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Compositions, Functions, and Testing of Friction Brake Materials and Their Additives

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Metals and Ceramics Division

Compositions, Functions, and Testing of
Friction Brake Materials and Their Additives

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Preface

This report was prepared as an information resource for the development of advanced brake materials for heavy vehicles. This research is sponsored by the U.S. Department of Energy, Office of Transportation Technologies. It is part of an initiative aimed at reducing the running resistance while improving the safety of on-highway heavy trucks. Selected information on aircraft brake materials was included for comparison purposes. Data in this report have been compiled from a variety of commercial and non-commercial sources. The validity of the data in this compilation is the responsibility of the originators, and information contained herein should be used mainly as a guide and for the sake of comparison. Normally, ISO units are used in ORNL reports, but in this case, the units have been reported in the measurement systems that were used in the original references. They reflect the diversity in current preferences for units of measure in the commercial brakes industry.

In addition to Dr. Sidney Diamond, DOE, Office of Transportation Materials, and Dr. Phil Sklad, Metals and Ceramics Division, ORNL, I would like to thank those who reviewed the drafts of this document and made useful suggestions for improvement. In particular, I'd like to thank Rena Hecht Basch, Dr., Sr. Technical Specialist, Ford Research Laboratory, Safety Research and Development Department, for her practical comments.

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1.0 Introduction

The purpose of friction brakes is to decelerate a vehicle by transforming the kinetic energy of the vehicle to heat, via friction, and dissipating that heat to the surroundings. As a part of a commercial truck or automobile, brake materials have additional requirements, like resistance to corrosion, light weight, long life, low noise, stable friction, low wear rate, and acceptable cost versus performance. There are two common types of friction brakes – drum/shoe brakes and disk/pad brakes. The design of the brakes affects heat flow, reliability, noise characteristics, and ease of maintenance.

History records the use of many kinds of materials for brakes ('friction materials'). For example, wagon brakes used wood and leather. In fact, many current brake materials still contain organic-based materials, like polymers and plant fibers. Emerging railroad technology in the 1800's required brake materials to perform under high loads and speeds. Friction experiments were conducted with iron brake shoes in the 1870's (see, for example, Fig. 1).

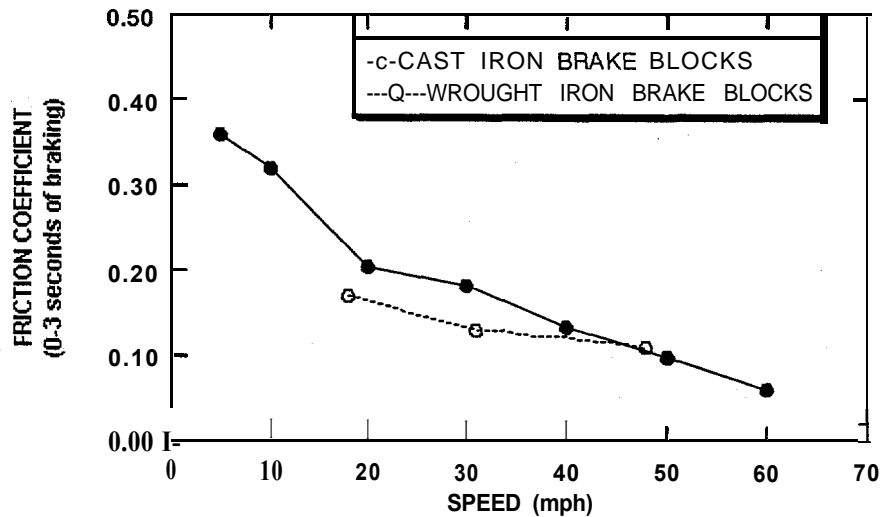


Figure 1. Test results from the work of Captain D. Galton (1878) using a special railroad wheel brake simulator and steel test wheels.

In order to achieve the properties required of brakes, most brake materials are not composed of single elements or compounds, but rather are composites of many materials. More than 2000 different materials and their variants are now used in commercial brake components [Weintraub (1998)].

According to Nicholson(1995), Herbert Froad is credited with inventing the first brake lining materials in 1897. It was a cotton-based material impregnated with bitumen solution and was used for wagon wheels as well as early automobiles. His invention led to the founding of the Ferodo Company, a firm that still supplies brake materials today. The first brake lining materials were woven, but in the 1920's these were replaced with molded materials that contained crysotile asbestos fibers, a plentiful mineral. Resin-bonded metallic linings were introduced in the 1950's, and by the 1960's so-called 'semi-mets' were developed. These contain a higher amount of metal additives. Table 1 from Nicholson (1995) lists some common brake materials.

Table 1. Historical Compositions of Automotive Friction Brake Materials

Material Description	Application(s)	Approximate Year
Cast iron on steel	railroad car brake blocks and tires	prior to 1870's
Hair or cotton belting (limited by charring at about 300° F)	wagon wheels and early automobiles	ca. 1897
Woven asbestos with brass and other wires for increased strength and performance	automobiles and trucks	ca. 1908
Molded linings with shorter chrysotile fibers, brass particles, and low-ash bituminous coal	“ “ “	ca. 1926
Dry-mix molded material to replace cast iron brake blocks that produced metallic dust that shorted electric train rails	London underground	ca. 1930
Flexible resin binders developed along with more complex formulations	brake drum linings	1930's
Resin-bonded metallic brake linings	industrial and aircraft applications	1950's
Glass fibers, mineral fibers, metal fibers, carbon and synthetic fibers to provide semi-metallics with higher performance than asbestos (beginning of safety issues with asbestos)	automotive and trucks	1960's
Non-asbestos (fiberglas) materials	brake drums on original equipment cars	1980's
Suggested use of carbon fibers	automotive brakes	1991

2.0 Purpose and Scope of this Report

The purpose of this report is to present a survey of commercial brake materials and additives, and to indicate their typical properties and functions, especially as regards their use in heavy trucks. Most truck pad and shoe materials described here were designed to wear against cast iron. Brake material test methods are also briefly described. This report does not address issues associated with the fabrication and manufacturing of brake materials. Since there are literally thousands of brake material additives, and their combinations are nearly limitless, it is impractical to list them all here. Rather, an attempt has been made to capture the primary constituents and their functions. An Appendix contains thermo-physical properties of some current and potential brake materials.

3.0 Brake Materials and Additive Functionality

Brake pad and shoe additives serve a variety of functions. Even a difference of a percent or two of additive concentration can affect performance, so composition control is important. This report lists additive materials by function. Information is referenced using the first author's name and year. If the information is from a handbook or commercial source, the reference will be listed by publisher or by company name. According to Nicholson (1995), it is conventional to list compositions of brake additives in volume percent, but not all authors do so.

One can group brake materials and additives based on their expected functions as follows:

Abrasives
 Friction Modifiers
 Fillers and Reinforcements
 Binder Materials

There is a little ambiguity in this categorization. Some of the additives can be placed into more than one category since they fulfill several functions. Consequently, there are some unavoidable overlaps in the tabular listings. In addition to the basic brake materials, some porosity (5-10% or more) is normally present.

To analyze the role of additives in friction and wear control, it is insufficient to simply know their composition, since their form, distribution, and particle size can affect friction and wear behavior. For example, rounded beads of a hard, abrasive material can have a different effect than angular grits on the formation and stability of the friction-induced surface films that control stopping behavior.

Asbestos has had a historical role as a brake additive. Section 3.5 is devoted to it.

3.1 Abrasives

Abrasives help maintain the cleanliness of mating surfaces and control the build-up of friction films. They also increase friction, particularly when initiating a stop (i.e., they increase “bite”).

Material	Description / Comment	Reference(s)
aluminum oxide	(1) hydrated form added as a polishing agent and for wear resistance, but can produce fade, (2) anhydrous form is still more abrasive, (3) fused is very hard and is the most abrasive form	Nicholson (1995)
iron oxides	hematite (Fe_2O_3) can act as a mild abrasive; magnetite (Fe_3O_4) also mildly abrasive	Nicholson (1995)
quartz	crushed mineral particles (SiO_2)	Eriksson (2000)
silica	may be natural or synthetically-produced (SiO_2)	Hooton (1969)
zirconium silicate	(ZrSiO_4)	Jang (2000)

3.2 Friction Producers / Modifiers

These materials lubricate, raise the friction, or react with oxygen to help control interfacial films.

Material	Description / Comment	Reference
antimony trisulfide	solid lubricant added to enhance frictional stability; lubricates $> 450^\circ\text{C}$; Sb_2S_3 is potentially toxic	Jang (2000), Nicholson (1995)
Brass	typ. 62% Cu – 38% Zn; sometimes used as chips or machine shop cutting swarf, said to improve wet friction and recovery, common additive	Nicholson (1995)

Material	Description / Comment	Reference
carbon (graphite)	cheap and widely-used; but there are many forms and sources, some of which can contain abrasive contaminants; burns in air at >700°C, friction level is affected by moisture and structure	Spurr (1972), Nicholson (1995)
ceramic "microspheres"	special product consisting of alumina-silica with minor iron or titanium oxides; size 10-350 μm, low-density filler said to reduce rotor wear and control friction; claim to also absorb rotor dust; 5-10% vol. loading typ.	PQ Corporation (1993)
copper	used as a powder to control heat transport but can cause excessive cast iron wear	Nicholson (1995)
"friction dust"	commonly consists of processed cashew resin, may have a rubber base; some additives used to reduce spontaneous combustion or help particle dispersion.	Nicholson (1995)
"friction powder"	may consist of Fe sponge, e.g. for semi-metallic brake pads; a number of different particle grades (sizes) are available depending on requirements for surface area, light-medium-heavy duty vehicle applications.	Hoegenaes (1990)
lead oxide	PbO has been used as a friction modifier, but has toxicity concerns	Nicholson (1995)
metals - fluxing compounds	Pb, Sb, Bi, Mo, as fluxing compounds serve as oxygen getters to stabilize friction-induced films and help to keep them from getting too thick	Hooton (1969)
metal oxides - various	magnetite (Fe ₃ O ₄) improves cold friction; ZnO lubricates but can cause drum polishing; Cr ₂ O ₃ raises friction	Nicholson (1995)
metal sulfides - various	Cu ₂ S, Sb ₂ S ₃ , PbS; studies show the effect of additives on disc brake pads with and without metal fibers; modify and stabilize the friction coefficient; highest μ for Sb (0.47-0.49), next PbS (0.40-0.47), most variable for Cu (0.36-0.52)- wear worst for Cu-S	Gudmand-Hoyer, et al. (1999)
metal sulfides – various	PbS – soft solid lubricant additive (2-8% by wt.) with thermal decomposition products also lubricating, said to reduce pad and rotor wear and reduce noise; MoS ₂ adheres more readily to metal surfaces than graphite and has broad temp. range (3-8% by wt typ.); ZnS is a low cost solid lubricant recommended for high loads and temperatures (5-10% by wt. typ.); metal sulfide mixtures are also used	BBU (1993)
mineral fillers (mullite, kyanite, sillimanite, alumina, crystalline silica)	mullite, kyanite, sillimanite are friable and help control frictional behavior while also controlling wear on the counterface due to their own fracturing	Hooton (1969)
mineral fillers	μ is roughly proportional to Mohs hardness; too much mineral filler tends to wear the counter-face	Spurr (1972)
molybdenum disulfide	(MoS ₂), a typical layer-lattice-type lubricant	Spurr (1972)
petroleum coke	low-cost, can lower friction, low ash	Nicholson (1995)

3.3 Fillers, Reinforcements, and Miscellaneous

Fillers are used to maintain the overall composition of the friction material, and some have other functions as well. They can be metals, alloys, ceramics, or organic materials.

Material	Description / Comment	Reference(s)
anti-oxidants	help to maintain the proper oxide film thickness on aircraft brakes – too much oxide leads to unstable friction (high at low speeds) and thick films that can wear off too readily; graphite is a common one in metal-ceramic composite brakes	Hooton (1969)
asbestos	most common filler in early brake materials (see 3.5)	Spurr (1972), Rhee (1974), Nicholson (1995)
barium sulfate (“barytes”)	(BaSO ₄) basically inert, but increases density and may aid in wear resistance, stable at high temperature	Nicholson (1995)
calcium carbonate	CaCO ₃ is a lower cost alternative to barytes, but not quite as stable at high temperatures	Nicholson (1995)
cashew nut shell oil (see improved discussion below)	improves resilience in the binder system and reduces brake noise (see also “friction dust” in 3.2)	Nicholson (1995)
cotton	reinforcing fiber for the matrix	Spurr (1972)
fibers – mixed oxide	reinforcement fibers, produced from a base slag mineral wool, can contain, for example, a mixture of silica (40-50 wt%), alumina (5-15 wt%), calcia (34-42 wt%), magnesia (3-10 wt%), and other inorganics (0-7 wt%); function is to control fade and increase braking effectiveness	Sloss (no year)
lime	Ca(OH) ₂ is used to avoid corrosion in Fe-additives, helps in processing, helps raise fade temperatures	Nicholson (1995)
potassium titanate	inert filler material; also, an insulator and structural participant to replace the role of asbestos	Jang (2000)
rubber – diene, nitrile	used as stabilizers to promote cross-linking and K. increase wear resistance in polymer composite brake materials containing asbestos fibers; rubber also modifies the compressibility (modulus/stiffness)	C. Gong et al. (1985)
rubber scrap	ground up tires (“tire peels”), decreases cost, must not contain road dirt	Nicholson (1995)
sea coal	general low-cost particulate filler, may contain harmful ash; not good for high temperatures	Nicholson (1995)
zinc oxide	ZnO imparts some wear resistance, but can polish drums	Nicholson (1995)

Cashew-containing friction dust is said to have the ability to absorb the heat created by friction while retaining braking efficiency. It is a major export product of India and the Asian subcontinent. The supposed advantage of cashew resin, compared with plain phenolic resin, is that it produces a softer material which is more efficient for wear when the brakes are relatively cold, as in temperatures generated by lower speed automobiles. Cashew friction dust is a granular, free flowing polymerised resin derived from Cashew Nut Shell Liquid (CNSL). The main component in processed cashew nutshell liquid (CNSL) is cardanol, a naturally occurring,

meta-substituted alkenyl phenol similar to nonylphenol. Cardanol is hydrophobic in nature and remains flexible and liquid at very low temperatures.

3.4 Binder (Matrix) Materials

Typical binder materials are phenolic resins in the case of automotive and truck pads. There are three common types of aircraft friction brake materials: (1) sintered metal (most widely used), (2) carbon-carbon, and (3) organic materials. Fe-based metallics tend to have a lower friction response than Cu-based matrix materials [Ref.: Tatarzycki and Webb (1992)]

Material	Description / Comment	Reference(s)
phenolic resin	common binder; too little – material weakness; if too much is used, there is a friction drop-off at high temperatures; the degree of polymer cross-linking affects behavior	Spurr (1972)
metallic alloys of Cu, Fe, Ni	aircraft brake matrix materials*	Hooton (1969); Tatarzycki (1992)
modified resins	a variety of modified resins is available; modifications to alter bonding characteristics and temperature resistance include cresol, epoxy, cashew, PVB, rubber, linseed oil, and boron	Borden (1994)

3.5 Asbestos

Asbestos is hydrated magnesium silicate $Mg_3Si_2O_5(OH)_4$. When it is used, the content of asbestos in vehicle brakes varies between about 30-70%. According to Nicholson (1995), the positive characteristics of asbestos are: (1) asbestos is thermally stable to 500°C above which it produces silicates, (2) asbestos helps regenerate the friction surface during use, (3) silicates produced by asbestos are harder and more abrasive than asbestos, (4) asbestos insulates thermally, (5) it processes well, (6) it wears well, (7) it is strong yet flexible, and (8) asbestos is available at reasonable cost. The fibrous character remains intact until about 1400°C.

According to Spurr (1972), asbestos becomes dehydroxylated at high temperatures. It tends to transform to forsterite and silica above 810°C. The wear debris contains forsterite or amorphous material. The kinetic friction coefficient (μ_k) of asbestos against clean iron is ~ 0.80. The type of asbestos used is important because of differences in cost, properties, and processing. Chrysotile is normally used but other asbestos minerals, amosite and crocokolite, may be used. Chrysotile makes up approximately 90%-95% of all asbestos contained in buildings in the United States [Ref. University of Minnesota Asbestos and Lead Management Group, Internet URL, <http://www.dehs.umn.edu/asbestos/>]. Three other types (Anthophyllite, Tremolite, and Actinolite) are rarer and found mainly as minor contaminants along with other minerals.

3.5.1 Wear of Asbestos Materials

The wear rate of asbestos brakes was studied and reviewed by S. K. Rhee of Bendix Corporation. The wear rate of an asbestos-reinforced lining, in drum-type tests, was investigated (1970, 1971, 1974), and the following general relationship was used to model the process (1970):

$$AW = \alpha P^a V^b t^c \quad [1]$$

where AW = wear loss (grams), P = normal pressure (psi), V = sliding speed (r-pm), and t = sliding time (min.). Proportionality factor α depends on testing geometry. Values of exponents a , b , and c are material pair-related. The wear rate of asbestos-containing friction materials is reported to be about constant up to 450° F (232° C), after which it increased exponentially.

3.5.2 Regulations and the Current Use of Asbestos in Brakes

Medical research showed that asbestos fibers can lodge in the lungs and induce adverse respiratory conditions. In 1986, the Environmental Protection Agency announced a proposed ban on asbestos. The ban would have required all new vehicles to have non-asbestos brakes by September 1993, and the aftermarket would have had until 1996 to convert to non-asbestos. The EPA's proposed ban was overturned in federal court, but it resulted in a major shift away from asbestos by most friction material suppliers and vehicle manufacturers. Ford was still using asbestos linings as recently as 1993 on its Crown Victoria model, but has since discontinued using them. A few high-end imports such as Land Rover are the only original equipment applications that still use asbestos.

Asbestos brake products are still used in the aftermarket despite the fact many people think asbestos was replaced by non-asbestos organics years ago. In 1996, MarketScope research (MarketScope, is a division of Babcox Publications, Inc.) reported that asbestos linings were still being installed on 9.5% of the vehicles serviced by its readers. *That is a significant percentage of the total brake market, considering that many people believe that asbestos is no longer even available.* Asbestos is still used because it's an economical fiber for low temperature brake applications, but it is gradually being phased out for the aforementioned reasons. [Ref. to website URL <<http://www.babcox.com/cm/cm99628.htm>>]

Mandatory OSHA requirements concerning asbestos in brakes can be found in OSHA Standard 1910.1001, Appendix F "Work practices and engineering controls for automotive brake and clutch inspection, disassembly, repair and assembly"; Subpart Number: Z "Toxic and Hazardous Substances.

"This mandatory appendix specifies engineering controls and work practices that must be implemented by the employer during automotive brake and clutch inspection, disassembly, repair, and assembly operations."

3.5.3 Possible Replacements for Asbestos in Brakes

Nicholson (1995) lists the following replacement materials for asbestos. None is exactly like asbestos but they offer some similar performance characteristics: wollastonite (calcium silicate), vermiculite (hydrated calcium aluminum silicate), mica (aluminum silicate), basalt fiber, rockwool (blast furnace slag or basalt), Fiberfrax® ceramic fiber, polyacrylonitrile (PAN), polyester, chopped glass fiber, and aramid fibers.

4.0 Brake Friction Designations and Typical Compositions

According to Anderson (1980), friction coefficients for brake material pairs span a range of 0.07 to 0.7, but practically, most vehicles operate within a narrower range. Typical values range from 'about 0.3 – 0.6 in friction coefficient. Anderson lists six classes of friction materials depending on operational capabilities. The higher the class number, the more severe the operating conditions. Materials must be formulated to withstand the energy dissipation requirements of use. Classes III and IV used in trucks, for example, must withstand 3 – 4 MPa of pressure and speeds of 35-50 m/s, respectively. The counterface temperatures can reach up to 600-800° C. This temperature range is at least 150°C above the estimated use temperature for aluminum metal matrix composites [see Section 4.2.3.2].

4.1 Edge Codes

The Society of Automotive Engineers (SAE) developed a Friction Identification System for Brake Linings and Brake Blocks (SAE Recommended Practice SAE J866a). Consisting of two letters, these so-called 'edge codes' were stamped on the sides of commercial brake replacement linings and blocks as a guide for motor vehicle maintenance and repair shops.

The first code letter represents the 'normal friction coefficient,' determined by averaging four points on the second fade curve in SAE brake material test method J661 ("Chase Machine"), measured at 200, 250, 300 and 400°F. The second is called the 'hot friction coefficient.' It averages 10 experimentally-determined points from the same test: 400 and 300°F on the first fade recovery; 450, 500, 550, 600, and 650°F on the second fade segment; and 500, 400, and 300° F on the second recovery segment. Additional qualifications are given in SAE J866a.

SAE Recommended Practice J866a lists the following codes and associated friction coefficients:

Code	Friction Coefficient
C	10.15
D	>0.15 but ≤ 0.25
E	>0.25 but ≤ 0.35
F	>0.35 but ≤ 0.45
G	>0.45 but ≤ 0.55
H	>0.55
Z	underclassified

In recent years, the value of edge codes has become controversial in light of the growing recognition that brake frictional response, and the apparent friction coefficient, are dependent not only on the material composition, but also on the environment, the mechanics of the system, and the duty cycles to which the brakes are subjected.

According to commercial literature there are significant limitations regarding the use of SAE edge codes:

- 1) Test specimens on the Chase Machine are 1” square pads and do not represent full-sized brake pads. Many, if not most, brake engineers believe that full-sized brake (inertial) dynamometer tests represent a better method for characterizing brake material response than the Chase Machine.
- 2) The edge code gives no indication of wear resistance.
- 3) Edge codes cannot and should not be used as the sole selection criterion for a replacement brake material.

4.2 Friction Brake Compositions for Aircraft and Ground Vehicles

The history of brake materials shows that some of the simplest compositions (fiber plus resin) can be effective, but there have been all kinds of commercial additives introduced and promoted. The ratio of resin to carbon to metallic fibers in semi-metallic brake materials has changed very little during the 20th century [27:30:43 +/- about 1%]; ref. Nicholson (1995)]. On the other hand, there are at least six types of resins alone. The reasons for so many additives are partly based on function but also on ingredient cost, availability, and processing issues, the latter including mixture blending, dimensional stability, and pre-forming capability. Nicholson (1995) reports that the same ingredients can be sent to several plants and the resulting brakes can have friction coefficients that vary by over a factor of 2. Therefore, friction brake composition is only a part of the picture in ensuring satisfactory brake performance.

It is worthwhile comparing some typical compositions of aircraft brakes with those of automotive and truck brakes because there is a certain amount of overlap in their functional requirements.

4.2.1 Aircraft Brake Formulations

Information in this section was compiled from several sources, Three notable sources, listed in 4.3 below, are (1) N. Murdie (2000), (2) Y. T. Tatarzicki and R. T. Webb (1992), and (3) N.A. Hooton (1969).

Aircraft brakes primarily consist of resin/steel, metallic linings, and carbon-carbon (C-C) combinations. The C-C combinations are more commonly used in high-performance brakes due to their high-temperature characteristics. For example, commercial aircraft, like the Airbus 319, MD-11, Boeing 767, and 777, use C-C brakes. Military aircraft, like the F-15E, F-18, F-22, and Joint Strike Fighter use C-C brakes. A number of varieties of carbon and C compounds are used as matrix materials in aircraft brakes: (1) resin, (2) coal tar/synthetic pitch, (3) petroleum pitch, and (4) pyrolytic carbon. These sometimes contain additives to adjust friction, temperature characteristics, and mechanical properties. Carbon materials can be characterized as graphitic or non-graphitic. Processing and heat treatment affects the degree of graphitization. Generally, as the disc heat treatment temperature increases, the degree of graphitization increases. Graphitizable C includes pitch, chemical vapor deposited C, and meso-phase pitch. So-called non-graphitizable carbon includes the resins and ‘PAN’-based material.

Starting materials for C-C brake discs include polyacrylonitrile (PAN), pitch, and mesophase Pitch. PAN produces C fiber material with somewhat lower modulus, lower density, but somewhat higher strength. Pitch materials have higher modulus, lower strength, higher density, and higher thermal conductivity. By adjusting the form and composition of fibers and matrices, a wide variety of properties can be produced in the C-C materials. Pitch tends to cost more than PAN.

C fibers generally exhibit varying degrees of property anisotropy. For example, heat transport is generally much higher longitudinally than transverse to the fiber axis. Therefore some C-C discs are made with fine-scale needle-like fibers oriented perpendicular to the plane of the disc to enhance heat flow. These needles are perpendicular to another structural mat (woven layer) of fibers that lies parallel to the disc face.

Antioxidants help protect the C-C discs from reacting with the environment when they frictionally heat. An example is a phosphate coating of Al, Zn, or Mn that is brushed on the edges of the brake discs and then ‘charred.’ The antioxidants are kept away from the rubbing surfaces of the discs because they can reduce friction.

The ability of the materials to stand up under rejected take-off (RTO) conditions is another important requirement. In that case, 10-40 million ft-lbs of work must be dissipated in 20-25 seconds (e.g., 0.75-0.9 MJ/kg for a commercial aircraft). There is interest in applying C-C materials to heavy trucks. C-C brakes have been tested on cars and racing vehicles. The friction coefficient for C-C varies significantly with interface temperature; therefore, braking performance varies under low and high-energy braking conditions.

In addition to friction and wear behavior, the following properties are reported to be important in C-C composite brakes:

- (1) density
- (2) porosity
- (3) thermal conductivity
- (4) specific heat
- (5) tensile strength
- (6) flexural strength
- (7) compressive strength
- (8) shear strength
- (9) impact strength

Selected, reported compositions of aircraft brake materials follow. Where descriptions are vague, like “friction dust” or “metals/oxides,” the compositions are proprietary. Even listing an element like “Fe” is a vague reference because there are many forms and sizes available (fibers, powder, sponge, etc.). Rarely, if ever, are the exact compositions and constituents of friction materials known by other than the producer.

4.2.1.1 Hooton (1969)

Aircraft brake Material “A” used against steel			
Function	Material	Amount	Comments
Matrix	Cu	31 vol %	
Friction producer	mullite	22 vol. %	
Antioxidant	graphite	32 vol. %	

Friction modifiers 15 vol. % 5 ingredients

Aircraft brake Material "B" used against steel

Function	Material	Amount	Comments
Matrix	Cu-Fe	34 vol. %	
Friction producer	mullite-silica	42 vol. %	
Antioxidant	graphite	22 vol. %	
Friction modifiers		2 vol. %	1 ingredient

4.2.2 Automotive Brake Pad Formulations

Automotive and truck brake pads and shoes usually contain a binder, performance modifiers, abrasives, lubricants, and fillers. A representative sample of compositions follows. Some examples list constituents by composition, but other examples are included here to illustrate the kinds of formulations that are specified by using commercial additive products of proprietary composition. Note that in a number of cases, a range of compositions is reported rather than a single value. This was done, at least in part, to conceal the actual compositions of the materials. Therefore, the percentages of the constituents may not add to a total of 100%. Note also that some of the compositions are given in weight percent and others are given in volume percent. Nicholson (1995) asserts that volume percent is the correct unit of measure for friction material composition. The exact compositions of commercial friction materials are almost never published in the open literature.

According to Bush et al. (1972), the average wear rate of a typical automotive brake pad material is 5×10^{-5} cm (0.5 micrometers) per brake application. This corresponds to approximately 3 mg of material loss per brake application.

4.2.2.1 Tsane et al. (1985)

Tsang et al. conducted friction tests of several asbestos-free materials that had the following compositions:

Asbestos-Free Material "I"

Function	Material	Amount (wt%)	Comments
Binder	resin	13-18	thermoset
Fiber reinforcements	fiberglas	6-24	
	inorganic fiber	8-16	
"friction dust"		0-20	
Elastomer	polymer	0-20	
Carbon / graphite	carbon	1-4	
Inorganics		12-32	
Metals / oxides		0 - 19	

Asbestos-Free Material "II"

Function	Material	Amount (wt%)	Comments
Binder	resin	8-14	thermoset
Fiber reinforcements	fiberglas	14-16	
	inorganic fiber	10-16	
"friction dust"		0-7	
Elastomer	polymer	0-7	

antioxidant / fric. mod.	carbon / graphite	18-34
Filler	barium sulfite	30
Inorganics		7-24
Metals / oxides		4 – 22
Other		0-10

Asbestos-Free Material “III”

Function	Material	Amount (wt%)	Comments
Binder	resin	10-20	thermoset
Metal fibers	steel	0-70	
Metal powder	iron	20-70	
“friction dust”	proprietary	0-18	
Elastomer	polymer	0-18	
antioxidant / fric. mod.	carbon / graphite	10-30	
Filler	barium sulfite	0-15	
Inorganics	proprietary	0 -10	

4.2.2.2 Jang et al. (2000)

Experimental composition of pads used against cast iron discs in a series of dynamometer tests of additive effects.

Function	Material	Amount (vol%)	Comments
Binder	phenolic resin	20	
Filler	aramid pulp	6	
	barium sulfate	20	
Fiber	ceramic fiber*	3	
Fiber	Cu fibers	3	
Additives – misc.	calcium hydroxide	3	
	cashew particles	10	
	vermiculite	3	
	mica	3	
Elastomer	rubber	3	
Friction producers/ modif.	MoS ₂	3	
	graphite	5	
	Sb ₂ S ₃	2-6	a variable in experiments
	ZrSiO ₄	2-6	a variable in experiments
	potassium titanate	balance	

4.2.2.3 The PQ Corporation Tests

Six automotive brake pad formulations were used to demonstrate the effectiveness of hollow ceramic microspheres (“Extendspheres FM”) in brake performance tests. Product names are used in this list of ingredients to illustrate using commercial additives. The ranges below spanned the six different pad compositions. They were tested in commercial dynamometers against cast iron brake rotors.

Material	Amount (wt%)	Comments
Barium sulfite	29 - 35	
Kevlar™	0.71 – 1.10	
PMF	9.9 – 23.5	mineral fiber reinforcement – Sloss Industries
Interfibe 230	3 – 3.5	
Phenolic	0 – 10.6	

HRJ 730	0 – 7.2	product of Schenectady Chemicals
Reclaimed rubber	4 – 4.7	
Vermiculite	4 – 4.7	
Wollastonite	0 – 11	
Graphite 3226	5 – 5.9	
Cashew particles	3.5 – 4.4	
Magnesium oxide	1.5 – 1.8	
Ceramic microspheres	0 – 11.8	
Rock wool	5 – 5.9	
HRJ 583	0 – 7.2	product of Schenectady Chemicals

4.2.2.4 Sloss Industries Sample Formulations

An automotive brake pad formulation was used to demonstrate the effectiveness of PMF® reinforcing fibers in brake performance tests. In the first example, the pad material was preformed at 1200 psi, hot-pressed at 300°F for six minutes at 2000 psi, and then post-cured at 400°F for eight hours. A proprietary resin composition was used. In the second example, a range of 3 compositions is provided. The third example is for a shoe/drum type brake shoe material.

Example 1:

<u>Material</u>	<u>Composition (wt%)</u>
Barytes	37.3
SP 60-18 resin	20.3
Cashews	4.0
Graphite	6.8
Rubber	6.2
Aramid fiber	2.8
PMF fibers	22.6

Example 2 – Range in compositions for three different pads.

<u>Material</u>	<u>Range in Composition (wt%)</u>
Barytes	21 – 22.5
FRJ-774 resin	14
PMF fiber 204	20
Graphite	0 - 2
Talc	8 - 10
Steel fibers	10
Brass chips	0 - 2
Vermiculite	12.5 - 15
Kevlar pulp	1.5
HRJ-2354 friction modifier	5 – 9

4.2.2.5 Chapman et al. (1999)

Pads were fabricated by reactive metal infiltration. They were tested against cast iron in a FAST (friction assessment and screening test) configuration (flat pad-on-disc at constant drag). No fade was observed, and μ was in the range of 0.3 – 0.45.

<u>Function</u>	<u>Material</u>	<u>Amount</u>	<u>Comments</u>
Base material	aluminum	not given	
Reinforcing particles	B ₄ C	not given	bi-modal particle size distribution (75 μm to < 1.0 μm, vol. fraction ~ 0.48-0.72)

4.2.2.6 Eriksson et al. (2000)

The typical composition of a Volvo 850 brake pad material was given as follows:

<u>Function</u>	<u>Material</u>	<u>Amount (wt%)</u>	<u>Comments</u>
Matrix	binder material	8	
	other	11	
Fillers	clay and iron oxide	8	
Fibers	steel, aramid, glass	30	
Friction modifiers	brass/bronze	15	
	graphite	15	
	metal sulphides	8	
Abrasives	quartz	5	

4.2.2.7 Wirth and Whitaker (1992)

Studies of the composition of transfer films were performed on brake pads of this composition sliding on gray cast iron.

<u>Function</u>	<u>Material</u>	<u>Amount (vol.%)</u>	<u>Comments</u>
Matrix	resin	40.0	
Fillers	vermiculite	20.0	
	barytes	30-38	
Fibers	steel	0 or 5	
Friction modifiers	molybdenum disulphide	0 or 2	
	lead sulphide	0 or 5	

4.2.2.8 Gudmand-Hover et al. (1999)

The effects of solid lubricants on disc brake behavior were investigated using a dynamometer. Volvo standard, unventilated rear brake discs were used. Conditions for test type 1: 600 stops from 50 km/h at 30 bars pressure and 70° C. Conditions for test type 2: 350 stops from 120 km/h at 40 bars pressure and 200° C. Friction films were formed under test 2 conditions. Under test 1 conditions, the solid lubricant additives had no significant effects.

<u>Function</u>	<u>Material</u>	<u>Amount (vol %)</u>	<u>Comments</u>
Matrix	resin and rubber	23-26	
Fillers	barytes, friction dust and vermiculite	25.5 - 41	
	brass	0 or 5	
	aramid	0 or 9	
Friction modifiers	metal sulphides	8	Cu, Pb, or Sb sulphides
Abrasives	zirconia	0 or 5	
	alumina	0 or 5	

4.2.2.9 Handa and Kato (1996)

Authors investigated the effects of Cu powder, barium sulphate, and cashew dust on friction and wear of friction materials against cast iron. A sub-scale flat pad-on-disc arrangement was used. Conditions: 25 braking applications, 588 N (on 350 mm² area => 1.68 MPa contact pressure), 5.6 m/s engagement speed. Fade effects decreased when the barium sulphate was removed, but wear rate greatly increased. Regression analysis predicted lowest friction for high cashew content, but low Cu and barium sulphate content. Maps of Cu, barite, and cashew composition versus friction and wear were calculated.

Function	Material	Amount (vol %)	Comments
Matrix	phenolic resin	20	
Fillers	barium sulphate	30-0, 0-40, 20	ranges for three series of tests
	cashew dust	30, 40-0, 40-0	ranges for three series of tests
Fibers	aramid	20	
Metal	Cu powder	0-30, 0-40, 20	ranges for three series of tests

4.2.2.10 Howell and Ball (1995)

Authors compared the friction and wear of an aluminum/SiC composite with that of cast iron against three pad materials. A modified drilling stand was used with a contact pressure of 1.034 MPa and sliding speeds of 0.52 to 3.16 m/s. The following pad compositions were reported. Friction and wear results were mixed, depending on material combination and severity of test conditions.

Function	Material	Organic pad (wt%)	Semi-met pad A (wt%)	Semi-met pad B (wt%)
Binder	phenolic resin	43	25	16
Fibers	organic fiber	20		
Metal	Cu	0.6	15	15
	Fe		43	3
	Al		3	2
Lubricant	graphite	15	7	4
Abrasive	alumina			5
Filler	rubber	2	5	
	paper	15		52
Other	unspecified	4.4	2	3

4.2.2.10 Kato and Soutome (2001)

Stochastic methods were used in an attempt to formulate brake pads. A subscale pad-on-disc tester was used to generate friction and wear data on the effects of each component. The standard disc material was cast iron. There were ten potential components in the pad material. The 'optimized' composition for the combination of highest friction coefficient ($\mu = 0.38$) and lowest wear rate was as follows:

Function	Material	Amount (vol %)	Comments
Matrix	phenolic resin	25.0	
Fillers	barium sulphate	0.02	
	cashew dust	19.4	
	calcium carbonate	0.0	studied, but not in the optimal composition

Fibers	aramid	3.0	
	ceramic	15.0	
Metal	Cu powder	20.0	
Abrasive	alumina	10.0	
Lubricant	graphite	7.3	
	molybdenum disulphide	0.0	studied, but not in the optimal composition

Summary. The compositions of commercial and experimental pad materials varied widely, although some constituents were common to nearly all of them. Typical ranges of the more common constituents are as follows:

Constituent	Range (vol%)	Typical value (vol%)
phenolic resin	10 – 45	20 – 25
barium sulphate	0 – 40	20 – 25
fibers	5 – 30	-
cashew particles	3 – 30	15 – 20
graphite	0 – 15	5 – 7
metal sulphides	0 – 8	0 – 5
abrasives	0 – 10	2 – 3
“friction dust”	0 – 20	-

As mentioned in 3.3, “friction dust” is an ambiguous term, yet it is used in describing many brake pad formulations. It is likely that friction dust actually contains some of the elements and compounds mentioned previously under other categories, like fillers and lubricants. Sometimes, however, the term ‘friction dust’ is used to describe brake and clutch additives that are based on cashew particles.

4.2.3 Passenger Car and Truck Brake Disc and Drum Materials

4.2.3.1 Cast Iron.

Automotive and truck discs and drums are typically produced using gray (also spelled *grey*) cast iron with Type A graphite (flakes having a uniform distribution and random orientation) with a pearlitic matrix of low ferrite and carbide content. Several of the typical cast iron grades used for brake materials and their C and Si contents are given in the following table. Data were obtained from the ASM Handbook, Vol. 1, 1990, ASM International, Materials Park, Ohio:

Application	Grade	Carbon Content (total carbon in wt%)	Silicon Content (wt%)
light-duty brake drums	2500	3.20 – 3.50	2.0 – 2.4
moderate service drums	2500a	3.40 min	1.6 – 2.1
medium duty brake drums	3000	3.10 – 3.40	1.9 – 2.3
heavy-duty drums requiring resistance to heat checking	3500b	3.40 min	1.3 – 1.8

extra heavy-duty drums	3500c	3.50 min	1.3 – 1.8
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Wear of gray cast iron in brake applications occurs by abrasive, adhesive and oxidative processes and cannot generally be represented by an Arrhenius type relationship. According to Anderson (1992), typical specific wear rates for cast iron drums are the order of 0.2 – 1 mg/MJ [$1.6 – 8.0 \times 10^{-5}$ in³/hp-hr], but rates as high as 5 – 16 mg/MJ can result when the lining material is very abrasive.

4.2.3.2 Aluminum-Based Metal Matrix Composites.

There has been interest in using aluminum-based metal matrix composites (MMCs) for brake disc and drum materials in recent years. While much lighter than cast-iron, they are not as resistant to high temperatures and are sometimes only 'used on the rear axles of automobiles because the energy dissipation requirements are not as severe compared with the front axle. Therefore, from a performance standpoint – especially' as regards long drags with excessive temperature buildup – there are serious performance issues with Al-MMCs. It was originally thought that reductions in brake noise and consumer warranty-related complaints would decrease with Al-MMCs, but this has not proven to be the case.

Commercial literature from Duralcan (1993) provides the following comparison of properties between Al MMCs with gray cast iron:

Property	Units	Al-MMC Type F3S.20S-T61	Al-MMC Type F3D20S-T5	Gray cast Iron Grade 30/35
Elastic modulus	Msi	14.3	16.5	13.0 – 17.2
Yield strength	ksi	49	57	31 – 39
Density	lb/in ³	0.0999	0.1019	0.257
Thermal conductivity	BTU/ft hr °F	105.	85.5	27.3
Specific heat	BTU/lb oF	0.200	0.198	0.096
Thermal expansion coefficient	(10 ⁶ / °F)	9.7	9.4	6.8

Howell and Ball (1995) compared the sliding wear of Al-MMC and cast iron disc materials against an organic and three semi-metallic pad materials. Tests were done on a modified vertical drilling machine with a torque cell mounted on the base. While the friction and wear of the Al-MMC were high at high speeds and loads, the behavior could be greatly improved, even beyond that of cast iron discs, given the correct match of pad and disc material. Organic pads were a better match for the Al-MMC than semi-metallic pads.

Oda et al. (1997) evaluated the wear of Al-MMC rotors containing various amounts of SiC. The base alloy was Al-10Si-Mg. Particles of SiC less than about 12 μm in size were dispersed by stirring them into the molten alloy. It was found that the temperature limitation for use was about 450° C. Above that temperature, there was excessive scoring.

Aluminum/boron carbide composites have shown promising friction and wear behavior as a candidate disc material using the Chase test [Chapman et al. (1999); see section 5.2 for a description of the Chase machine]. Specimens were produced by reactive metal infiltration.

Overall, the future for using Al-MMC materials for discs is not clear. While they reduce weight, they tend to be more expensive than conventional gray cast iron and have not shown distinct performance advantages.

4.2.3.3. Carbon and Ceramic Brakes

Carbon-carbon brakes with ceramic additives have been developed by Brembo S.p.A (Curno, Italy). Having a density of 2.2-2.4 g/cm^3 , they offer the advantage of light weight, and the manufacturer claims they exhibit uniform frictional behavior. The 2000 model year Porsche offers premium ceramic brakes (trade name - SIGRASIC, by SGL GmbH) as an option, but cost is high. There is also interest in using aircraft brake technology as a basis for new automotive and truck brake materials, but a major challenge is in ensuring that the frictional performance remains stable over a range of operating temperatures. Materials development efforts are underway in this area.

5.0 Brake Material Test Methods and Apparatus

A number of materials tests (compression tests, hardness, thermal conductivity measurements, etc.) are employed during the development of brake materials and additives, but the final qualification test for brake materials involves extensive on-vehicle tests with full-sized components. *Brake performance is affected not only by the materials and vehicle hardware design, but also significantly by driver behavior, the vehicle usage, the state of adjustment of the brake hardware, and the overall environment in which the vehicle is driven.* Add to these considerations the possible influences of braking control systems, engine braking, and the aerodynamics in the wheel well, and no laboratory test can simulate driving conditions precisely.

To reduce preliminary material qualification costs and to facilitate research, a variety of laboratory-scale test machines have been developed. These range from massive, inertial dynamometers with electronic controls and sensors to small, rub-shoe machines that can sit on a bench-top. Some off-vehicle test systems involve instrumented skid pads onto which a fully-loaded vehicle can drive and apply the brakes. Instrumented roll-on-type systems can test one set of vehicle axles at a time. The amount of data obtained from this wide range of tests varies greatly, and friction data from one type of brake test may not **directly** correlate with that from another type. Added to this concern is the fact that many of the larger dynamometer units are custom, one-of-a-kind units. Therefore, data for different materials are usually ranked in relative terms within the confines of the given test method, and can agree between one method and another.

The following summarizes the various levels of brake material testing:

I. Vehicle Road Tests

- II. Vehicle Skid-Pad Tests
- III. Vehicle Drive-on Dynamometers (in-ground or portable)
- IV. Inertial Dynamometers (full-scale hardware)
- V. Inertial Dynamometers (sub-scale hardware)
- VI. Laboratory Tribometers

Off-vehicle brake material test methods (IV-VI) range from simple drag tests at constant speed and contact pressure, to complex, multi-stage qualification tests involving programmed changes in contact pressure, speed, temperature, and repetitive contacts that simulate vehicle braking events (e.g., SAE J 1652).

The following subsections describe several common laboratory-scale friction material testing machines. The basic elements include a means to apply a force, use of conformal contact, and a means to measure frictional torque. Some tests involve constant speed, but others involve deceleration. Use of multiple load applications is common, as is temperature measurement.

5.1 The FAST Machine

The Friction Assessment and Screening Test (FAST) machine was introduced in the mid-1960's by Ford Motor Company as a quality assurance test. It uses small block specimens, about 6.35 mm square, dragging on the circumference of a test ring at constant torque (actuator pressure is adjusted to maintain torque) for 90 minutes. Some investigators have attempted to use this to evaluate new materials for vehicles, but it was only intended as a quality assurance tool for brake materials, not as a development tool. According to some reports, the FAST machine does not replicate road conditions well enough to be used in brake materials R&D.

According to Nicholson (1995), higher friction materials that contain more abrasive additives tend to clean the ring specimen and produce steadier results on the FAST machine than on the Chase machine, described subsequently. However, the relatively high pressures generated during FAST tests (due to the small contact area of the block) can produce significant evidence for fade that is not observed during more realistic types of tests, like inertial dynamometer brake tests.

5.2 The Chase Machine

The Chase Machine is used to perform SAE test J661a and was involved in the development of edge codes. It consists of a rotating drum with a 25.4 mm square pad of friction material loaded against the inner diameter of the drum (279.4 mm ID) by an air pressure system. Friction and wear data can be obtained. The wear is usually reported in terms of weight loss of the pad and thickness loss for the drum. A comparison of Chase Machine data for several material combinations with that from an inertial dynamometer was reported by Tsang et al. (1985). The test results from the two machines were inconsistent.

5.3 Other Sub-Scale Testing; Machines

Sub-scale testing machines, other than inertial dynamometers have been designed for use in brake materials research. Such machines are usually custom-built, one-of-a-kind units. Depending on the focus of the research, they can be instrumented for torque (friction), temperature, and vibrational measurements. While not duplicating every aspect of on-vehicle braking, they can be used to study fundamental responses of materials to braking-like levels of energy input under carefully-controlled conditions. Phenomena like fade, thermo-elastic instability ('hot-spots'), pad wear, and friction-induced film formation can be studied using sub-scale testing machines.

Depending on the type of brake phenomena under investigation (e.g., noise, vibration, friction level, thermo-elastic effects, etc.) good correlations may or may not exist between sub-scale and full-scale tests, like inertial dynamometer tests. For certain studies, however, sub-scale machines constitute a cost-effective tool for brake materials developers. For example, when the amount of experimental materials is limited or when the fabrication costs for full-scale prototypes possessing a range of material compositions is prohibitively expensive, sub-scale tests can provide enough screening information to down-select the most promising candidates.

5.4 Inertial Dynamometers and FMVSS Tests

Inertial dynamometers use one or more shaft-mounted weights to store a given amount of energy which must then be dissipated by the brake materials during testing. Such machines vary in size from laboratory-scale, sub-size units to huge, full-size units that can test aircraft and heavy truck brake components.

Federal Motor Vehicle Safety Standard (FMVSS) tests for brake materials require full-size inertial dynamometers. FMVSS 121 identify three main characteristics: effectiveness, fade, and recovery. Effectiveness measures the efficiency of braking under different line pressures. Fade refers to the ability to decelerate quickly time after time (10 applications) without the need to exert unduly high line pressure. Recovery involves 20 stops at lesser rates of acceleration under a maximum allowed line pressure of 85 psi. FMVSS 135, scheduled to have taken effect in 2000, is an attempt to harmonize US standards with international automotive brake tests.

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Appendix

Thermophysical Properties of Selected Materials

Table 1. Thermophysical Properties of Selected Materials

Table 2. Thermophysical Properties of Selected Materials

Table 3. Thermophysical Properties of Selected Materials

Appendix Thermophysical Properties of Selected Materials

Material	Thermal Conductivity			Thermal Diffusivity			Coefficient of Thermal Expansion		
	Temperature (C)	Units (W/m.K)	Data Source	Temperature (C)	Units (cm ² /s)	Data Source	Temperature (C)	Units (x10 ⁻⁶ /K)	Data Source
ELEMENTAL METALS and ALLOYS									
Grey cast iron (3.43-3.51%C) – range of 3 US made brake rotors	room	52.1 – 57.1	1	room	0.156 - 0.172	1			
	300	42. – 44.		300	0.095 – 0.105				
	500	–38		500	~ 0.08				
Grey cast iron (3.69%C)– Japanese brake rotor	room	62.4	1	room	0.189	1			
Grey cast iron (3.79%C) – German brake rotor	room	65.7	1	room	0.199	1			
Grey cast iron	25	42.	10						
Cast iron (typ.)	room	46. – 52.	2				room	8.1 – 19.3	2
Iron – elemental	room	80.4	4				room	11.8	4
Iron aluminide (Fe ₃ Al) based alloy – Fe-28 at% Al-2 at% Cr							room	14.8	3
							300	15.4	
							500	17.0	
							1000	22.6	
Aluminum - elemental	room	247.	4				room	22.8	4
Aluminum – Alloy 3003	room	159.	7				room	23.2	7
Aluminum – Alloy 6061	room	180.	8						
Aluminum MMC – Alloy A357 + 20 vol % SiC	room	182.	10						
Copper – elemental	room	400.	8						
Copper - elemental	room	398.	4				room	16.5	4
CARBON, CERAMICS, and MINERALS									
Carbon, graphite – hexagonal, with the grain	room	1.67 – 518.8	2				room	0.1 – 19.4	2
Carbon, graphite	room	23.9	4				room	0.6 – 4.4	4
Carbon, graphite fiber – high conductivity	room	1000.	8						
Carbon, foam ligament	room	1700.	8						
Carbon, diamond	room	2500.	8						
Asbestos	room	0.063	5						

Appendix - Continued

Material	Temperature (C)	Thermal Conductivity (W/m.K)	Data Source	Temperature (C)	Thermal Diffusivity (cm ² /s)	Data Source	Temperature (C)	Coeff. of Thermal Exp. (x10 ⁻⁶ /K)	Data Source
Asbestos - building board	room	0.04 - 0.16	9						
CARBON, CERAMICS, and MINERALS (continued)									
Silicon - elemental	room	156.	4				room	2.62	4
Silica sand - dry	room	0.33	5						
Glass wool	room	0.04	9						
Silicon carbide - hexagonal, sintered	127	63. - 155.	2				room	4.3 - 5.6	2
Silicon carbide - cubic, CVD	127 1327	121. 34.6	2				room	5.5	2
Silicon nitride - Type NT-451	30 400 600	19.8 15.2 14.6	6	30 400 600	0.087 0.045 0.040	6	200 400 600	2.0 2.4 2.7	6
Aluminum oxide - hexagonal	127 1127	27.2 5.8	2				room	7.2 - 8.6	2
Boron nitride - compacted	room	18.0	5						
Zirconium oxide - partially stabilized	room	1.8 - 2.2	2				room	8.9 - 10.6	2
Mica	room	0.43	5						
Quartz	room	1.38	5						
Rock wool	room	0.04-0.06	9						
Soapstone (talc)	room	1.63	5						
POLYMERIC and ELASTOMERIC MATERIALS									
Phenolic resin - cast	room	0.16	5						
Rubber - synthetic	room	0.14	5						
Rubber - silicone	room	0.22	5						
Teflon	room	0.25	5						

Note: Ref's. 5 and 9 data were converted from English units to ISO units as follows: k [BTU in /hr ft² °F] x 0.14413 = W/m-K

Data sources follow:

Appendix - Continued

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