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DEVELOPMENT OF AIRCRAFT BRAKE MATERIALS

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16. Abstract

A study has been carried out to study and develop high temperature aircraft brake materials. The requirements of brake materials were outlined and a survey made to select materials to meet these requirements. Based upon their physical and thermal properties, a number of metals and ceramic materials were selected and evaluated in sliding tests which simulated aircraft braking. These were nickel, molybdenum, tungsten, ZrO_2, high temperature cements and carbons. Additives were then incorporated into these materials to optimize their wear or strength behavior with particular emphasis on nickel and molybdenum base materials and a high temperature potassium silicate cement. Optimum materials were developed which had improved wear behavior over conventional brake materials in the simulated test. The best materials were a nickel, aluminum oxide, lead tungstate composition containing graphite or molybdenum disulphite; a molybdenum base material containing LPA100 (an intermetallic compound of cobalt, molybdenum, and silicon); and a carbon material (P5).

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FOREWORD

This work was conducted as part of NASA Grant NGR 33-018-152 from the Office of University Affairs, Washington, D. C. 20546. Mr. C. David Miller of NASA's Aerospace Safety Research and Data Institute was the technical monitor. Mr. R. L. Johnson, Manager of NASA's Lubrication Research Branch was the technical advisor. Dr. F. F. Ling, Chairman of RPI's Mechanics Division was the principal investigator. Acknowledgement is made of the many helpful suggestions made by C. David Miller and R. L. Johnson of NASA during the course of this investigation, and of Mr. S. Weiss who is the present technical monitor.

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SECTION 1

SUMMARY

A study has been carried out to study and develop high temperature aircraft brake materials. The requirements of brake materials were outlined and a survey made to select materials to meet these requirements. Based upon their physical and thermal properties, a number of metals and ceramic materials were selected and evaluated in sliding tests which simulated aircraft braking. These were nickel, molybdenum, tungsten, ZrO_2, high temperature cements and carbons. Additives were then incorporated into these materials to optimize their wear or strength behavior with particular emphasis on nickel and molybdenum base materials and a high temperature potassium silicate cement. Optimum materials were developed which had improved wear behavior over conventional brake materials in the simulated test. The best materials were a nickel, aluminum oxide, lead tungstate composition containing graphite or molybdenum disulphite; a molybdenum base material containing LPA100 (an intermetallic compound of cobalt, molybdenum, and silicon); and a carbon material (P5). These will be evaluated in actual brake tests.

SECTION 2

INTRODUCTION

The trend in aircraft brake materials has always been for higher energy adsorptions per unit mass of brake materials, Brake temperatures have risen through the years so that organic materials were replaced by copper and iron base metallics. Brake temperatures have now risen to the point where even these materials become inadequate under certain conditions of operation and higher temperature materials are needed. Accordingly, a research project "Mechanics of High Energy Brake Systems" was initiated by NASA in the Mechanics Division of Rensselaer Polytechnic Institute to study aircraft brake systems. This study includes fundamental studies of temperature and wear behavior, materials, pad design, improved brake system designs and brake evaluations. For the past two years, as one phase of this program, a study has been under way to select, develop, and evaluate potential brake materials with capability for higher temperature operations. The following report is a summary of this work. Initial investigations of materials behavior was reported in Reference 1.

SECTION 3

REQUIREMENTS OF BRAKE MATERIALS

Based upon our research and reviews of the literature the following requirements for aircraft brake materials can be applied:

Adequate strength to operating temperature
Minimum oxidation at operating temperature
Reasonable cost
Nongalling (no transfer)
Constant friction over operating conditions
Minimum wear
High thermal conductivity
High specific heat
High density
Low expansion
Low elastic modulus

Of these requirements the first four are the most significant. Any material considered would need to have at least these properties. The other requirements are important but can be compensated for in other ways.

The problem is that no material will meet all of these requirements and some compromises must be made. This is difficult at the present time since the relative significance of each of the factors is not known. Accordingly, in conjunction with the material development program, a study has been underway to determine what properties are most important for brake material development. Basically this study consists of an analysis of the wear mechanisms for brake materials and determination of those properties which are most significant for improved performance from a safety point of view. These results will be subsequently reported.

In the following sections each of the requirements are briefly discussed. The statements made in many cases are not established facts but represent current thinking.

Adequate Strength

No absolute strength requirements can be specified, however, the current materials are very fragile and must be contained in a steel jacket. This has been shown to be undesirable and should be eliminated if at all possible. The brake materials are fragile because a considerable amount of sand or Al_2O_3 is added to prevent transfer. If the transfer could be prevented by other means, higher strength materials could be used. Since the wear rate is more or less directly proportional to strength under these conditions, it is desirable to have the maximum strength obtainable consistent with the other requirements. Furthermore, the higher the strength-temperature behavior, the higher will be the surface temperature which can be reached without transfer or excessive wear.

Since it is desirable to have the maximum strength at the highest possible temperature, the melting point can be used as an indication of suitability for the selection of base materials. The melting points of some of the common metals and ceramics are listed in Table 1.

It can be seen that many potential candidate materials are available which have melting points above copper. The ceramic materials are brittle and some have poor thermal shock resistance, however, so are the present brake materials. There are means to design around the problem of brittleness should it become necessary. Thermal shock, however, cannot be compensated for by design. For thermal shock resistance, a high fracture strength, low elastic modulus and low thermal expansion is needed. Some nonmetallics such as BN, Carbon, SiC, TiC, WC, SiO_2, and BeO are reported to have excellent shock resistance. This, however, is a problem which must be dealt with very specifically in relation to design.

Oxidation Resistance

Minimum oxidation is required to maintain the integrity of the materials at elevated temperatures. However, oxidation affects both the wear rate and the dissipation of frictional heat. Wear studies have indicated that increased surface oxidation gives increased wear; thus it is desirable to keep oxidation to a minimum. Investigations (Ref.2) have indicated that thin oxide films at the sliding interface can significantly increase the surface temperature. An analysis of used pads indicates that only a thin film remains on the surface after sliding, however, there is considerable oxidation throughout the brake material. How significant this is in raising the surface temperature has not been fully established to date, however, such internal oxide is in no way beneficial and should be avoided. Care must be taken not to completely eliminate the surface oxide from metals since this has a major influence in stabilizing friction and in preventing metal transfer.

TABLE 1

MELTING POINTS OF SOME HIGH TEMPERATURE MATERIALS °C

Tungsten	3410	Carbon	3700
Tantalum	2996	ThO_2	3310
Molybdenum	2625	TiC	3150
Columbium	2420	MgO	2800
Hafnium	1871	BN	2730
Zirconium	1760	ZrO_2	2700
Titanium	1816	BeO	2530
Stainless Steels	1427-1538	ZrO_2 SiO_2	2500
Iron	1539	SiC	2250
Cobalt	1495	MgO Al_2O_3	2050
Nickel	1455	Al_2O_3	2050
Ni Base Alloys	1427	MgO_1 SiO_2	1910
Co Base Alloys	1410	SiN_4	1900
Monel	1325	Al_2O_3 SiO_2	1810
Beryllium	1283	SiO_2	1710
Silicon Bronze	1088	$NaSiO_4$	1090
Copper	1083	$KSiO_4$	1010

Oxidation resistant metals and non metals are available or additives are available to control oxidation and should not pose any significant problems in materials development.

Cost

The cost is a very significant but nebulous factor. The present pads cost \$2.00 each, from which about 1000 landings are obtained. Thus the cost of the pad is considered to be about .2 cents/landing. Higher cost materials could be used if the wear rate was significantly improved so that the cost of the landing remains about the same. Furthermore, higher strength materials which could be used without the steel jacket would eliminate some of the present costs. A brief survey was made of the present costs of metal powders as shown in Table 2. Any low melting metals or rare metals have been eliminated, (Ref.3).

The absolute values are not important but are intended to only illustrate the relative costs. From these data it has been concluded that no material listed up to titanium should be eliminated. Titanium and zirconium have very poor thermal properties and probably can be eliminated on that basis.

Nongalling

The most important frictional property of material is that there should be no galling, surface damage, or metal transfer in sliding. If any of these occur there will be large variations in friction, unstable operation and usually excessive wear. If any material is to be considered as a brake material, it must be first rendered nongalling. Galling can be considered as a surface, metal deformation process. High adhesion and low ductility increase the probability of galling. Many criteria have been suggested by which nongalling alloys can be identified, (Ref.4), however, all of the metals listed in Table 2 with the possible exception of tungsten, molybdenum and cobalt would be subject to galling and additives must be included to compensate for this; with non-metals this factor is usually not a problem. Where galling is a problem the following approaches can be used to prevent it:

1) Addition of abrasives such as Al_2O_3, SiC, or SiO_2
2) Additives to decrease the ductility
3) Additives to increase low temperature oxidation (if they do not increase oxidation at high temperatures)
4) Addition of lubricants.

TABLE 2

COST OF METAL POWDER

METAL POWDER	LARGE QUANTITIES COST/Kg	SMALL QUANTITIES COST/Kg	COST/LITER
Fe	$0.62	$7.90	$4.88
Cu	1.45	8.80	6.70
304 SS	1.98	10.30	9.15
Co	1.98	10.30	31.10
Ni	2.20		
Mo		17.60	177.00
W		15.40	91.50
Ti	9.90	99.00	12.80
Zr		110.00	
Ta		121.00	1,280.00
Cb		165.00	146.50

Each of these approaches has been used in the present investigation.

Constant Friction

The brake material must operate at temperatures to near the melting point, velocities to 30.5 m/sec and nominal pressures to 10.5 kg/cm^2. In reality, the contact area changes due to thermal distortions so the actual pressures are probably much higher. Since the formation of oxide films usually brings about large reductions in friction, the best approach would be to use nongalling materials which would not oxidize under the sliding conditions or ones which would form the oxide relatively easily and retain it through the operating range. Listed below (Table 3) are some of the temperatures where the oxide is formed in light load temperature cycling experiments, (Ref.5).

TABLE 3

FRICTION REDUCTION DUE TO OXIDATION

METAL	TEMPERATURE (C)
Fe	62
Cu	230
304 SS	985
Co	570
Ni	760
Mo	456
W	-
Ti	-
Zr	27

Generally alloys which contain these materials in significant amounts will show friction reductions at a similar temperature. It can be seen that with certain metals such as iron, copper, and zirconium, the oxide film may be retained throughout the operating range. With the others some compensations will have to be made at low temperatures.

The importance of this factor is not really known. In previous work (Ref.1) it was found that the opposing steel surface determined the frictional behavior. If this is the case, then the friction properties of the brake materials are of somewhat less importance.

The approach used in this investigation was not to select or eliminate materials based on their probable friction behavior. Materials were evaluated and selected without regard for their frictional behavior.

Minimum Wear

There is no theoretical means to predict wear. Wear in fact takes many forms and some methods of reducing one type of wear will increase another. Empirically, it is found that higher hardness and lower elastic modulus will reduce wear. If surface films are formed, the rate of their formation and removal by fatigue determine the wear rate. Furthermore, this surface film should be neither so hard that it causes abrasion of the other surface or so soft that friction is easily abraded by the other surface.

The approach used was to select materials based upon other considerations and to improve their wear properties by adding lubricants or additives to modify the nature of the surface film.

Thermal Properties

Based upon the studies the present conclusions are that high conductivity is important in equalizing the temperature on the surface of the pad, however, due to the poor external dissipation of heat from the brake, the specific heat is probably the most important factor. Based upon a simple thermal analysis, two thermal factors can be used to evaluate materials, (ρc) and $(k\rho c)^{\frac{1}{2}}$. Values of these were collected for a large number of metals. Some of the most significant are shown in Table 4.

The following points are worthy of special note. Copper base materials have the best values of $(k\rho c)^{\frac{1}{2}}$ followed by tungsten. Tungsten has the advantage of having a much higher melting point and could withstand higher temperatures.

As far as specific heat is concerned, certain alloys are superior to copper. These are stainless steel, monel, low expansion nickel alloys, and cobalt base super alloys. Of particular interest here is monel with a (ρc) factor of 1.12. This alloy is comprised of approximately 65% Ni and 34% Cu. The cobalt base super alloys are interesting because they have good sliding behavior at high temperatures. The low expansion alloys are of interest because of the factors considered in the next section.

TABLE 4

THERMAL PROPERTIES

MATERIAL	MELTING POINT ,	ρ	ρc	$(k\rho c)^{\frac{1}{2}}$
Fe	1539	7.87	.866	.495
Cu	1083	8.95	.824	.863
304 SS	1454	9.02	.966	.190
Co	1495	8.86	.877	.379
Ni	1455	8.90	.935	.453
Mo	2625	10.2	.662	.473
W	3410	19.4	.658	.504
Monel	1325	8.84	1.12	.214
Cobalt Super Alloys		9.13	1.09	.280
Low Expansion Nickel		8.19	1.01	.20
Brake Material		4.95	.594	.154

Units

ρ gm/cm^3

ρc $cal/cm^3 - {}^oC$

$(k\rho c)^{\frac{1}{2}}$ $cal/cm^2 - {}^oC - sec^{\frac{1}{2}}$

Of particular interest is the fact that the present brake materials are much poorer than any of the materials listed with respect to both factors. This, of course, is due to the fact that the additives included to prevent transfer and wear, plus the porosity have been very harmful to the thermal properties. Some values of the thermal factors for ceramic type material are shown in Table 5. Units are in the cgs system.

It should be noted here that several of these materials (Al_2O_3, SiC, MgO, ZrO_2) are equal to the metals in the thermal factors, and have much higher melting points. In this regard they are also much better than the present brake materials. It should also be noted that several of these materials are of a sufficiently low hardness that they would not abrade the steel disk. The main question to be answered is whether the low conductivity will be a limiting item in the use of either the metal or the ceramic. A second question to be answered is if such materials have sufficient thermal shock resistance. Accordingly, several ceramic type materials, either commercial or developmental, have been included in the present program.

Thermal Expansion

Low thermal expansion is not only important for thermal shock resistance but also to maximize the area of contact. It has been found in simple sliding tests (Ref.6) and in recent pad tests (Ref.7) that the area of contact is not constant during sliding but is continuously shifting from one point to another. This shifting is due to the fact that the frictional heat causes nonuniform thermal expansion so that isolated contact points carry the total load. This process continues until the surface temperature at one point is so high that rapid wear results. The contact then shifts to another point and the whole process begins all over again. If the thermal expansion of the material is very low, this process would be retarded. Accordingly, it is hypothesized that low thermal expansion is a desirable property. The thermal expansion of some of the previously suggested materials are shown in Table 6.

Of the potential materials, molybdenum, tungsten, polycrystalline glass (pyroceram), silicon carbide and several other materials have very low values of thermal expansion. Although values were not found for the silicates, they would be expected to have property values similar to those of the polycrystalline glasses.

TABLE 5

THERMAL PROPERTIES OF CERAMIC MATERIALS

MATERIAL	MELTING POINT (°C)	DENSITY	ρc	$(k\rho c)^{\frac{1}{2}}$	MOH HARDNESS
Titanium carbide	3140	7.2	1.0	.22	8.5
Alumina ceramics	2050	4.0	.80	.256	9
Micas	-	3.8	.95	.039	-
Silicon carbide	2250	3.1	1.02	.344	9.5
Polycrystalline glass	1500	2.6	.493	.064	
Boron carbide	2350	2.5	.50	.174	9-10
Boron nitride	2730	1.9	.38	.23	2
Graphite	3500	1.9	.342	.405	1
Carbon	3500	1.6	.288	.076	2.5
Magnesium silicate	1910	3.22	.708	.011	5.5
Magnesium oxide	2800	3.6	1.02	.334	5.7
Zirconium oxide	2700	6.0	.96	.215	6.5
Potassium silicate	1015	2.5	.55	.026	5.0
Sodium silicate	1088	2.4	.53	.025	5.0

Units

Density (ρ) gm/cm^3

ρc $cal/cm^3 - {}^{o}C$

$(k\rho c)^{\frac{1}{2}}$ $cal/cm^2 - {}^{o}C - sec^{\frac{1}{2}}$

TABLE 6

ELASTIC MODULUS AND THERMAL EXPANSION COEFFICIENTS

METALS	α	E	NONMETALS	α	E
Fe	11.7	21.0	Alumina	9.37	35.0
Cu	16.5	11.9	Silicon carbide	3.96	47.6
304 SS	18.4	20.3	Polycrystalline glass	0.9	12.1
Co	12.2	21.0	Boron nitride	7.74	8.7
Ni	13.3	21.0	Carbon	5.0	1.4
Mo	4.9	32.9	MgO	13.5	28.0
W	4.3	41.3	ZrO_2	6.6	16.8
Ti	9.7	13.3	Sodium silicate	-	-
Monel	12.9	18.2	Potassium silicate	-	-
Cobalt super alloys	16.9	25.2			
Low expansion	9.8	16.8			

α = thermal expansion cm/cm/^{o} C $\times 10^{6}$

E = elastic modulus $\times 10^{-5}$ kg/cm^{2}

Modulus of Elasticity

Originally it was felt that a low modulus would be desirable since this would yield larger surface contact areas and thus lower surface temperatures. The low modulus would also retard the previously described process of the continuous shifting of the contact area. However, in other tests (to be reported) it appeared that the high modulus material TZM gave the most uniform surface temperatures. It was hypothesized that this may be due to the method of load applications. If the load is applied to the center of the low modulus pad a "bell shaped" pressure distribution will result with the maximum at the center of the pad. A high modulus material will give a much more uniform pressure distribution. Thus at the present time it cannot be stated whether a high modulus or low modulus is desirable. It depends to a large degree upon how the load is applied. What would be most desirable would be a low modulus surface layer backed up by a high modulus material.

From Table 6 and other data it can be seen that high expansion materials generally have low modulus and vice versa. The exceptions are glasses and the carbons which have both low expansion and low modulus.

Minimum Space and Weight

Space and weight savings are very important to aircraft design and operation. Every kilogram, it is said, which is added to a commercial aircraft costs $22,000 more in yearly operation. Unfortunately reduced space and weight mean higher temperatures. Some latitude is possible for example by using higher specific heat and lower density materials (the beryllium brake), however, the ρc value for beryllium is .83. This is lower than many conventional materials (like steel). Thus a sacrifice in temperature results unless more material is used which means more space. In the present study major consideration was not given to these factors.

Materials Approach

If, one examines the properties of a large number of materials, it turns out that no one material even comes close to giving all the desired properties; almost any material is a compromise to a large degree. Thus one must select those requirements which are most significant and concentrate on them.

The approach taken in the present study was to first select reasonably priced oxidation resistant materials which have greater high temperature strength than copper based materials. Since there are many such materials, further refinements were made based on either their known high temperature frictional properties, their thermal properties, or on the low modulus, low expansion criterion.

The basic materials were first evaluated in a simple sliding test under simulated brake conditions. From this test the best materials were selected for further development. Improved materials were fabricated by powder metallurgy techniques and various additives used. The types of additives used are shown in Table 7.

TABLE 7

ADDITIVES FOR IMPROVED PROPERTIES

TYPE OF ADDITIVE	TYPICAL
Improved frictional properties at lower temperatures	Graphite, MoS_2
Reduced metal transfer	SiC, Al_2O_3, SiO_2, Mullite, Wc
Improved friction properties at high temperatures	$BaSO_4$, CaF_2, WO_4 Co_3O_4, $CuMoO_4$, $PbWO_4$
Improved thermal properties	
Specific heat Conductivity	Monel, nickel, stainless steel, Copper, tungsten
Improved high temperature strength	
For metals	Steel or tungsten fibers
For nonmetals	Glass or carbon fibers

SECTION 4

APPARATUS AND PROCEDURE

Apparatus

A photograph of the test apparatus is shown as Figure 1; a sketch of the rig and the test specimen geometry is shown in Figure 2.

Essentially the test rig consists of a 30.5 cm diameter rotating steel disk (0.79 cm thick) with test buttons or pads loaded against opposite faces. For most studies 1.9 cm diam. by 1.9 cm long buttons were used.

The rotating disk is mounted on the drive shaft of a 30,000 Watt motor. The test pads are mounted in a holder which is held in a water cooled jacket. These are mounted in a standard commercial caliper brake. The caliper brake is mounted on an arm which is affixed with strain gages so that the total braking torgue can be determined.

The load is applied to the brake with a pressure from a high pressure cylinder; the maximum load being 1100 kilograms. The load is measured with a 210 kg/cm^2 pressure gage in the air line which indicates rapid changes in pressure. The out-put of this gage is indicated on a high speed chart recorder. All other data read out is recorded simultaneously on the same device so that direct comparison of changes can be made. Also recorded are the torgue, the instantaneous sliding velocity, specimen temperatures, and the sliding time.

The specimen temperature was measured by mounting a thermo-couple within 1.59 mm from the sliding surface.

Procedure

For each test the disk was resurfaced to a finish of approximately 32rms and cleaned with solvent. The test buttons were weighed and mounted in the holders. The disk was brought to a speed of 1750 rpm. The load was applied to the brake for a given period of time and measurements made of the friction, load, and temperature. The test buttons were then removed, reweighed to determine wear, and the surface inspected for damage both macroscopically and microscopically. Surface profile traces were made of the sliding surface and its finish determined. In most cases, micro-hardness measurements were also made.

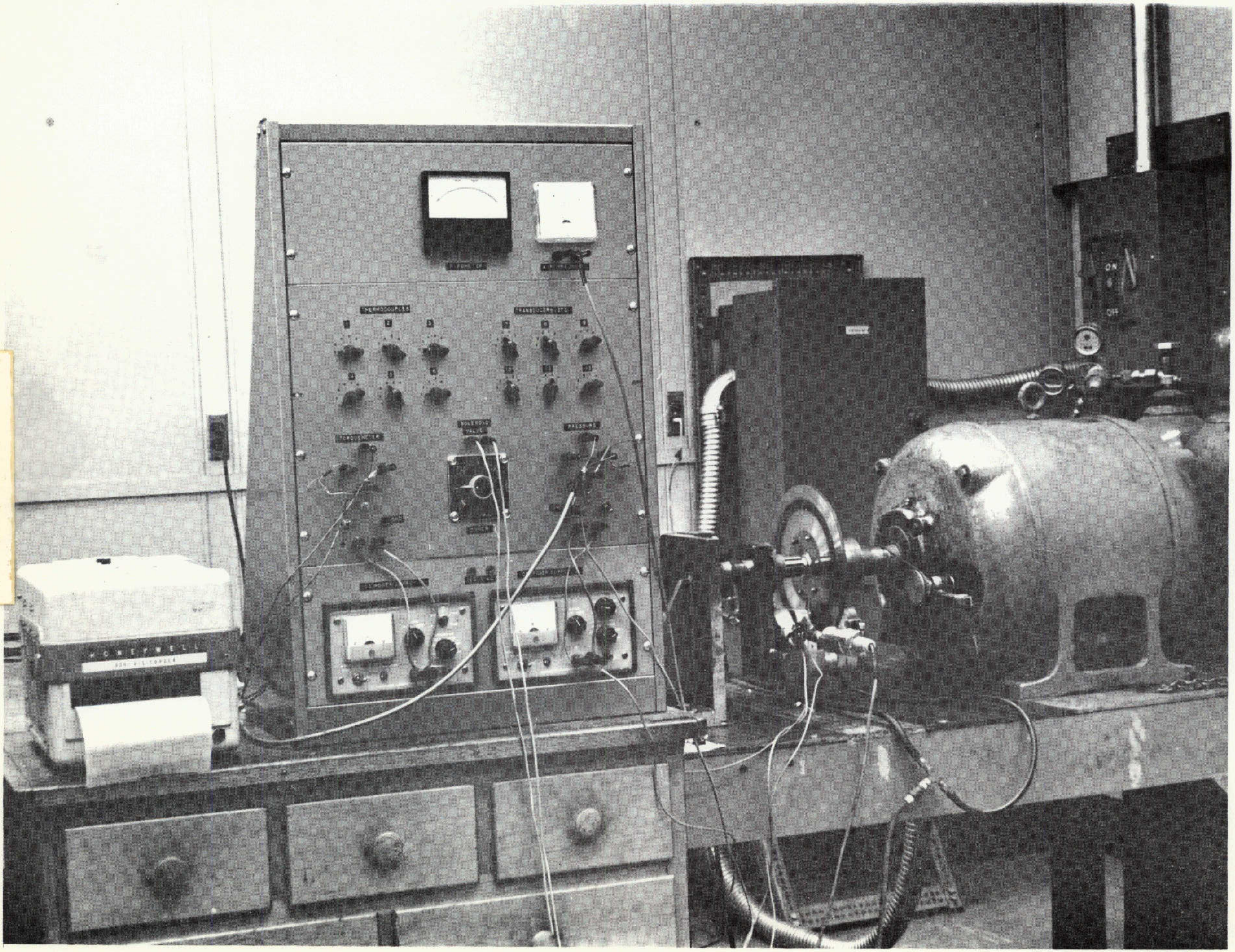


Figure 1. Photograph of Brake Test Apparatus.

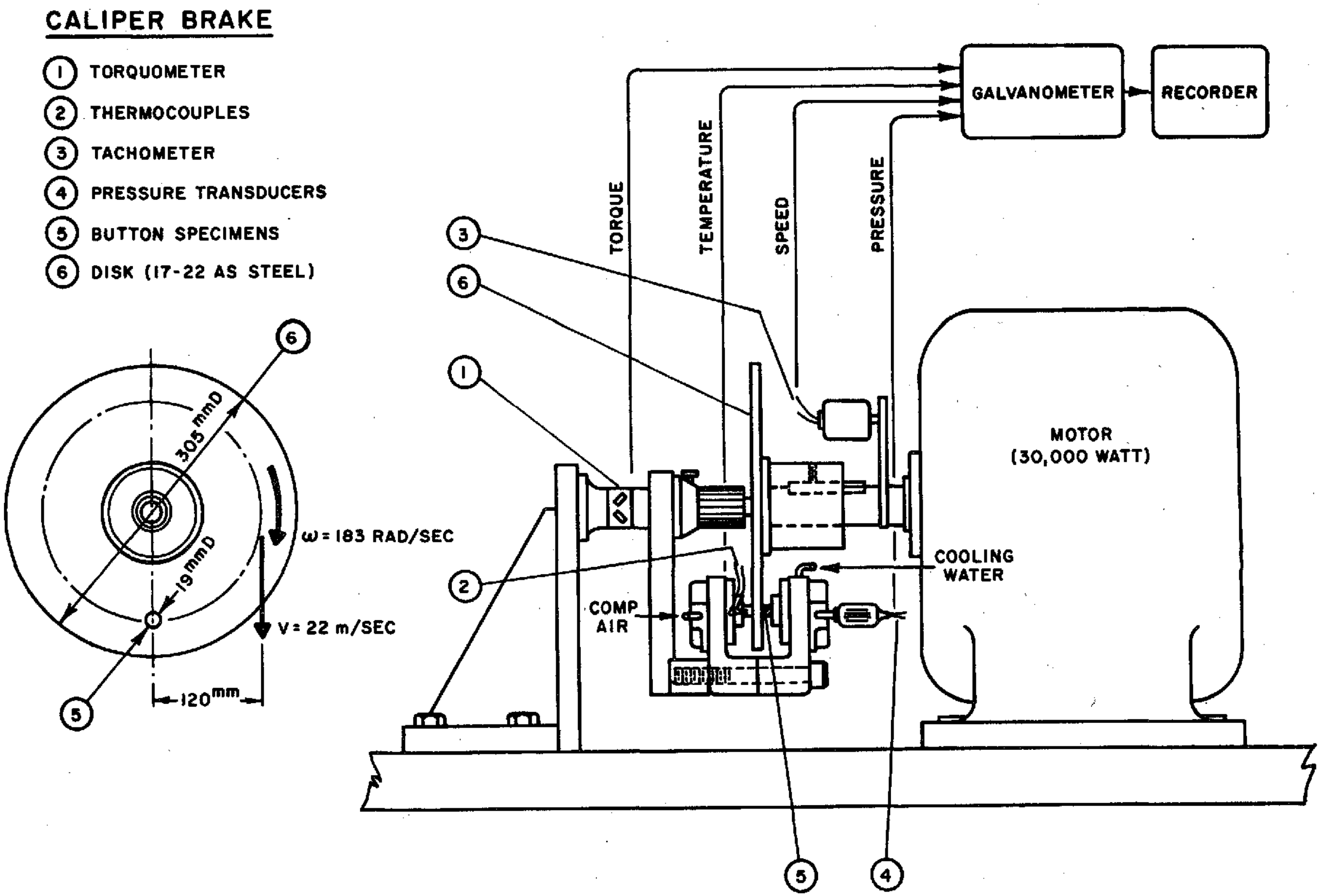


Figure 2. Diagram of Test Apparatus.

Two different types of tests were run. In the first test the sliding time was increased in increments (1,3,5,10,15,20 sec) until a twenty second test was run. The velocity was 22 m/sec and the load 27 kilograms (9.5 kg/cm^2 on specimen of 1.9 cm diameter). This simulates the condition of aircraft braking except that a constant velocity was used to maintain constant conditions. The purpose of this test was to rapidly screen materials to determine if they could operate under typical braking conditions. Particular attention was given to the surface damage, wear, and transfer to the steel disk. If such was evident that button material was eliminated. In many cases this occurred during the first, 1 sec, test. If a material was found to operate satisfactorily for 20 sec., successive twenty second tests were run and wear measured until a more or less constant wear rate was found. This value was then reported.

For those materials which would operate successfully for 20 seconds, a second test was often run; that with increasing load. Twenty second tests were run at increasing load levels until failure occurred. This is a standard procedure in brake material testing and results in increasing surface temperatures. Failure generally occurs by excessive wear when a critical surface temperature is reached. The same measurements were made after each load increment as in the previously described "screening" tests.

SECTION 5
MATERIALS

Disk Material

The rotor disk is made from 17-22 AS steel. This low-alloyed steel is of the chromium-molybdenum-vanadium-silicon type. The chemical limits to which this steel are produced are as follows: (Table 8)

The unheat-treated 17-22 AS steel has a hardness of Rc 17. After heat treatment there is a hardness range from Rc 44 to Rc 50. The heat-treat specifications are given in Table 9.

Standard Materials

The materials used in the primary searching for new base of brake material were all obtained from commercial sources. Their composition is given in Table 10.

Cements

A series of tests were run using several shock resistant high temperature cements. The cements (#29, 31, 33 and 65) used here have relatively high temparature resistance (up to 1,100^{0}C). A description of them is given in Table 11.

Powdered Metals

Table 12 shows the powdered metals used in this investigation and their particle size. Primary interest is in these two factors, however, the compressibility and particle shape are also very important for the compacting process and sintering mechanism. These will be considerations in the future studies.

Additives

A wide variety of compounds which were added into base metal matrices to improve the braking behavior are listed in Table 13.

Method of Preparation of Metal Specimens

The basic techniques of powder Metallurgy were used to prepare the experimental button specimens of which the composition was easily controlled for a variety of functions. There were three processes briefly described as follows.

1. Mixing

The metal powder was mixed with additives in a mixer for four to five hours in order to get a homogeneous mixture.

2. Pressing

A high compacting pressure from 9 to 11 × 10^3 kg/cm^2 was applied on the powder mixture by a hydraulic press.

3. Sintering

The sintering temperature and the sintering time depend upon the kind of specimens. The nickel specimens were sintered at 1010°C for 2 hours and LPA100/Mo at 1220°C for 1/2 hour. Both kinds of specimens were sintered in vacuum furnace and cooled in N_2 to avoid the oxidation.

TABLE 8

CHEMICAL COMPOSITION OF 17-22 AS STEEL

ELEMENT	MIN. (%)	MAX. (%)
C	0.27	0.33
Mn	0.45	0.65
Si	0.55	0.75
P	-	0.030
S	-	0.025
Cr	1.00	1.50
Mo	0.40	0.60
V	0.20	0.30

TABLE 9

HEAT TREATMENT OF 17-22 STEEL DISK

1. Austenitize at 871 ± 15°C for ½ hour
2. Quench into salt at 204°C (Cataract cool)
3. Allow to air cool
4. Temper in salt bath at 204°C for 2 hours

TABLE 10

STANDARD MATERIALS

NAME	COMPOSITION %
Annealed 1095 Drill Rod	98.5Fe 0.95C 0.4Mn
M-2 Steel	82Fe 6W 5Mo 4Cr 2V 0.85C
304 S.S.	71Fe 19Cr 10Ni
NiMo (B)	61Ni 28Mo 5Fe 2.5Co 1Cr 1Mn 1Si
Monel	67Ni 30Cu
"S" Monel	63Ni 30Cu 4Si
CoCr (25)	50Co 20Cr 15W 10Ni 2Fe 1Mn
CoCr (6B)	59.8Co 30Cr 4.5W 3Fe 1.5Mo 1.2C
TZM	99Mo 0.5Ti 0.1Zr
LPA100/Mo	53Mo 47LPA100

TABLE 11

CEMENTS

NAME	BASE MATERIAL	SPECIFIC PROPERTIES
#29	Zirconium	Low expansion
#31	porcelain	acid-proof
#33	synthetic porcelain	adhesive
#65	Potassium silicate	corrosion resisting

TABLE 12

PARTICLE SIZE OF METAL POWDERS

NAME	SIZE (Mesh)
B	-325
Co	-230
Cu	-325
Mo	-100
Monel	-325
Ni	-325
Ni-Cr	-
Sn	-325
St.Steel	-
CoCr (6B)	-325

TABLE 13

ADDITIVES

NAME	FORMULA	FUNCTION
Graphite flake	C	Lubricant
Graphite powder	C	"
Molybdenum disulfide	MoS_2	"
Aluminum oxide	Al_2O_3	Abrasive
Mullite	$3Al_2O_3$ $2SiO_2$	"
Silicon carbide	SiC	"
Silicon oxide	SiO_2	"
Tungsten carbide	WC	"
Tungsten oxide	WO_3	"
Barium sulfate	$BaSO_4$	High Temperature Lubricant
Lead Tungstate	$PbWO_4$	"
Barium fluoride	BaF_2	"
Calcium fluoride	CaF_2	"
Copper molybdate	$CuMoO_4$	"
Cobalt oxide	CoO, Co_3O_4	"
Copper oxide	CuO	"
Calcium oxide	CaO	"

SECTION 6

RESULTS AND DISCUSSION OF RESULTS

Approach

In this study the approach taken was to first select the basic materials for consideration using the general criteria discussed in Section 3. Those which appeared most promising were evaluated for their damage, wear, and frictional behavior. This included pure metals, alloys, ceramics, high temperature cements, carbons, and any composite or experimental material currently available. Based on the preliminary testing, a number of materials were selected for further development to overcome obvious deficiencies. This usually included additives to reduce transfer, damage, or wear or additives to improve strength. The goal of the work was to suggest materials capable of operating a higher generated interface temperatures as indicated by wear-load curves. Comparisons were made with a conventional copper based brake material now in use. Special pad tests were run with the most promising materials. The results are described in the following sections.

Pure Metals and Alloys

The results for the increasing time tests are shown in Table 14 and 15 for pure metals and alloys respectively. These alloys were chosen because of their high temperature capability or because they have been shown to have good sliding behavior at high temperatures (Ref.8). In the tables the friction coefficient for each time increment is given along with the damage to the test specimens after the longest "time" run. If severe damage was found during any time increment, the test was discontinued. The wear was only recorded if the twenty second test was run.

The results showed that of the materials tested only the brake material, tungsten, molybdenum, copper, and leaded bronze slid without significant surface damage. The copper, however, gave high friction. These results show immediately the advantage of working with copper base materials at lower temperatures. They yield little damage and high friction. The leaded bronze gave good sliding behavior and wear values comparable to the brake material, however, low friction was recorded. For molybdenum and tungsten, friction values may be too low. Nickel performed surprisingly well. After sliding, its surface consisted of very fine scratches and the disk surface consisted of isolated patches of smooth

TABLE 14

Components of Specimens		Friction Coefficient f_1	f_3	f_5	f_{10}	f_{20}	f_s	Wear ($\times 10^{-3}$ gm) / 20 secs	Surface Observation: Specimens (Films)	Surface Observation: disk (Transfer)
Copper	(Cu)	.21	.42						Polished	Isolated Smooth Transfer
Tungsten	(W)	.16	.20	.19					Polished	Blue Tracks Almost no Damage
Nickel	(Ni)	.18	.19						Fine Scratches	Isolated Smooth Transfer
Iron	(Fe)	.16							Heavy Scratches	Heavily Transferred
Molybdenum	(Mo)	.25	.25	.19	.14	.12			Oxidized (Purple) Polished	Scratches Transferred
Titanium	(Ti)	.21							Heavy Grooved	Transferred in large isolated lumps
Cobalt	(Co)	.23							Fine Scratches	Considerable Smooth Transfer
Leaded Bronze		.08	.09	.08	.11	.14		6	Polished	Isolated Smooth Transfer
Brake Material		.17	.22	.24	.25	.29		10	Fine Scratches	Dark Smooth Transferred Film

TABLE 15

Components of Specimens	Friction Coefficient						Wear ($\times 10^{-3}$ gm) / 20 secs	Surface Observation	
	f_1	f_3	f_5	f_{10}	f_{20}	f_s		Specimens (Films)	disk (Transfer)
Annealed 1095 Drill Rod	-	.10	.12					Polished	Scratches
304 Stainless Steel	.11							Fine scratches	Heavy Transfer
M-2 Steel	.20							Scratches	Heavy Transfer
NiMo(B)	.17	.14						Polished	Fine Transfer
CoCr (6B)	.23							Polished	Heavy Transfer
CoCr (25)	.09	.09						Grooved	Streaky Transfer
(TZM)	.20							Scratches	Transfer
"S" Monel	.15							Scratches	Heavy Transfer
Monel	.22	.22						Light Scratches	Very Heavy Transfer

transferred metal. Cobalt was similar but gave deeper surface scratches and more transfer.

Except for 1095 steel and NiMo(B) most of the alloys damaged the disk surface or produced considerable transfer. The 1095 steel only gave superficial scratching of the surface.

Based upon these results, development efforts (in the metals area) were concentrated on nickel, tungsten, molybdenum, and high carbon steels. Efforts were also devoted to improving the strength of copper base material at high temperatures.

Basic Ceramics and Cements

Based upon the considerations of Section 3, several ceramic materials were selected for evaluation. Also chosen were several high temperature cements. These were included not only for their high temperature behavior but also for their thermal shock resistance. The results for these tests are shown in Table 16. Of these materials satisfactory performance was obtained for the ZrO_2 ceramic and the 65 cement. The silicon carbide and quartz gave severe surface damage, the other cements cracked or crumbled at the edges of the specimen.

The mechanism of sliding of the ZrO_2 and the cements appeared to be the same. A black polished film was generated on their surface which appeared to be the be the result of transfer from the disk. Although the wear was higher than that with the brake material, this may be reducible with additives. These materials gave much higher coefficient of friction than most of the metals, comparable to the brake material, so they offer considerable promise for further development.

TABLE 16

Components of Specimens	Friction Coefficient						Wear ($\times 10^{-3}$ gm)	Surface Observation	
	f_1	f_3	f_5	f_{10}	f_{20}	f_s	20 secs	Specimens (films)	disk (Transfer)
Quartz	.26	.18	.18	.19				grooved crumbled	transferred grooved
KT SiC	.14	.15						hard	grooved
Dense ZrO_2	.17	.16	.16	.15	.15		6	gray polished	scratches
Porous ZrO_2	.21	.20	.22	.27	.31		18	brown polished	polished
#31 Cement					.15	.31	30	crumbled thin transferred	fine scratches
#33 Cement	.21	.18	.19	.20	.21		95	crumbled no transferred	fine scratches
#65 Cement	.26	.21	.19	.22	.25	.31	29	uniform black transfer film	no damage
#65 Cement	.27	.20	.22	.24	.23	.35	42	" "	" "

Carbons

A series of carbons were evaluated in the increasing time test (Table 17). All of these behaved satisfactorily from a wear and damage point of view. The wear was considerably lower than that for the brake material. The basic material strength appeared adequate since there was little evidence of cracking and chipping of the carbon. The friction coefficients are low, therefore, higher loads would be required to obtain the same braking torgue. The main question would be if they could withstand the high temperatures generated in braking without oxidation. They can be adequately protected to approximately 649°C. The dwell time above that temperature may be sufficiently short to make them useful in certain applications.

TABLE 17

Components of Specimens	Friction Coefficient						Wear $(\times 10^{-3}$ gm)	Surface Observation	
	f_1	f_3	f_5	f_{10}	f_{20}	f_S	20 secs	Specimens (films)	disk (Transfer)
P 5007			.07		.08		< 1	Polished	No damage
P 4229	.08	.08			.08		< 1	Polished	No damage
4800	.08	.08			.08		< 1	Polished	Smooth transfer film
P 5	.11	.12			.12		< 1	Polished	Smooth transfer film
L 56	.09	.10			.10		3	Polished	Smooth transfer film
P 03	.07	.08			.08		< 1	Polished	Smooth transfer film

Special Materials

In Table 18 are listed the results for several special galling resistant composite metals. The Fe-Co and Fe-Al alloys were prepared by NASA and the LPA100 materials by DuPont. The LPA100 materials are an intermetallic compound (laves phase) of Co-Mo-Si in a metallic matrix; in this case iron, stainless steel, and molybenum. The best results were obtained with the LPA100/Mo in the ratio 50/50. A second test wherein the specimens were pressed and sintered at RPI gave similar results. A low wear rate was obtained with polished surfaces on both the buttons and the disk. An 80/20 mixture was unsatisfactory and resulted in damage to the disk. The iron cobalt and the iron aluminum alloys were satisfactory in themselves but did cause scratching of the disk. However, this damage was only slightly more severe than that for the 1095 steel.

TABLE 18

Components of Specimens	Friction Coefficient						Wear ($\times 10^{-3}$ gm) / 20 secs	Surface Observation	
	f_1	f_3	f_5	f_{10}	f_{20}	f_s		Specimens (Films)	disk (Transfer)
Fe 49.5 AT% Co 49.5 Si 1.0	.25	.35						Scratches	Transfer
Fe 49.0 Co 49.0 Si 2.0	.28	.26						Scratches	Transfer
Fc 47.5 Co 47.5 Si 5.0	.22	.23	.26	.27	.26			Scratches	Transfer
Fe 47.5 Co 47.5 B 5.0	.26	.29	.31	.29				Scratches	Transfer
Fe 75. Al 25.	.26	.27						grooved	Heavy Transfer
Fe 50. Al 50.	.24	.26	.27	.27	.27		25	scratches	Transfer
St. Steel 50% LP 50%	.12	.14	.15	.11				grooved	transfer
LPA 100 50% Fe 50%	.22	.20	.21	.16	.14			Scratches (a few grooves)	Transfer Scratched
LPA 100 50% Mo 50%	.27	.26	.21	.20	.20			fine scratches	No damage
LPA 100 50% Mo 50%	.23	.20	.20	.19	.20		11	polished	No damage
LPA 100 80% Mo 20%	.24	.21	.16	.15				scratches	Transferred film

Increased Load Tests

The best materials from the previous tests were then subjected to further tests at increasing load levels. In these tests the wear and friction were first determined at a load of 27 kilograms (the same as the previous screening tests) and then increased in 9.1 kilogram increments until a load of 109 kilograms (38.7 kg/cm^2 for specimen of 1.9 cm diameter) or failure resulted.

In Figure 3 the data for a conventional brake material is shown. The wear, friction, and temperature (measured 1.59 mm from the surface) are plotted against load. The friction coefficient averaged about 0.35. The temperature increased nearly linearly with load reaching levels to 730^{o}C at 109 kilograms. These temperatures are similar to those encountered in aircraft braking. The actual interface temperatures would, of course, be considerably higher. The wear increases linearly with load to 82 kg. (600 C) where it begins to increase more rapidly.

In Figure 4 data are shown for the carbons, 65 cement, LPA 100/Mo and ZrO_2. The carbons, the LPA 100/Mo and the brake material carried the full load without damage; the brake material, however, wore considerably. The 65 cement gave excessive wear at relatively low levels of load. ZrO_2 fractured at load of 63.7 to 82.0 kilograms.

It would appear that all of these materials would have promise for further development. The LPA 100/Mo and the carbons may be usable in their present form since the lower friction can be compensated for by an increase in load to obtain the same braking torgue. The ZrO_2 may have to be strengthened, however, the load is higher than that conventionally used in services. The 65 cement needed wear reducing additives. Attempts to make these modifications are described in later sections.

It should be noted that these materials generally have lower friction than the brake material. This means that they would have to be operated at a higher load to obtain the same friction torgue. It also means that they would be sliding at a lower temperature since the temperature is directly proportional to friction. This is taken into consideration when the materials are tested as pads.

Cu Base Materials

In the previous section the results with commercially available materials

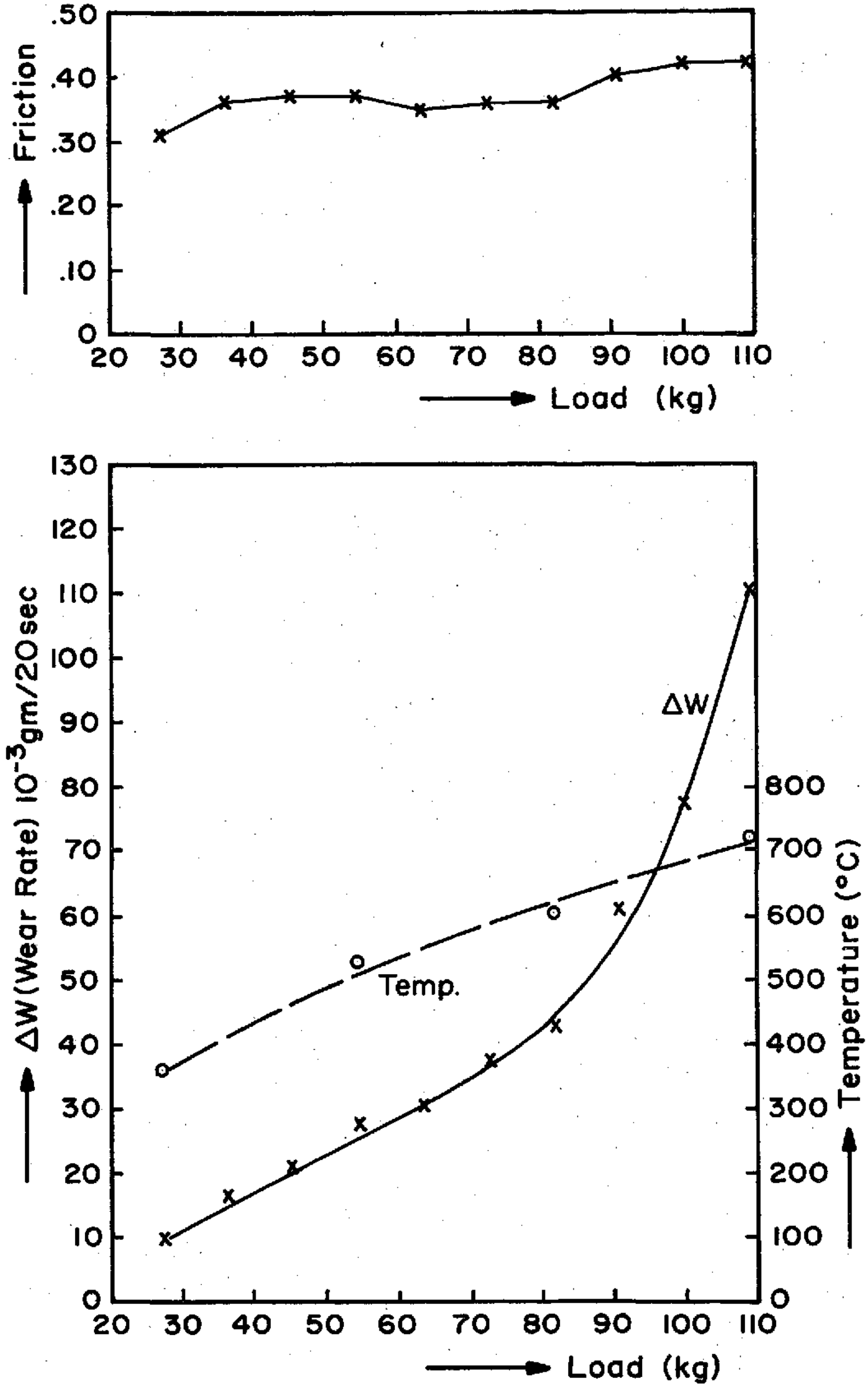


Figure 3. The Effect of Load on the Friction, Wear and Surface Temperature of a Copper Base Brake Material.

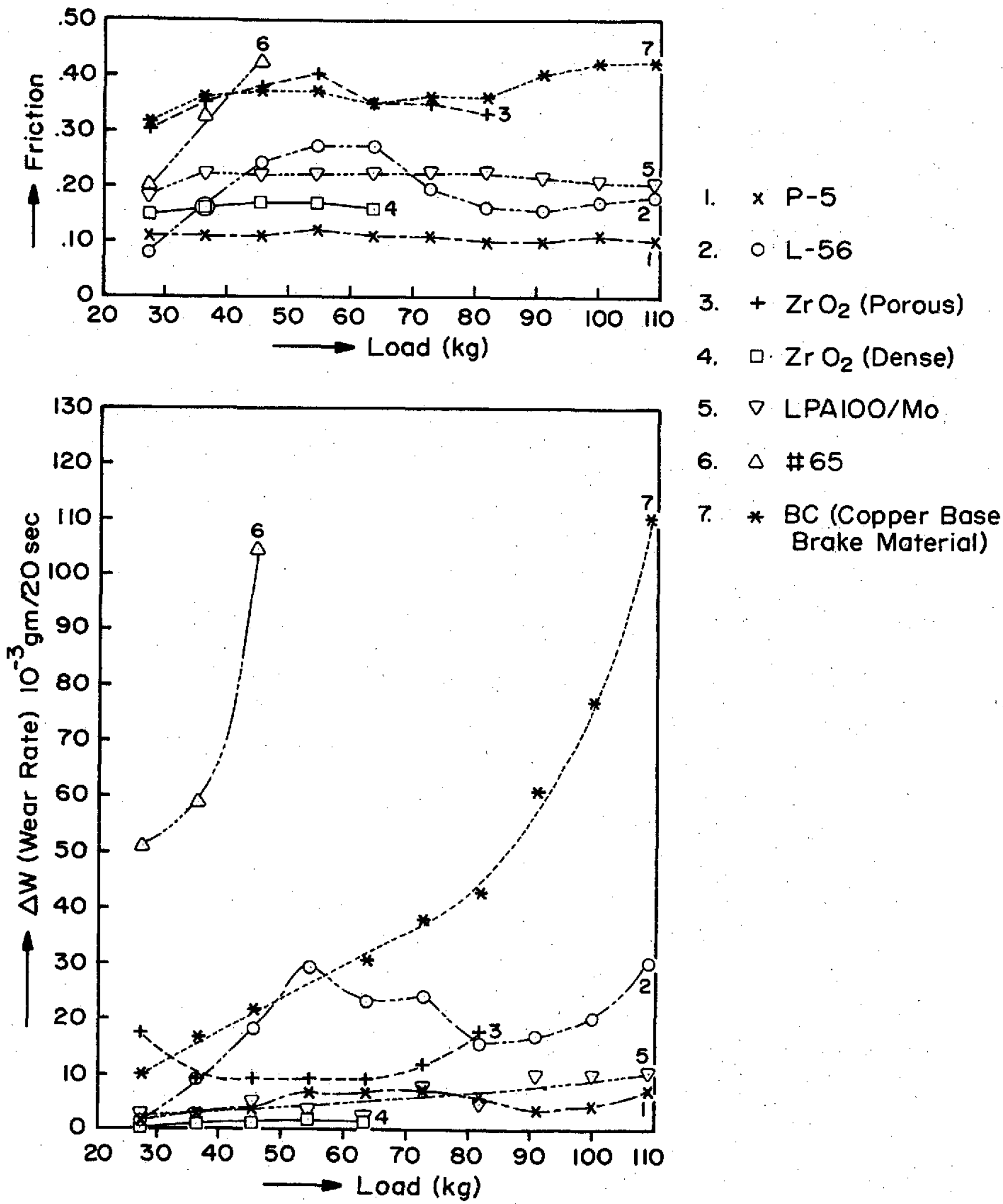


Figure 4. The Effect of Load on the Wear and Friction for Several Promising Materials.

were investigated, for developmental materials, initial efforts were directed to several approaches to improve copper base materials.

The first approach considered the use of copper plated 1080 steel wire. (Ref.9) Here 20 mil steel fibers 0.3 Cm long plated with copper were pressed and sintered to a density of 85%. Final composition was 75% steel, 25% copper by volume. Initial experiments indicated that galling occurred unless the specimens were subsequently heat treated to a hardness of approximately 50 Rockwell C. This treatment was then used for all specimens.

The screen test result for the CuFe specimen is shown in Figure 5. At the initial load, the wear value was 25 milligrams with almost no damage to its surfaces; there was, however, some scratching of the disk. In order to reduce this damage and the wear, a series of lubricating additives (Graphite, $PbWO_4$, WO_3, Co_3O_4, $BaSO_4$) were incorporated into the structure during the pressing process. The load tests with these materials are shown in Figure 5. It can be seen that all of the additives lowered the wear. The maximum load capacity was obtained with $PbWO_4$ and graphite.

Further efforts were made to improve the load capacity by incorporating a variety of additives and combination of additives into the structure. The best results were obtained with a combination of graphite, mullite, and $PbWO_4$. These results are shown in Figure 6.

Although these materials did show promise, it was found that the hardened steel fibers gradually softened during the course of the testing. Since this annealing would cause surface damage, as was found in the initial experiments, efforts along these lines were discontinued.

Since tungsten was found to be one of the best sliding materials, has high temperature strength, and good heat transfer properties, it was felt to be a suitable fiber for strengthening the copper matrix. Accordingly, 10 mil fibers 0.3 cm long were mixed, pressed and sintered with copper powder to yield two volume percentages(74 Cu 26 W and 79 Cu 21 W). Wear load tests were run on these composites; the results are given in Figure 7. Although the results are somewhat erratic due to the difference in wear between the two buttons of a single test, it is clear that the addition of the tungsten fiber improved the wear over that for copper alone, where it could not be run even at the lighest load for twenty seconds. Because of this result, a number of composites were compared

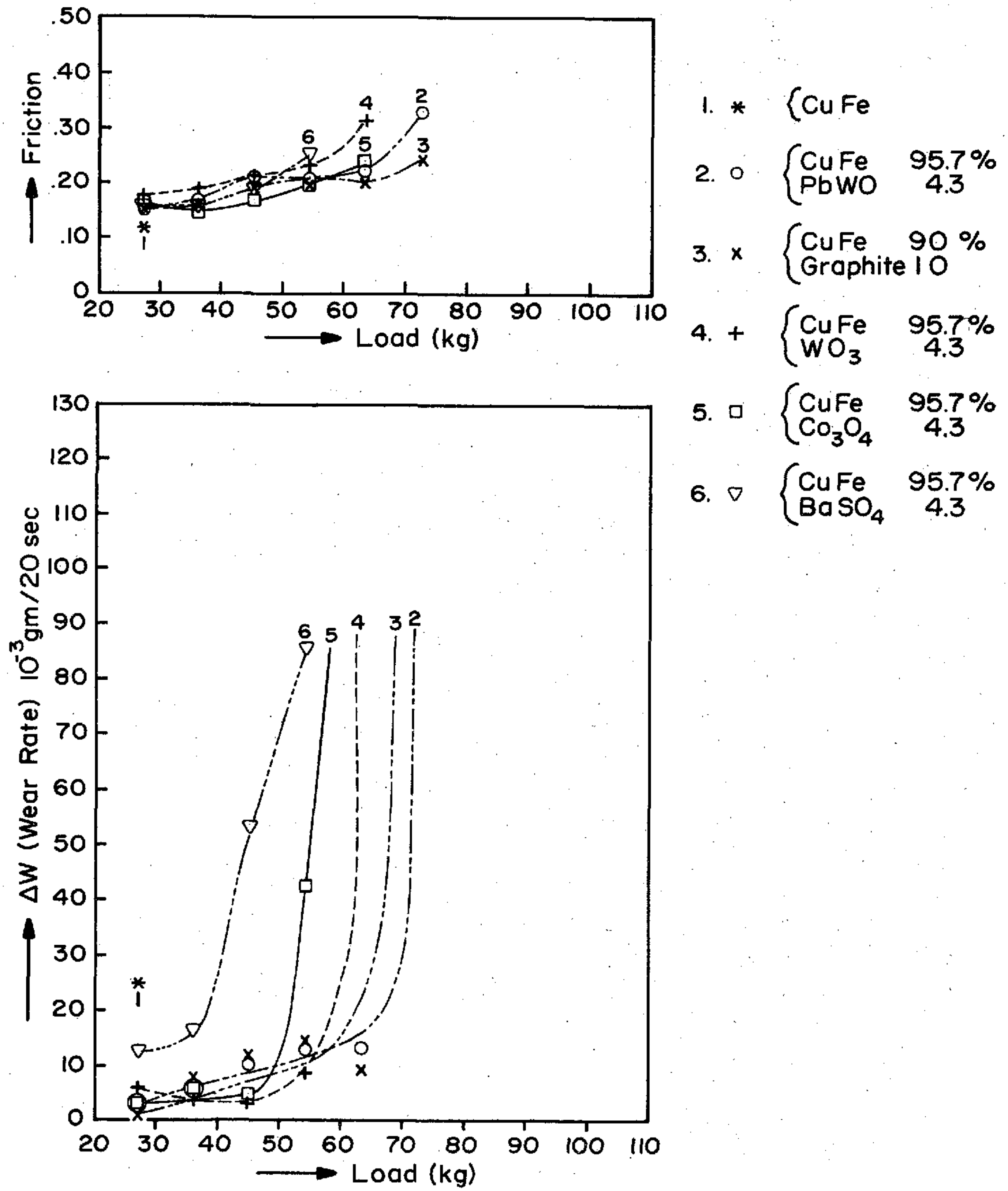


Figure 5. The Effect of Load on the Friction and Wear Behavior of Several Copper Bonded Steel Fiber Composite Materials.

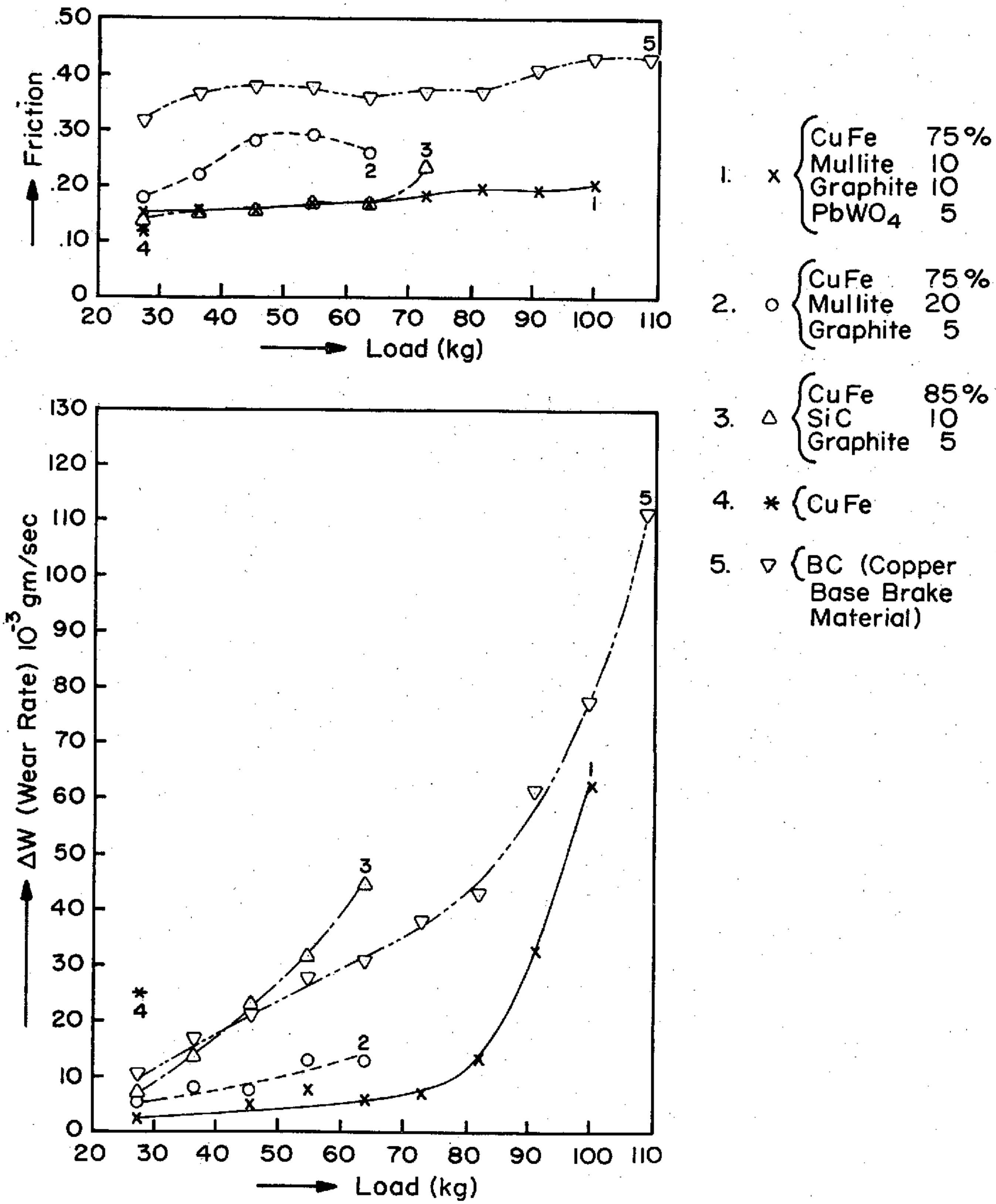


Figure 6. The Effect of Load on the Friction and Wear Behavior of Several Copper Bonded Steel Fiber Composite Materials.

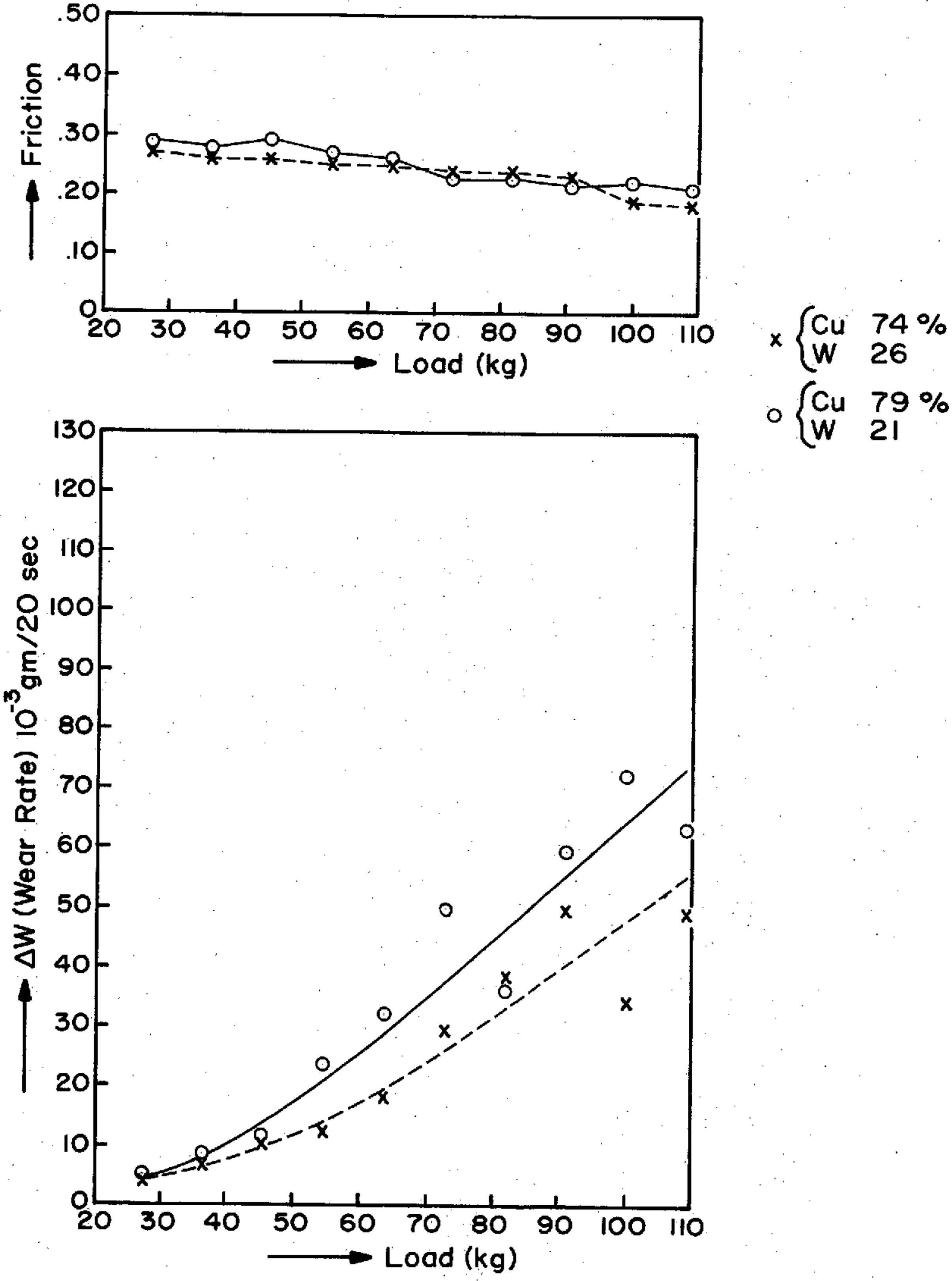


Figure 7. The Effect of Load on the Friction and Wear Behavior of Copper Bonded Tungsten Fiber Composite Materials.

with a series of additives; the best results are shown in Figure 8. With both of these materials low wear and reasonable friction values were obtained to loads of 109 kiligrams. It is quite possible that even further improvements could be made in the wear with an improvement in the additive package, however, it was flet that since the use of the copper base materials was temperature limited, this approach was not carried any further.

High Temperature Cements

In the original screening tests a potassium silicate base high temperature cement (#65 cement) gave high friction with no surface damage under simulated braking conditions. Its wear rate under these conditions however was about four times that of a conventional brake material. Furthermore, a wear load test (Fig.4) showed that its wear rate increased rapidly as the load was increased, as did the friction coefficient.

Because of its apparent potential, a great deal of effort was spent in trying to improve the wear properties of 65 cement with the use of a variety of additives. The interest was not so much in this material but in demonstrating that such materials could be used as brake materials since they have the required high temperature capacity and thermal shock resistance. Samples were water quenched from 980°C without apparent damage. They, of course, have poor thermal conductivity; however, this is of less significance and may be compensated for by their higher temperature capability.

The cement powder and the additives were mixed with liquid binder and cast to size into acrylic molds. They were dried for 24 hours in air. The test buttons were then sanded flat for testing.

Several hundred specimens were prepared with metal, ceramic, and lubricating powders, fibers, cloths, gauze and inserts in various percentages. In this discussion, the results are given for only those which proved to be the most satisfactory in the "increasing load" wear test. These data are shown in Figure 9.

A variety of lubricating materials were considered. Many of these, such as PbO reacted with the cement and prevented its proper "set up". Others absorbed the water which prevented casting. It was also found that volume percentages of additives greater than 15% made the final product too weak to be practical. Successful specimens were made with 5, 10, and 15% of graphite,

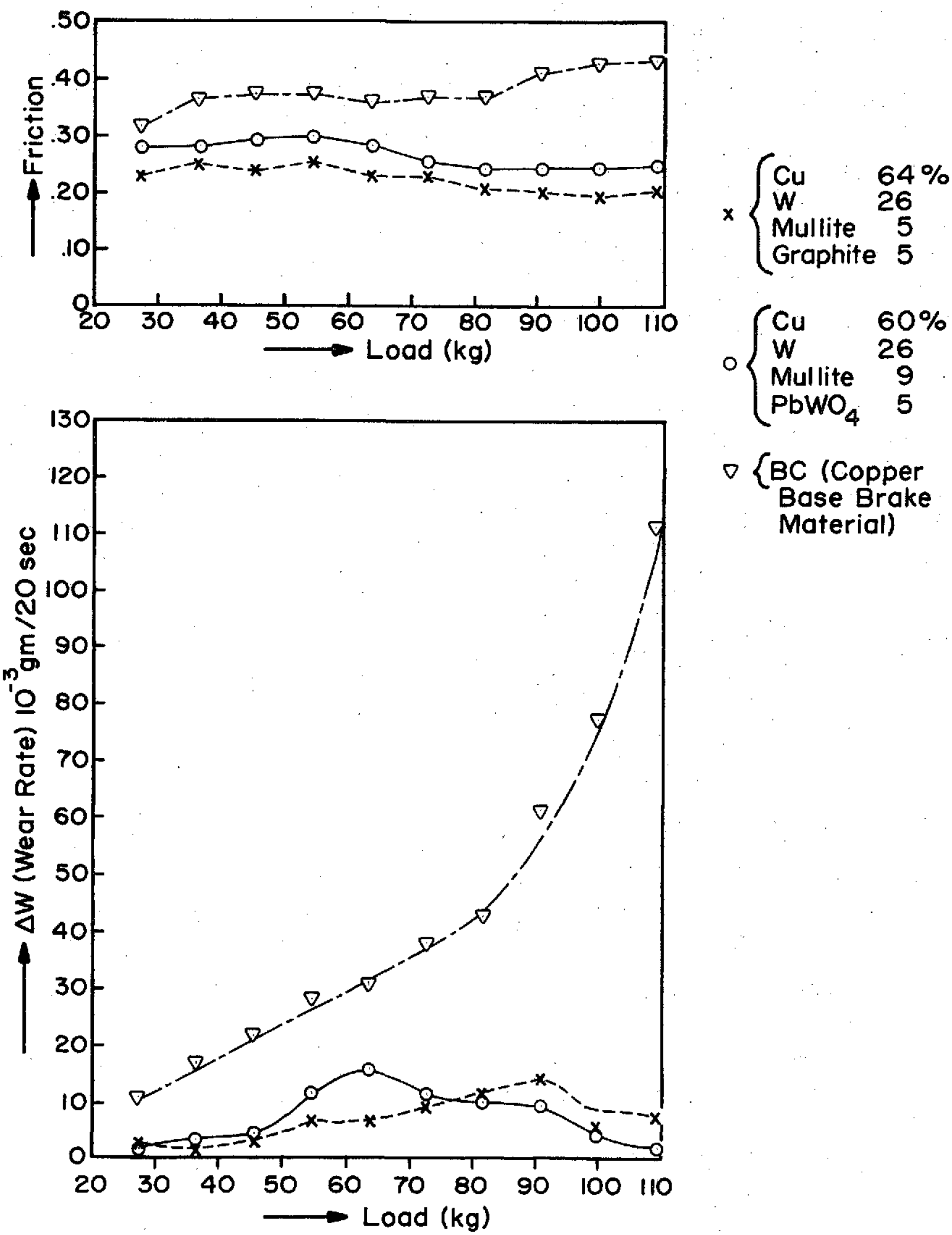


Figure 8. The Effect of Load on the Friction and Wear Behavior of Copper Bonded Tungsten Fiber Composite Materials.

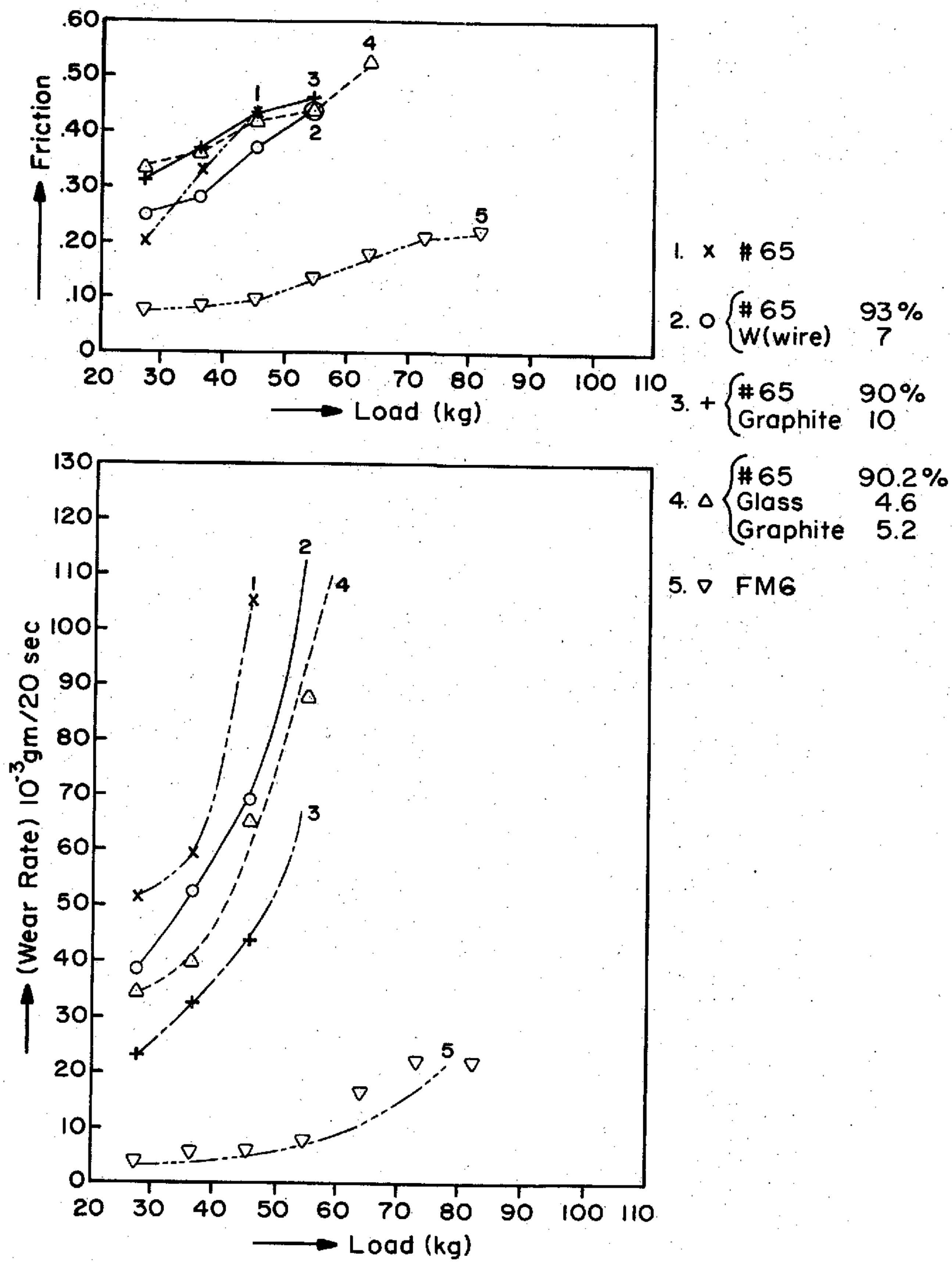


Figure 9. The Effect of Load on the Friction and Wear Behavior of Filled Potassium Silicate Cements.

$CuMoO_4$, CaF_2, $BaSO_4$, and WO_3. Tests showed that of these, only graphite (Fig.9) gave any significant wear reduction.

It was concluded that some strengthening additive must be found which eventually could be combined with the graphite for optimum surface behavior. Many approaches were tried. These consisted of fibers of CuFe, W, graphite, and glass; powders of Co, Al_2O_3, Cu, Monel, W, Mo, and WC; stainless steel gauze; and fabrics of glass and graphite. Screening tests were run and those indicating the greatest potential were evaluated in the "increasing load test". These are also shown in Figure 9.

It can be seen that only one approach (FM 6) gave any significant improvement over that for the graphite alone. This specimen was the 65 cement molded with large carbon chunks.

The difficulty with the cement materials was their poor strength. Additives in significant proportions made the resulting product weaker unless elaborate reinforcing techniques can be used, such as a three dimensional matrix. A much more "in depth" study would be required which takes into consideration the chemistry of the cement and its interaction with various additives. This could be undertaken if other approaches prove to be unsuccessful.

One additional approach was tried to determine the optimum concentration for such a matrix. Since graphite was the most suitable additive, various shapes of P5 carbon were cast into the 65 cement buttons. The resulting geometrics and volume percentages are shown in Figure 10. Also shown is the wear-load and the friction-load behavior. It can be seen that all the composites gave friction and wear values between those for the cement and the carbon alone. Twenty five to twenty nine percent carbon was needed to approach the carbon behavior with basically cement matrix. The interesting fact is that this is the amount of lubricant found necessary in later studies with the nickel matrix.

<u>Nickel Base Materials</u>

In the original selection of basic materials, it was preferred to work with monel (Cu-Ni) alloys because of their higher heat capacity and because copper would, by virtue of the formation of copper oxides, possibly give greater wear protection at higher temperatures. However, Nickel was found to have better sliding characteristics than monel, cobalt, iron and their alloys in the initial

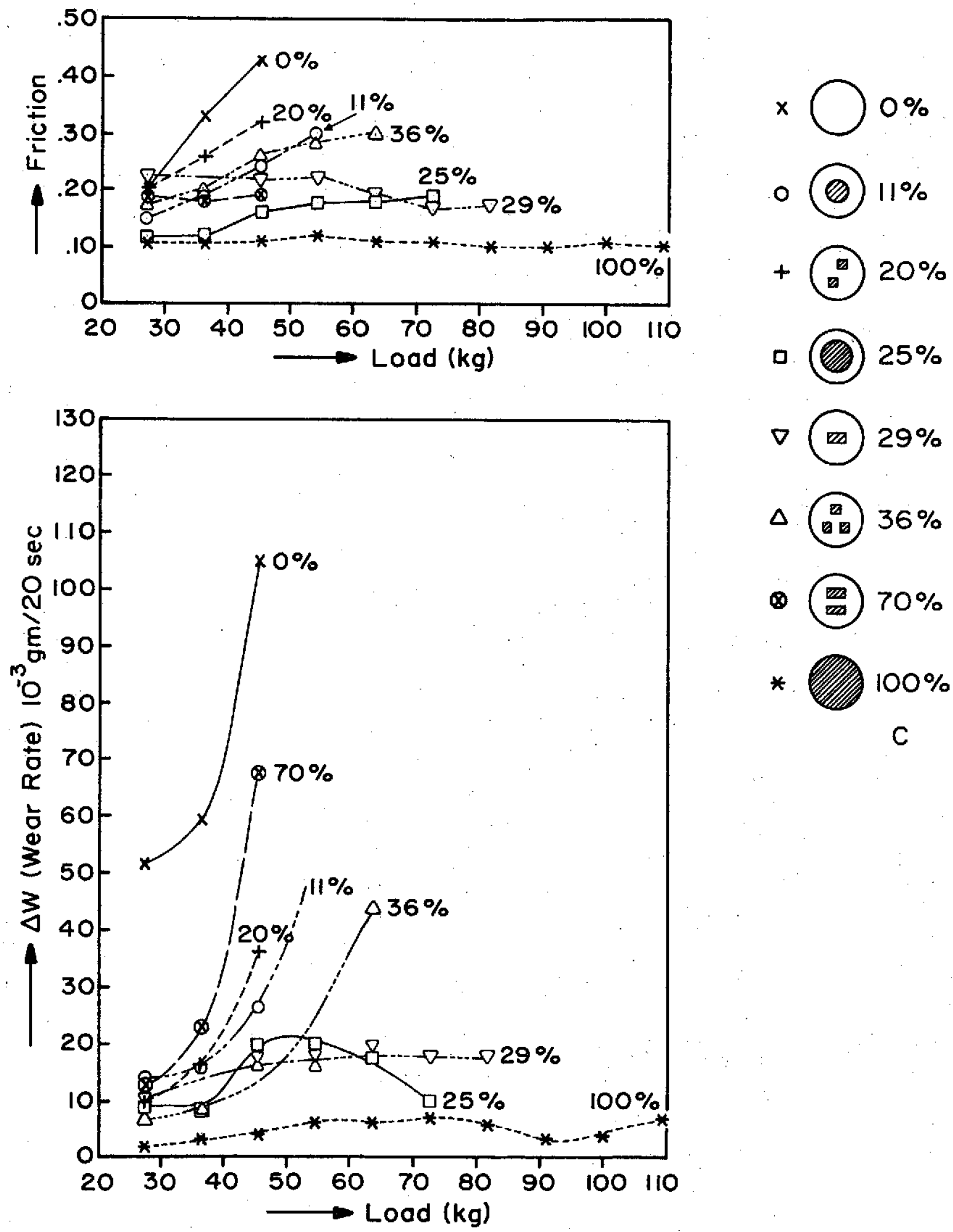


Figure 10. The Effect of Load on the Friction and Wear Behavior of a Potassium Silicate Cement Filled with Carbon Inserts.

screening tests. Furthermore, in trial experiments, the particular type of nickel used, was found to press to a higher density and sinter without cracking with typical additives. Accordingly, the approach taken was to concentrate on developing nickel into a suitable brake material with appropriate additives. Once this had been accomplished, the same additive package could be used for other metals, at least as a starting point.

As a first step in this investigation, 15% and 25% of a variety of additives were added to nickel and specimen prepared. The additives and the rationale of their usage were as follows:

Material	Mechanism of action
Al_2O_3, Mullite, SiC, SiO_2	Hard abrasive to prevent metal transfer
WC	Hard additive to prevent wear
Graphite, MoS_2, WO_3	Lubricants
Mo, W, Cu	Oxide lubricant formers
B, Si	Hardening Agents

With each of these specimens 1 second sliding tests were run under the conditions of the "time increment" tests. The short sliding time was chosen so that excessive damage would not take place and the equipment would not be damaged. For these tests the friction, surface damage, finish and the microhardness were measured after sliding. The results for the 15% additive are shown in Table 19. These results showed that only the Al_2O_3, graphite, mullite, and boron additions prevented metal transfer. Photographs of the sliding surfaces of these specimens are shown in Figure 11. Many of the additives improved the surface finish over that found for nickel alone; however, this was not considered to be significant if appreciable transfers occurred or the resulting material scratched the disk (as was found for silicon carbide and boron). Those materials, which gave the best surface finishes, were run under the same conditions (1 second sliding) only with 25% volume additions. These data are shown in Table 20. Essentially, the same results were found; the best additives to prevent damage were aluminum oxide, mullite, and graphite.

In order to determine the effect of the additives on wear, 5 second tests were run on the 15% additive materials. The surface finish of the specimen,

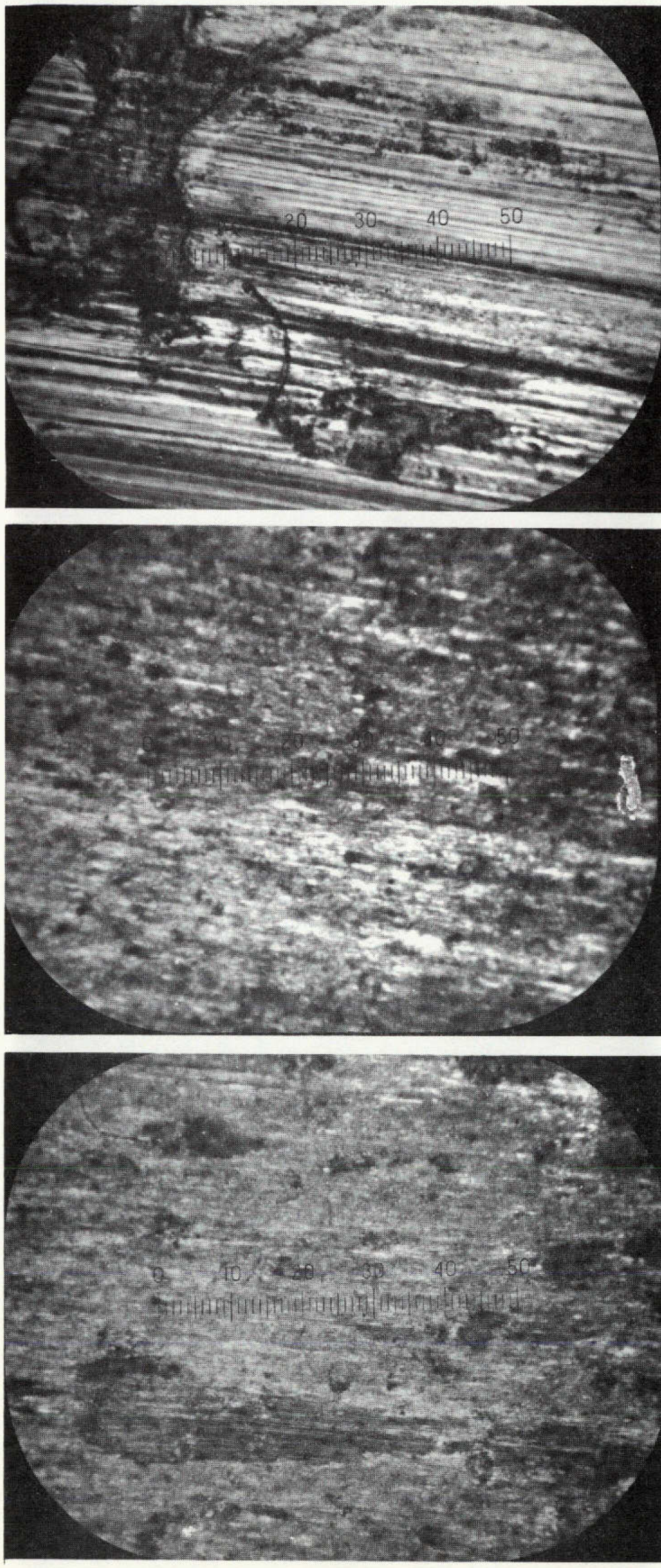
TABLE 19

NICKEL (85%) + ADDITIVE (15%) -

(AFTER 1 SECOND SLIDING AGAINST STEEL DISK)

ADDITIVES	M.P. (°C) OF ADDITIVES	f_1 *	SPECIMEN CLA	DISK TRANSFER
Al_2O_3	2050	0.29	44	very little
Mullite	1850	0.29	47	little
SiC	> 2700	0.15	33	little
SiO_2	1670	0.26	130	heavy
WC	2777	0.26	61	moderate
WO_3	1473	0.30	113	heavy
Graphite	3527	0.19	91	little
MoS_2	1185	0.18	38	moderate
Mo	2620	0.18	48	moderate
W	3370	0.29	78	moderate
Cu	1083	0.35	100	heavy
B	2300	0.22	23	very little
Si	1420	0.23	43	moderate

* Friction coefficient after 1 second of sliding



Ni 85%
Graphite 15%

CLA = 50

100×

Ni 85%
Al_2O_3 15%

CLA = 73

100×

Ni 85%
Mullite 15%

CLA = 78

100×

Figure 11. Photomicrographs of Sliding Surfaces of Ni Specimens with 15% Additives After 5 Sec. Screening Test.

TABLE 20

NICKEL (75%) + ADDITIVE (25%)

(AFTER 1 SECOND SLIDING AGAINST STEEL DISK)

ADDITIVES (25%)	M.P.(^oC) OF ADDITIVES	f_1	SPECIMEN CLA	DISK TRANSFER
Al_2O_3	2050	0.26	33	uniformly
Mullite	1850	0.32	50	moderate
SiC	> 2700	0.29	95	scratched and grooved
Graphite	3527	0.15	29	very little
MoS_2	1185	0.18	106	moderate
Mo	2620	0.22	58	moderate to heavy
B	2300	0.21	66	moderate to heavy
Si	1420	0.23	28	moderate

average wear of both specimens, friction coefficient, hardness after sliding and damage to the steel disk are shown in Table 21. The least damage to the steel disk was found for Al_2O_3, mullite, graphite and MoS_2. Apparently the MoS_2 needs the additional "run in" time. The lowest wear was found for graphite, boron, silicon carbide, and MoS_2; however, both the silicon carbide and the boron damaged the disk. The low wear with the boron additions was undoubtedly due to its high hardness. Differences in frictions coefficient were small except that the highest values were found with Al_2O_3 and mullite.

Based on the overall results of these tests, it was concluded that the most suitable additives would be some combination of Al_2O_3, mullite, graphite and MoS_2.

Attempts were made to obtain some correlation between hardness and the frictional behavior of the brake materials. In Figure 12 is shown a plot of initial hardness and hardness after sliding for the one and five second sliding tests with 15% additives. The additives are arranged on the abscissa in accordance with increasing levels of initial hardness. It is apparent that certain additives either increase or decrease slightly the hardness of nickel. Several points are of interest. Molybdenum and Boron increased hardness to much greater levels than the other additives indicating that some sort of a reaction (or other mechanism) had occurred during sintering. After sliding, a general increase in hardness of approximately 75 points results for nickel and nickel with all additives regardless of the initial hardness. Thus the phenomena can probably be attributed to the work hardening of the nickel surface. With the harder additives (SiO_2, SiC, WC, mullite, Si, W, Al_2O_3, and Mo) the hardness is higher after 5 second sliding than after one second sliding. If some sort of a reaction or intermetallic compound formation has <u>not</u> occurred, then this increased hardness could be attributed to the concentration of these additives in the surface. Further experiments, however, would be necessary to prove that such is the case.

Attempts were made to correlate friction, wear, and surface finish with the surface hardness after sliding. The results shown in Figure 13 demonstrate that no real correlation exists. Friction is seen to be independent of hardness and almost all values of wear and roughness result within a narrow hardness range indicating independence on this variable. The apparent correlation of increasing wear and increasing roughness with increasing hardness is based primarily on the data points for graphite and Si.

TABLE 21

NICKEL (85%) 2 ADDITIVE (15%)

(AFTER 5 SECOND SLIDING AGAINST STEEL DISK

ADDITIVES (15%)	f_5	WEAR 10^{-3} gm/5 sec	SPECIMEN CLA	SPECIMEN HARDNESS(V)	DISK TRANSFER
B	0.24	6.6	27	501	moderate to heavy
Mo	0.18	37.5	79	257	moderate
SiC	0.14	18.7	29	214	moderate to heavy
MoS_2	0.26	25.3	36	195	uniformly
W	0.25	54.0	75	218	heavy
Mullite	0.32	38.3	78	229	moderate to heavy
Si	0.19	82.7	92	283	heavy
WC	0.25	62.4	81	257	moderate
Al_2O_3	0.29	36.0	73	239	uniformly
Graphite	0.20	4.1	50	137	no transfer black film
SiO_2	0.20	359.6	300	177	very heavy

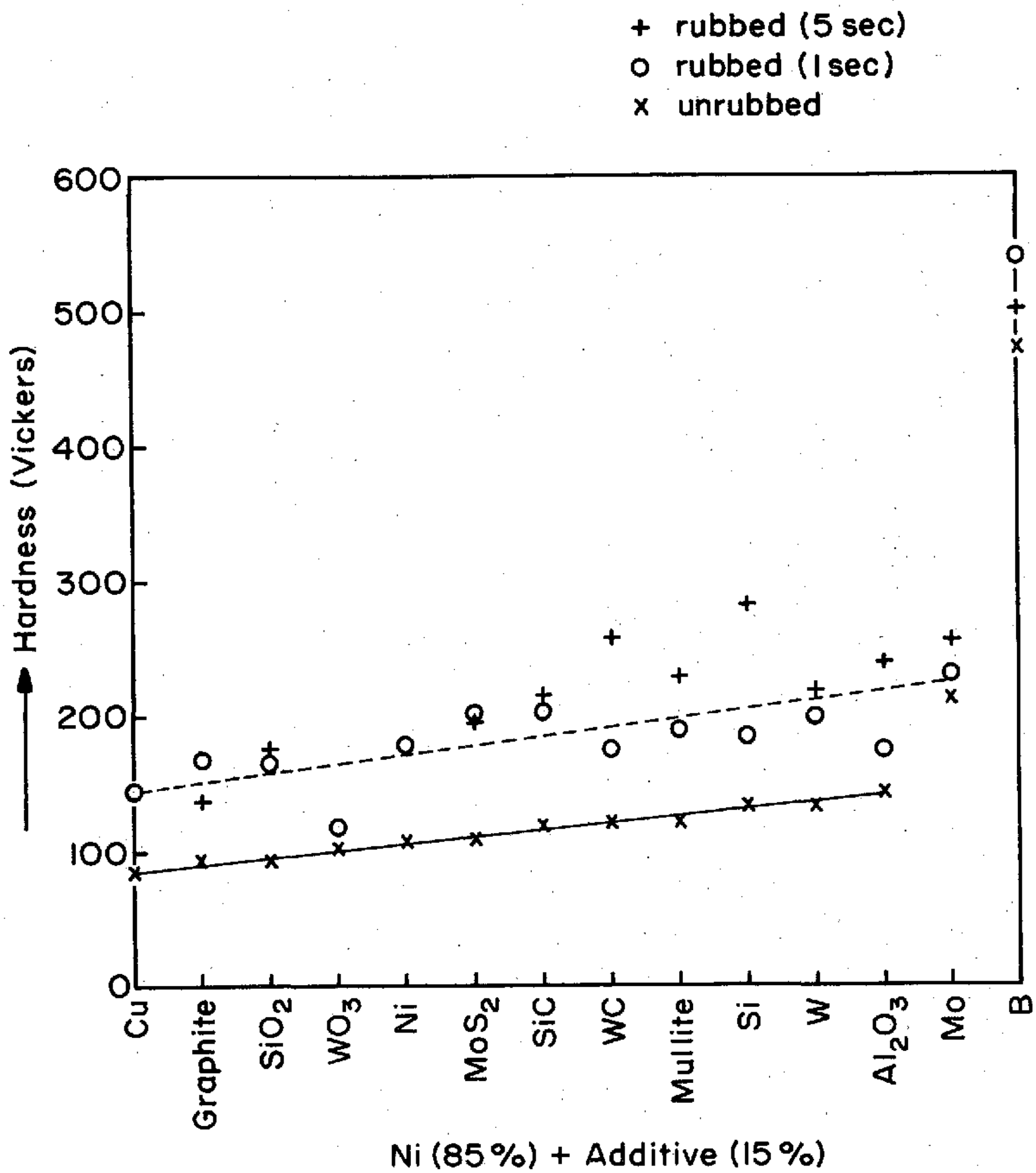
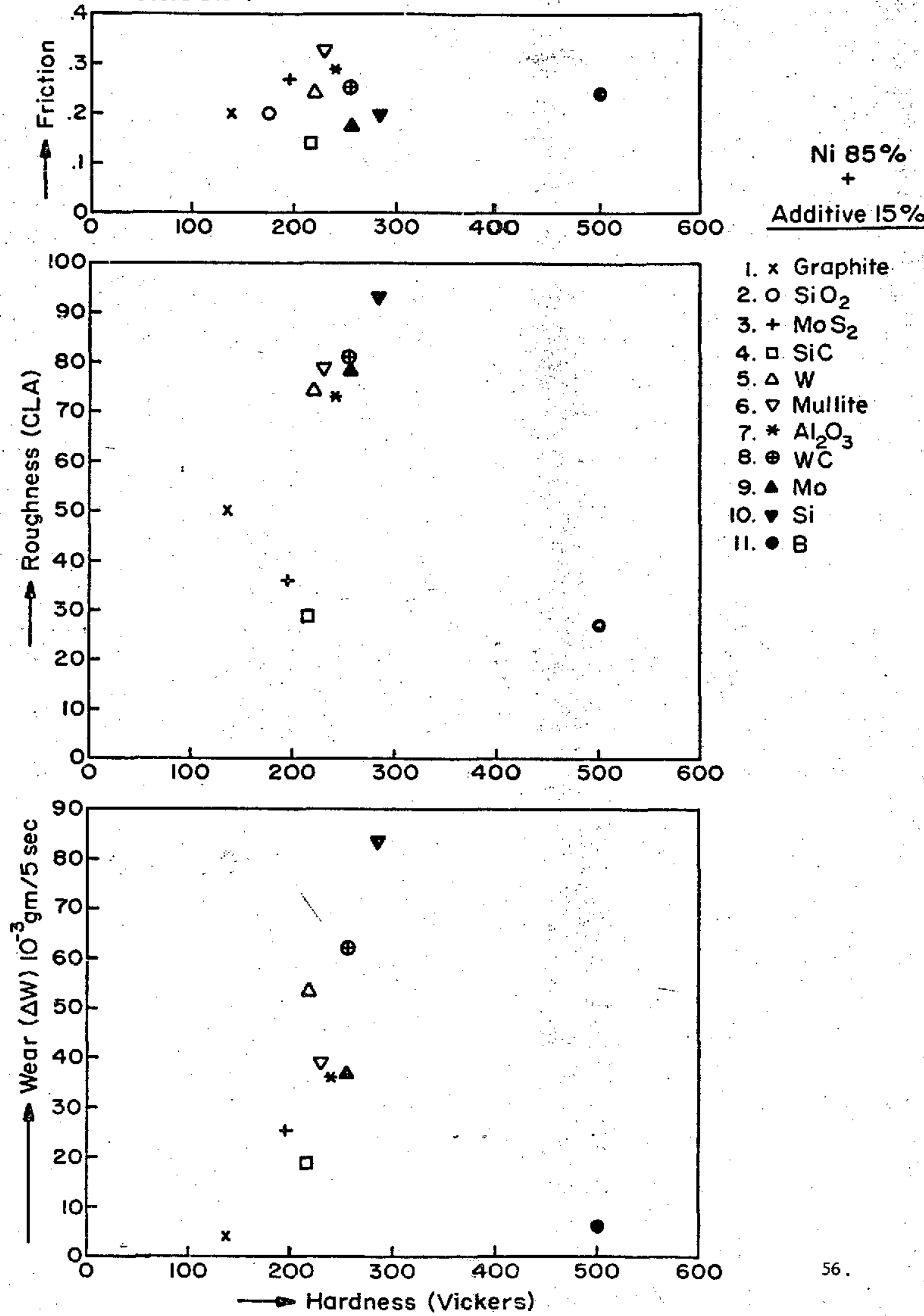


Figure 12. Hardness of Nickel Specimens with 15% Additives.

Friction, Wear and Roughness After 5 Sec. Sliding Against Steel Disk.



The intent of the previous study was to select the best additives. It was then necessary to optimize their quantity in nickel to achieve minimum wear under simulated braking conditions. This is not an easy task when multiple additives are anticipated since the optimum concentrations of one additive may be a function of the quantity of a second additive present. In order to circumvent this dilemma, various percentages of mullite were added to nickel and to nickel with 10% graphite and 5% $PbWO_4$. The graphite was added as a low temperature lubricant and the $PbWO_4$ as a high temperature lubricant. This selection was based primarily on the results with CuFe and Cu-W which showed this to be the optimum additive concentration. The results show that both with and without the other additives, the optimum volume ratio of mullite to nickel was 0.417.(Fig.14) This amounts to 70.5% Ni 29.5% mullite without the additives and 60% Ni, 25% Mullite with the additives. Although speculations could be made as to why the ratio should be constant, it was felt that sufficient data had not been taken to justify it. Accordingly, this ratio was accepted without further explanations.

Using a ratio of mullite to nickel of 0.417 by volume and 5% $PbWO_4$ a series of experiments were run with various ratios of graphite to nickel. The wear and friction data under standard conditions of sliding (20 sec 27 kilogram load 22m/sec velocity) are shown in Figure 15. It can be seen that increasing the graphite to nickel ratio decreases wear and increases friction slightly. The optimum ratio appears to be about 0.578 (27.5%). No further benefit was derived from increasing the concentration above 27.5%.

Finally using volume ratios of 0.417 $\frac{\text{Mullite}}{\text{Ni}}$ and 0.578 $\frac{\text{Graphite}}{\text{Ni}}$ the optimum ratio of $PbWO_4$ was determined using the same test conditions as in previous experiments. The results (Figure 16) show that wear changes only slightly as the amount of $PbWO_4$ is increased. There was steel transferred to the specimen when this ratio is greater than 0.3. Based upon these results the 5% volume concentration was retained $\left(\frac{PbWO_4}{Ni} = 0.105.\right)$

Thus the final concentration of additives was Ni 47.6% Mullite 19.8% Graphite 27.5% and $PbWO_4$ 5%. This is a high percentage of additives, however, it is similar to that for current brake materials (Cu 31% Mullite 22% graphite 32% others 15%. (Ref.8)

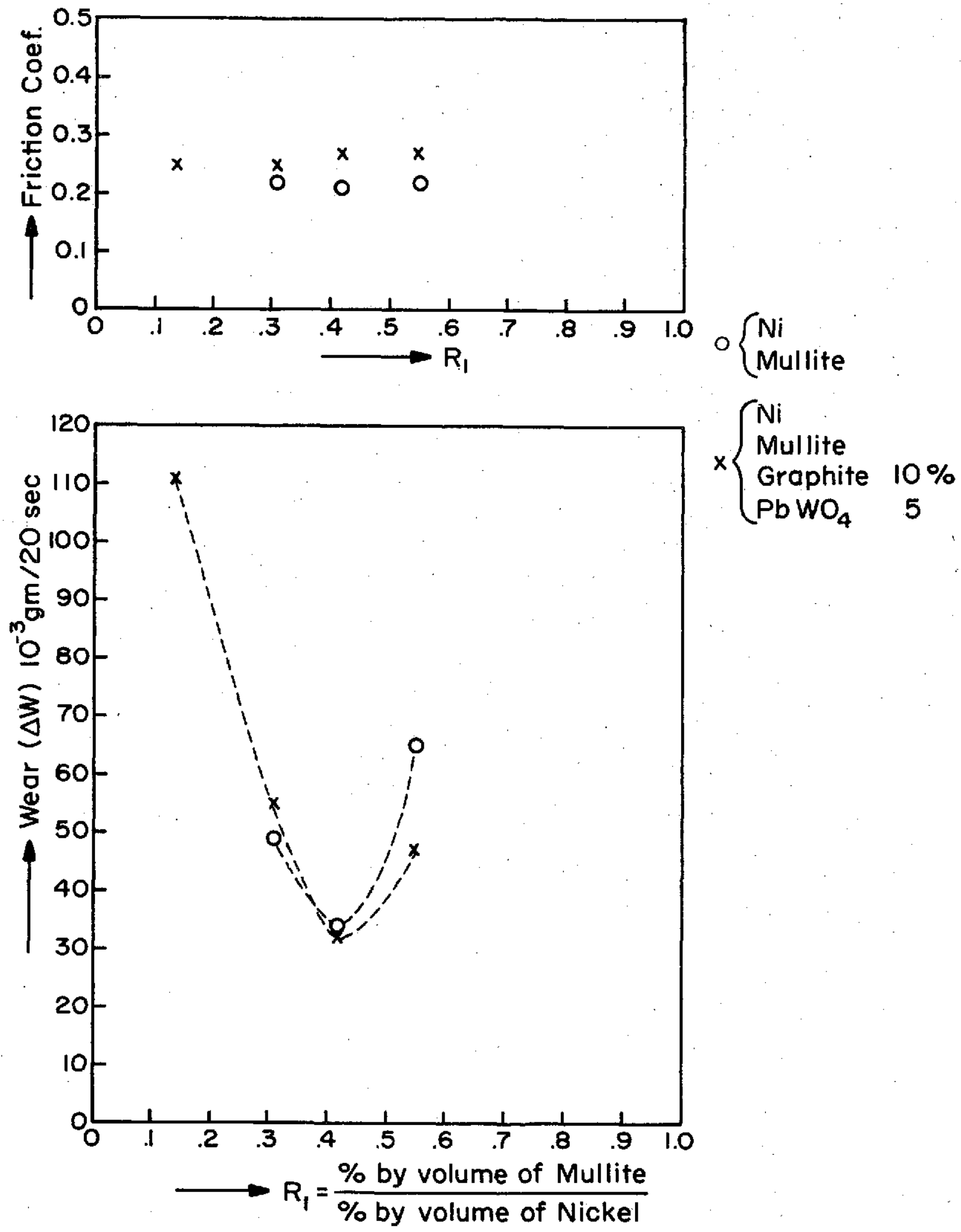


Figure 14. The Effect of Mullite Concentration on the Friction and Wear of Nickel and Nickel with Lubricant Additives.

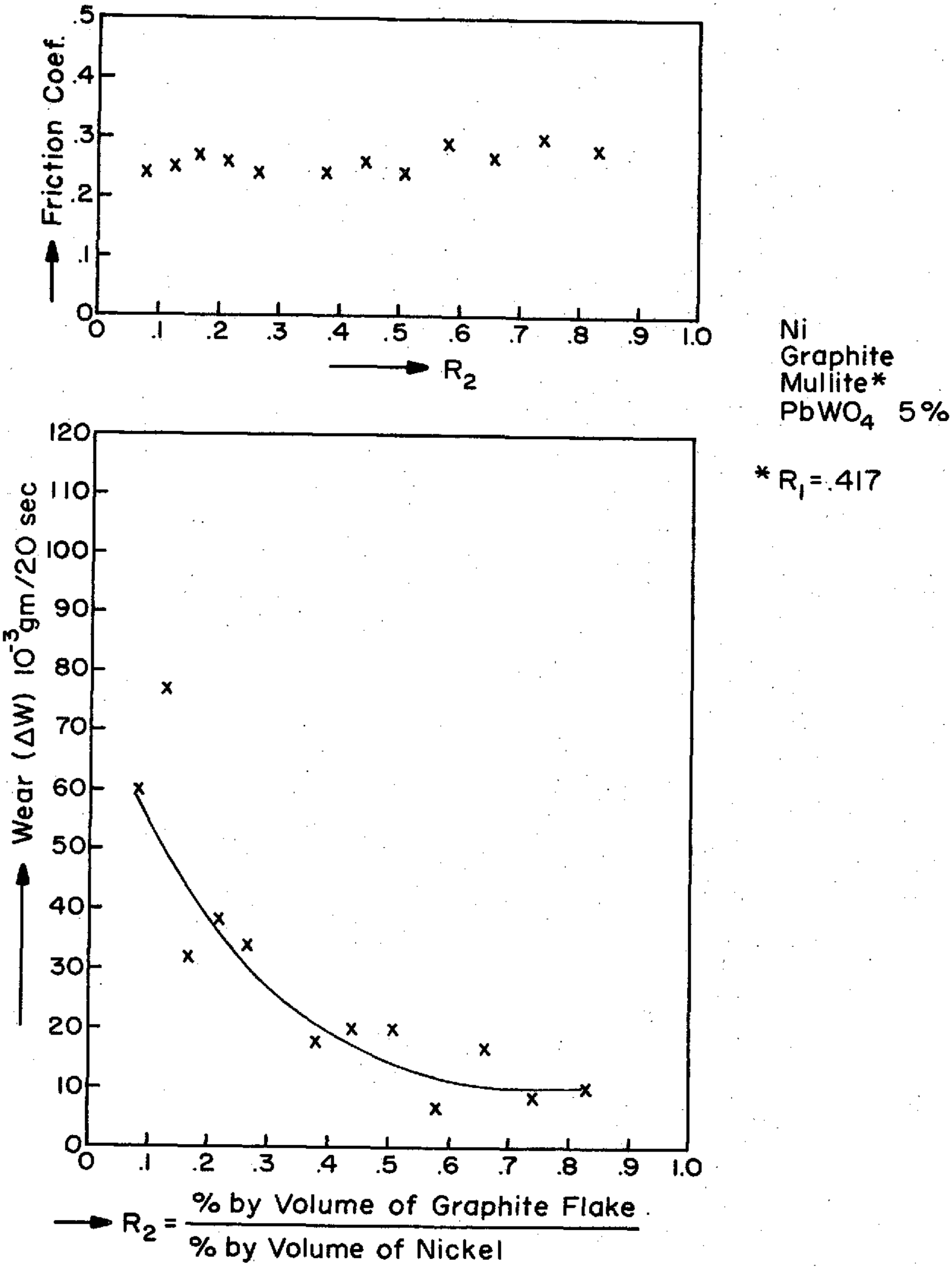


Figure 15. The Effect of Graphite Concentration on the Friction and Wear Behavior of Nickel, Mullite, $PbWO_4$ Composites.

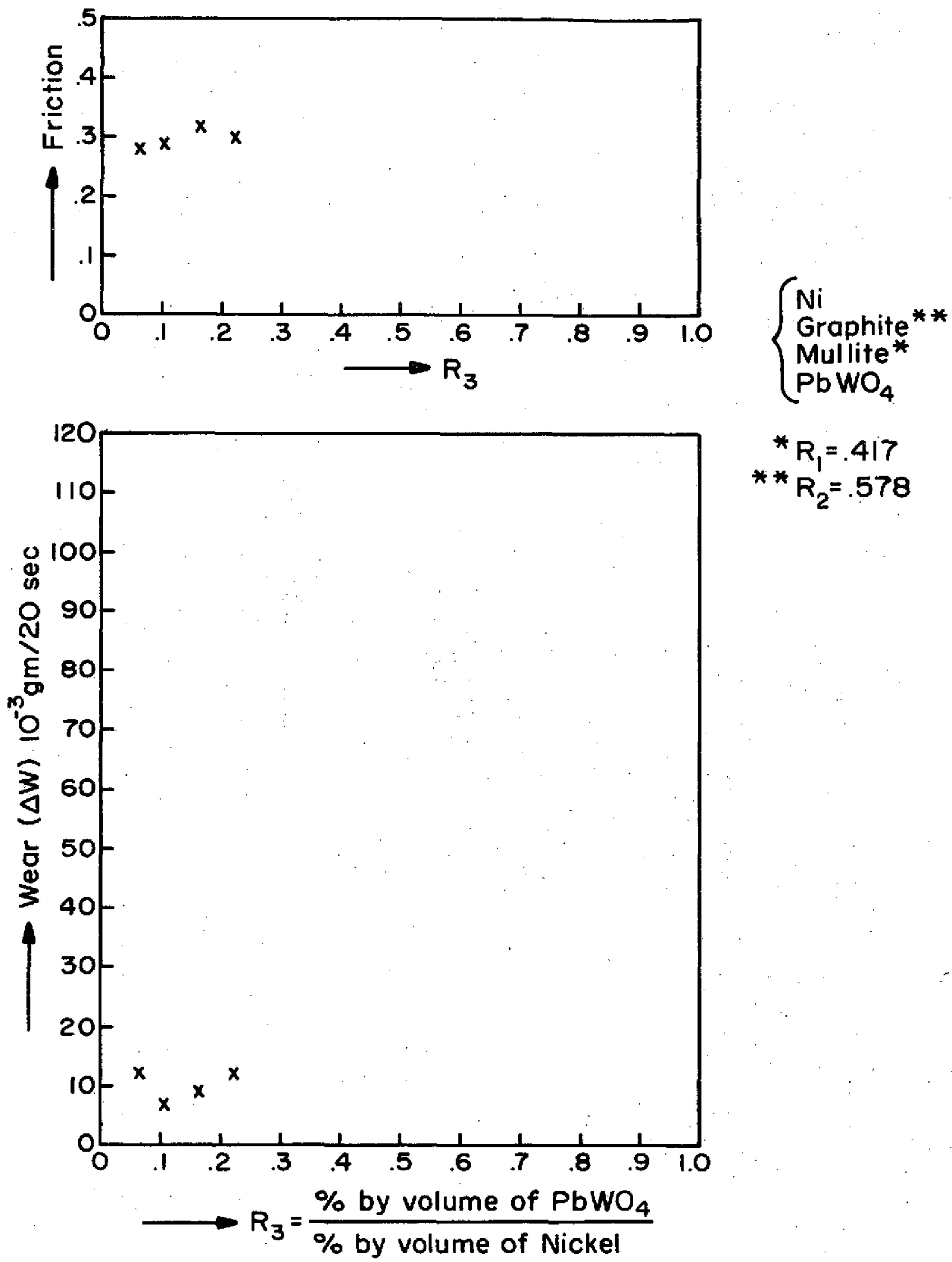


Figure 16. The Effect of $PbWO_4$ Concentration on the Friction and Wear Behavior of Nickel Graphite Mullite Composites.

It should be pointed out that the present button test, for which this material was optimized, does not reach the temperatures which could be encountered in an actual brake. If a higher temperature test was run, it might be expected that higher percentages of the high temperature lubricant ($PbWO_4$) might be necessary. This would reduce the nickel content and the graphite content.

Load tests were run on these combinations of materials. These data are shown in Figure 17. It can be seen that although the wear is lower than the brake material at low loads it is higher at increased loads. Because of this, attention was directed toward finding improved additives. Those selected were Al_2O_3 and MoS_2 based upon the initial additive experiments.

Using the 0.417 $\frac{\text{Mullite}}{\text{Ni}}$ ratio and the 5% $PbWO_4$ as was done for graphite wear-load tests were run for various $\frac{MoS_2}{\text{Nickel}}$ ratios. These data are shown in Figure 18. It can be seen that the minimum wear was obtained with the ratio of 0.510 (25% MoS_2) which was very similar to that found for graphite (27.5%). The load-wear curve for this material can be compared with that for the graphite material and the brake material in Figure 17. It can be seen that this material has somewhat higher load capacity than those. However, the differences are considered to be small and much more significant improvements were sought.

As a first step substitutions were made for the $PbWO_4$ since it was more or less arbitraily selected. Load tests were run (Figure 19) with 5% of $BaSO_4$, CoO CaO, CaF_2, and BaF_2. The results show that these additives yielded wear-load curves which were very similar to that found when no high temperature lubricant was added. The curves were also very similar to that found for the brake material. Apparently the wear-load curve with the $PbWO_4$ is very unique and higher loads do not yield increasing wear.

As a final step Al_2O_3 was substituted directly for mullite in the optimized ratios for nickel (Ni 47.6% Mullite 19.8% graphite 27.5% $PbWO_4$ 5% and Ni 49.4% Mullite 20.6% MoS_2 25% $PbWO_4$ 5%). The wear load curves for these compositions are also shown in Figure 17. It can be seen that each of these represent a significant improvement over the mullite and the brake material. The MoS_2 yields the lowest wear, however, it also has the lowest friction so it would have to be operated at higher pressures to obtain the same braking torgue.

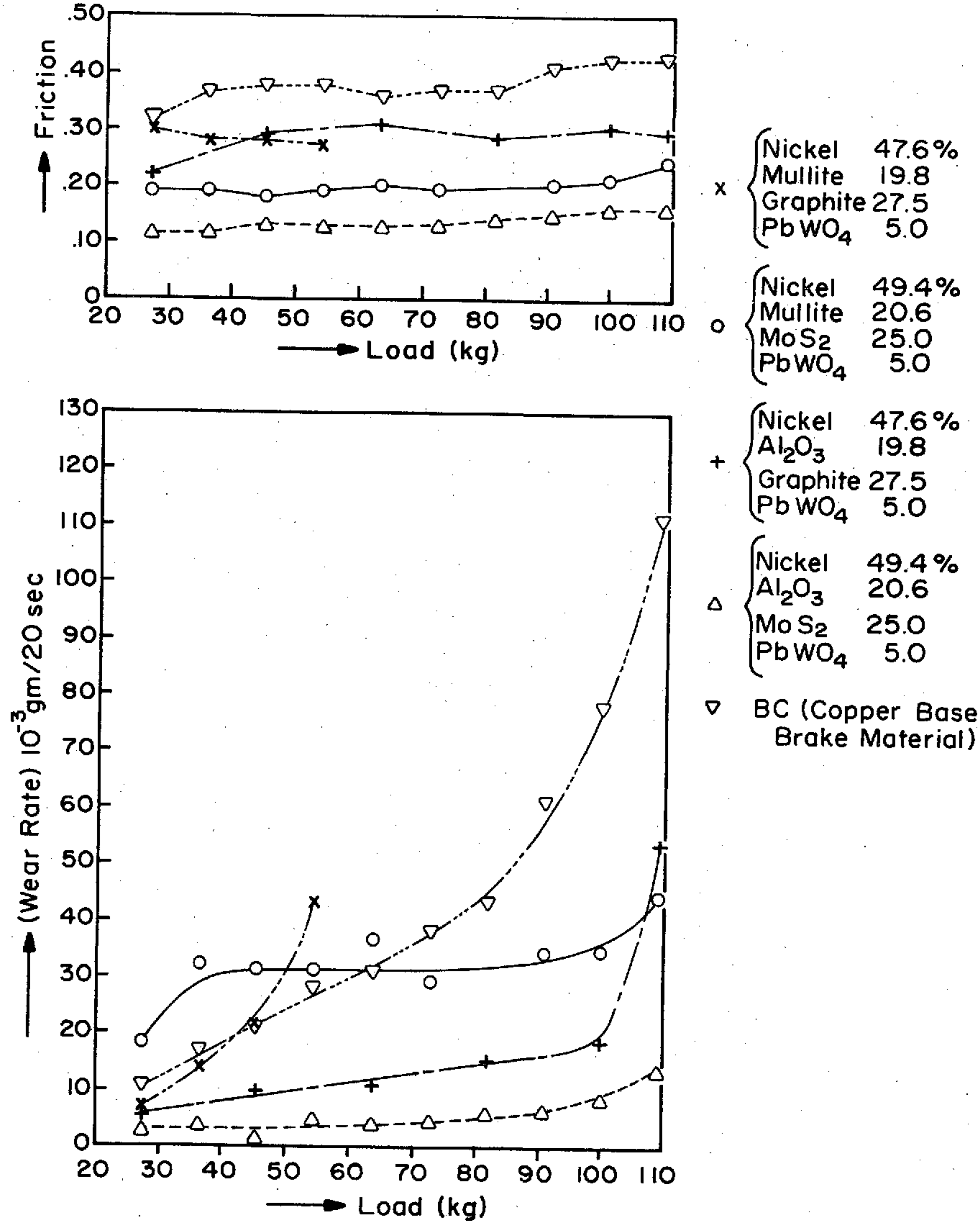


Figure 17. The Effect of Load on the Friction and Wear of the Most Promising Nickel Base Materials.

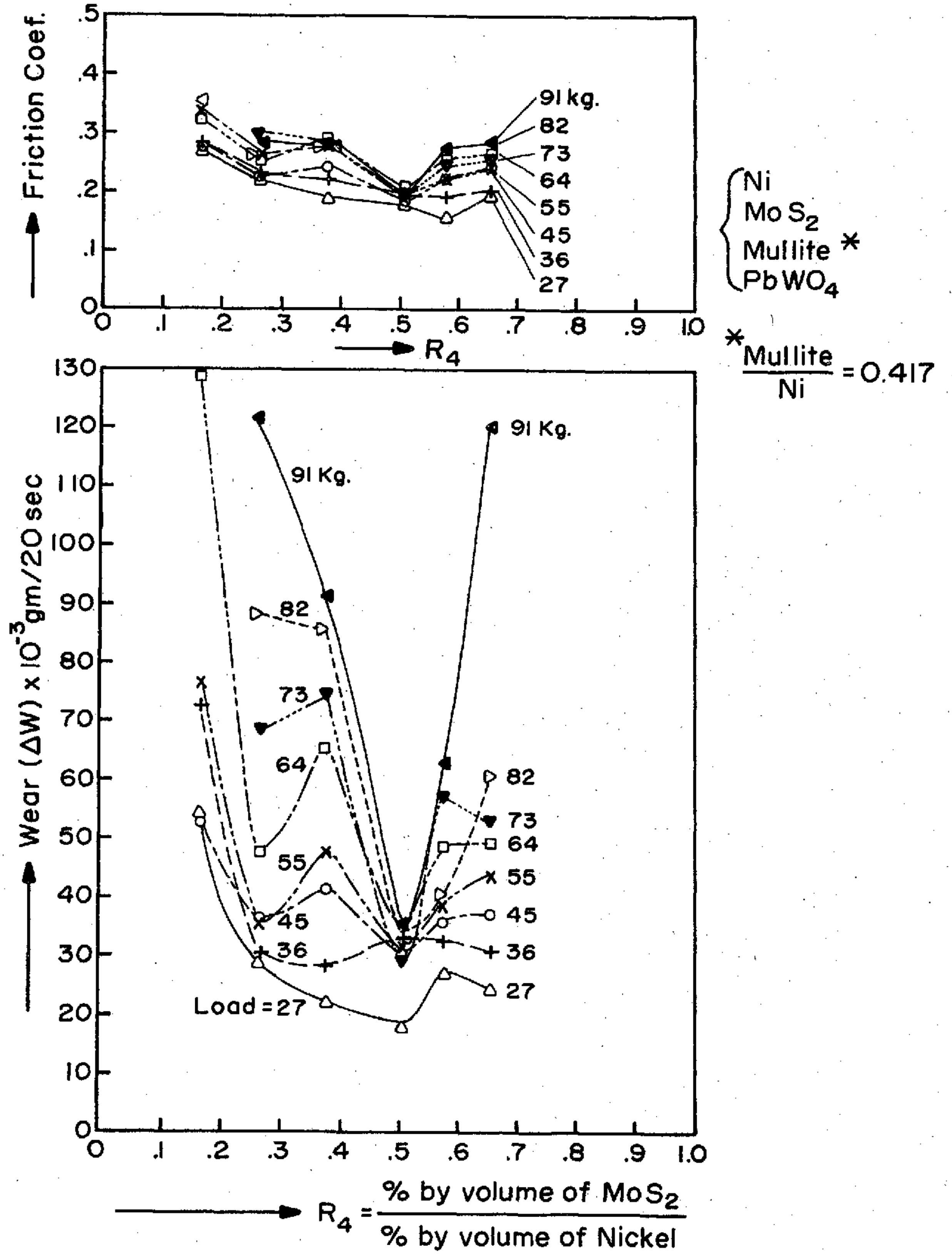


Figure 18. The Effect of MoS_2 Concentration on the Friction and Wear Behavior of Nickel, Mullite, $PbWO_4$ Composites.

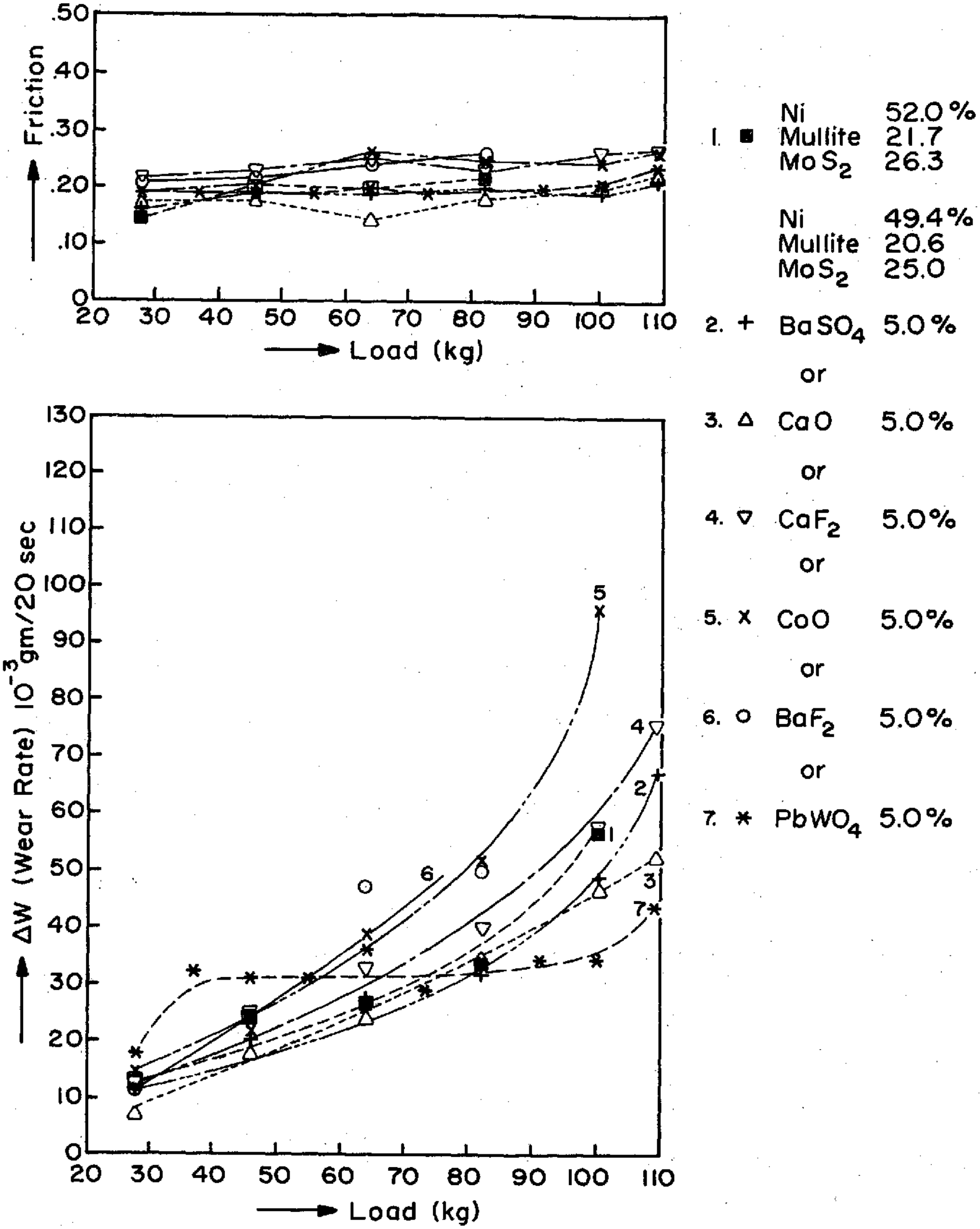


Figure 19. The Effect of Load on the Friction and Wear Behavior of Nickel, Mullite, MoS_2 Composites with Various Additives.

Further experiments were carried out with larger particle size Al_2O_3. These data are shown in Figure 20. It can be seen that there is very little difference between the compositions for either the MoS_2 or the graphite. Only one point (graphite 109 kilograms) is outside of experimental error.

Summary of Button Tests

A summary of the wear-load and friction-load behavior of the best materials found in this study is given in Figure 21. It can be seen that under the conditions of these tests a number of materials give improved wear performance over that found for conventional brake materials. These materials have been discussed in detail in previous sections of the report but further comments can be made. Of these materials it is difficult to say which is the most practical. The nickel base materials (especially with graphites) are very similar to the present copper base materials and might be considered a direct substitute for them. The LPA 100/Mo is a commercial material and should have adequate strength to extremely high temperatures. It may have lower friction at higher temperatures but this can be compensated for by an increase in load or by material modifications. The carbons too have low friction and may need to be contained to prevent fracture.

In addition to these questions other practical questions will have to be answered, such as cost, which were beyond the scope of the present investigation. Long term effects will have to be investigated since the present tests were conducted with the materials in their original conditions. It can be asked if the wear rate would be the same after soaking at high temperatures.

It should be pointed out that the intent of the tests was merely to screen potential combinations of materials. Optimization for these conditions does not mean optimization for an actual brake which sees a whole variety of conditions, some of which are unique to it. Thus the conclusion drawn from this investigation is a limited one, which suggests certain material approaches. Further investigations using an actual brake are planned.

In the meantime in order to gather some data under higher energy inputs into the disks, pad tests were run as described in the following section.

Pad Tests

Button tests are an effective screening technique since they allow running a large number of tests; this is necessary when there are so many variables to

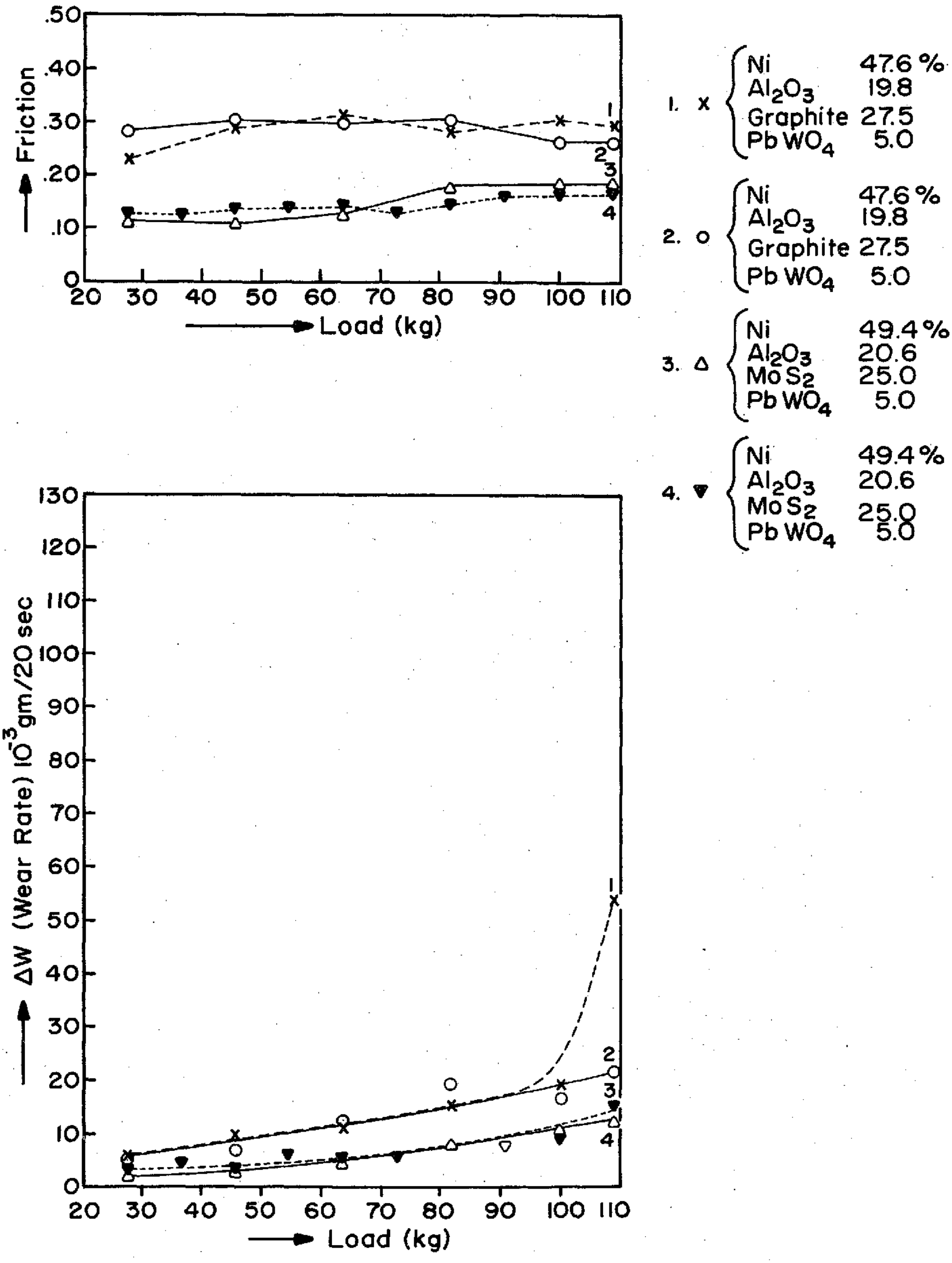


Figure 20. The Effect of Load on the Friction and Wear Behavior of Nickel Base Materials with Larger Particle Size Al_2O_3.

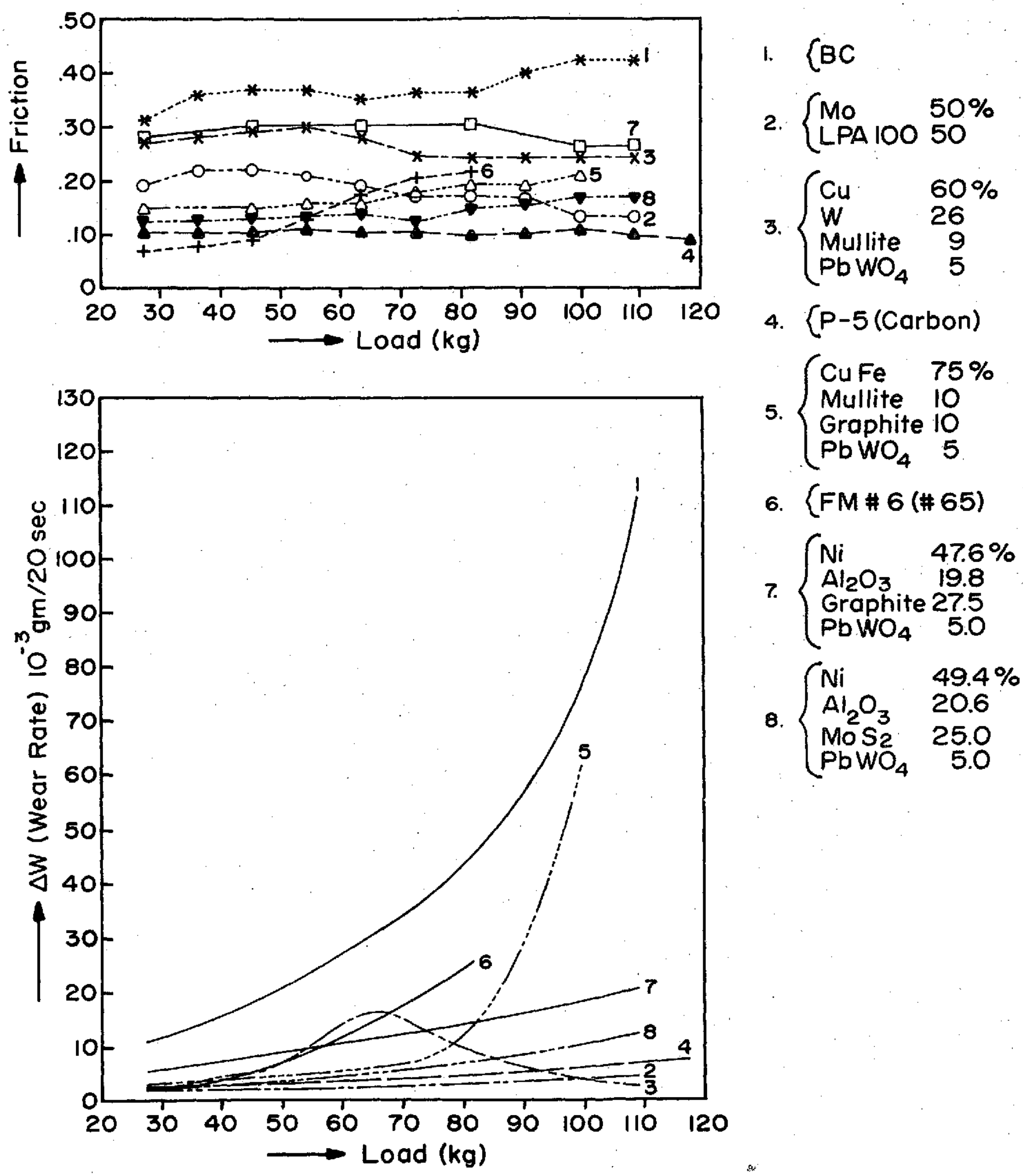


Figure 21. A Summary of the Load Tests of the Best Suggested Materials Compared with the Load Test for Copper Base Brake Material.

optimize. However, these tests do not simulate the most severe temperature braking conditions. It can be argued with some justification that wear may be more severe at lower temperatures since there are no surface protecting oxides, however, at higher bulk temperatures the material softens and wear may increase.

In order to evaluate these materials under conditions of higher energy inputs into disk (higher disk temperatures) pad tests were run. A drawing of the pad is shown in Figure 22. Essentially it consists of three buttons mounted in a triangular arrangement in an aluminum base. They are held in place with an interference fit, however set screws are also provided. Each button contains a thermocouple mounted at its center 1.59 mm from the surface. This allows the chosen materials to be evaluated on a temperature basis as well as on a load basis. The sliding direction (as shown) is chosen to eliminate overlapping of the track.

This specimen arrangement allows the test to be run at three times the load for a single button test, however, it was also chosen for other reasons. It may be a practical method of mounting the brake material in service. Work reported elsewhere (Ref.10) has shown that contact with the complete pad only takes place at isolated points which shift about on the pad due to thermal distortions. These thermal distortions cause the brake material to fracture and wear. The button arrangement avoids flexture in the brake material and concentrates it in the aluminum backing. Furthermore, the length of the sliding path is short on a button which restricts heat buildup and provides for air cooling around the specimens. In an actual brake this same pattern of buttons would be repeated in disk form.

The results of the load tests on several materials are shown in Figure 23. Ten, twenty second engagements, were made at each load using a given pair of pads. The average wear per engagement is plotted in the figures. It can be seen that the new materials give lower wear rates than a conventional brake material. When plotted on a temperature basis (which takes into account the frictional differences) (Fig.24) similar results are observed, however, the difference between the brake material and Ni/mullite are much smaller. The Mo/LPA 100 and the Ni/AL_2O_3 are capable of operating to higher temperatures than the conventional brake material.

There also appears to be two regions of wear. At low temperatures wear is more or less independent of temperature. At high temperatures the wear is directly proportional to temperature.

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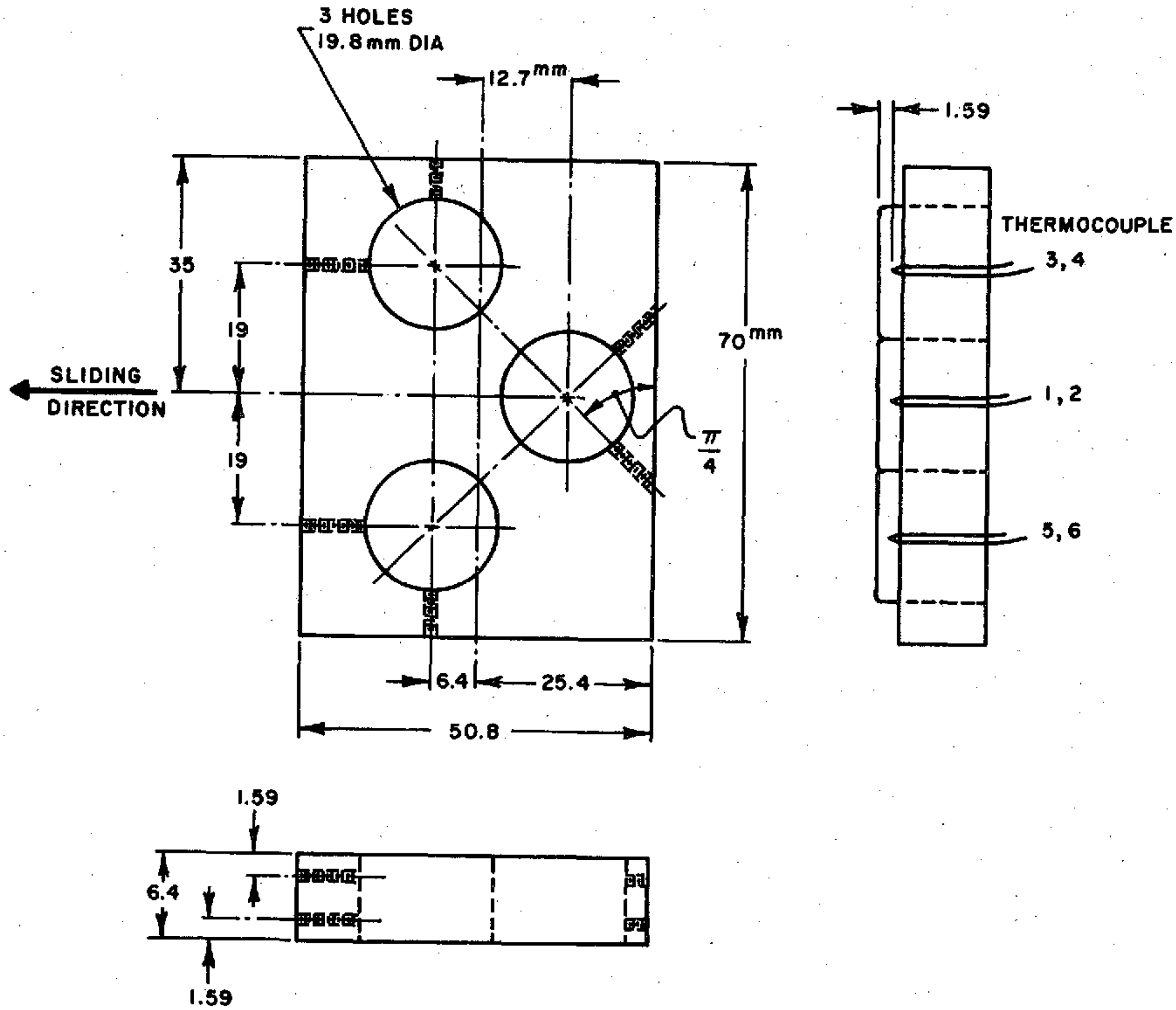

Figure 22. Friction Pad.

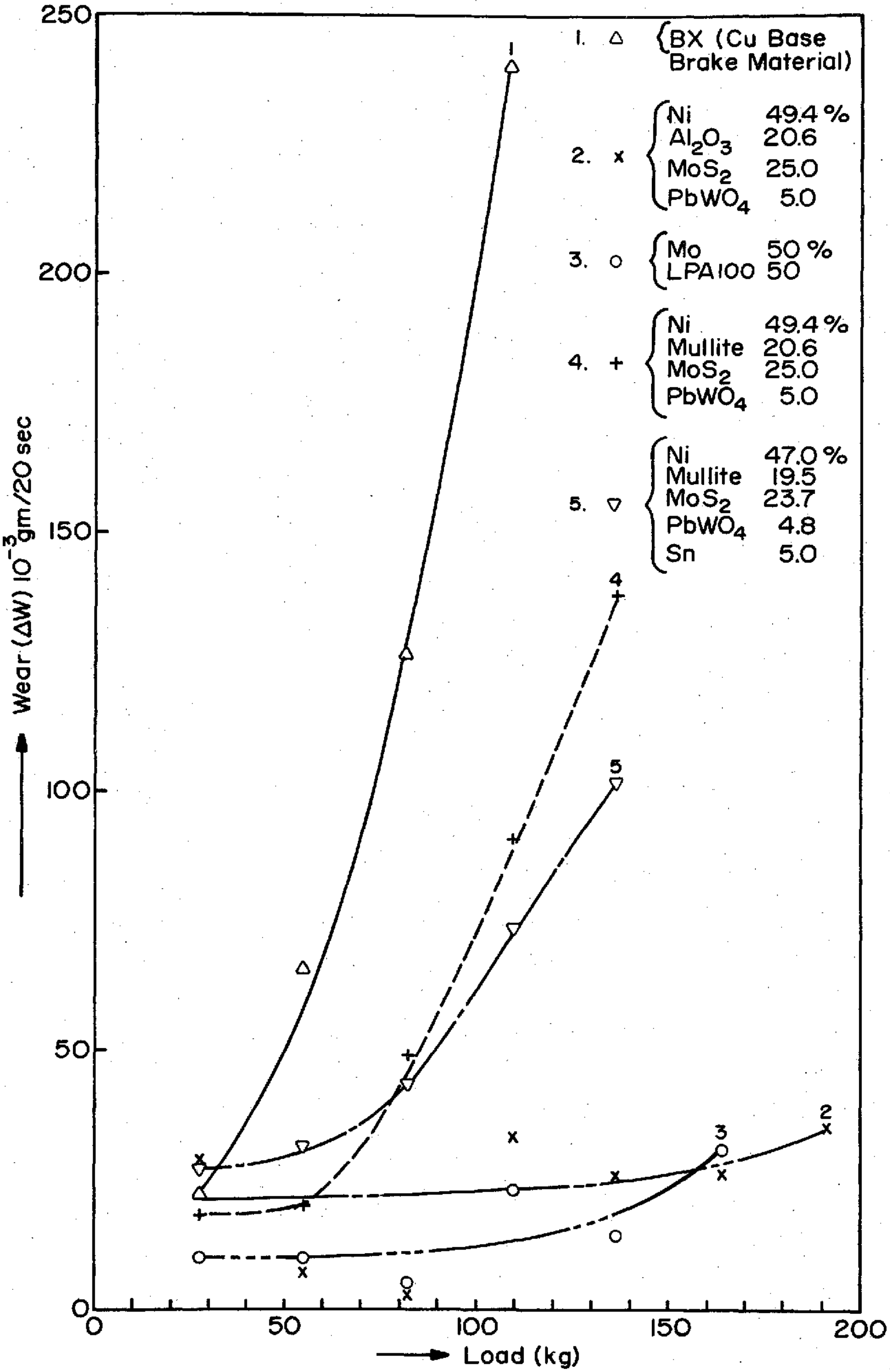

Figure 23. A Summary of the Pad Tests (Wear Rate vs. Load).

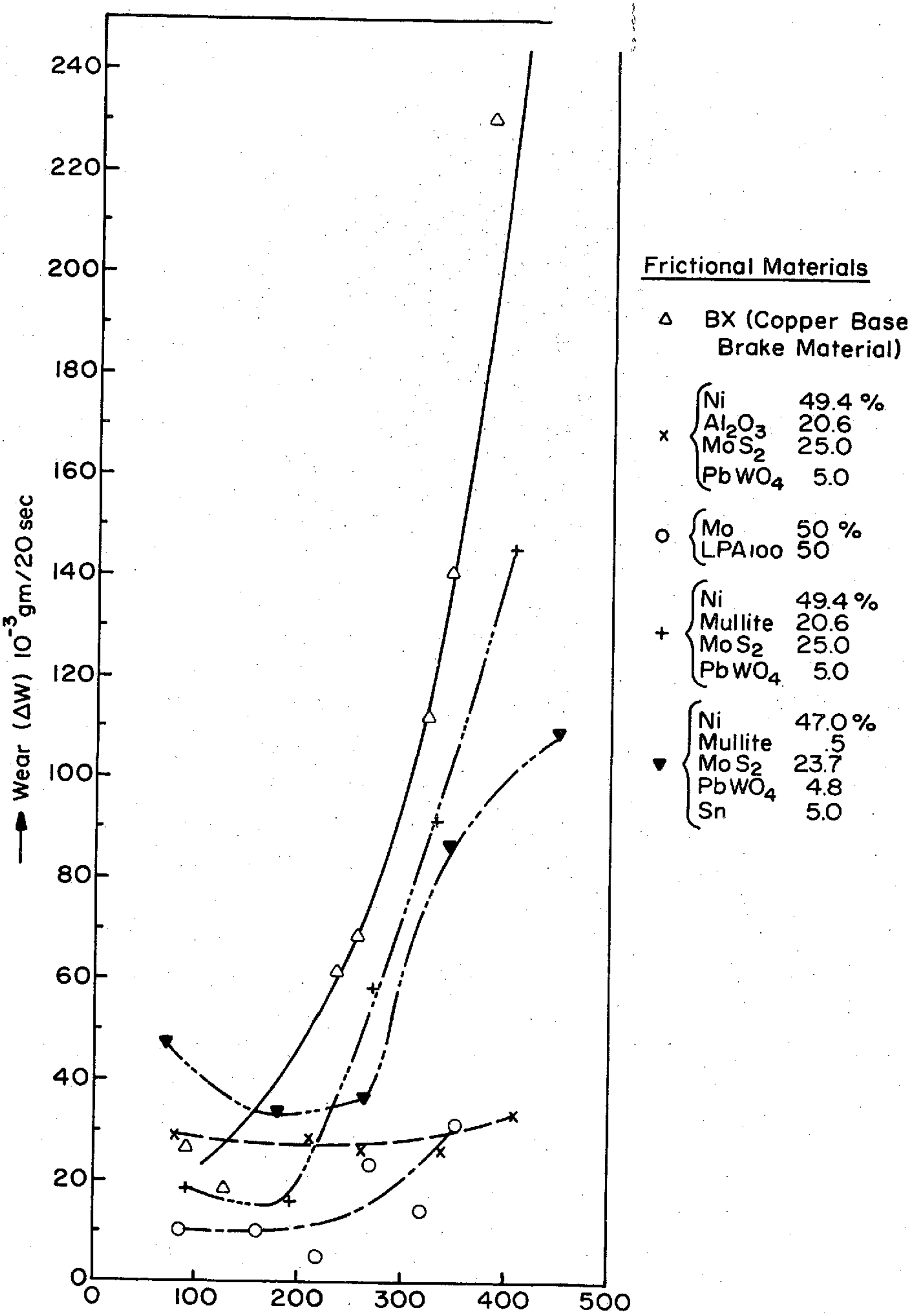

Figure 24. A Summary of the Pad Tests (Wear Rate vs. Temperature).

SECTION 7

SUMMARY OF RESULTS

An investigation to develop improved aircraft brake materials has been conducted. Under the conditions of the tests the following results have been obtained.

(1) Based upon properties of materials and their sliding behavior against steel the following materials appear to have the greatest potential for improved brake materials: Nickel, molybdenum, tungsten, carbon, ZrO_2, and High Temperature cements.

(2) Improvement in wear behavior resulted from the incorporations of tungsten fibers into copper base materials.

(3) A high temperature potassium silicate based cement filled with graphite gave good wear and friction behavior but in its present form did not have adequate strength.

(4) A Nickel base material consisting of Nickel (47%) Al_2O_3 (20%) graphite (28%) and $PbWO_4$ (5%) and Nickel (50%) Al_2O_3 (20)% MoS_2 (25%) $PbWO_4$ (5%) gave the best high temperature wear behavior.

(5) A molybdenum base material which included 50% of an intermetallic compound (Co Mo Si) also gave excellent wear behavior.

(6) Carbon gave the best wear behavior of all materials studied.

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THE FOLLOWING PAGES ARE DUPLICATES OF ILLUSTRATIONS APPEARING ELSEWHERE IN THIS REPORT. THEY HAVE BEEN REPRODUCED HERE BY A DIFFERENT METHOD TO PROVIDE BETTER DETAIL