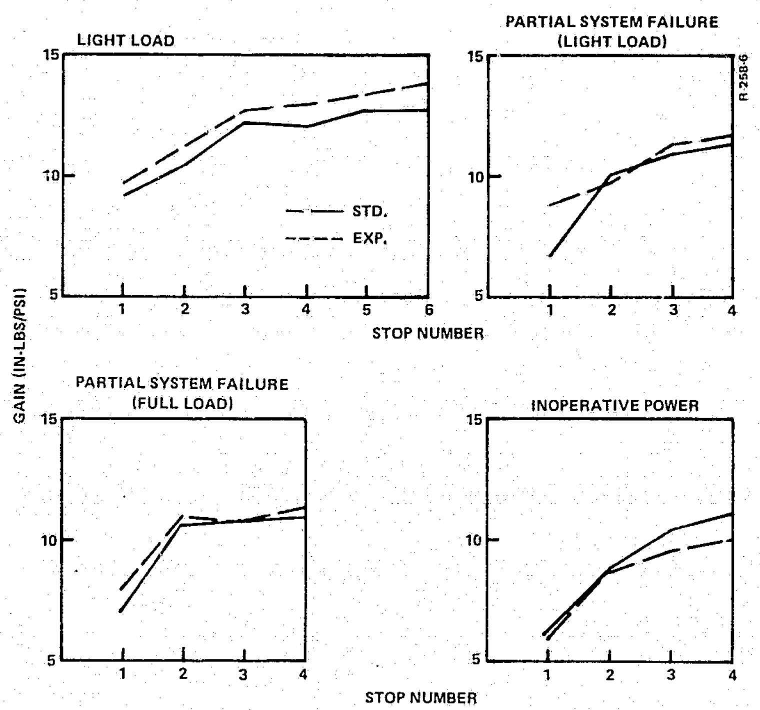

Figure 4-28 - Gain as a Function of Stop Number for Light Load, Partial System Failure and Inoperative Power Simulation, 60 mph

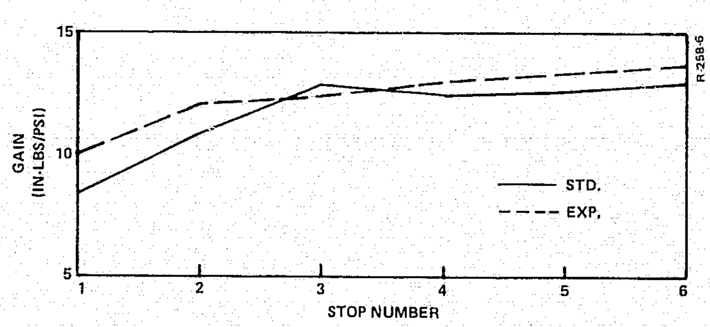

Figure 4-29 - Gain as a Function of Stop Number for Spike Effectiveness Check, 60 mph

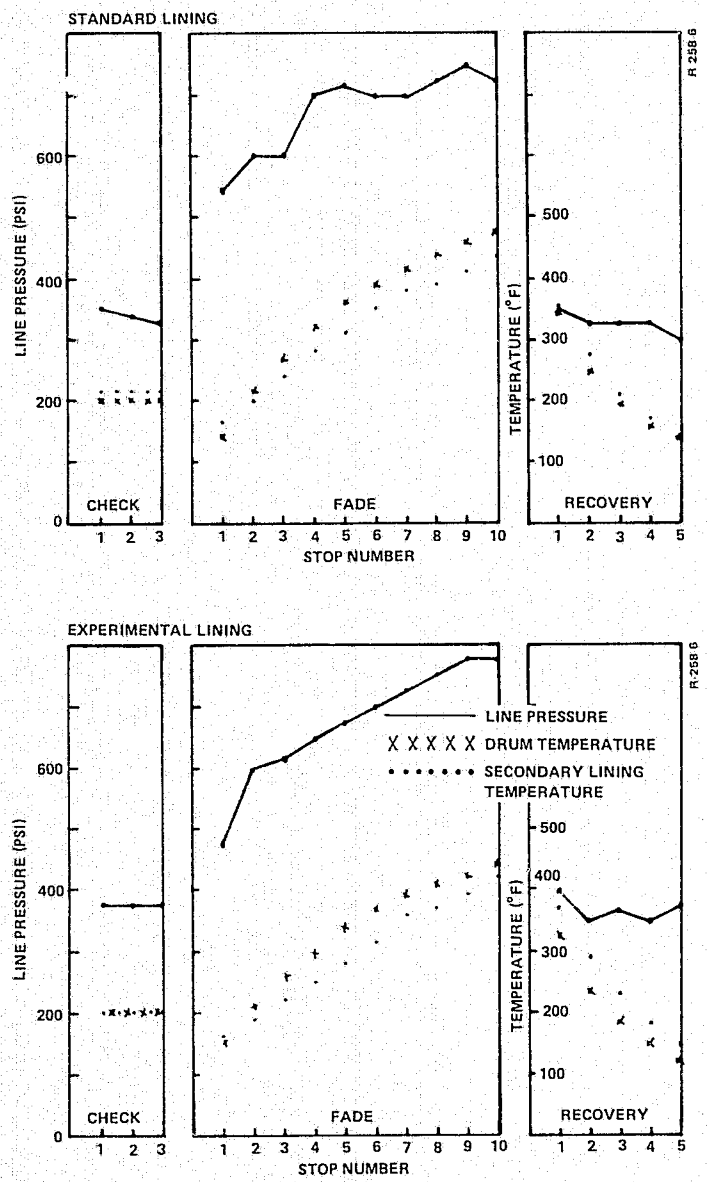

Figure 4-30 – First Fade and Recovery Line Pressure and Secondary Lining and Drum Temperatures versus Stop Number

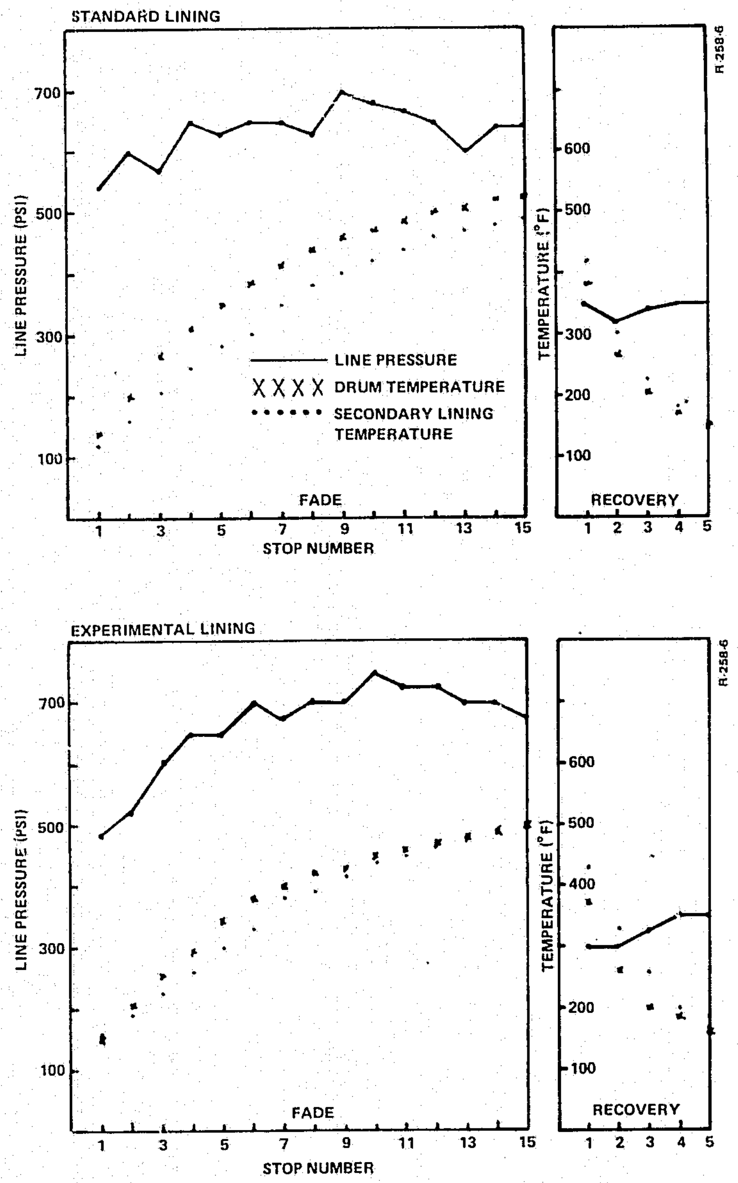

Figure 4-31 – Second Fade and Recovery Line Pressure and Secondary Lining and Drum Temperature versus Stop Number

4.2.7 Wear as a Function of Temperature

The full-scale inertial dynamometer test described in the previous section allowed a determination to be made of the relative frictional performance of the experimental and standard linings. However, this tells us essentially nothing about the relative wear properties of the two linings, as can be seen for the total wear figures for the tests included in Appendix H. A different test was therefore performed, in which the wear was measured several times, each after a series of applications at a number of successively higher temperatures. This test was described in Section 3.3.2.1. Results of the wear measurements are given in Appendix I. Plots of weight wear and average thickness wear as a function of temperature are shown in Figures 4-32 and 4-33 for the standard and experimental linings, respectively. The standard primary was again used in combination with both standard and experimental secondaries. The experimental secondary was of the "segmented" fabrication type, as described in Section 3.2.2.2.

These graphs illustrate that the same kind of information can be obtained from either the weight or the thickness measurements. Note that the wear of the secondary lining is higher than that of the primary, even though the primary lining wear was an order of magnitude higher than that of the secondary in sample dynamometer tests. However, it must be recalled that, in the sample dynamometer the same load was applied in all tests. But in the full-scale drum system, the Duo-Servo principle comes into play, as described in Section 2, and the secondary lining is the one that does most of the work and thus has the greater wear. This is why the decision was made early in the program to concentrate our experiments on the secondary lining.

Average sustained line pressures are plotted as a function of temperature in Figure 4-34. Line pressures are inversely related to the friction, i.e., a low line pressure indicates good friction. Since the effect of both the primary and secondary linings is involved, it is not possible to calculate a coefficient of friction from the line pressure. Both sets of linings have very similar behavior. The standard

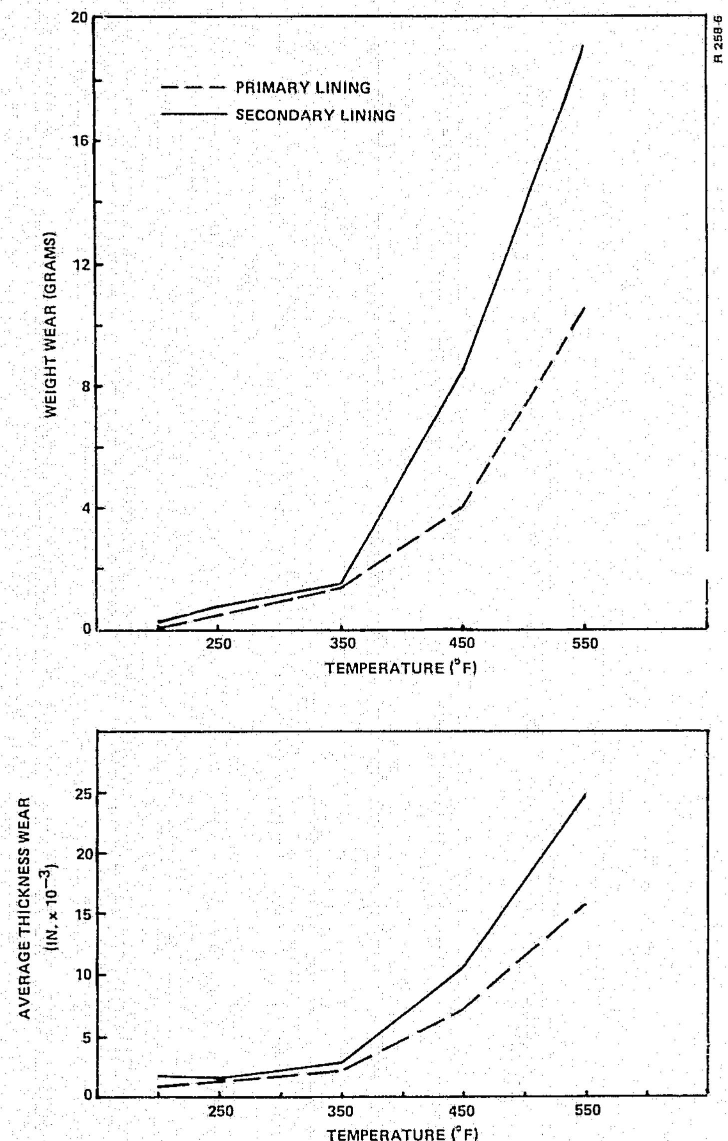

Figure 4-32 - Weight Wear and Average Thickness Wear as Functions of Temperature for Standard Lining Combination

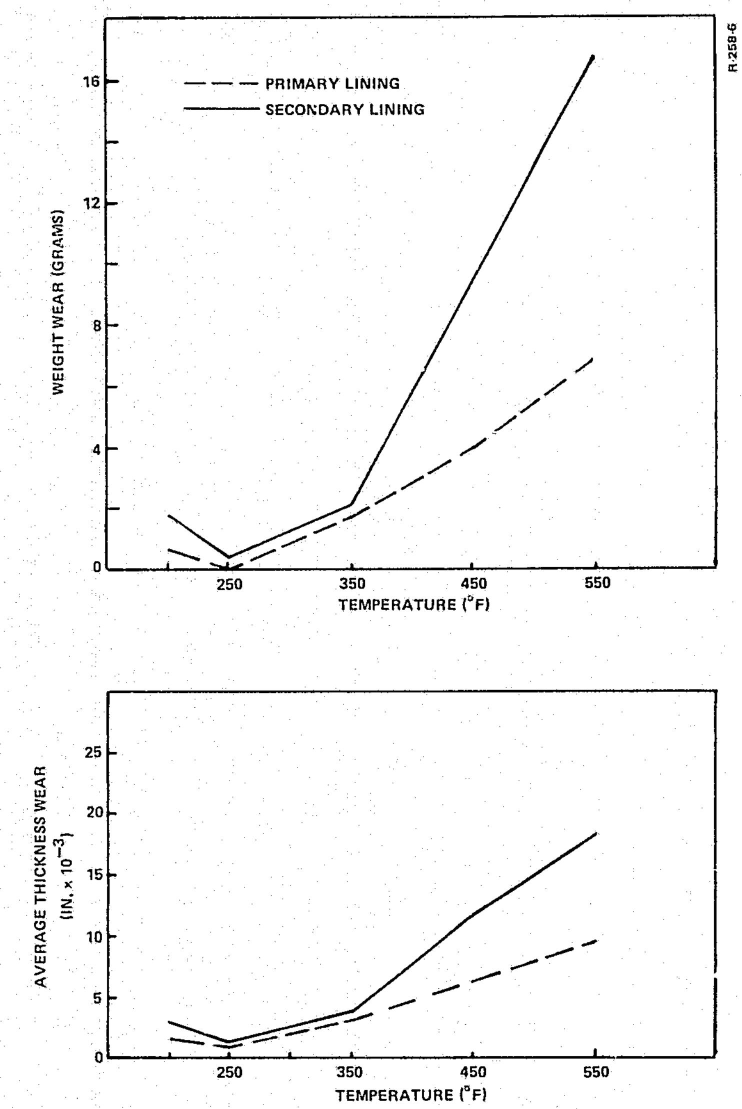

Figure 4-33 - Weight Wear and Average Thickness Wear as Functions of Temperature for Experimental Lining Combination

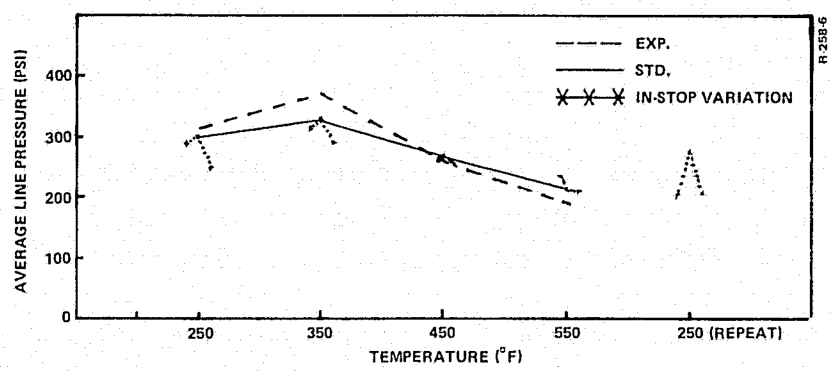

Figure 4-34 - Average Line Pressure as a Function of Temperature

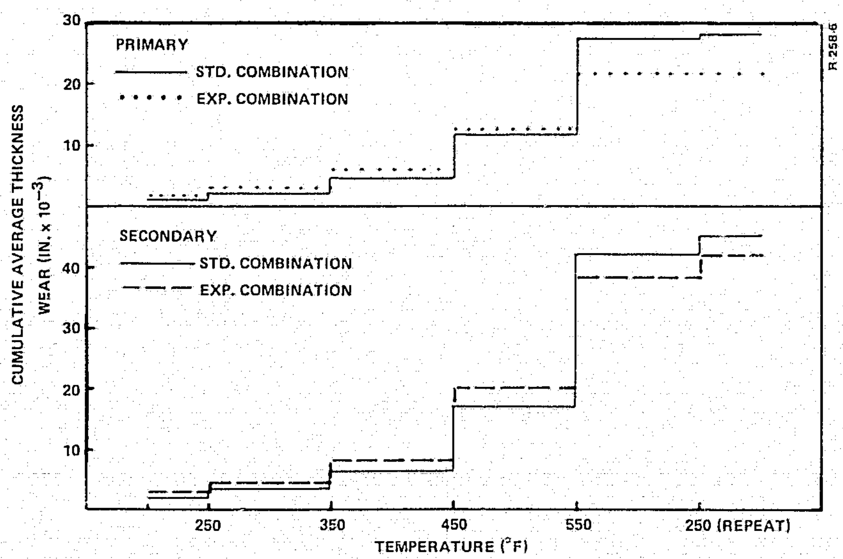

Figure 4-35 - Comparison of Cumulative Average Thickness Wear as a Function of Temperature has slightly better low-temperature friction, and the experimental is slightly better at higher temperature. An indication of friction behavior within a stop can be obtained from the points plotted on each side of the central one at each temperature, which represent average initial and final pressures at that temperature. Friction seems to be higher at the beginning and end of the stop at 250 and 350°F (121 and 177°C), but is quite constant through the stop at 450 and 550°F (232 and 288°C). Standard and experimental behave alike.

Comparison of the wear of the standard and experimental linings is shown on a cumulative basis in Figure 4-35, and on an incremental basis in Figure 4-36. Focusing on the all-important secondary, we find that there is very little difference between the two linings up to 450°F (232°C), with the standard having a minute possible advantage. At higher temperatures the experimental seems to show a definite improvement over the standard of the order of 30%. It is interesting to note that this behavior is paralleled exactly by the corresponding primaries, though the formulation was the same in both cases. This test suggests, then that the experimental secondary lining at high temperature has superior wear resistance to that of the standard, and it is even capable of removing some of the load from the primary, so that the wear of the pair is improved in a parallel fashion. This is the result of a single test, however, and extreme caution must be excersied in reaching a definitive conclusion regarding the actual improvement before these results are confirmed. (Another test, similar to the one just described, was performed on a set of similar but not identical linings; results of this test are included in Appendix I.)

4.2.8 Summary of Results with Potassium Titanate Fiber

To recapitulate this section, we have found that partial substitution of potassium titanate fiber for asbestos, together with a resin adjustment, can allow the fabrication of a secondary lining material with improved high temperature friction and wear. The formulation in which resin has been increased by 40%, and in which one half of the original asbestos has been replaced appears to be near an optimum

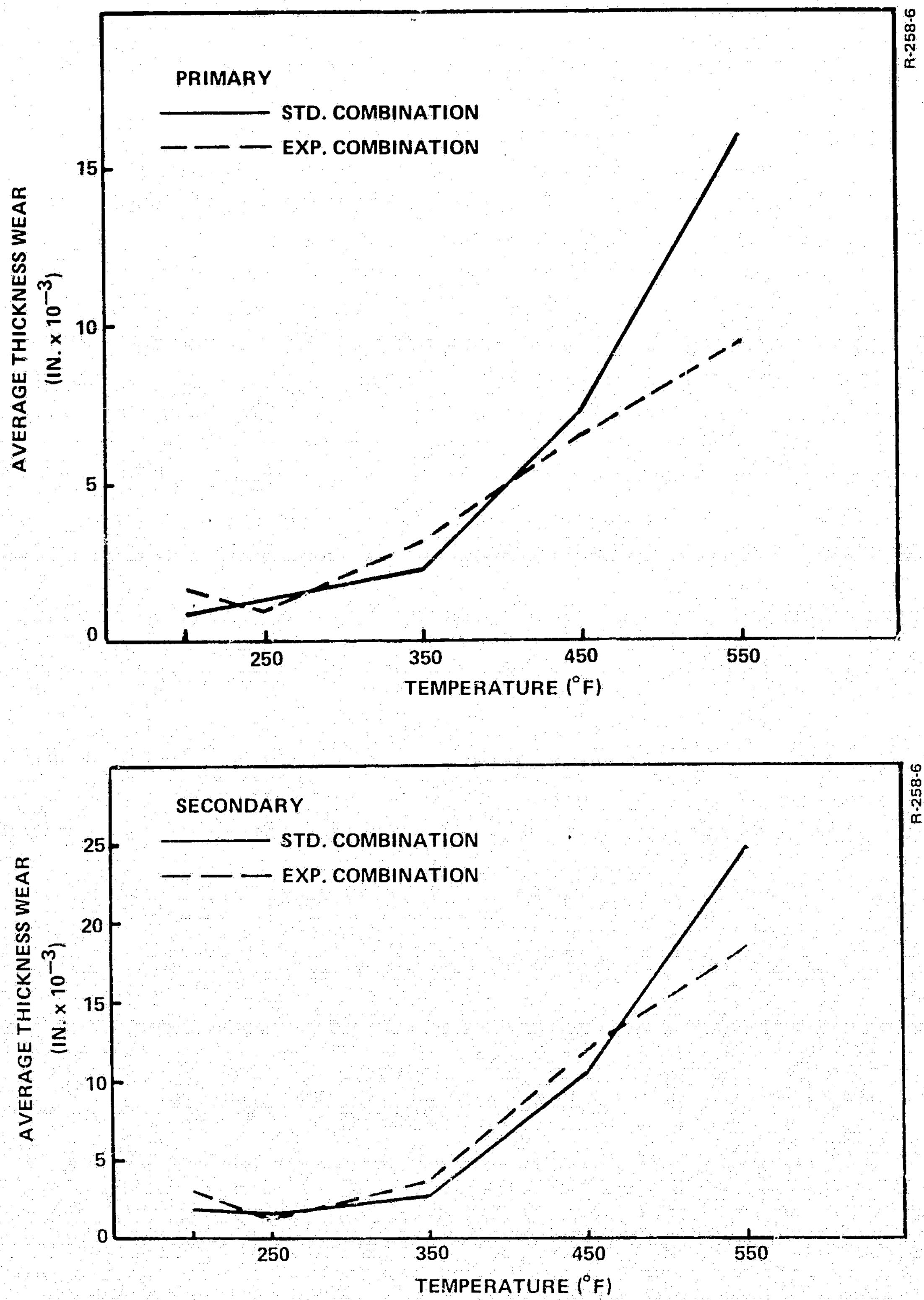

Figure 4-36 - Comparison of Incremental Average Thickness Wear as a Function of Temperature and was tested on a full-scale inertial dynamometer. Advantages were found in friction stability and in speed spread, enhancing the lining's ability to allow a system to meet the requirements of FMVSS 105-75. A clear advantage in wear resistance in full-scale tests has not been established, but an improvement of about 30% at high temperatures is indicated.

4.3 POLYPHENYLENE SUBSTITUTION

4.3.1 Total Substitution of Cured Polyphenylenes for Cashew Friction Particles

Wear and friction curves for the screening of samples based on total substitution of cashew friction particles with polyphenylene are shown in Figure 4-37. Note that many of the curves do not span the entire temperature range: this indicates complete or partial abortion of a test due to extremely low friction obtained with the samples in question. In those instances, wear figures could not be obtained at all, while the values for friction coefficient are estimated.

Of the three initially supplied polyphenylenes, those cured at 750°C and 1000°C are unacceptable when they replace the cashew friction dust completely, as shown in Figure 4-37. The 650°C cured material is superior to the other two, though it still has unacceptably low friction.

However, we observe a trend toward better friction with decrease in the cure temperature of the polyphenylene. These observations led to the brief investigation of two means of improving the friction of the formulations, namely: (a) partial substitution of polyphenylene for cashew particles, and (b) use of polyphenylene that was not exposed to the high-temperature cure.

4.3.2 Partial Substitution and Uncured Polyphenylene Substitution

The formulations under discussion are summarized in Table 4-6 and results are shown in Figures 4-38 to 4-42. Substitution at the 50% and 10% level, Figures 4-38 to 4-40 clearly illustrate the fact that earlier trends are maintained, with respect to cure temperature, with uncured polyphnylene giving the highest overall friction.

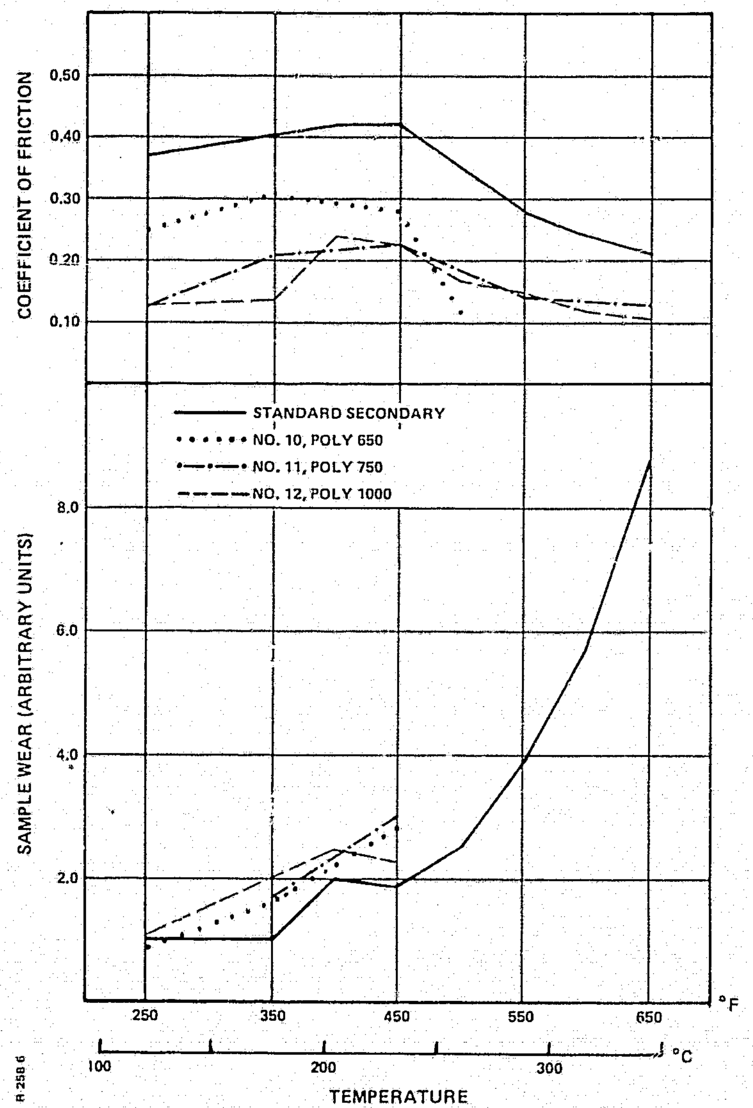

Figure 4-37 - Friction and Wear of Experimental Samples Containing Polyphenylenes Cured at Three Different Temperatures

Table 4-6 - Summary of Samples Fabricated with Partial Polyphenylene Substitution and with Uncured Polyphenylene

Sample No.	Cure Temp.	% Subst.	For
22	650°C	50	Cashew particle
28	650	10	Cashew particle
23	750	50	Cashew particle
24	1000	50	Cashew particle
30	550	100	Cashew particle
49	Uncured	100	Cashew particle
59[a]	Uncured	100	Cashew particle
50	Uncured	50	Cashew particle
60[a]	Uncured	50	Cashew particle
51	Uncured	10	Cashew particle
47[b]	Uncured	100	Cashew particle
21[b]	650	50	Cashew particle
13	Uncured	5	Asbestos
14	Uncured	15	Asbestos
58	Uncured	15	Asbestos
19	Uncured	30	Organic Modifier X
20	Uncured	100	Organic Modifier Y

NOTES:

(a) Samples 59 and 60 are the identical samples tested as 49 and 50, respectively; they were subjected to a second complete sample dynamometer test to check for possible changes in friction level.

(b) The polyphenylene pre-polymer for these samples was extracted with chloroform before processing.

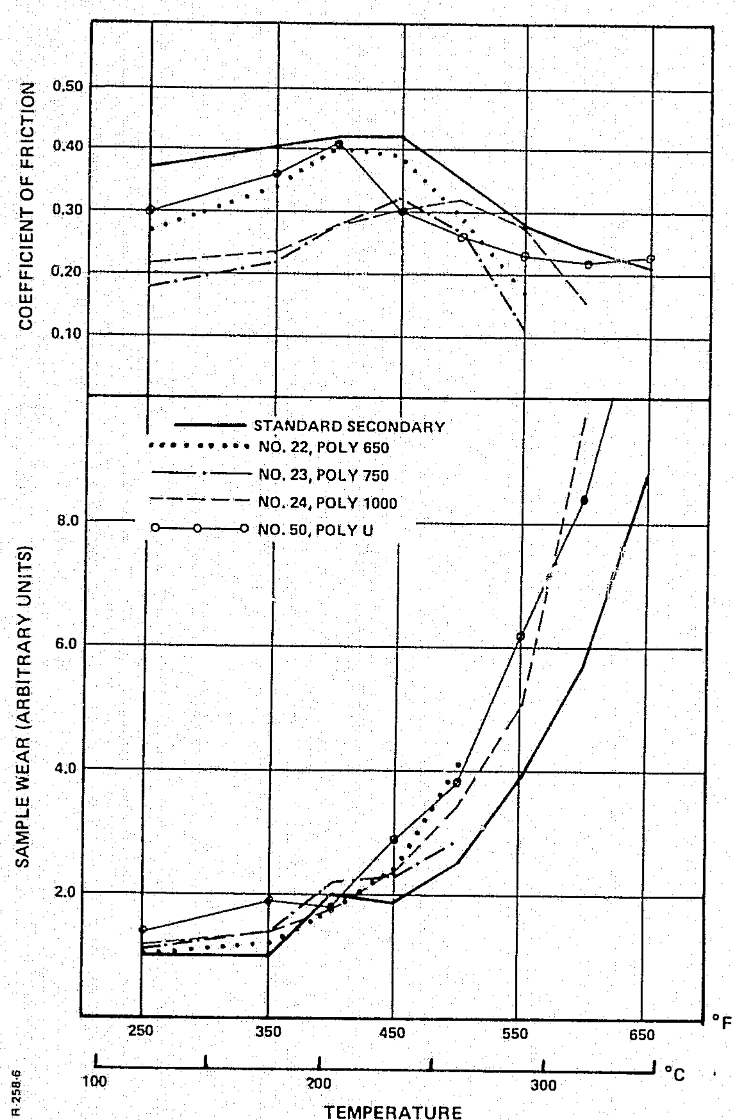

Figure 4-38 - Friction and Wear of Experimental Samples in Which 50 Percent of Cashew Friction Particle was Replaced by Polyphenylene

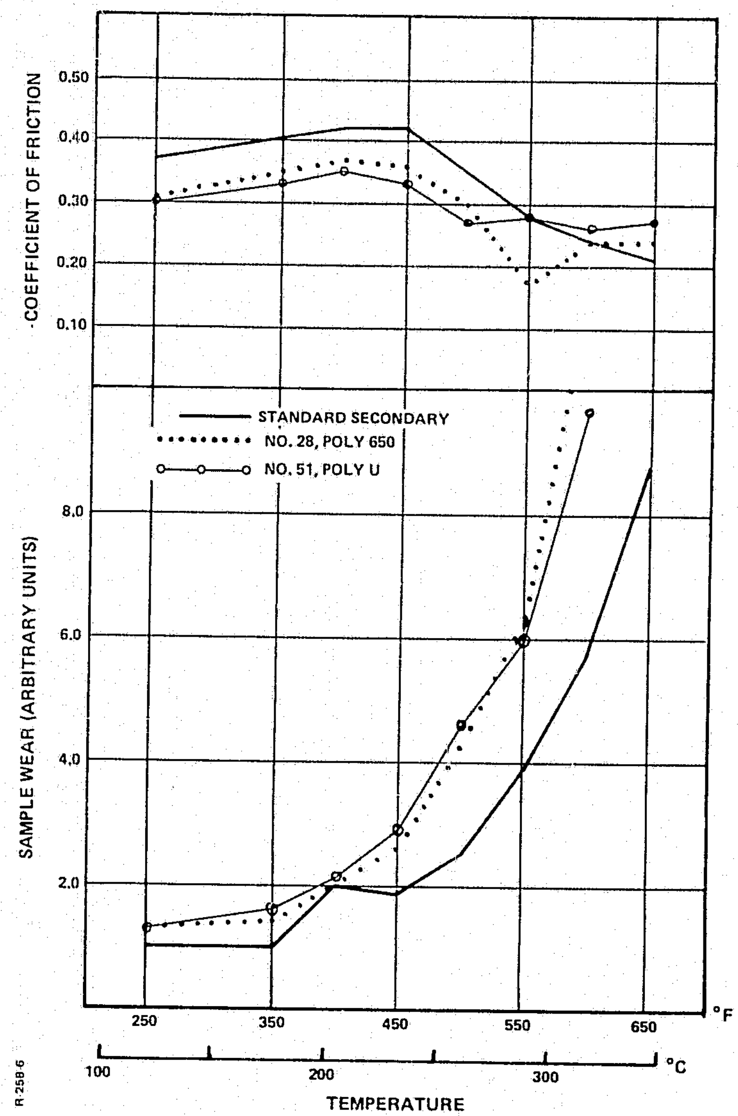

Figure 4-39 - Friction and Wear of Experimental Samples in Which 10 Percent of Cashew Friction Particles was Replaced by Polyphenylene

At 50% substitution of polyphenylene for cashew friction particle (Figure 4-38), the addition of polyphenylenes that have been cured at temperatures of 650°C (1202°F) or higher has resulted in exceedingly low friction at temperatures in the region of 550°F (288°C). For the sample with uncured polyphenylene, however, the friction coefficient did not fall below 0.22. Comparison of the curves in Figure 4-38 and 4-39 shows in addition that, as polyphenylene is taken out, the properties of the friction materail improve and tend toward those of the standard secondary lining.

It was observed that many of the friction curves had a characteristic dip, e.g., 450-550°F (232-288°C) for polyphenylene cured at 650°C, followed by a recovery in friction above 550°F (288°C). It was deemed possible that this was due to the exudation of a substance from the composite, between 450 and 550°F (232-288°C) that acts as a lubricant. Above 550°F (228°C), the exuded substance is either removed or altered sufficiently to allow a return to a higher friction level. This reasoning suggested further that, if a sample were subjected to a second dynamometer test after the first, that it might show higher friction levels. Results of two such tests are shown in Figures 4-40 and 4-41, in which curves 59 and 60 are for repeated sample dynamometer tests of samples 49 and 50, respectively. Both indicate improved friction above 400°F (204°C), supporting the above reasoning; however, the wear of these samples was totally unacceptable, especially at low temperatures. If it were correct that friction testing to bulk sample temperature of about 550°F (288°C) reduced the amount of a hypothetical lubricant, then the lubricant should have been reduced or eliminated during the high temperature polyphenylene cure. Nevertheless, composites containing polyphenylene that was cured at 650°C (1202°F) or higher exhibited extremely low high temperature friction; this low friction was evidently created by mechanisms other than the presence of a lubricant.

Early work in a study of the effectives of cure temperature on chlorinated polyphenylene by Lerner (the completed study is reported in Reference 4-6), suggested that polyphenylene becomes increasingly

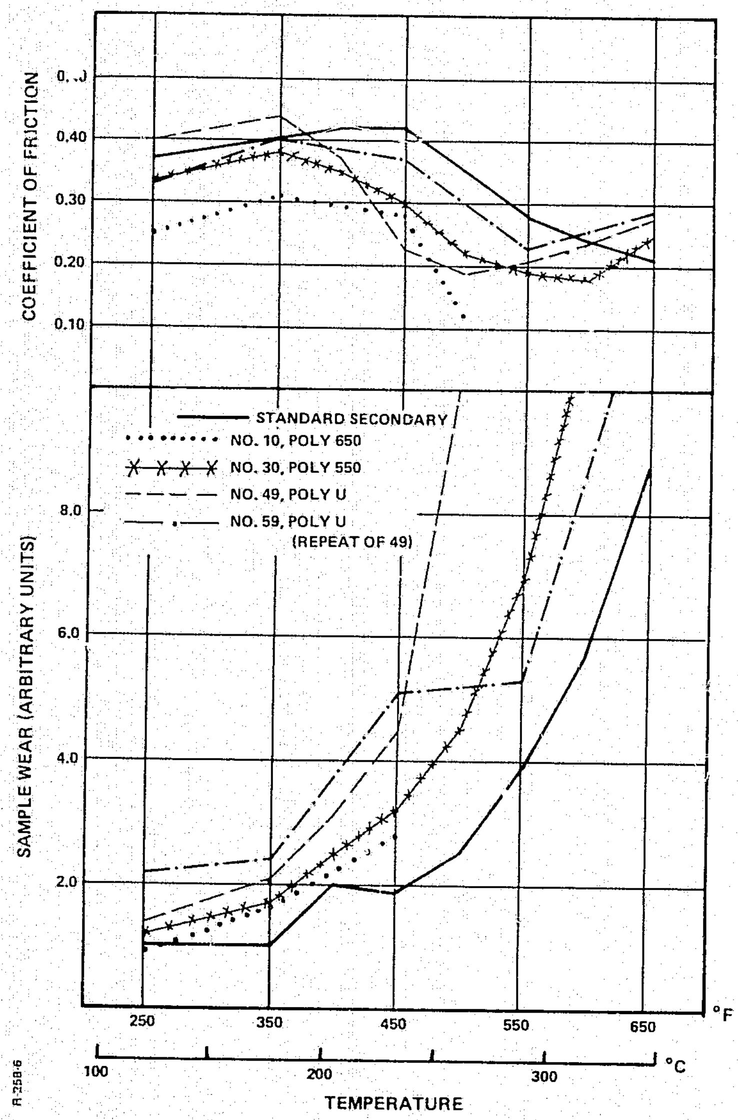

Figure 4-40 - Friction and Wear of Experimental Samples in Which Cashew Friction Particle is Completely Replaced by Polyphenylene

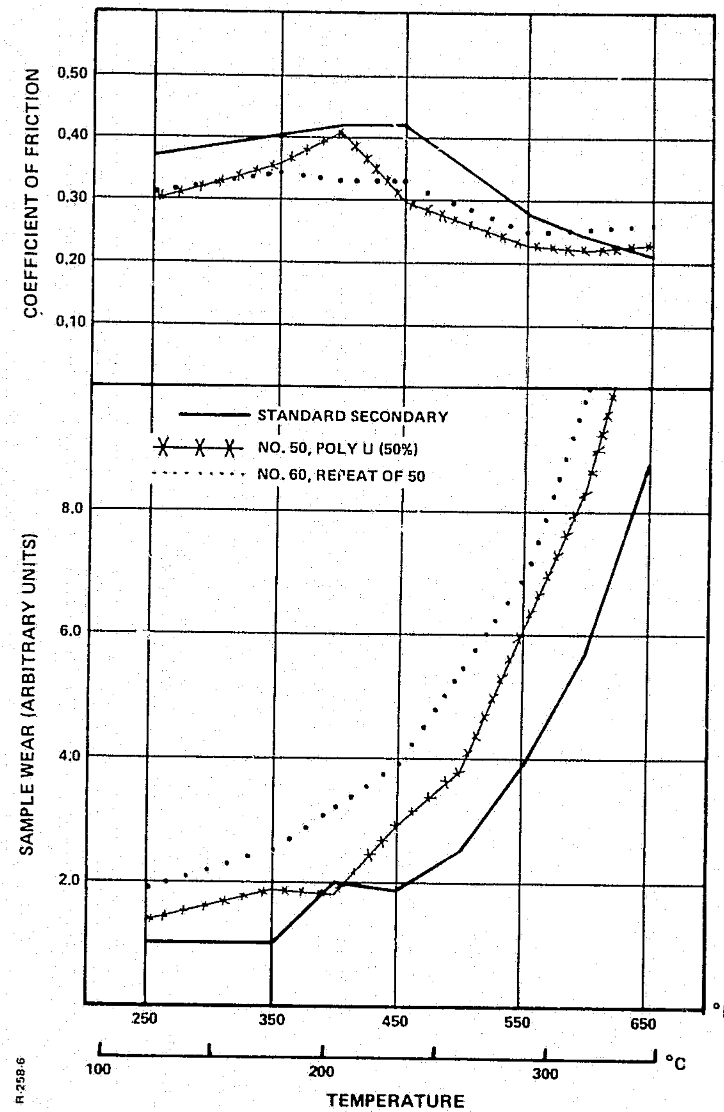

Figure 4-41 - Friction and Wear of Experimental Samples Showing Effect of Repetitive Testing sensitive to oxidation with increased cure temperature. This factor may account for the reduced friction. For this reason, a single sample was fabricated (No. 30) which contained polyphenylene that had been cured at the reduced polyphenylene cure temperature of 550°C (1022°F); this temperature should reduce or eliminate the lubricant, and may further reduce oxidative sensitivity. The test results from this sample are given in Figure 4-40. It can be seen that the high temperature friction is substantially higher than for samples containing polyphenylene cured at 650°C (1202°F). Note also that the latter sample contained less polyphenylene. However, it can be seen that a high temperature friction dip and recovery was obtained; this is characteristic of the corresponding sample containing uncured polyphenylene, and this result tends to negate further the supposition of the presence of a lubricant.

At the same time, it was learned in work with the polyphenylene prepolymer that a small quantity of an unidentified substance was present in the prepolymer that was soluble in chloroform. (The prepolymer is not soluble in chloroform.) A sample was fabricated that contained uncured polyphenylene that had been extracted with chloroform until no observable trace of the substance remained. The test results from this sample (No. 47) are given in Figure 4-42. Once again, the characteristic high temperature friction dip and recovery are present.

At this time work with polyphenylene was discontinued so that a greater portion of the remaining effort could be devoted to work with potassium titanate fiber. The work with polyphenylene has been, at best, exploratory and incomplete. The results, though not promising, must be regarded as inconclusive. Should further studies be attempted with polyphenylenes of the type discussed here, it would seem advisable to work with materials cured at much lower temperatures, of the order of 200-300°C rather than 650-1000°C. This is because the oxidation resistance is now known to be improved in the lower temperature range, as demonstrated by Lerner.[4-6]

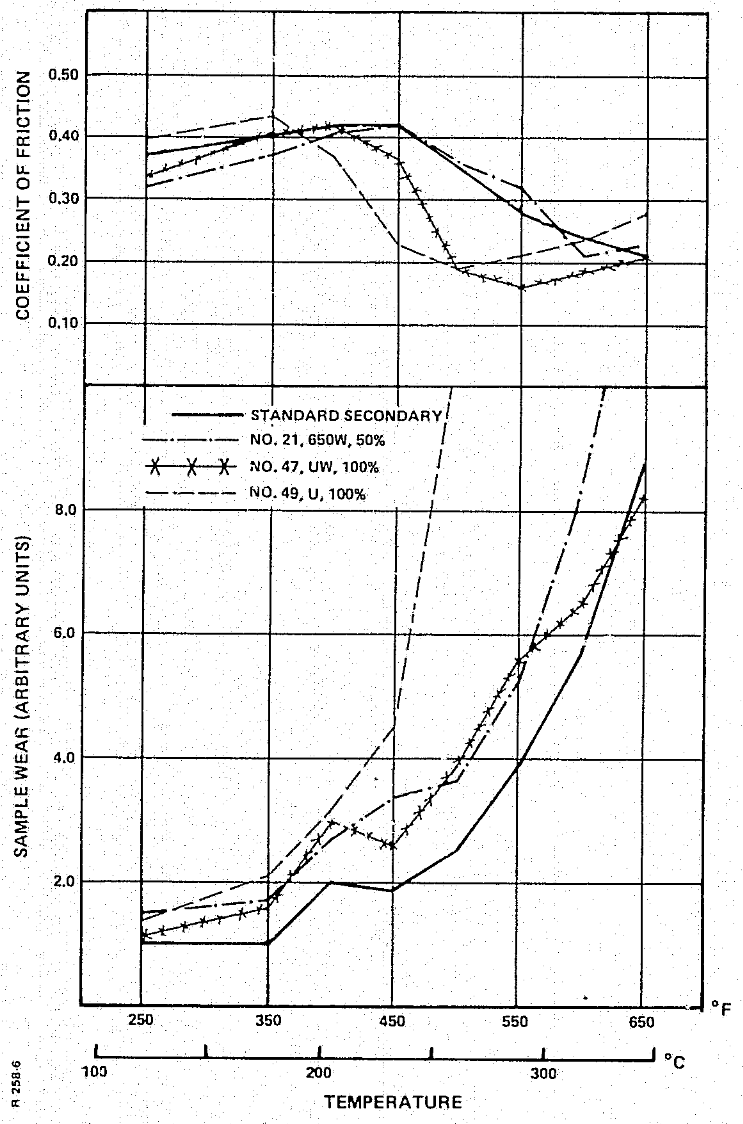

Figure 4-42 - Friction and Wear of Experimental Samples Showing Effect of Washing Polyphenylene Prepolymer

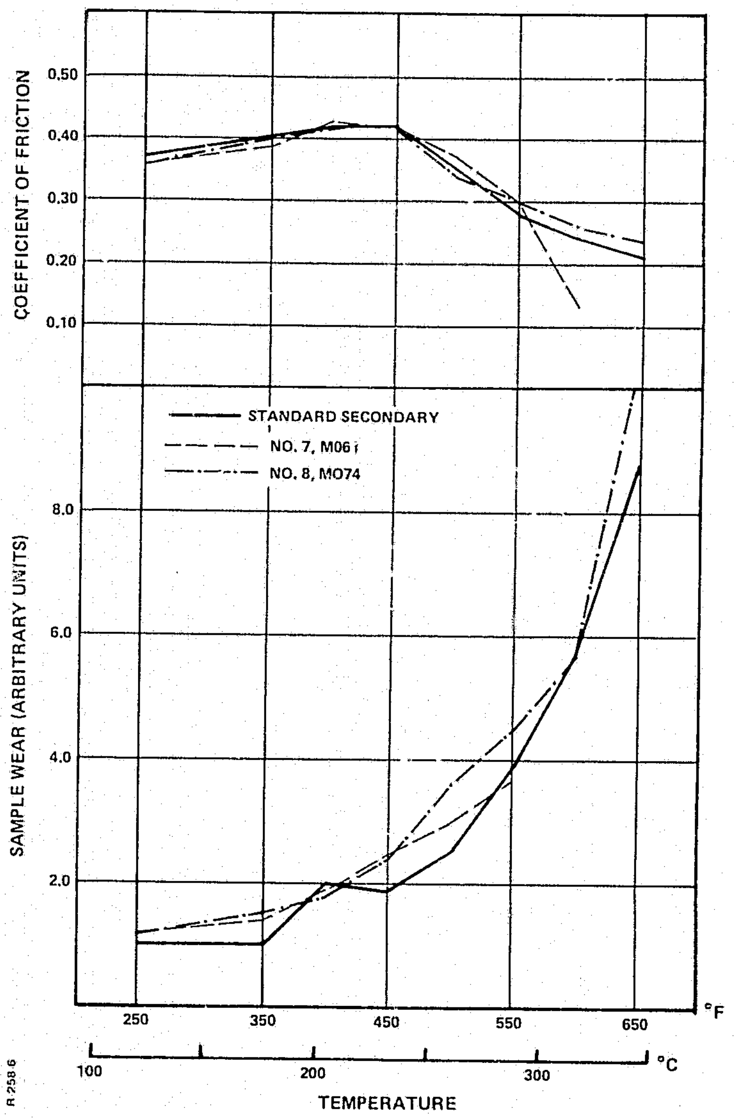

Figure 4-43 - Friction and Wear of Experimental Samples in Which Phenolic Resin Binder was Completely Replaced With Polyimide Resins

4.4 POLYIMIDE RESIN SUBSTITUTION

Experiments with the resin binder system followed the same general procedure already outlined, in which total substitution in the standard formula was tried initially. Subsequent investigation, though necessarily brief, included substitution of mixtures of polyimides, polyimides and phenolic, as well as combinations of resin, fiber and modifier substitutions.

4.4.1 Substitution for Resin Only

When Maleimide 061 (M061) and Maleimide Type 074 (M074) replaced the phenolic resin in the standard secondary lining completely, the two resulting samples gave friction and wear curves that were comparable to those of the standard lining, as shown in Figure 4-43. It can be seen, however, that the sample containing M061 experiences a sharp drop in friction above 550°F (228°C). Furthermore, it was observed that cured M074 was a brittle material and that samples containing pure M074 as the only binder had a tendency to fracture and chip easily. Nevertheless, it was felt that the wear curves for the two initial screening samples were sufficiently close to that for the standard to warrant further study of the polyimide resins.

Since the composite material represents such a complex system, and since we were not prepared to carry out a detailed study of the interactive effects of the several resins, we adopted an empirical approach based on our observations. A summary of the samples thus prepared and studied can be found in Table 4-7. First, in an attempt to combine the superior thermal stability of M074 with the better mechanical properties of cured M061, several blends of the two were tested. The results are shown in Figures 4-44 and 4-45. The blend containing 3 parts of M061 exhibited both poorer friction and wear (No. 17), while that with 3 parts of M074 still appeared quite promising (No. 18), especially in its high temperature wear. But a duplicate sample of the latter, while still comparable to the standard, did not show enough improvement for continued evaluation at this stage in the program. Discontinuities in the wear curve also show brittleness still to be a

Table 4-7 - Summary of Samples Containing Polyimide Resins

Sample No.	Substitution for Phenolic (Percent of Std.)	Polyimide Resin Composition (Percent) M061	M074	Fiber Composition (Percent) Asbestos	Titanate
17	100	75	25	100	0
18	100	25	75	100	0
57	100	25	75	100	0
35	100	15	85	100	0
32	70	100	0	100	0
33	70	0	100	100	0
54	100	25	75	50	50
55	140	25	75	50	50
56	140	70	0	50	50

37 Resin - M074 for phenolic, raised to 140%.
Fiber - Potassium titanate for asbestos, 50%.
Modifier - M074 for cashew friction dust, 100%, and potassium titanate fiber for minor organic modifiers, 100%.
Processing - press at 482°F (250°C), no post cure.

38 Resin - (25% M061 + 75% M074) for phenolic, raised to 140%.
Fiber - Same as in 37.
Modifier - Same as in 37.
Processing - No post cure.

39 Resin - Same as in 37.
Fiber - Same as in 37.
Modifier - Same as in 37, but staged M074. (See Section 3.2.2.1)
Processing - No post cure.

40 Resin - Same as in 38.
Fiber - Same as in 37.
Modifier - Same as in 37.
Processing - Post cure 4h at 250°C (482°F).

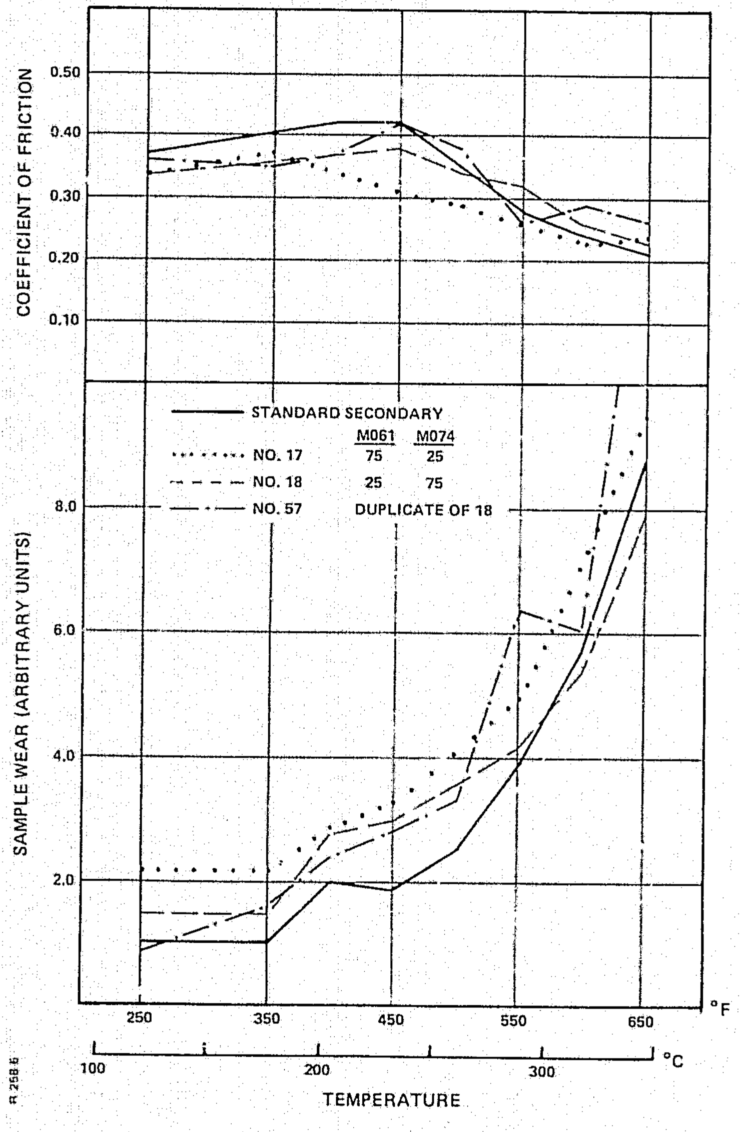

Figure 4-44 - Friction and Wear of Experimental Samples in Which Blends of Polyimide Resins Replaced Phenolic

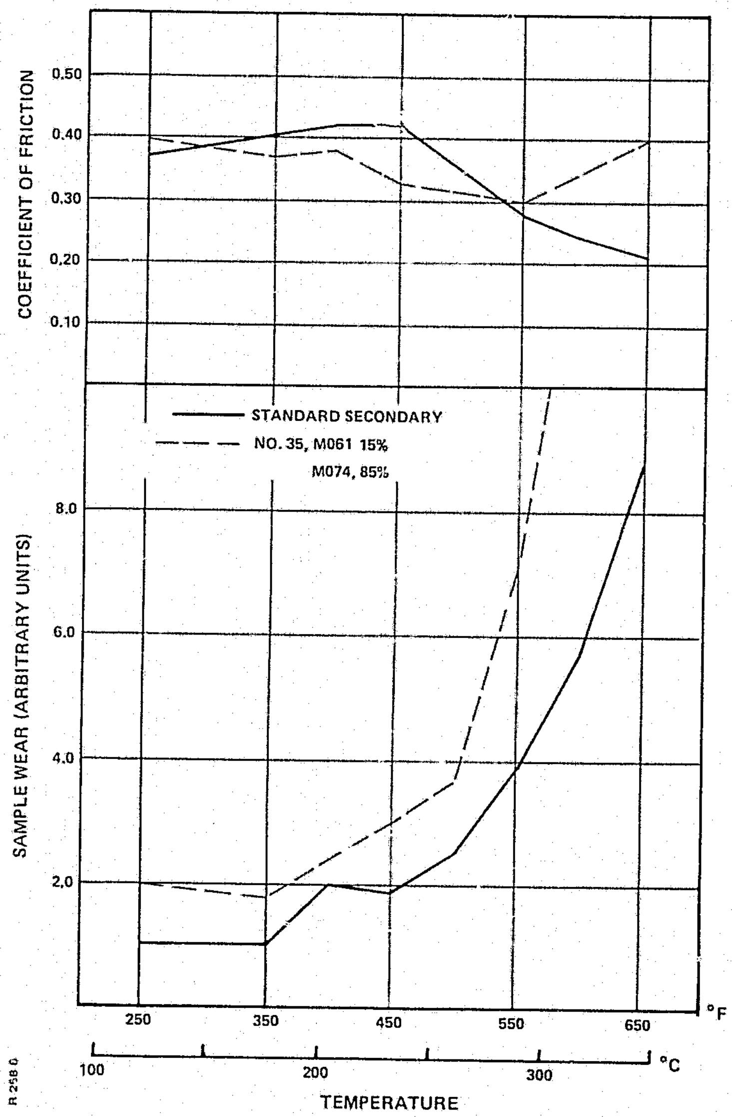

Figure 4-45 - Friction and Wear of Experimental Sample Containing a Blend of Polyimide Resins problem. A single sample in which the proportion of M074 was increased to 85% still maintained good friction but had unacceptably high wear, as shown in Figure 4-45.

As an alternate approach to maintaining the mechanical strength while improving thermal stability, partial replacement of phenolic resin (70%) with each of the polyimides was attempted, and results are shown in Figure 4-46. In this case, M061 is somewhat superior in its wear behavior, a reversal of the indications when total substitution was tried; however, the dip in friction of the sample with M061 is still observed above 550°F (288°C). Once again it was felt that a potential still exists for friction material improvement by polyimide resin addition, but a detailed investigation was not possible in this program.

4.4.2 Resin and Fiber Substitution

By this stage in our investigation of polyimide resins we had already found that substitution of 50% potassium titanate fiber for asbestos in a phenolic bound composite could have some beneficial effects, especially if the resin level was increased. We wished to check for analogous effects with the polyimide resins; therefore, several samples were fabricated which contained polyimide resin and potassium titanate fiber. Results are shown in Figure 4-47. The 25/75 mixture of M061 and M074 was explored at the 100% and 140% levels in samples 54 and 55. The effect of the potassium titanate fiber in maintaining a high value of the friction coefficient at elevated temperature is once again dramatically demonstrated. Sample 54 had the highest and steadiest friction level observed in this program over the temperature range studied. As expected, however, the resin level was too low; the sample lost small lumps of material above 500°F (260°C) and generally had poor wear. Increasing the resin to give sample 55 improved wear somewhat, while good frictional properties were maintained. This composition could well serve as a point of departure for a future study, should it be considered desirable. Very similar behavior was found in sample 56, in which 70% of the phenolic resin was replaced by M061 at the higher resin level; but in this case friction was slightly lower than with pure polyimide resin, especially below 400°F (204°C), making this composition slightly less attractive.

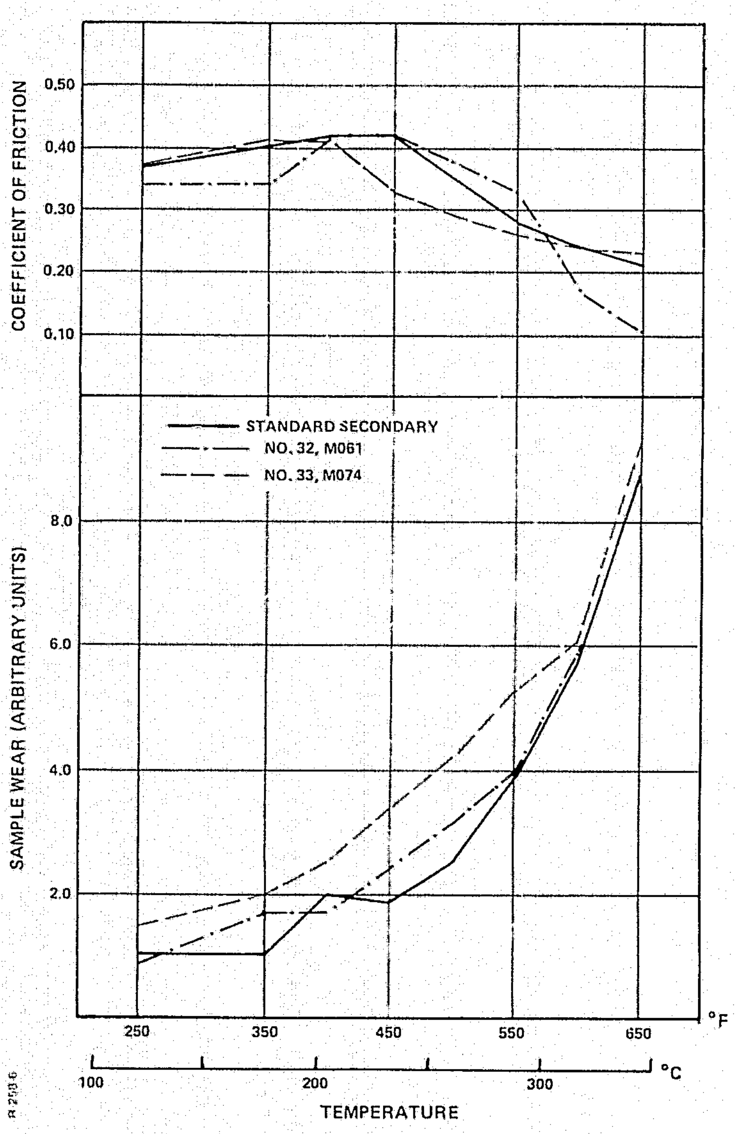

Figure 4-46 - Friction and Wear of Experimental Samples in Which 70 Percent of Phenolic Resin Binder Was Replaced by Polyimide Resins

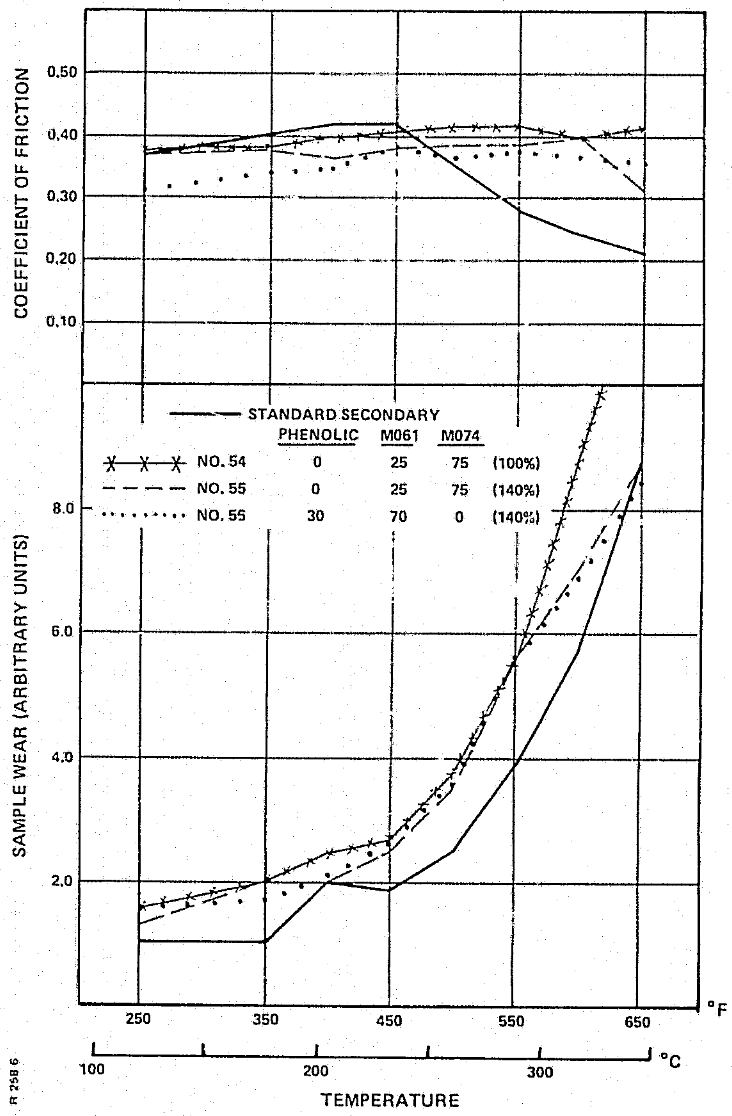

Figure 4-47 - Friction and Wear of Experimental Samples in Which 50 Percent of the Asbestos Was Replaced by Potassium Titanate Fiber and in Which Polyimide Resins Replaced All or Part of the Phenolic

One final set of samples was prepared, in which all of the conventional standard ingredients were replaced by the more thermally stable experimental ones. We were prompted to do this for the following reason: our earlier investigations had shown that (a) the polyimide resins had good thermal stability, and (b) the composites containing polyimides could be processed and cured to have adequate strength. The lack of success in improving the wear of friction materials containing these resins may therefore have been due to the presence of other organic materials of lower thermal stability, such as cashew friction particles which did not allow curing above 420°F (216°C). Replacement of these ingredients by the more stable experimental ones would allow curing of the resin at the potentially more favorable temperature of 482°F (250°C).

The samples identified as Nos. 37 to 40 in Table 4-7 were fabricated and tested; the composition was based on the successful 50% substitution of potassium titanate for asbestos and increase of resin by 40%. Organic modifiers were replaced by potassium titanate fiber, while the cashew friction particle, which also has some of the properties of a phenolic binder, was replaced by polyimide resin. Friction and wear results are shown in Figures 4-48 and 4-49, and can only be called terrible. Reasons for the poor wear and friction are unknown, but we can speculate that the mechanism is probably not a thermal one. The quantity of binder and modifier, its state of cure, mechanical strength of the composite, and its microstructure, all are areas for potential further work. This could form the basis for a future materials study that would be of great value to the development of new friction materials. We were unable pursue this line of investigation because of the limited scope of the program, and discontinued further work with polyimide resins in favor of more depth in the potassium titanate fiber study which was described previously.

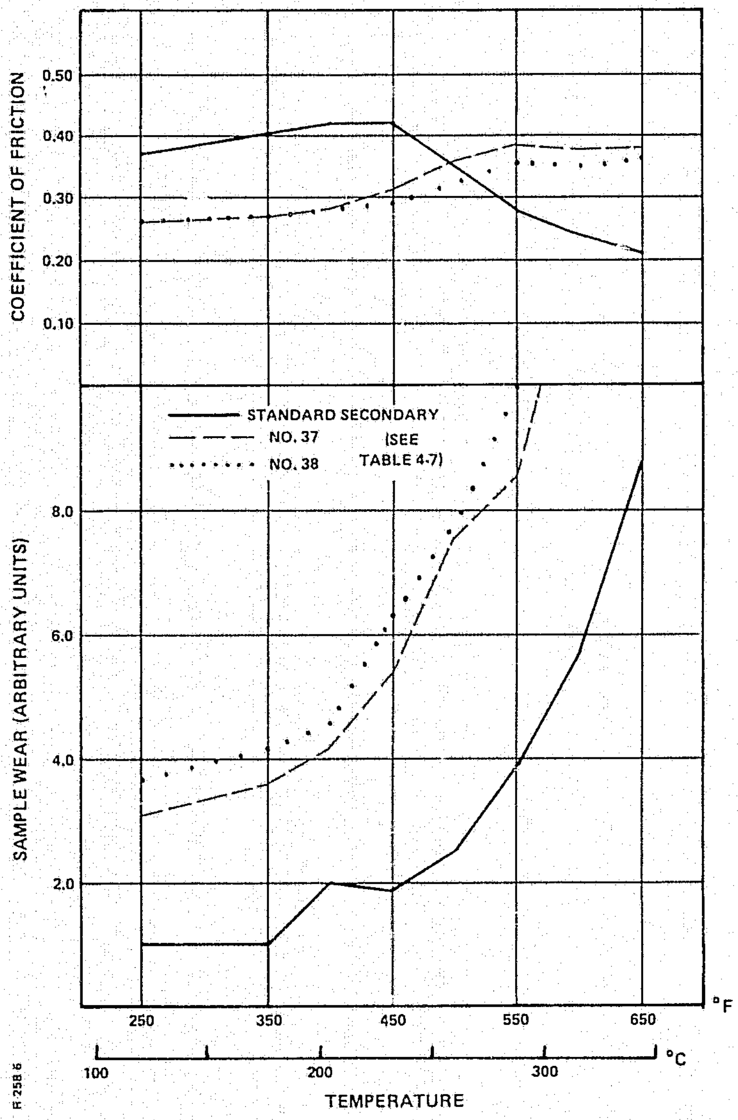

Figure 4-48 – Friction and Wear of Experimental Samples 37 and 38 Containing Only Asbestos, Potassium Titanate Fiber and Polyimide Resin

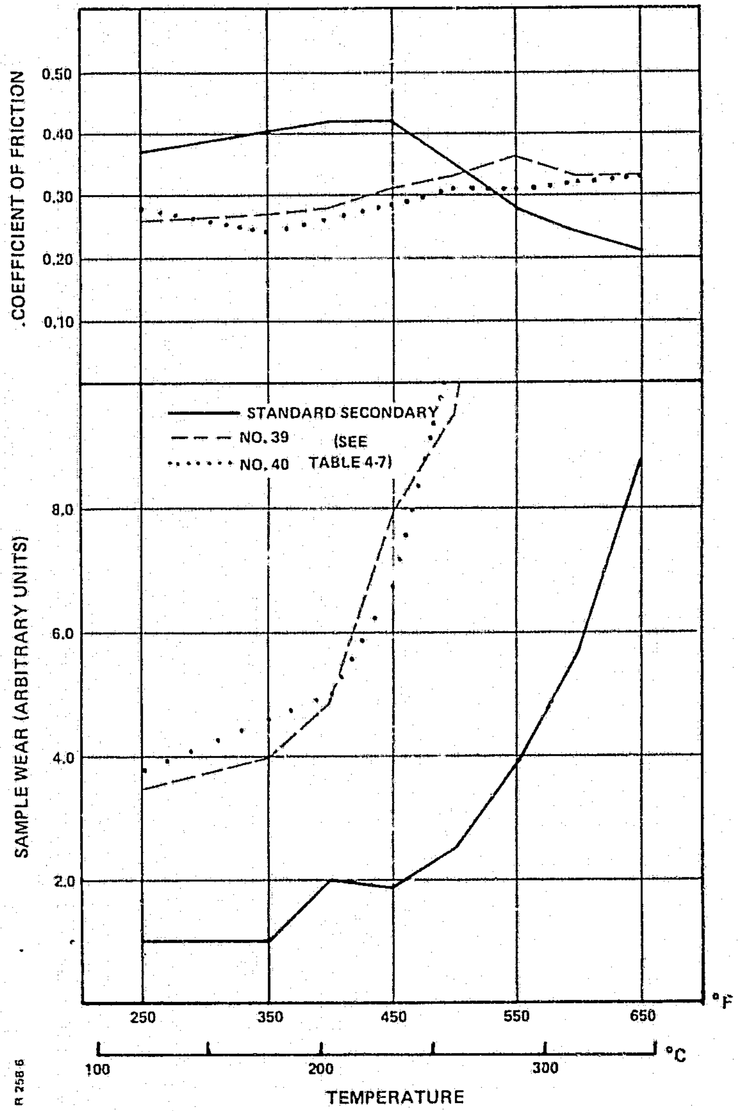

Figure 4-49 – Friction and Wear of Experimental Samples 39 and 40 Containing Only Asbestos, Potassium Titanate Fiber and Polyimide Resins

4.5 REFERENCES

(4-1) S. K. Rhee, "Influence of Rotor Metallurgy on the Wear of Friction Materials in Automotive Brakes," SAE Transactions, 80, 992 (1971).

(4-2) S. K. Rhee, "Wear Mechanisms at Low Temperatures for Metal-Reinforced Phenolic Resins," Wear, 23, 261 (1973).

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(4-4) M. G. Jacko, W. M. Spurgeon, R. M. Rusnak, and S. B. Catalano, "Thermal Stability and Fade Characteristics of Friction Materials," Paper No. 680417, presented at the Midyear Meeting, Society of Automotive Engineers, Detroit, Michigan, May 1968.

(4-5) Federal Motor Vehicle Safety Standard 5715 105-75-1, effective date 1 September 1975.

(4-6) N. R. Lerner, "ESR and Chemical Study of p-Polyphenylene Formed Using an $AlCl_3$-$CuCl_2$ Catalyst," J. Polymer Science, Polymer Chemistry Edition, 12, 2477-2495 (1974).

SECTION 5
CONCLUSIONS

As we now look back to evaluate the program and its accomplishments, we find that certain aspects of the work are rather clear-cut, while others will require further clarification. Some of the problems were anticipated at the inception of the program, while others became apparent only as the work progressed. In general, they were resolved satisfactorily.

The major finding of this work was the demonstration of the potential of potassium titanate fiber for the improvement of a friction material of the secondary lining type. For example, the maintenance of a mean friction level of 0.35 between 450 and 650°F (232 and 343°C) becomes possible in the presence of the titanate fiber, as opposed to a value of 0.30 in its absence. This becomes even more significant if it is pointed out that the corresponding mean values are 0.33 and 0.25 in the 600 to 650°F (316-343°C) range: fade can definitely be improved by incorporation of potassium titanate fiber. Wear improvement of the order of 30 to 40% also becomes possible by proper adjustment of resin content and potassium titanate fiber to asbestos ratio. Having been demonstrated, this principle now remains to be exploited for general application in the friction material industry.

Actual development of an improved formulation has also been accomplished, as based on the results of sample drag dynamometer tests and single-wheel full-scale inertial dynamometer tests. This formulation is based on the standard lining, in which one half of the asbestos has been replaced by potassium titanate fiber and in which the resin content has been increased by 40%. A brief exploration within the range of compositions that are possible and that can be fabricated indicated that the cited composition is near an optimum for friction and wear improvement. However, further study is needed to establish whether other composition ranges exist in which friction and wear improvement is possible.

Full-scale testing also suggested that this formulation offers the potential for greater friction stability and less speed spread than the standard, and thus is more favorable for meeting the FMVSS 105-75 requirements.

Among the questions that still must be examined, should this specific lining formulation be a candidate for development in commercial applications, are those concerning its behavior in a vehicle test and its large scale manufacturability. First of all, the vehicle test would establish in actual usage the lining's performance in a FMVSS 105-75 test; it would also establish the wear pattern of the lining in actual usage such as the industry's Detroit or Los Angeles Traffic Tests. In addition it would allow the evaluation of the effect of potassium titanate fiber on drum wear and on the more subjective but crucial requirement of minimal brake noise. The lining will not be considered acceptable before it is established that it satisfactorily meets the above requirements. As for its manufacture, additional development is necessary; either the composition or the processing or both may require adjustment before it can be fabricated on a large scale. This is part of the normal development process, and it is not possible at this time to predict what difficulties may or may not be encountered.

In the program just completed, about eighty pieces of friction material were fabricated and tested in order to evaluate the properties imparted by three types of experimental ingredients. Potassium titanate fiber was found to improve high temperature friction and to allow formulation of compositions with improved high temperature wear. A brief but systematic study discovered one formulation showing both improved friction and wear relative to the standard lining. Polyphenylene was found to cause a deterioration in properties, while polyimide resins did not bring about any significant improvements when substituted in a standard commercial secondary lining formulation.

APPENDIX A

RESULTS OF THERMAL ANALYSIS OF COMPOSITE SAMPLES THAT WERE PREPARED TO DETERMINE THE BEST CURE CONDITIONS FOR POLYIMIDE RESINS

Refer to Section 3.1.3.2.3 for discussion of these curves. Samples are numbered as in Table 3-3 of the text.

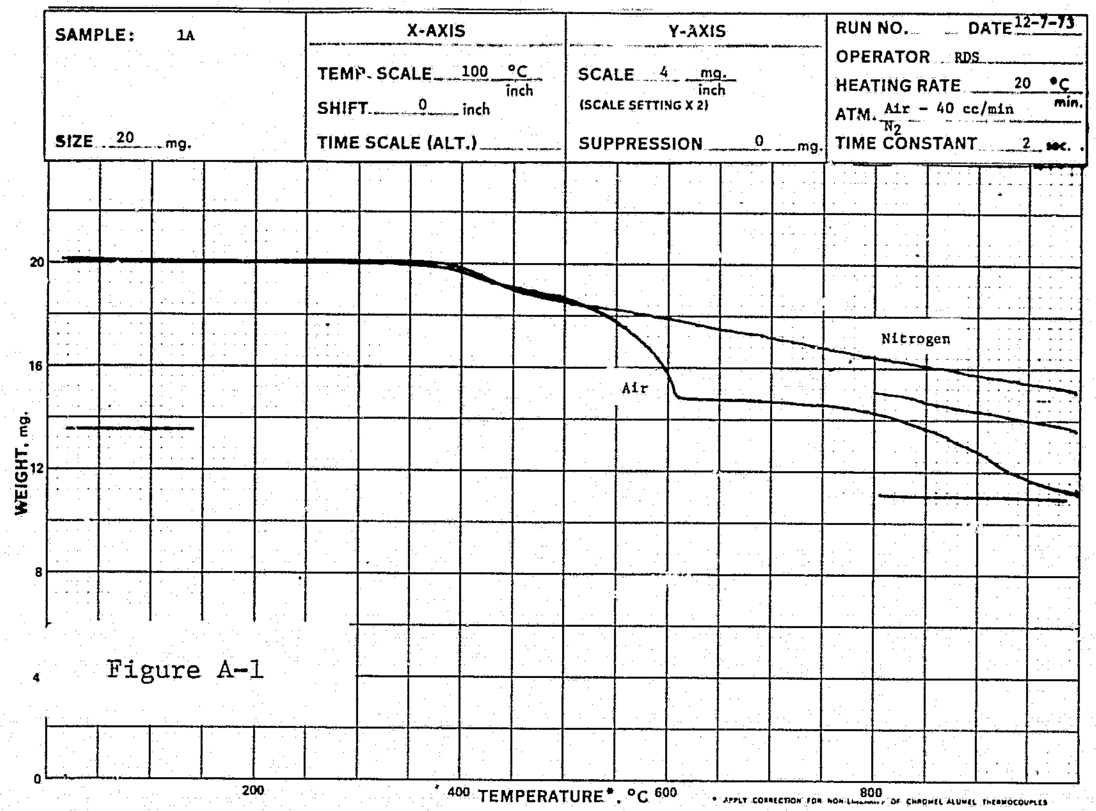


Figure A-1

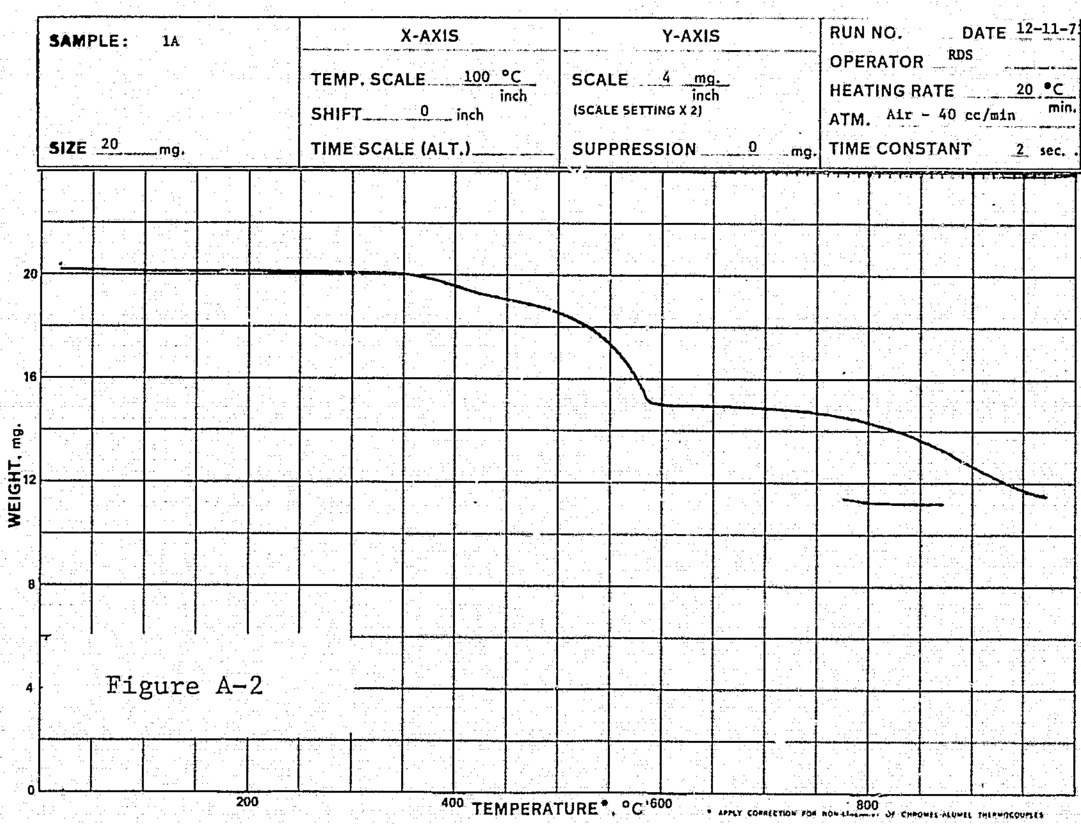


Figure A-2

SAMPLE: 1B SIZE 20 mg.	X-AXIS TEMP. SCALE 100 °C/inch SHIFT 0 inch TIME SCALE (ALT.)	Y-AXIS SCALE 4 mg./inch (SCALE SETTING X 2) SUPPRESSION 0 mg.	RUN NO. DATE 12-12-73 OPERATOR RDS HEATING RATE 20 °C/min. ATM. Air - 40 cc/min N_2 TIME CONSTANT 2 sec.

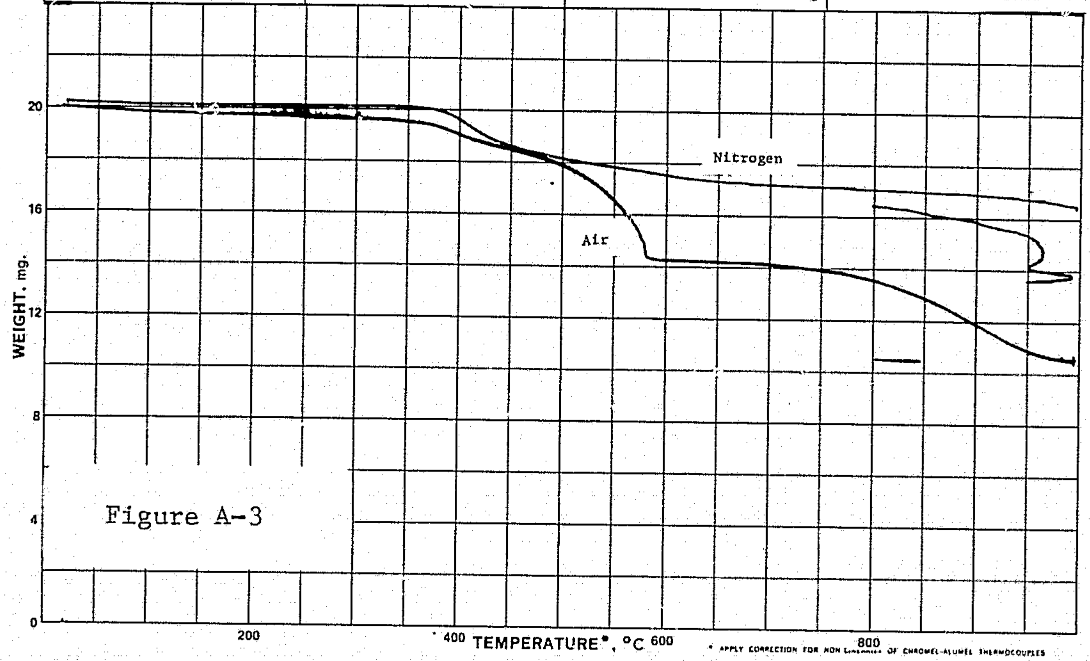


Figure A-3

SAMPLE: 5B SIZE 20 mg.	X-AXIS TEMP. SCALE 100 °C/inch SHIFT 0 inch TIME SCALE (ALT.)	Y-AXIS SCALE 4 mg./inch (SCALE SETTING X 2) SUPPRESSION 0 mg.	RUN NO. DATE 12-10-73 OPERATOR RDS HEATING RATE 20 °C/min. ATM. Air - 40 cc/min TIME CONSTANT 2 sec.

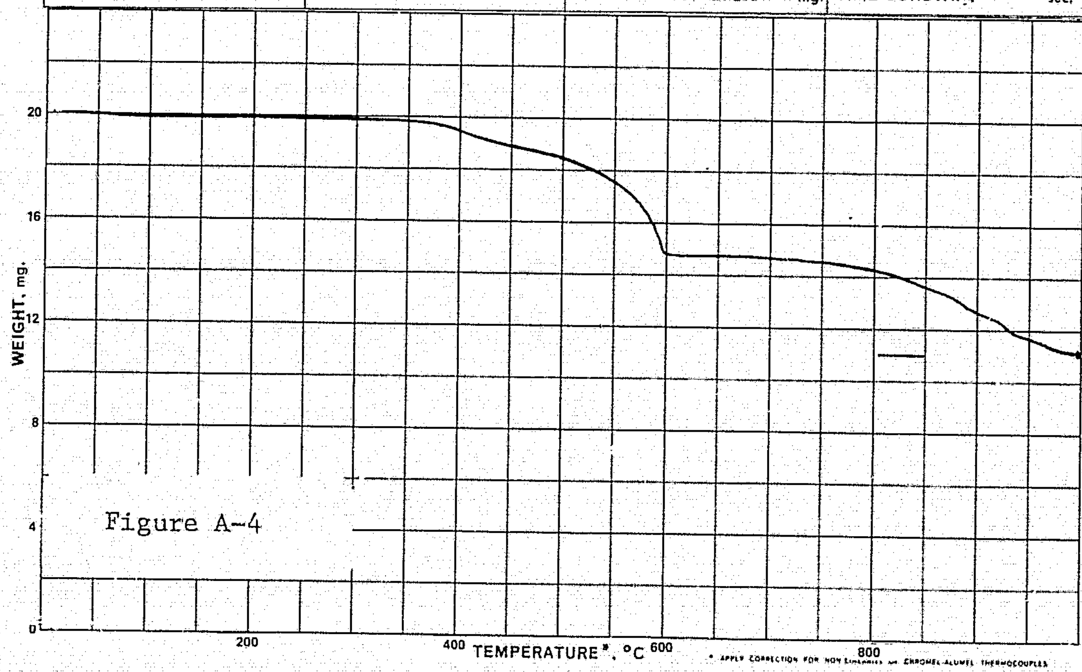


Figure A-4

SAMPLE: 5B	X-AXIS	Y-AXIS	RUN NO. DATE 12-12-73
	TEMP. SCALE 100 °C/inch	SCALE 4 mg./inch (SCALE SETTING X 2)	OPERATOR RDS
	SHIFT 0 inch		HEATING RATE 20 °C/min.
SIZE 20 mg.	TIME SCALE (ALT.)	SUPPRESSION 0 mg.	ATM. Air - 40 cc/min
			TIME CONSTANT 2 sec.

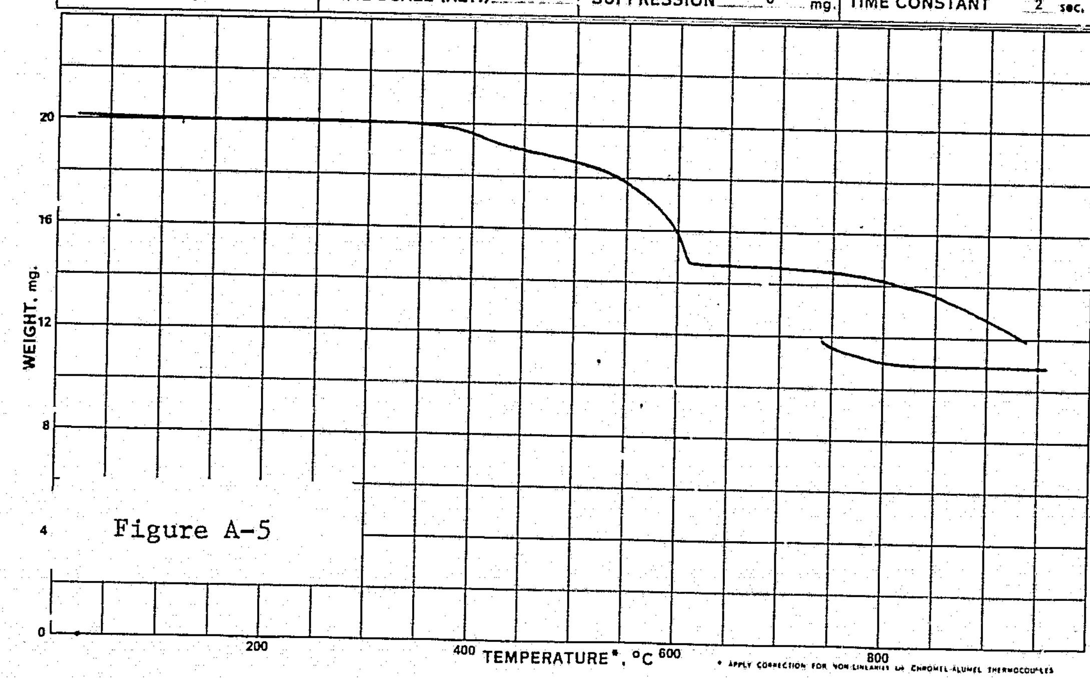


Figure A-5

SAMPLE: 8A	X-AXIS	Y-AXIS	RUN NO. DATE 12-11-73
	TEMP. SCALE 100 °C/inch	SCALE 4 mg./inch (SCALE SETTING X 2)	OPERATOR RDS
	SHIFT 0 inch		HEATING RATE 20 °C/min.
SIZE 20 mg.	TIME SCALE (ALT.)	SUPPRESSION mg.	ATM. Air - 40 cc/min N_2
			TIME CONSTANT 2 sec.

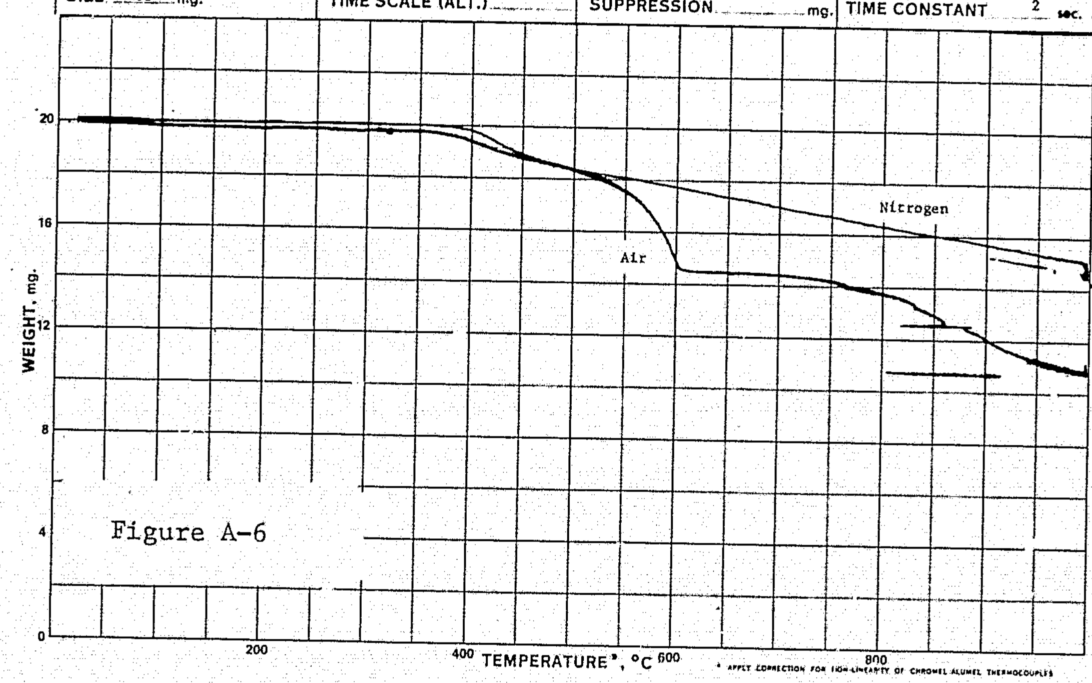


Figure A-6

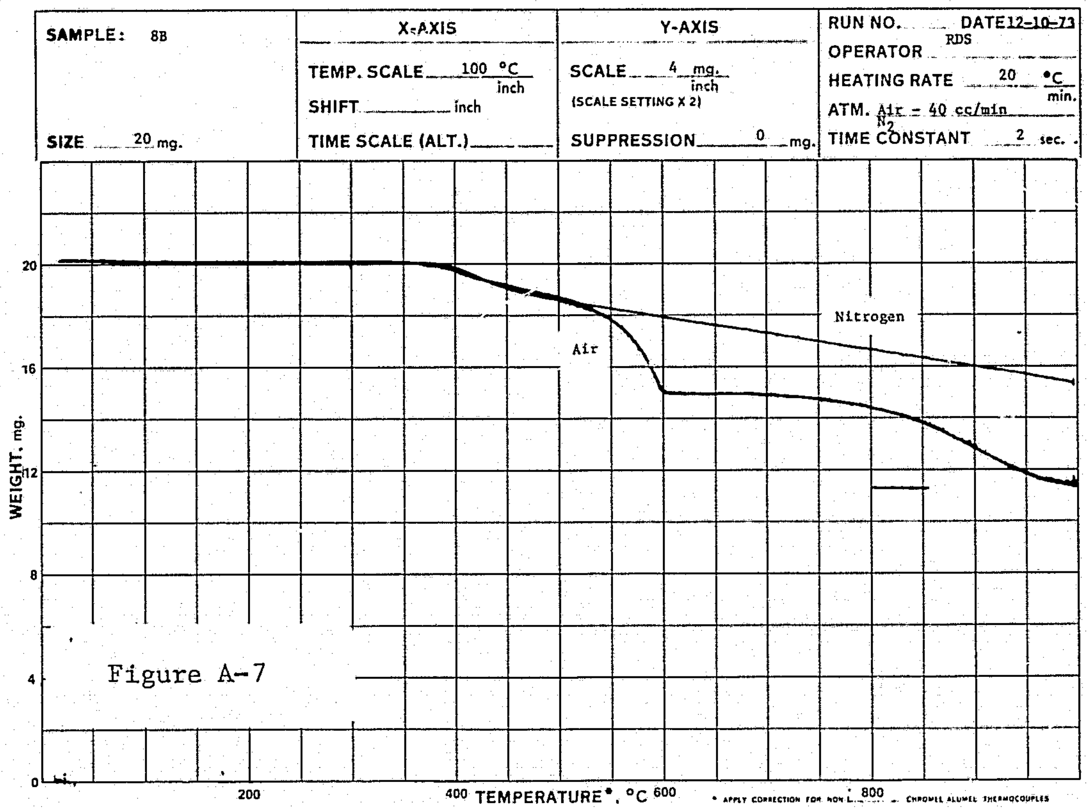


Figure A-7

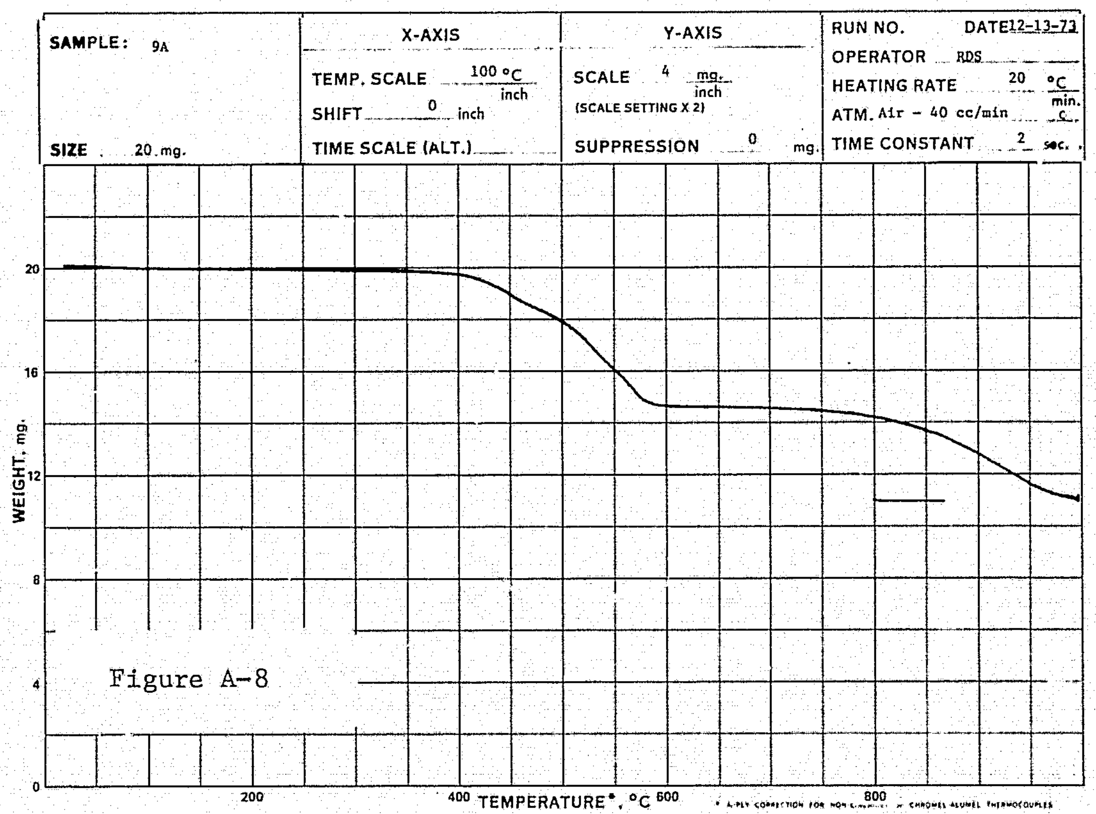


Figure A-8

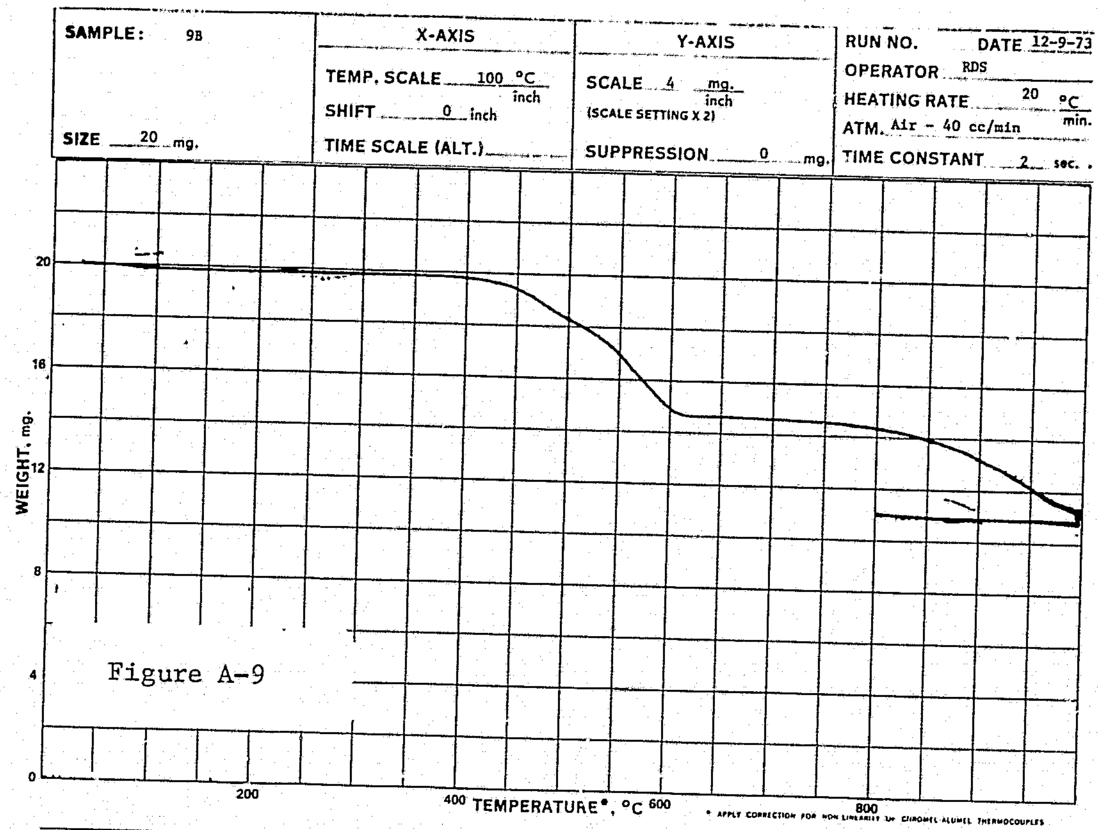


Figure A-9

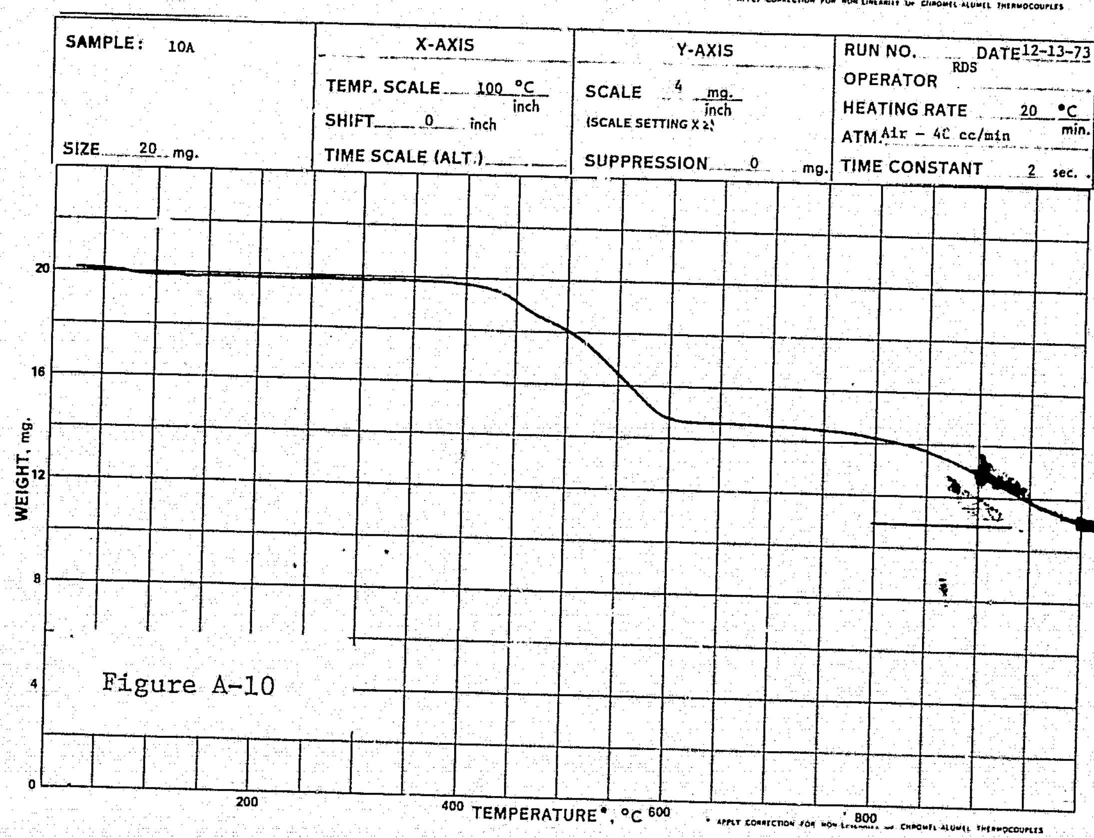


Figure A-10

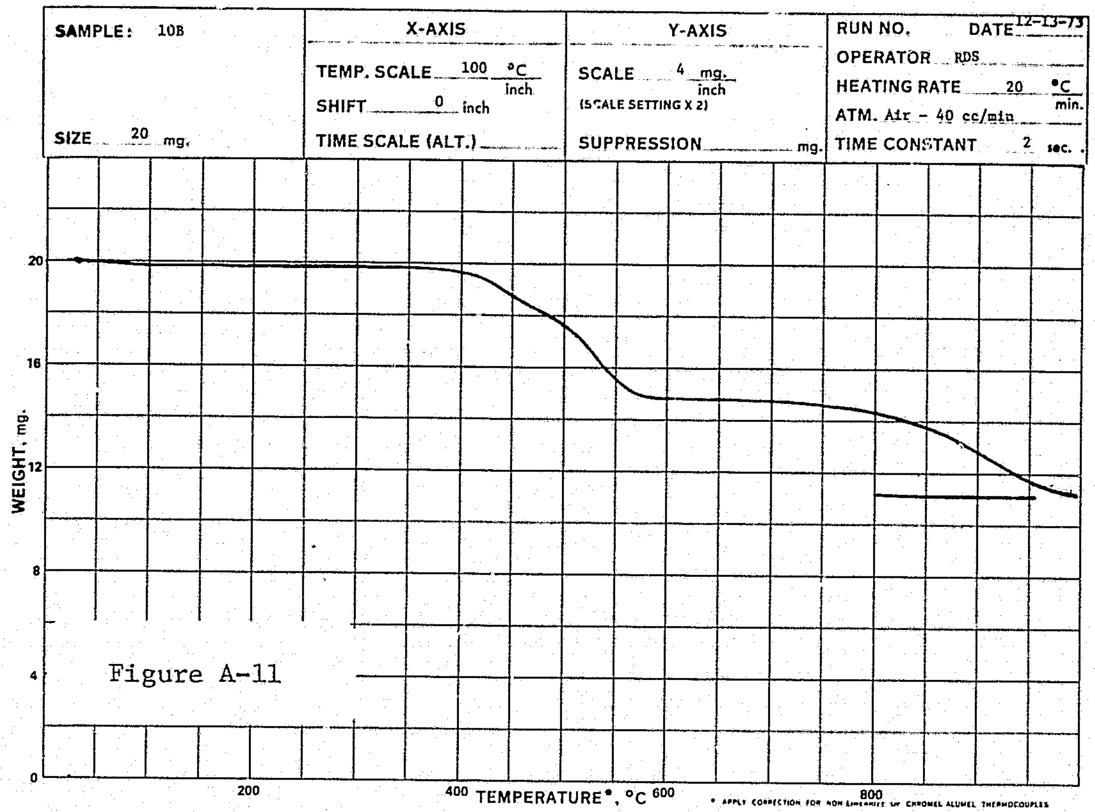


Figure A-11

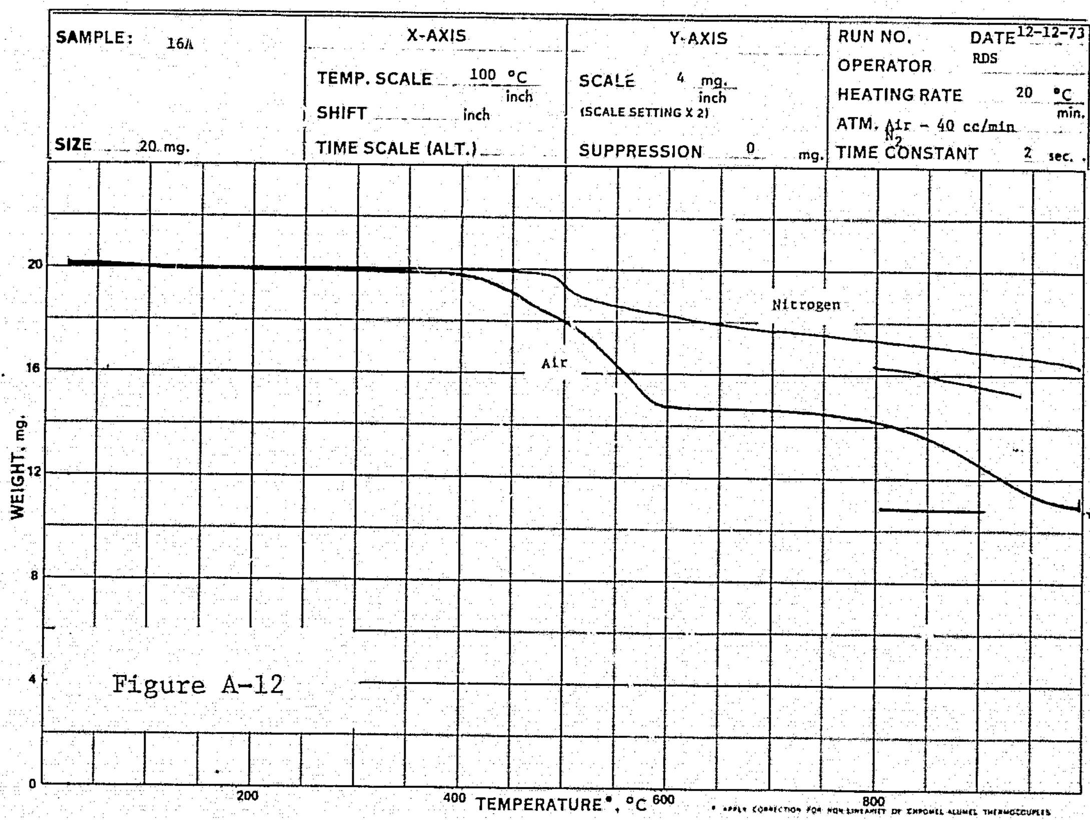
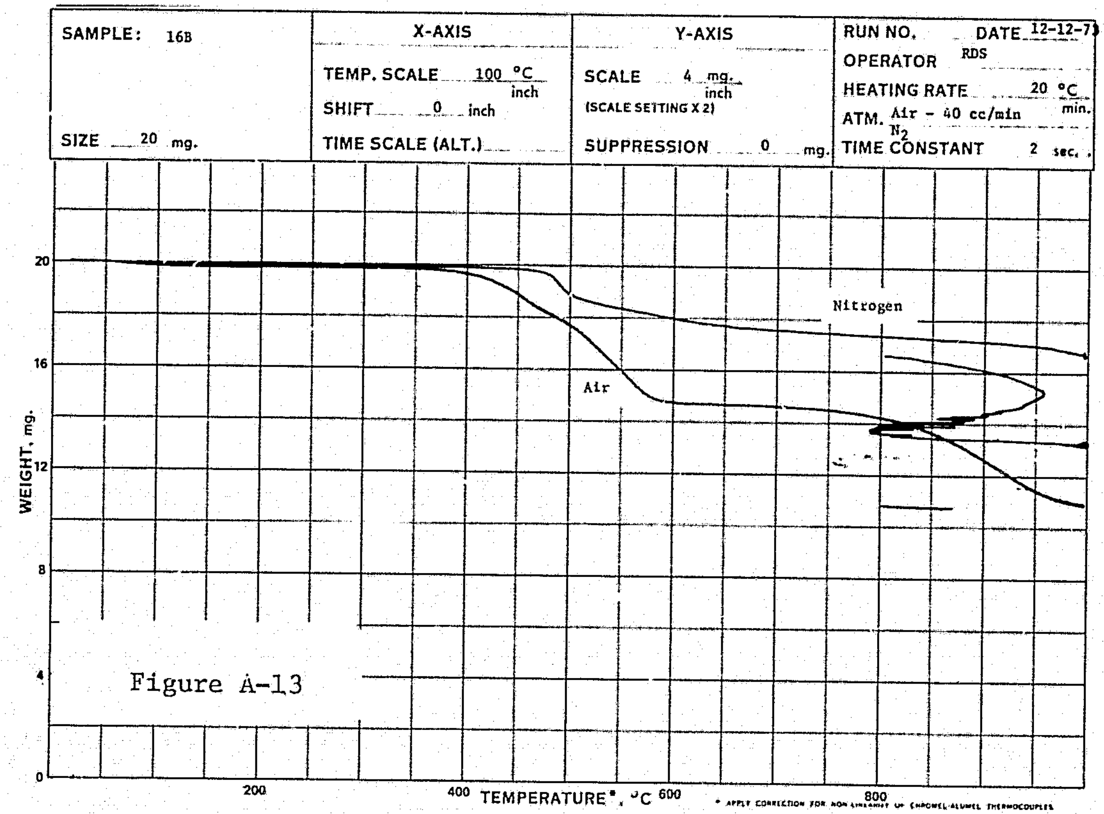


Figure A-12



SAMPLE: 16B
SIZE 20 mg.
X-AXIS
TEMP. SCALE 100 °C inch
SHIFT 0 inch
TIME SCALE (ALT.)
Y-AXIS
SCALE 4 mg. inch
(SCALE SETTING X 2)
SUPPRESSION 0 mg.
RUN NO.
DATE 12-12-73
OPERATOR RDS
HEATING RATE 20 °C min.
ATM. Air - 40 cc/min N2
TIME CONSTANT 2 sec.
Nitrogen
Air
WEIGHT, mg.
20
16
12
8
4
0
200
400
TEMPERATURE*, °C
600
800
* APPLY CORRECTION FOR NON-LINEARITY OF CHROMEL-ALUMEL THERMOCOUPLES

Figure A-13

APPENDIX B

SAMPLE CALCULATION

1	2	3	4 = 2X3	5
Ingredient	Volume Percent	Density (g/cm^3)	Weight per 100 Volumes	Weight Percent
Asbestos	50	2.5	125.0	68.5
Resin	25	1.2	30.0	16.4
Modifier	25	1.1	27.5	15.1
	100		182.5	100.0

Theoretical density of friction material = 1.825 g/cm^3

In order to calculate the actual quantity of each ingredient needed, we must decide how much friction material we want to make. Suppose we wish to make two pads, and that the volume of each pad is 50.0 cm^3. If we then make enough mix to give 105 cm^3, we will have a 5 percent safety margin to assure complete filling of the mold, and for possible small losses during handling.

Total weight required = 105 cm^3 x 1.825 g/cm^3 = 191.6 g for two pads.

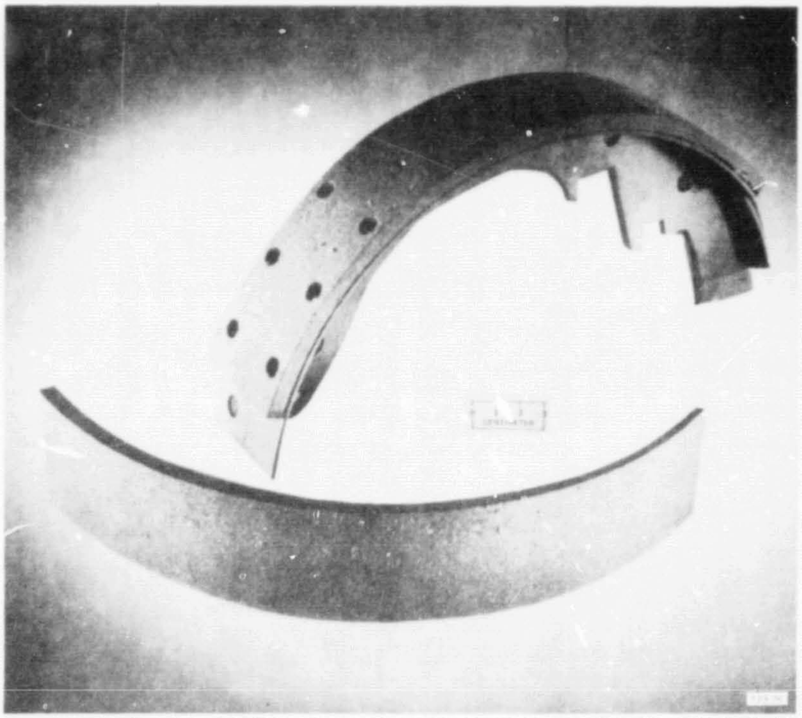
The weight of each ingredient required is:

Ingredient	Weight Percent	X	Total Weight Required	=	Weight of Ingredient To Make Two Pads
Asbestos	68.5	X	191.6g	=	131.2g
Resin	16.4	X	191.6	=	31.4
Modifier	15.1	X	191.6	=	29.0
					191.6 (checks)

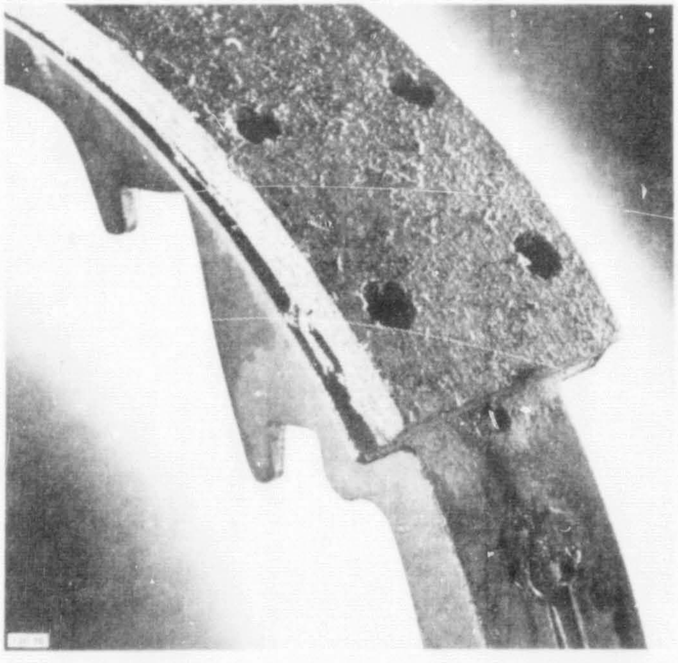
APPENDIX C

DESCRIPTION OF ATTEMPTS TO MANUFACTURE FULL SCALE EXPERIMENTAL LININGS OF OPTIMUM COMPOSITION BY CONVENTIONAL LARGE SCALE TECHNIQUES

Specifications for full-scale secondary linings were provided to Bendix Friction Materials Division, Troy, NewYork, where a number of attempts were made to fabricate drum linings of the best experimental formulation, i.e., formula Number 26, containing 40 percent additional resin and with one half of the asbestos replaced by potassium titanate fiber. Blistering problems were encountered repeatedly, however, and processing conditions had to be adjusted until an acceptable arced lining could be made. Finally, with a pressing temperature of 330°F (166°C) and several added pressure-relief cycles, a batch was processed successfully, although some of the linings still had laminations. Several "good" linings of this batch were submitted for the inertial dynamometer tests, but now a strength problem became evident: when the linings were riveted to the shoes in the conventional way, portions of the material pulled loose and did not allow proper fastening of the lining to the shoe. A photograph of this phenomemon is shown in Figure C-1. Even though these linings could not be tested, it proved feasible to bond, rather than rivet, this material to a shoe. Such a configuration successfully underwent a wear test, which will be discussed in Appendix I.



(a) Experimental Secondary Lining and Identical Lining Showing Cracks When it was Riveted to Brake Shoe



(b) Close-Up Showing Separation of Lining From Shoe After Riveting

Figure C-1

APPENDIX D

INERTIA DYNAMOMETER BRAKE LINING WEAR TEST PROCEDURE
(WEAR VERSUS TEMPERATURE)

1. Introduction - This inertia dynamometer brake lining wear test procedure is intended to be used as a preliminary screening test. Under controlled laboratory conditions, it enables relative comparisons to be made of the durability of brake linings under increasingly severe conditions of usage.

2. Equipment and Instrumentation

2.1 Equipment

2.1.1 An inertia type brake dynamometer.

2.1.2 Means for varying brake cooling.

2.2 Instrumentation

2.2.1 Required

2.2.1.1 Means for recording application pressures.

2.2.1.2 Means for recording brake torques.

2.2.1.3 Means for recording brake lining temperatures.

2.2.1.4 Means for recording shaft speed.

2.2.1.5 Cooling air temperature indicators.

2.2.2 Optional Instrumentation

2.2.2.1 Cooling air velocity indicators

2.2.2.2 Drum or disc temperature indication and/or recording equipment.

2.2.2.3 Fluid displacement indicators.

2.2.2.4 Stopping time indicator.

2.2.2.5 Revolutions to stop indicator for measurement of equivalent stopping distance.

2.3 System Accuracy

2.3.1 Accuracy of Instrumentation

2.3.1.1 The overall system accuracy for all recording or indicating instruments shall be $\pm$ 2% of full scale or better.

2.3.2 Control Parameter Accuracy

2.3.2.1 Pressures, Torques and Temperatures shall be maintained within ± 5% of the desired value.

2.3.2.2 Speed shall be maintained within ± 2% of the desired value.

2.3.2.3 Test moment of inertia shall be within ± 20 ft. - lb. - sec^2 (± 27 Nm^2) of value calculated from item 3.7.

3. Test Preparation and Installation

3.1 Friction Material Preparation - Attach and finish friction material per manufacturer's specifications, unless otherwise noted.

3.1.1 Initial Measurement - Measure overall thickness of linings at fixed reference points per data sheet. Use one sheet for each brake. Weigh, to nearest gram, each shoe and lining assembly and record on data sheet.

3.2 Thermocouples - Install plug type thermocouple in each brake recessed approximately .040 inch (1 mm) below the rubbing surface. All thermocouples are to be located in the approximate center of the most heavily loaded lining. Indicate exact location on data sheet.

3.3 Brake Drum Assembly - New drums should be used for each test. Surface finish, dimensional characteristics (with special emphasis on thickness variation and runout of rubbing surface) and material properties to be in accordance with manufacturer's specifications.

3.3.1 Make and record the necessary measurements for wear determination using one data sheet for each drum.

3.4 Brakes to be prepared in accordance with manufacturer's specifications. Adjust brakes to manufacturer's specifications where applicable.

3.5 Brake Mounting - To be mounted essentially as in service.

3.6 Application System - Shall incorporate all necessary components to simulate the vehicle system being tested.

3.7 Test moment of inertia - calculate moment of inertia required as follows:

$$I = \frac{Wr2N}{g}$$

Where I = Moment of inertia: required in ft.-lb.-sec.^{2} (Nm^2).

W = Total vehicle test weight (lbs.) (N).

r = Effective radius of tire in feet. (m)

$$r = \frac{5280}{2\pi \text{ x wheel rev/mile}} \text{feet} = \frac{1000}{2\pi \text{ x wheel rev/km}} \text{ meters}$$

g = 32.2 FPSPS.(9.80665 m PSPS)

N = Fraction of total vehicle brake torque the brake being tested produced on the vehicle being simulated.

3.8 Test RPM - As required to simulate specified test speeds. Calculate RPM as follows:

$$RPM = \frac{14.02 \text{ x MPH}}{r}, \text{ or } RPM = \frac{\text{Tire revs. per mile x MPH}}{60} \quad RPM = \frac{2.65\text{xkm Per hr.}}{\text{r meters}}$$

where r = effective tire radius in feet (m).

3.9 Test Deceleration - All control decelerations shall be converted to torque for dynamometer settings by the following formula:

$$R = \frac{W \text{ x } r \text{ x } a \text{ x } N}{g}$$

where T = Total torque required in foot-lbs. (Nm) (for brakes being tested), a = control deceleration in feet per second per second (m/sec^2), W,r,g,N from 3.7.

3.10 Dynamometer loading, speed and deceleration rate to be chosen so as to simulate conditions for the loaded vehicle for which brake is designed.

3.11 Log sheets must be maintained by the machine operator to record the data required by the procedure. Log sheets must also note at all times during the test such features as roughness, brake noise and other peculiarities of performance such as odor, smoke, etc.

4. Definitions

4.1 Test Notes

4.1.1 "Initial brake temperature" is defined as immediately before stop, brake off.

4.1.2 If brakes require warming to reach specified initial temperature, use burnish procedure and shorten intervals if necessary.

4.1.3 Hydraulic pressure input must be controlled for all phases of the procedure at an 800 to 1200 psi increase per second. Record actual rate of pressure rise.

4.1.4 "Stop Time" is defined as commencing upon reaching 100 psi hydraulic pressure and ending at zero torque.

5. Test Procedure

5.1 Prior to measuring and weighing, the shoe and lining assemblies should be cleaned off with a stiff non-metallic bristle brush. Lining measurements should be recorded on attachment II in the appropriate location. Weigh each lining assembly using a gram scale to the hundredth and round off to the nearest tenth.

Care must be exercised not to contaminate lining during measurement and weighing handling.

5.2 Cooling air during all stops shall be room ambient obtained by using only dyno exhaust for system. Run 100 burnish stops as follows:

5.2.1 Stop Speed - 40-0 MPH

5.2.2 Stop Deceleration - 12 feet per sec^2.

5.2.3 Stop Interval - As required to maintain 250°F initial brake drum temperature.

5.2.4 Cooling Speed - 40 MPH

5.2.5 Dwell After Stop - Not to exceed 20 seconds. Resume cooling speed as soon as possible.

5.2.6 Inspection

5.3 Measure and weigh shoe and lining assemblies after brushing off dust.

5.4 Run 300 stops from 50 to 0 MPH at 12 ft/sec^2 decell with a starting rotor temperature of 250°F. Record data only on the 1, 50, 100, etc. stops using a suitable record sheet.

5.5 Repeat paragraphs 5.3 and 5.4 for 350°F, 450°F, and 550°F.

5.6 Repeat paragraph 5.4 at 250°F after completion of the 300 stops at 550°F.

6. Data Reduction

APPENDIX E

DYNAMOMETER PROCEDURE: FMVSS 105-75 SIMULATION

1. <u>Ten Stop Instrumentation Check</u>
   Make 10 stops from 30 MPH (48 km/h) at 0.31g deceleration to check instrumentation. Do not exceed 250°F (121°C) disc temperature.
2. <u>First (Pre-Burnish) Effectiveness</u>
   30 MPH (48 km/h) - Make one stop each at 0.3g, 0.5g, 0.7g, 0.8g, 0.9g and 1.0g deceleration.
   60 MPH (97 km/h) - Make one stop each at 0.3g, 0.5g, 0.7g, 0.8g, 0.9g and 1.0g deceleration.
3. <u>Burnish</u>
   Make 200 stops from 40 MPH (64 km/h) at 0.38g deceleration for vehicles less than or equal to 10,000 lbs. (4540 kg) GVWR. Control to 250°F (121°C) IBT.
4. <u>Second Effectiveness</u>
   30 MPH (48 km/h) - Make one stop each at 0.3g, 0.5g, 0.7g, 0.8g, 0.9g, and 1.0g deceleration.
   60 MPH (97km/h) - Make one stop each at 0.3g, 0.5g, 0.7g, 0.8g, 0.9g and 1.0g deceleration.
   80 MPH (129 km/h) - Make one stop each at 0.3g, 0.5g, 0.7g and 0.8g deceleration.
   (Run only if vehicle is capable of attaining 84 MPH (135 km/h) in two miles (3.2km) and has a GVWR less than or equal to 10,000 lbs. (4540 kg).)
5. <u>First Reburnish</u>
   Same as Item 3, except make 35 stops instead of 200.
6. <u>Third Effectiveness - 60 MPH (97 km/h) Light Load</u>
   Change wheel load to 755 lbs (343 kg). Make one stop each at 0.3g, 0.5g, 0.7g, 0.8g, 0.9g and 1.0g from a speed of 60 MPH (97 km/h).
7. <u>Partial System Failure - Light Load</u>
   Change wheel load to 1443 lbs. (655 kg). Make one stop each at 0.1g, 0.2g, 0.3g and 0.4g from a speed of 60 MPH (97 km/h).

8. Partial System Failure - GVWR

Change wheel load to 1643 lbs. (746 kg). Repeat Item 7.

9. Inoperative Power

Change wheel load to 980 lbs (445 kg). Repeat Item 7.

10. First Fade and Recovery

Check Stops - Make 3 check stops from 30 MPH (48 km/h) at 0.31 g deceleration for vehicles less than or equal to 10,000 lbs. (4540 kg) GVWR.

Fade - For vehicles less than or equal to 10,000 lbs. (4540 kg) GVWR, make 10 stops from 60 MPH (97 km/h) at 0.47g, starting the first stop at 150°F (66°C) IBT. (Use pressure limiting so as not to exceed a pressure equivalent to 150 lbs. (667N) pedal force for the brake system under test.) Time interval between stops is to be 36 seconds.

Recovery - For vehicles less that or equal to 10,000 lbs. (4540 kg) GVWR, make 5 stops from 30 MPH (48 km/h) at 0.31g deceleration. Start the first stop 2 minutes after the last fade stop, and make the remaining stops at 2 minute intervals.

11. Second Reburnish

Repeat Item 5.

12. Second Fade and Recovery

Repeat Item 10, except make 15 fade stops instead of 10 stops.

13. Third Reburnish

Repeat Item 5.

14. Fourth Effectiveness

30 MPH (48 km/h) - Make one stop each at 0.3g, 0.5g, 0.7g, 0.8g, 0.9g and 1.0g deceleration.

60 MPH (97 km/h) - Make one stop each at 0.3g, 0.5g, 0.7g, 0.8g, 0.9g and 1.0g deceleration.

80 MPH (129 km/h) - Make one stop each at 0.3g, 0.5g, 0.7g and 0.8g deceleration.

(Run only if vehicle is capable of attaining 84 MPH (135 km/h) in 2 miles (3.2 km) and has a GVWR less than or equal to 10,000 lbs. (4540 kg).)

15. Spike Stops

Make 10 stops from 30 MPH (48 km/h) at 1.0g deceleration, with a minimum pressure rise rate equivalent to a pedal force rise rate of 2500 lbs/sec. (1.11×10^4 N/sec.), and from a 150°F (66°C) IBT.

16. Spike Effectiveness Check

60 MPH (97 km/h) - Make one stop each at 0.3g, 0.5g, 0.7g, 0.8g, 0.9g and 1.0g deceleration.

17. Data Reduction

Symbols and abbreviations

g = acceleration of gravity

= 32.2 ft./sec.^{2} = 980.7 cm/sec^2

IBT = initial brake temperature

GVWR = gross vehicle weight

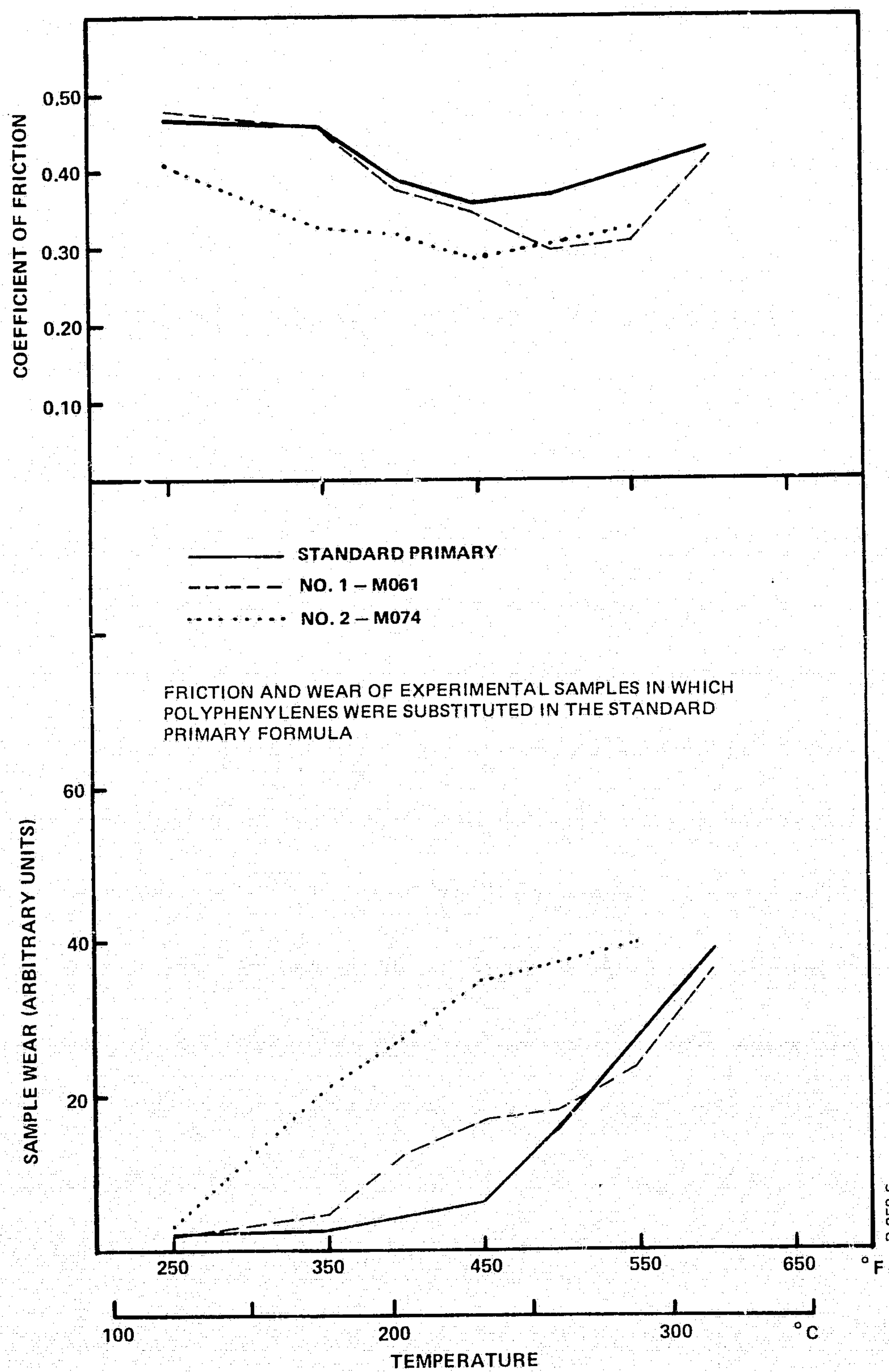
APPENDIX F

SUBSTITUTION OF EXPERIMENTAL INGREDIENTS IN THE STANDARD PRIMARY LINING

Evaluation of the experimental ingredients in the primary lining is shown in Figure F-1 for the polyimide binder and Figure F-2 for polyphenylene. Recall that replacement of asbestos with potassium titanate fiber could not be accomplished because the formula was not processable.

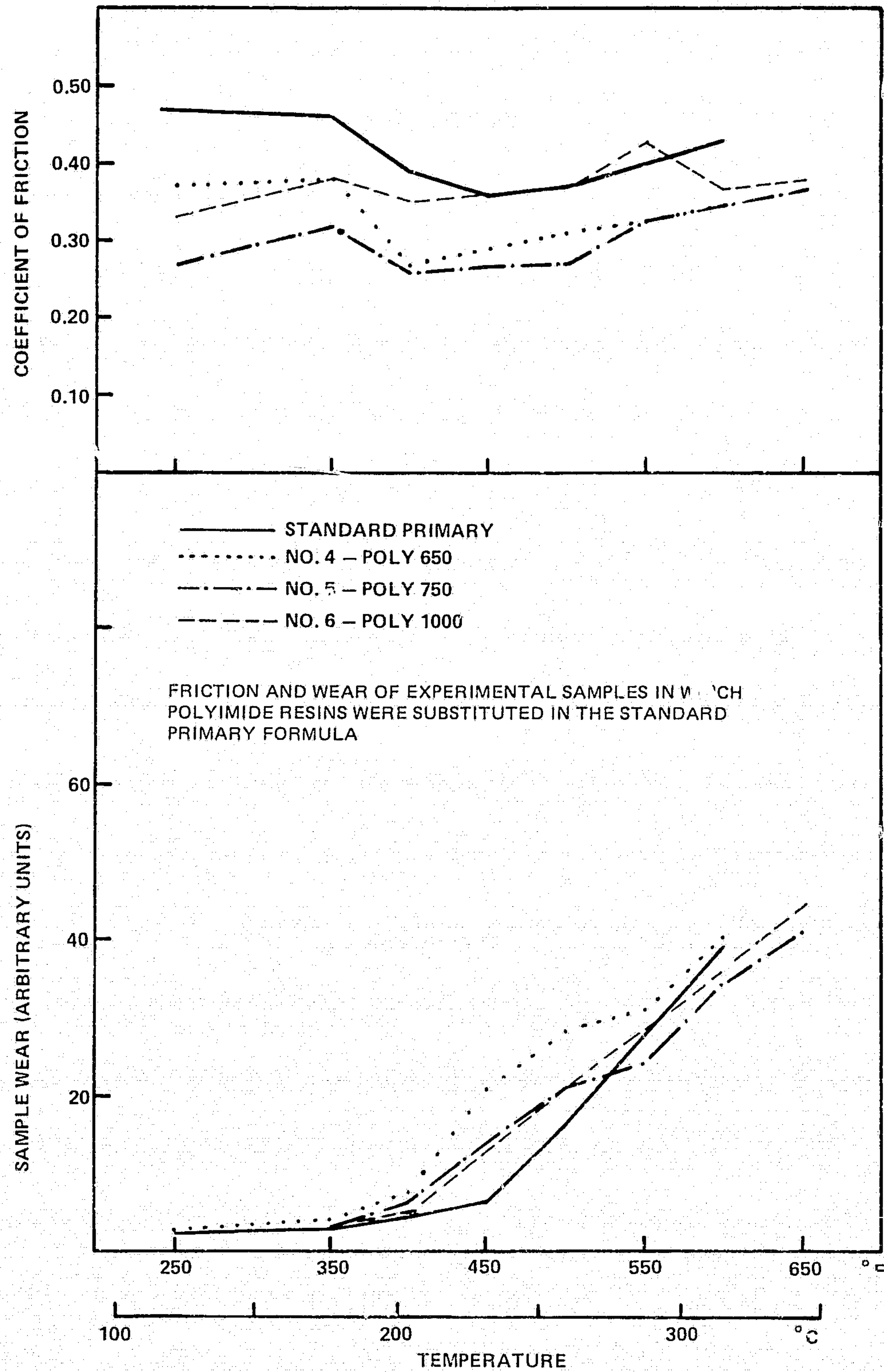
Of the two resins, the sample with Maleimide 061 performs considerably better than that with Maleimide 074, although the former suffers loss of friction between 450 and 600°F (232-316°C), relative to the standard. As for the polyphenylenes, a severe loss in friction is observed for all three types up to 450°F (232°C), where the sample with the 1000°C cure has friction comparable to the standard, up to 600°F (316°C). The wear of the two samples with the higher curves is comparable to that of the standard, but cannot be considered superior.

On the basis of these results, and because of the particular requirements of primary linings - they must have high friction but can tolerate moderately high wear - it was decided to concentrate on improvement of the secondary lining during the next phase of the screening. If an improved secondary lining could be formulated, it was thought possible to find a compatible primary lining from among existing formulas.



COEFFICIENT OF FRICTION
0.50
0.40
0.30
0.20
0.10
STANDARD PRIMARY
NO. 1 – M061
NO. 2 – M074
FRICTION AND WEAR OF EXPERIMENTAL SAMPLES IN WHICH POLYPHENYLENES WERE SUBSTITUTED IN THE STANDARD PRIMARY FORMULA
SAMPLE WEAR (ARBITRARY UNITS)
60
40
20
R-258-6
250
350
450
550
650
°F
100
200
300
°C
TEMPERATURE

Figure F-1



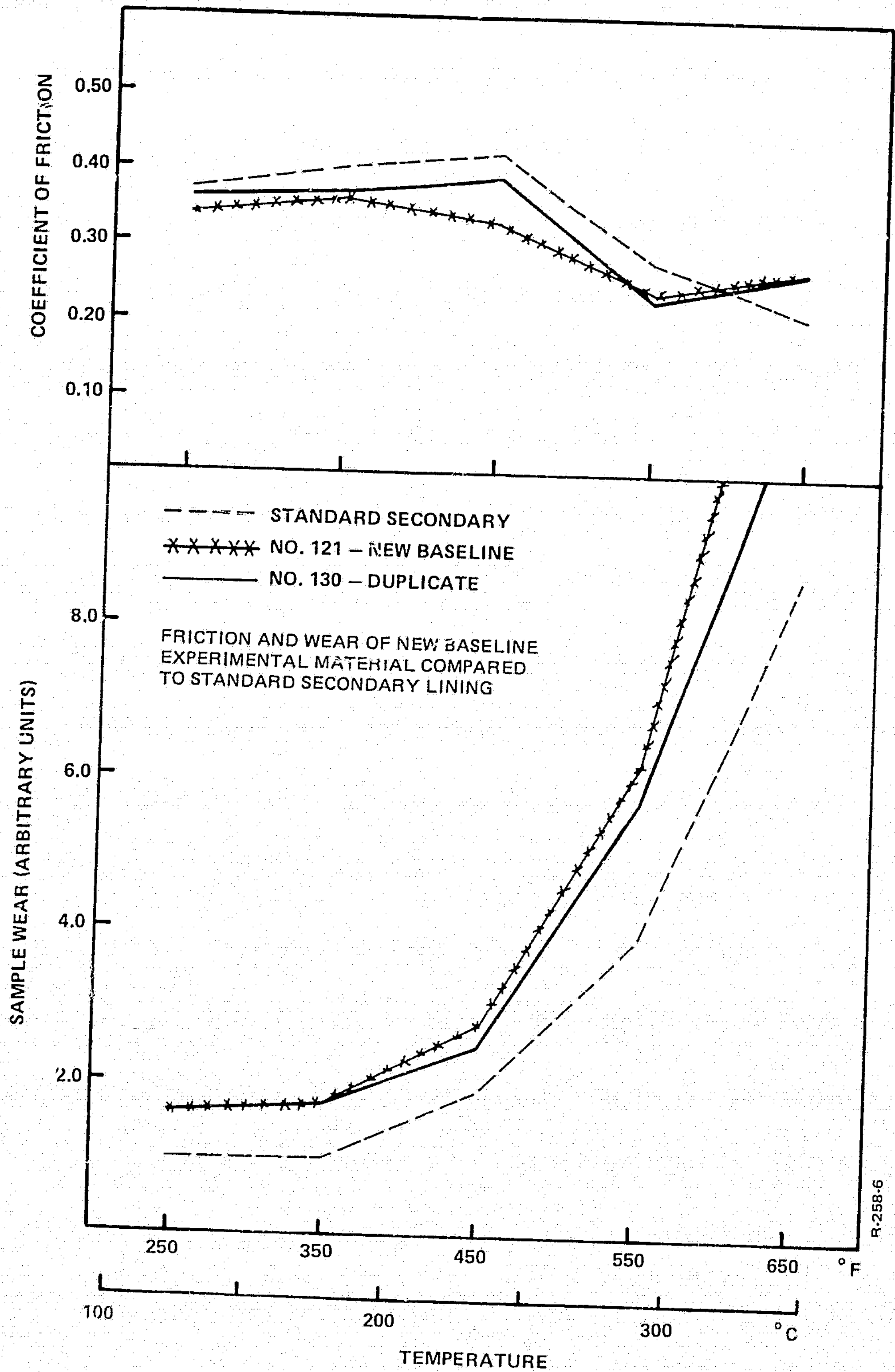
0.50
0.40
0.30
0.20
0.10
COEFFICIENT OF FRICTION
STANDARD PRIMARY
NO. 4 – POLY 650
NO. 5 – POLY 750
NO. 6 – POLY 1000
FRICTION AND WEAR OF EXPERIMENTAL SAMPLES IN W 'CH
POLYIMIDE RESINS WERE SUBSTITUTED IN THE STANDARD
PRIMARY FORMULA
60
40
20
SAMPLE WEAR (ARBITRARY UNITS)
R-258-6
250
350
450
550
650
°F
100
200
300
°C
TEMPERATURE

Figure F-2

APPENDIX G

FRICTION AND WEAR VS. TEMPERATURE - NEW BASELINE MATERIAL

Results of sample dynamometer tests are presented in Figures G-1 to G-6. In Figure G-1, the new baseline is compared to the commercial standard. It is somewhat on the high side in wear, but is within the observed variation in friction (compare Figure 4-2). The effect of increasing the resin without adding potassium titanate fiber is illustrated in Figure G-2. All three materials behave quite similarly, with better wear than the standard, but with a definite indication of loss of high temperature friction with 60% added resin. The rest of the graphs through Figure G-6 show definite trends toward improved wear resistance as the resin is increased up to 60%, as well as an improvement in high temperature friction as up to 60% of the asbestos is replaced by potassium titanate fiber.



COEFFICIENT OF FRICTION
0.50
0.40
0.30
0.20
0.10
STANDARD SECONDARY
NO. 121 – NEW BASELINE
NO. 130 – DUPLICATE
FRICTION AND WEAR OF NEW BASELINE EXPERIMENTAL MATERIAL COMPARED TO STANDARD SECONDARY LINING
SAMPLE WEAR (ARBITRARY UNITS)
8.0
6.0
4.0
2.0
250
350
450
550
650
°F
100
200
300
°C
TEMPERATURE
R-258-6

Figure G-1

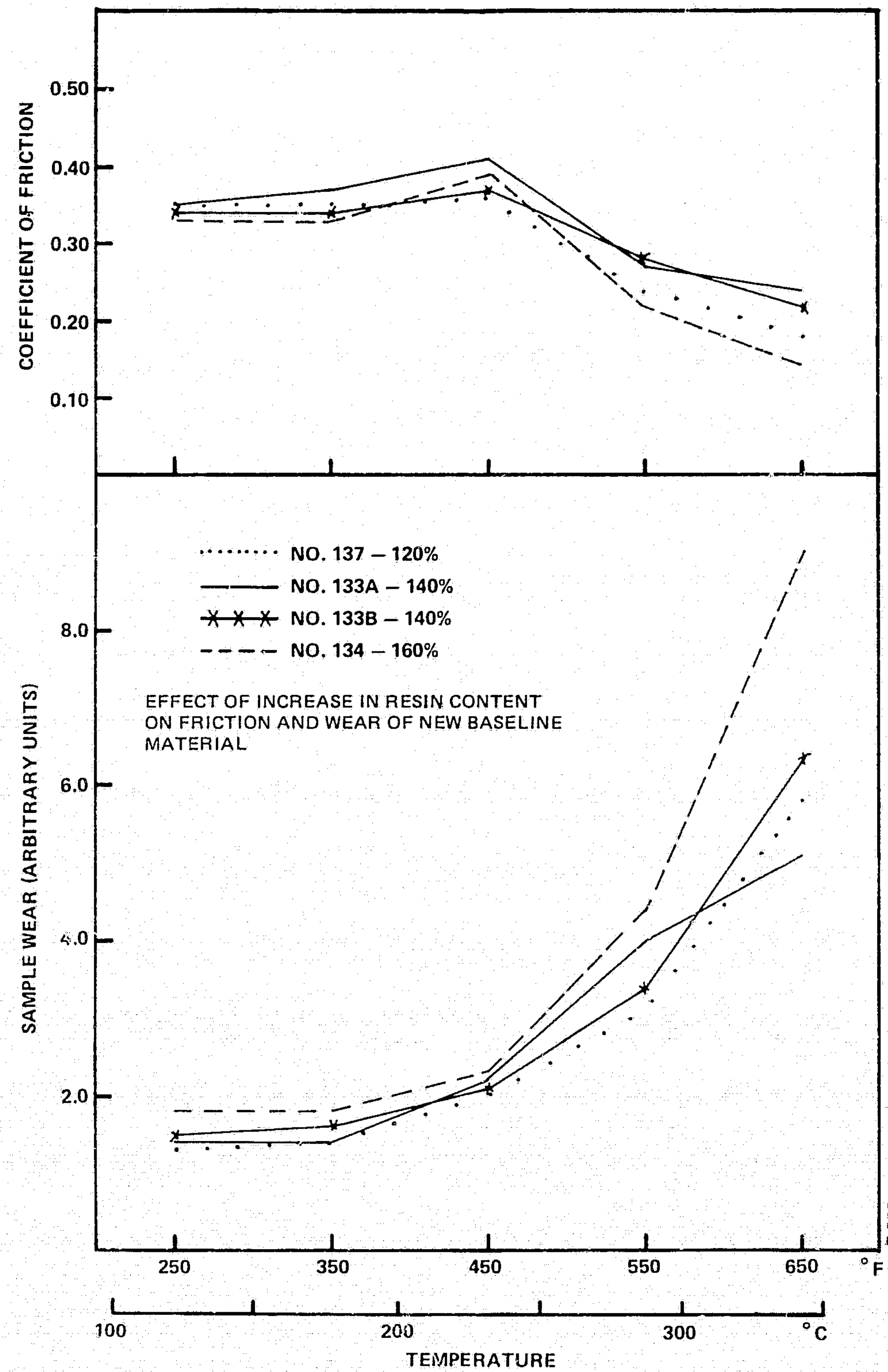

COEFFICIENT OF FRICTION
0.50
0.40
0.30
0.20
0.10
SAMPLE WEAR (ARBITRARY UNITS)
8.0
6.0
4.0
2.0
NO. 137 – 120%
NO. 133A – 140%
NO. 133B – 140%
NO. 134 – 160%
EFFECT OF INCREASE IN RESIN CONTENT
ON FRICTION AND WEAR OF NEW BASELINE
MATERIAL
R-258-6
250
350
450
550
650
°F
100
200
300
°C
TEMPERATURE

Figure G-2

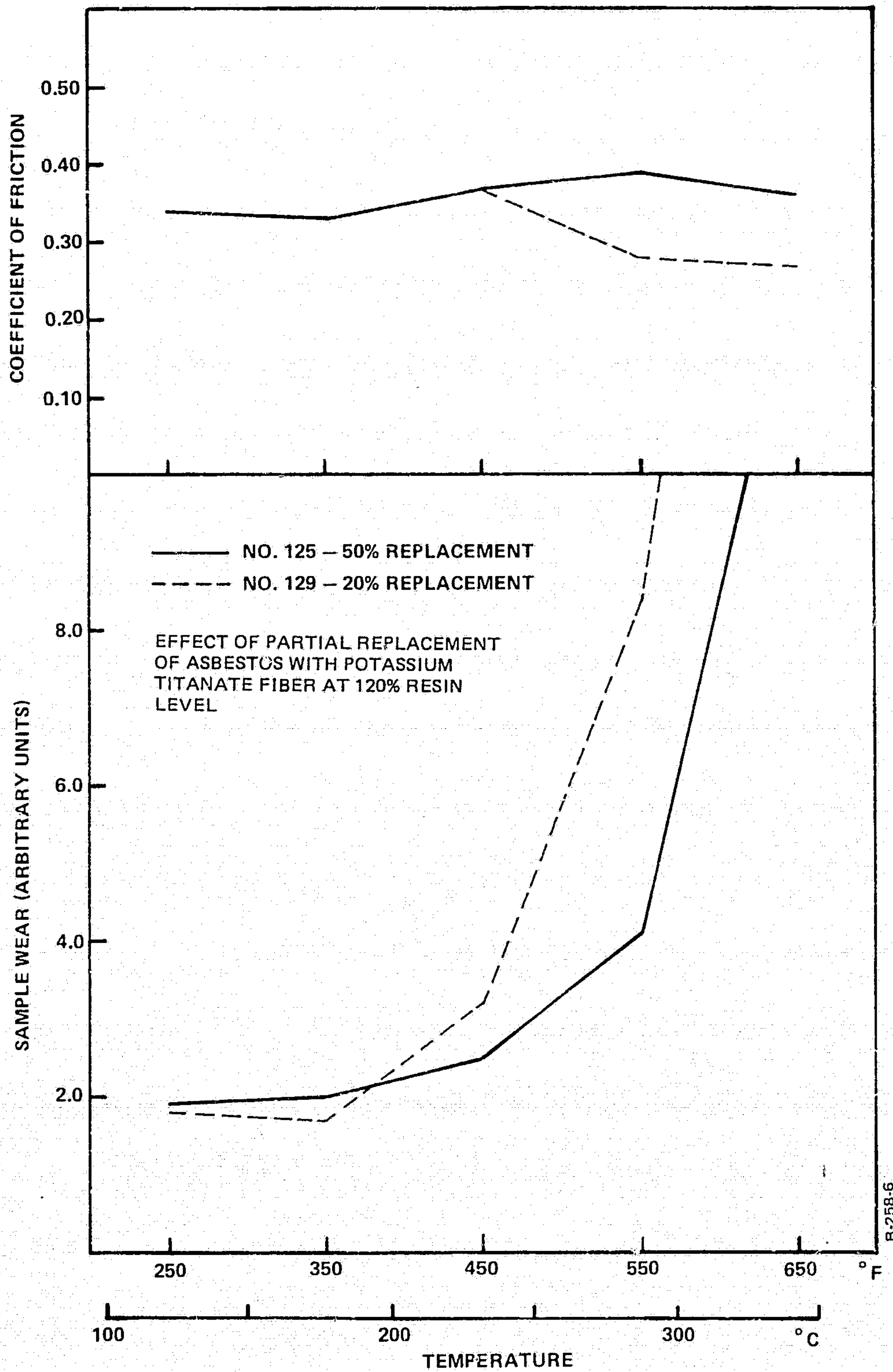
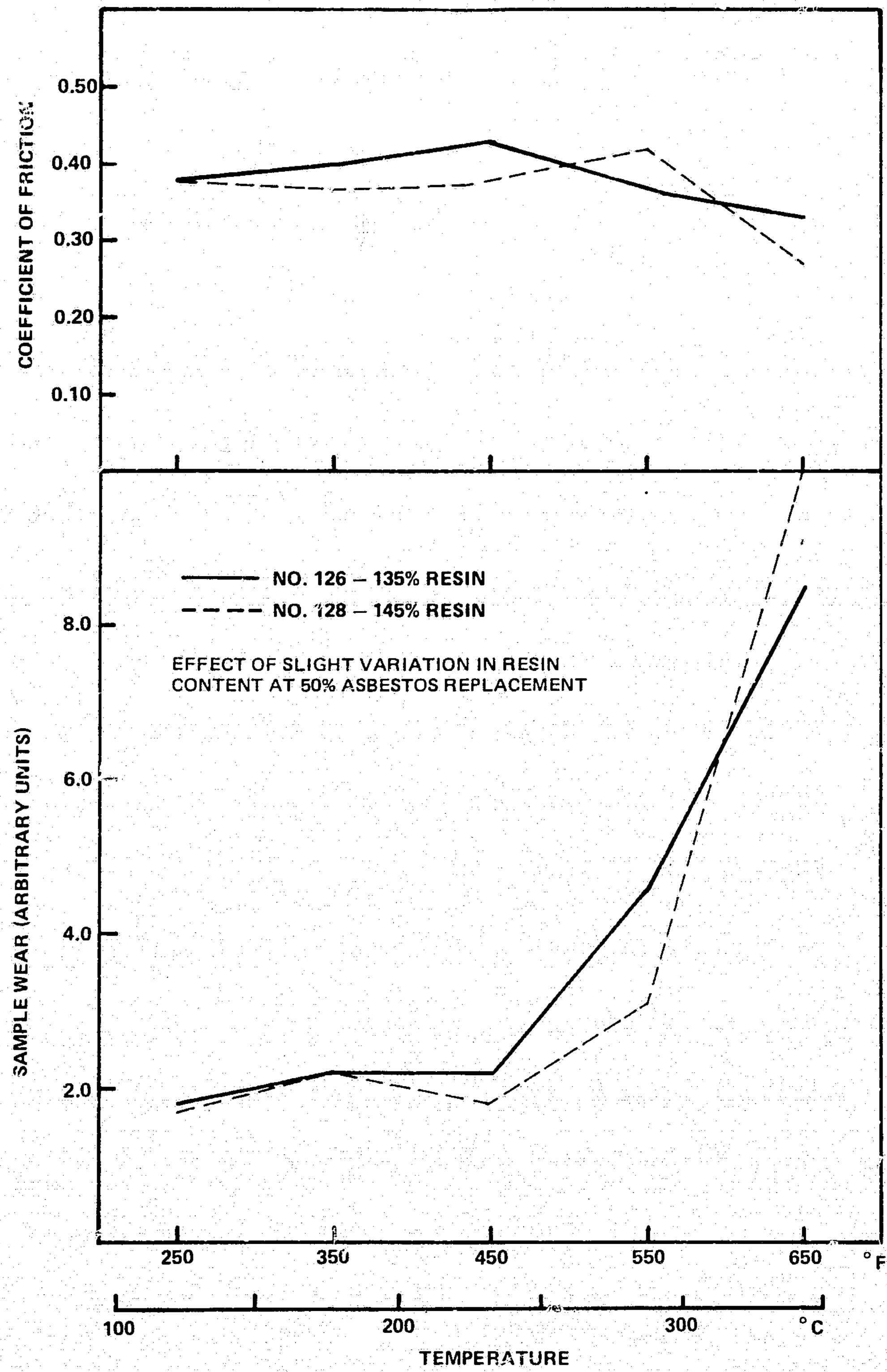

COEFFICIENT OF FRICTION
0.50
0.40
0.30
0.20
0.10
NO. 125 – 50% REPLACEMENT
NO. 129 – 20% REPLACEMENT
EFFECT OF PARTIAL REPLACEMENT
OF ASBESTOS WITH POTASSIUM
TITANATE FIBER AT 120% RESIN
LEVEL
SAMPLE WEAR (ARBITRARY UNITS)
8.0
6.0
4.0
2.0
250
350
450
550
650
°F
100
200
300
°C
TEMPERATURE
R-258-6

Figure G-3



COEFFICIENT OF FRICTION
0.50
0.40
0.30
0.20
0.10
NO. 126 – 135% RESIN
NO. 128 – 145% RESIN
EFFECT OF SLIGHT VARIATION IN RESIN CONTENT AT 50% ASBESTOS REPLACEMENT
SAMPLE WEAR (ARBITRARY UNITS)
8.0
6.0
4.0
2.0
R-258-6
250
350
450
550
650
°F
100
200
300
°C
TEMPERATURE

Figure G-4

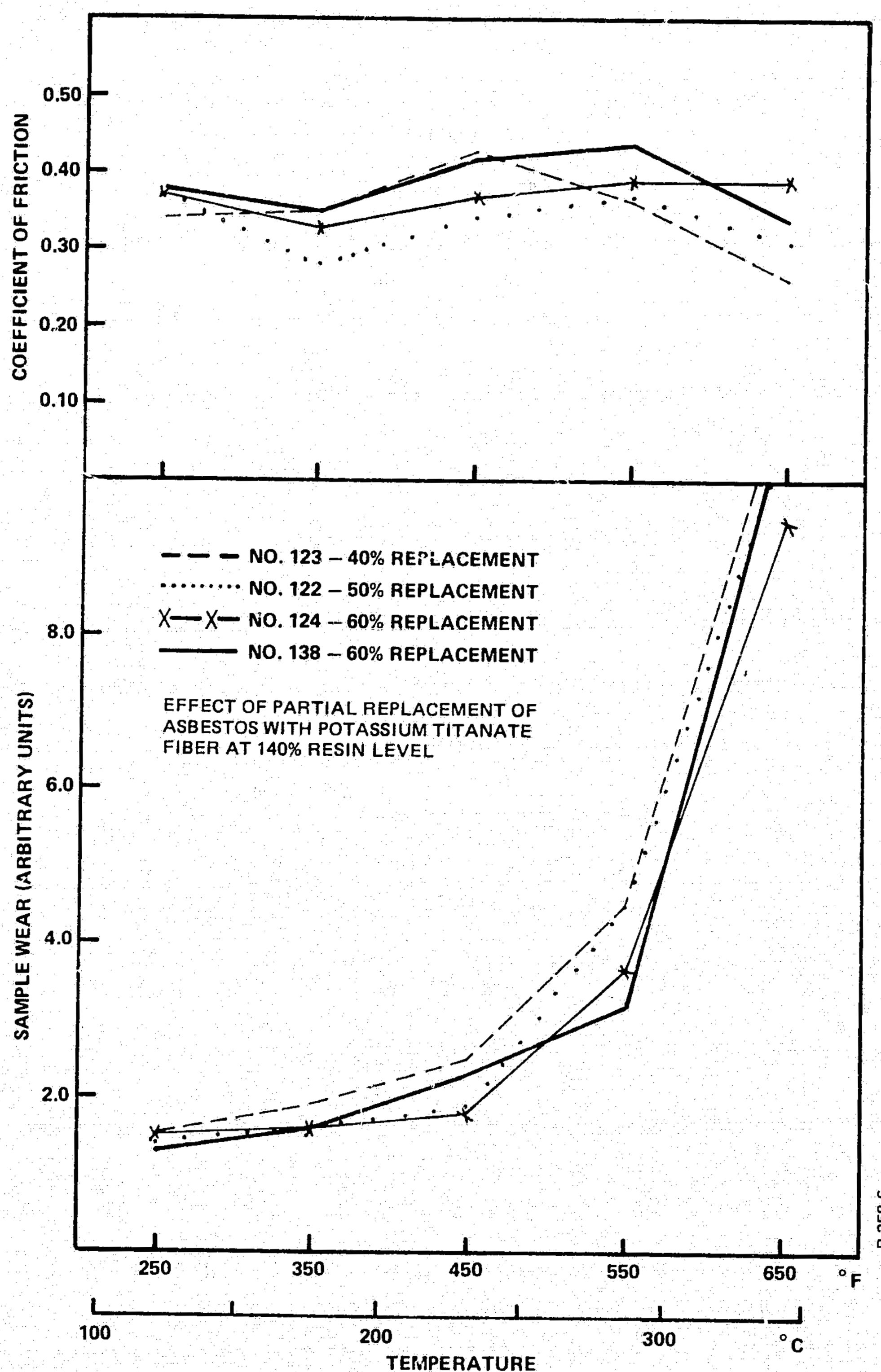
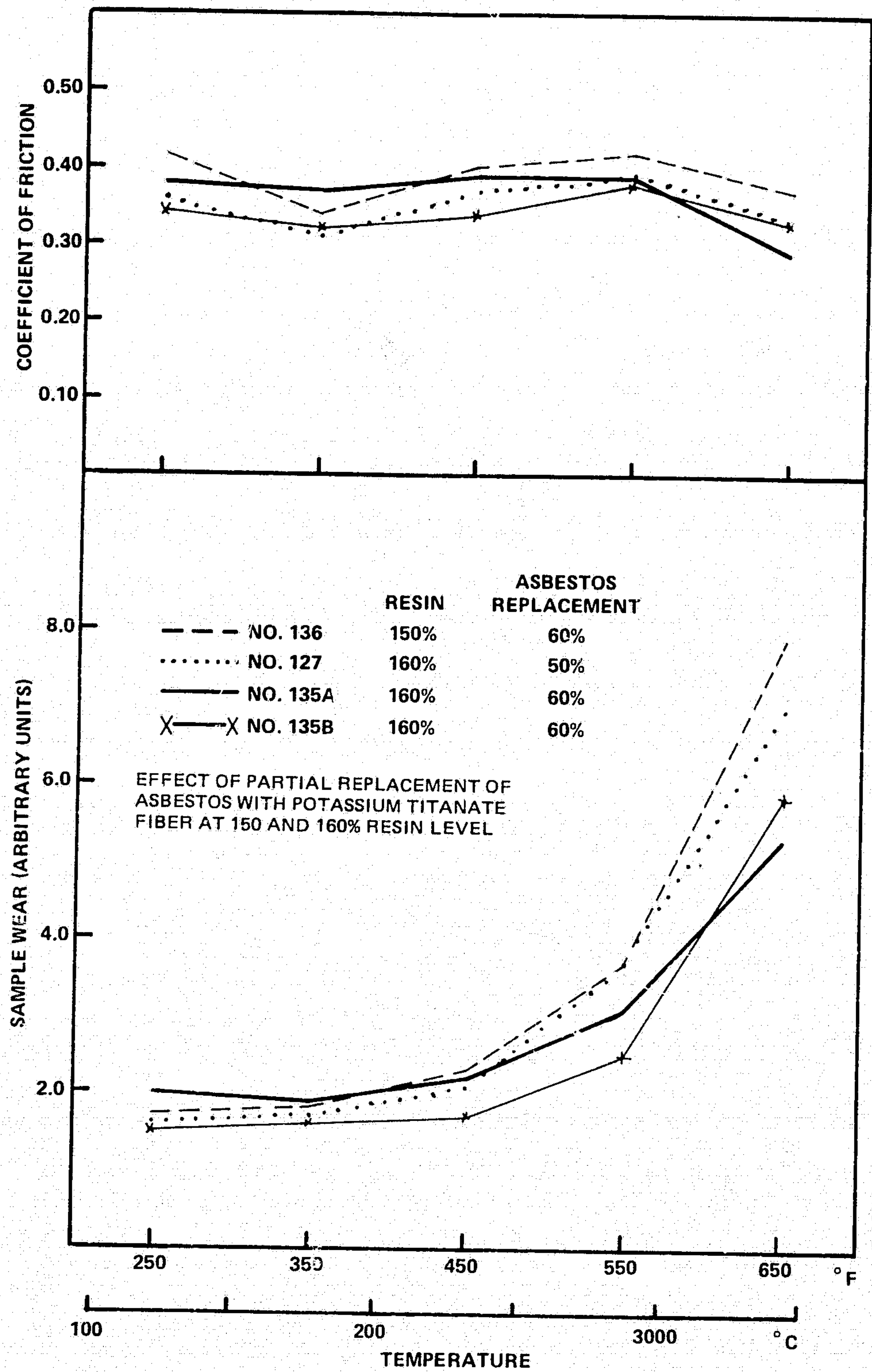

COEFFICIENT OF FRICTION
0.50
0.40
0.30
0.20
0.10
NO. 123 – 40% REPLACEMENT
NO. 122 – 50% REPLACEMENT
NO. 124 – 60% REPLACEMENT
NO. 138 – 60% REPLACEMENT
EFFECT OF PARTIAL REPLACEMENT OF ASBESTOS WITH POTASSIUM TITANATE FIBER AT 140% RESIN LEVEL
SAMPLE WEAR (ARBITRARY UNITS)
8.0
6.0
4.0
2.0
R-258-6
250
350
450
550
650
°F
100
200
300
°C
TEMPERATURE

Figure G-5



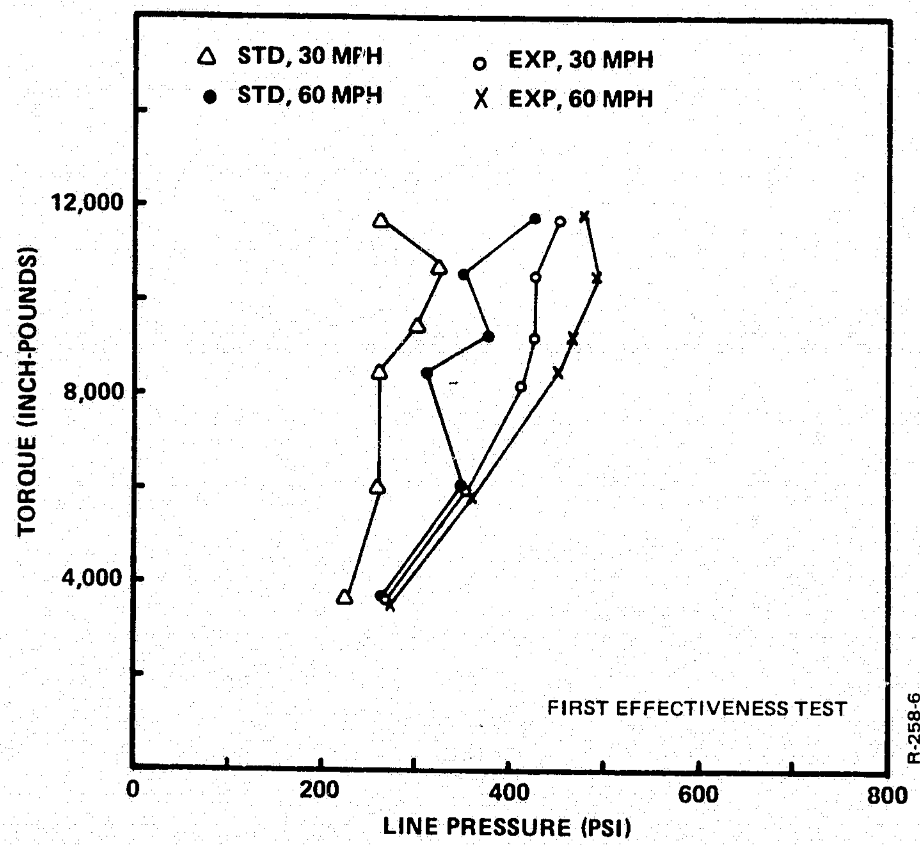
0.50
0.40
0.30
0.20
0.10
COEFFICIENT OF FRICTION
8.0
6.0
4.0
2.0
SAMPLE WEAR (ARBITRARY UNITS)
RESIN
ASBESTOS REPLACEMENT
NO. 136 150% 60%
NO. 127 160% 50%
NO. 135A 160% 60%
NO. 135B 160% 60%
EFFECT OF PARTIAL REPLACEMENT OF ASBESTOS WITH POTASSIUM TITANATE FIBER AT 150 AND 160% RESIN LEVEL
250
350
450
550
650
°F
100
200
3000
°C
TEMPERATURE
R-258-6

Figure G-6

APPENDIX H

PLOTS OF EFFECTIVENESS TESTS PERFORMED ON FULL-SCALE INERTIAL DYNAMOMETER FOR STANDARD AND EXPERIMENTAL LININGS

These plots were made from the primary data obtained in the FMVSS 105-75 simulation tests. They were found to be somewhat more difficult to interpret than the gain plots discussed in Section 4.2.6.



STD, 30 MPH
EXP, 30 MPH
STD, 60 MPH
EXP, 60 MPH
12,000
8,000
4,000
TORQUE (INCH-POUNDS)
FIRST EFFECTIVENESS TEST
R-258-6
0
200
400
600
800
LINE PRESSURE (PSI)

Figure H-1

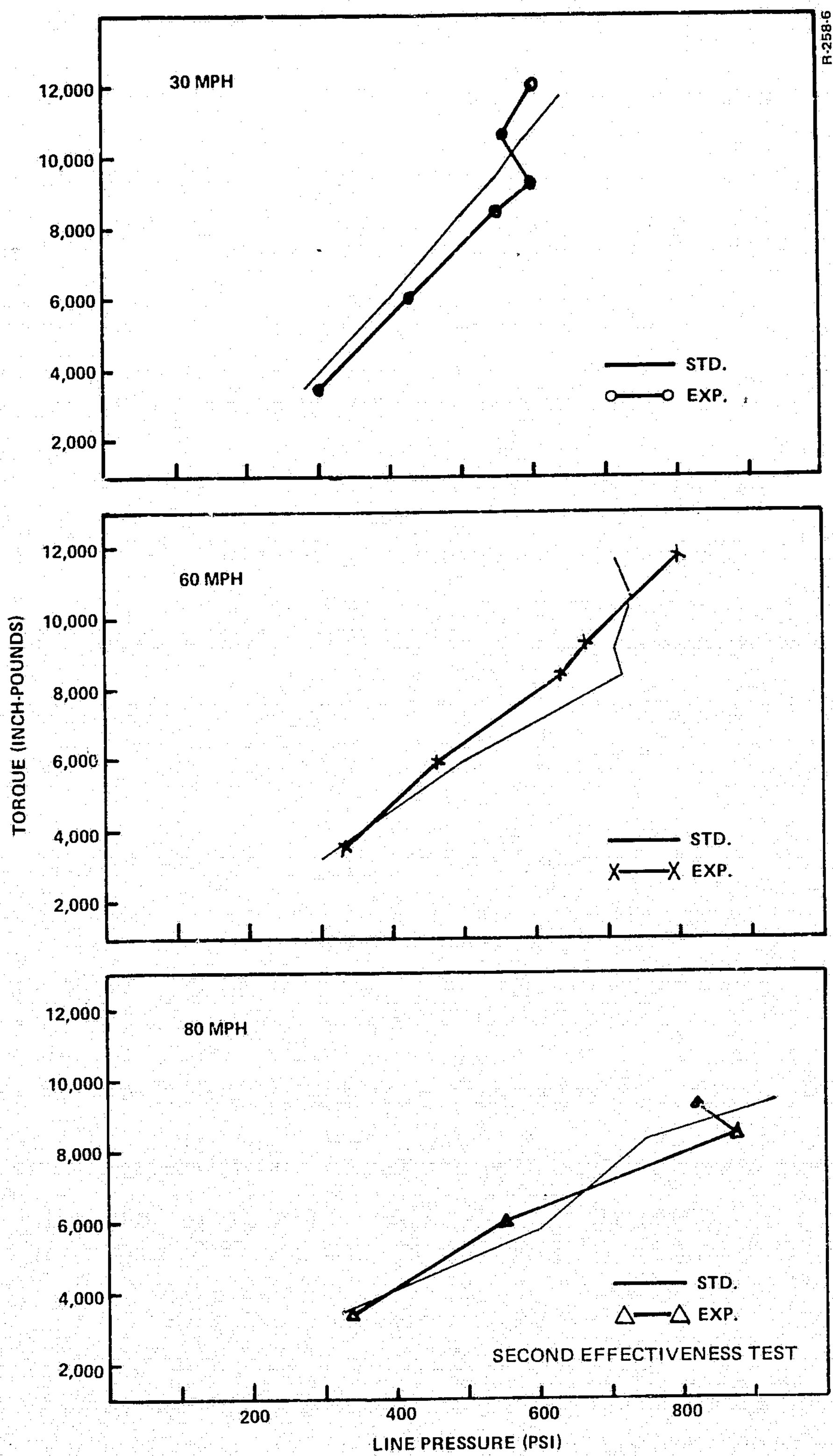

R-258-6
30 MPH
12,000
10,000
8,000
6,000
4,000
2,000
STD.
EXP.
60 MPH
TORQUE (INCH-POUNDS)
STD.
EXP.
80 MPH
STD.
EXP.
SECOND EFFECTIVENESS TEST
200
400
600
800
LINE PRESSURE (PSI)

Figure H-2

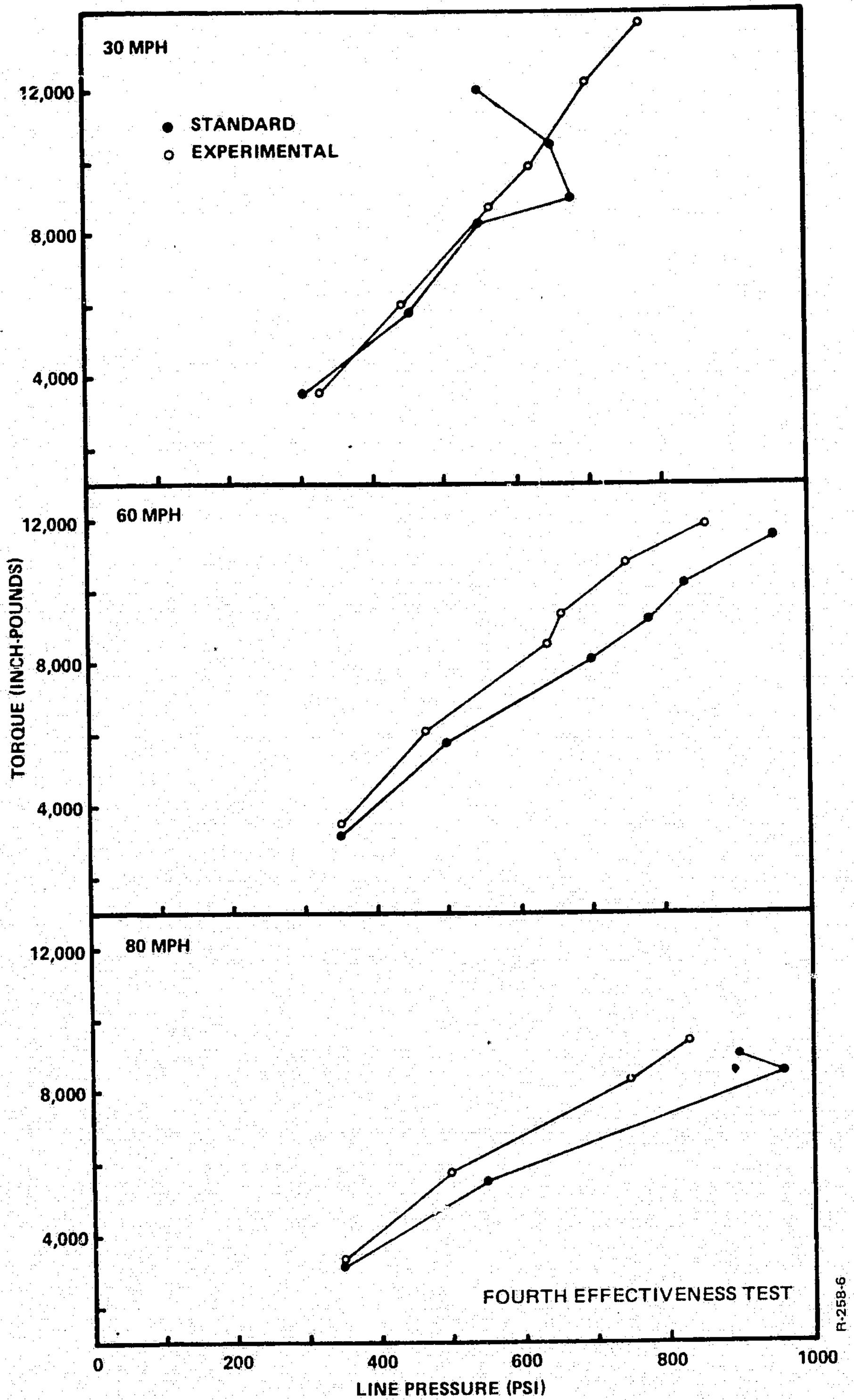

30 MPH
STANDARD
EXPERIMENTAL
60 MPH
80 MPH
FOURTH EFFECTIVENESS TEST
R-258-6
TORQUE (INCH-POUNDS)
12,000
8,000
4,000
0
200
400
600
800
1000
LINE PRESSURE (PSI)

Figure H-3

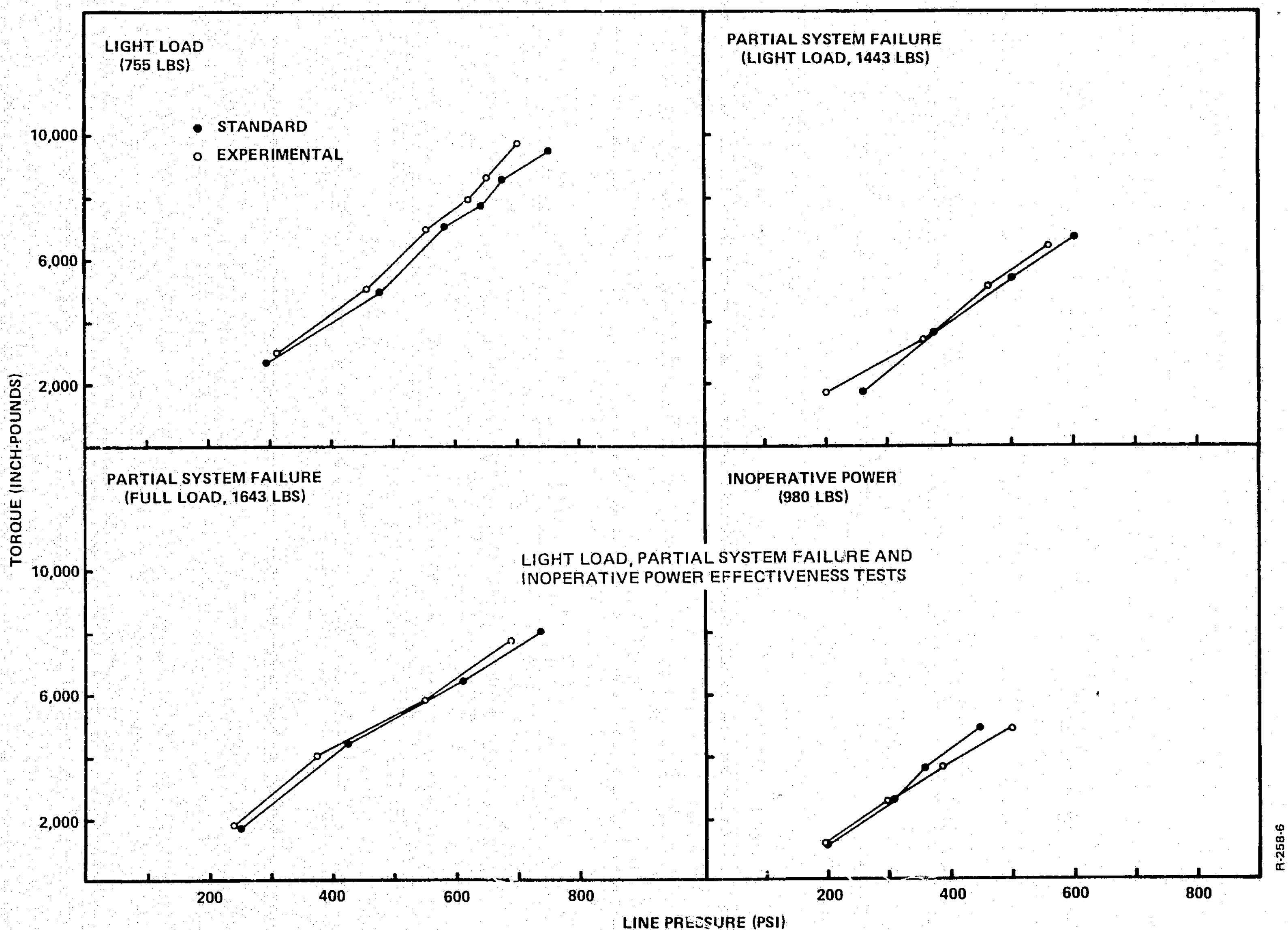

LIGHT LOAD
(755 LBS)
STANDARD
EXPERIMENTAL
PARTIAL SYSTEM FAILURE
(LIGHT LOAD, 1443 LBS)
PARTIAL SYSTEM FAILURE
(FULL LOAD, 1643 LBS)
INOPERATIVE POWER
(980 LBS)
LIGHT LOAD, PARTIAL SYSTEM FAILURE AND INOPERATIVE POWER EFFECTIVENESS TESTS
TORQUE (INCH-POUNDS)
10,000
6,000
2,000
200
400
600
800
LINE PRESSURE (PSI)
R-258-6

Figure H-4

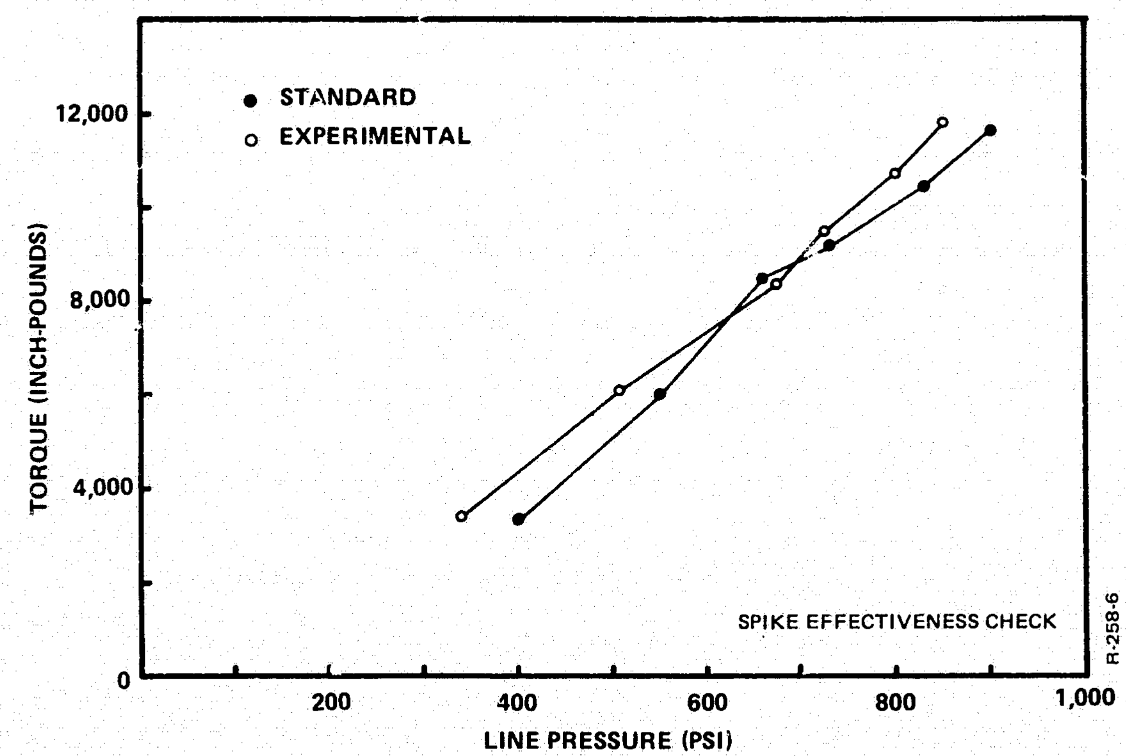

STANDARD
EXPERIMENTAL
12,000
8,000
4,000
0
TORQUE (INCH-POUNDS)
200
400
600
800
1,000
LINE PRESSURE (PSI)
SPIKE EFFECTIVENESS CHECK
R-258-6

Figure H-5

APPENDIX I

RESULTS OF FULL-SCALE DYNAMOMETER WEAR VS. TEMPERATURE TEST FOR SEGMENTED LINING AND FOR EXPERIMENTAL FACTORY-MADE LINING

Tables I-1 and I-2 are the results of wear measurements from which the plots in Figures 4-32 to 4-36 were made.

In addition to the test described in Section 4.2.7, another set of Wear vs. Temperature tests actually was performed, in which the experimental secondary lining which had been fabricated at the factory, described in Appendix C, was used. Results are included in Table I-3 below, together with plots of line pressure and wear as a function of temperature. The line pressure curves (Figure I-1) are again very similar to each other and to those of the test described in Section 4.2.7, though the average line pressures are 50 to 100 psi (3.4 to 6.9 x 10^6 N/m^2) higher here. The average wear curves (Figure I-2), however, are somewhat enigmatic, particularly that of the primary used in combination with the standard secondary. Interpretation is therefore not clear. Nevertheless the general trends described in Section 4.2.7 still seem to hold with the standard secondary lining having somewhat better wear below 450°F (232°C), and the experimental superior above that temperature. The combination of unknown factors associated with the manufacture and test results interpretation have led us, therefore, to include these results for the sake of completeness, but argue against calling this test a duplicate of the one described in Section 4.2.7.

Table I-1
WEAR VS. TEMPERATURE - STANDARD LINING

	WEAR	BURNISH	TEMPERATURE 250 (121)	 350 (177)	 450 (232)	 550 (288)	 250 (121)	 (°F) (°C)
PRIMARY	Average Thickness	0.9	1.3	2.3	7.3	16.0	0.5	
	Cumulative Average Thickness	0.9	2.2	4.5	11.8	27.8	28.3	
	Maximum Thickness	2	2	3	12	21	1	
	Weight	0.1	0.5	1.4	4.1	10.6	0.1	
	Cumulative Weight	0.1	0.6	2.0	6.1	16.7	16.8	
SECONDARY	Average Thickness	1.9	1.7	2.9	10.7	24.9	2.9	
	Cumulative Average Thickness	1.9	3.6	6.5	17.2	42.1	45.0	
	Maximum Thickness	4	3	5	18	35	4	
	Weight	0.3	0.8	1.5	8.5	19.0	1.7	
	Cumulative Weight	0.3	1.1	2.6	11.1	30.1	31.8	

Table I-2
WEAR VS. TEMPERATURE - EXPERIMENTAL LINING (SEGMENTED)

	WEAR	BURNISH	TEMPERATURE 250 (121)	350 (177)	450 (232)	550 (288)	250 (121)	(^{o}F) (^{o}C)
PRIMARY	Average Thickness	1.7	1.0	3.2	6.5	9.5	0.4	
	Cumulative Average Thickness	1.7	2.7	5.9	12.4	21.9	22.3	
	Maximum Thickness	3	2	6	9	14	3	
	Weight	0.7	0.0	1.7	4.0	6.9	0.1	
	Cumulative Weight	0.7	0.7	2.4	6.4	13.3	13.4	
SECONDARY	Average Thickness	3.1	1.3	3.8	11.9	18.5	3.4	
	Cumulative Average Thickness	3.1	4.4	8.2	20.1	38.6	42.0	
	Maximum Thickness	6	2	7	18	26	6	
	Weight	1.8	0.4	2.1	9.4	16.8	2.1	
	Cumulative Weight	1.8	2.2	4.3	13.7	30.5	32.6	

Table I-3

WEAR VS. TEMPERATURE
STANDARD LININGS (FACTORY-MADE)

	WEAR	BURNISH	TEMPERATURE 250 (121)	350 (177)	450 (232)	550 (288)	250 (121)	(°F) (°C)
PRIMARY	Average Thickness	0.7	2.6	9.9	29.9	22.0	1.9	
	Cumulative Average Thickness	0.7	3.3	13.2	43.1	65.1	67.0	
	Maximum Thickness	2	5	17	47	38	6	
	Weight	0.8	4.4	6.5	16.3	14.7	0.7	
	Cumulative Weight	0.8	5.2	11.7	28.0	42.7	43.4	
SECONDARY	Average Thickness	1.3	1.0	3.3	7.8	36.9	5.9	
	Cumulative Average Thickness	1.3	2.3	5.6	13.4	50.3	56.2	
	Maximum Thickness	3	2	7	12	81	10	
	Weight	0.3	3.5	2.7	2.5	30.9	3.2	
	Cumulative Weight	0.3	3.8	6.5	9.0	39.9	43.1	

EXPERIMENTAL LININGS (FACTORY-MADE)

	WEAR	BURNISH	250 (121)	350 (177)	450 (232)	550 (288)	250 (121)
PRIMARY	Average Thickness	0.8	0.7	2.0	9.1	10.0	3.2
	Cumulative Average Thickness	0.8	1.5	3.5	12.6	22.6	25.8
	Maximum Thickness	3	2	4	16	17	6
	Weight	0.1	0.5	1.3	8.7	7.1	1.0
	Cumulative Weight	0.1	0.6	1.9	10.6	17.7	18.7
SECONDARY	Average Thickness	2.2	1.4	5.7	21.3	29.4	7.5
	Cumulative Average Thickness	2.2	3.6	9.3	30.6	60.0	67.5
	Maximum Thickness	5	3	10	33	44	8
	Weight	1.1	0.9	4.3	19.1	24.6	3.5
	Cumulative Weight	1.1	2.0	6.3	25.4	50.0	53.5

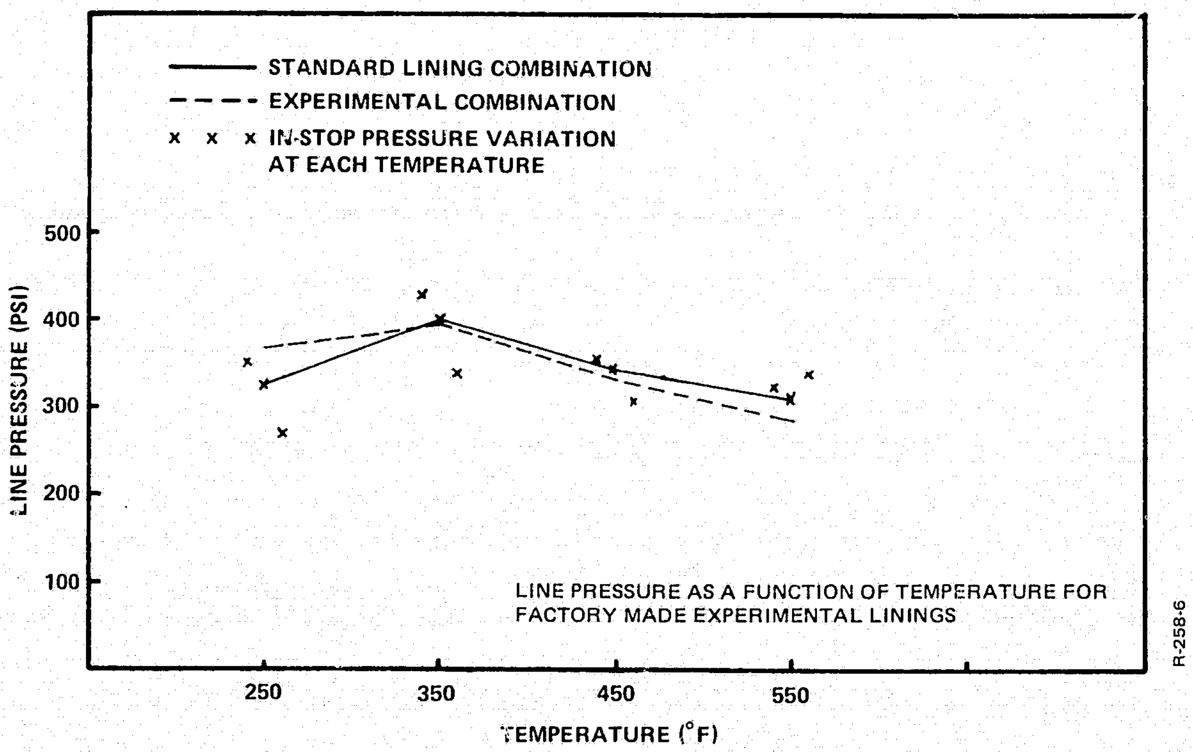

STANDARD LINING COMBINATION
EXPERIMENTAL COMBINATION
IN-STOP PRESSURE VARIATION AT EACH TEMPERATURE
500
400
300
200
100
LINE PRESSURE (PSI)
LINE PRESSURE AS A FUNCTION OF TEMPERATURE FOR FACTORY MADE EXPERIMENTAL LININGS
R-258-6
250
350
450
550
TEMPERATURE (°F)

Figure I-1

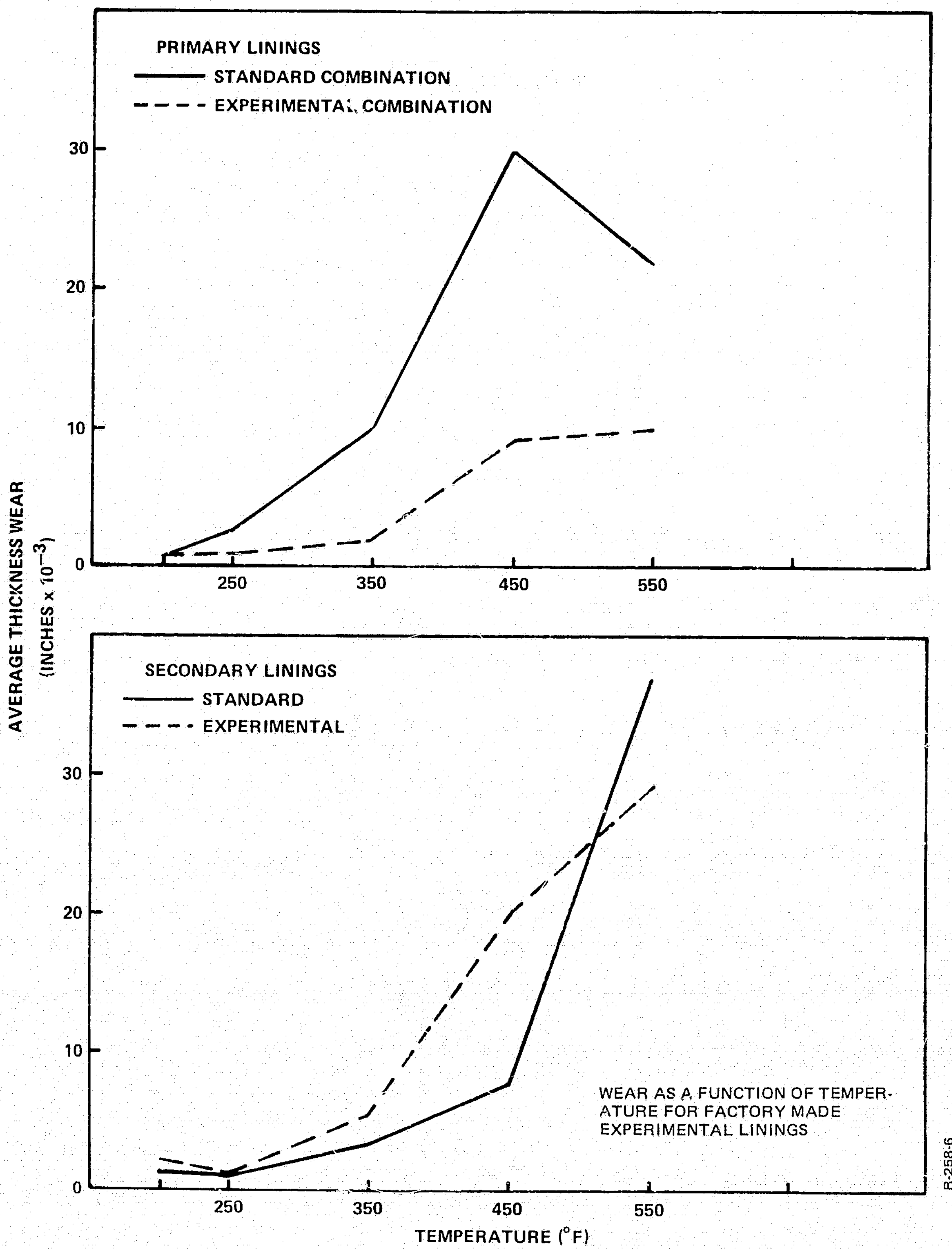

PRIMARY LININGS
STANDARD COMBINATION
EXPERIMENTAL COMBINATION
30
20
10
0
250
350
450
550
AVERAGE THICKNESS WEAR
(INCHES x 10^-3)
SECONDARY LININGS
STANDARD
EXPERIMENTAL
30
20
10
0
250
350
450
550
TEMPERATURE (°F)
WEAR AS A FUNCTION OF TEMPERATURE FOR FACTORY MADE EXPERIMENTAL LININGS
R-258-6

Figure I-2