

Small Oil-Free Bearings

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An investigation was made of materials that may be suitable for use as oil-free bearings in aircraft clocks and similar instruments between -55° and $+70^{\circ}$ C, to replace lubricated jewels that do not give satisfactory operation at subzero temperatures because of congealing of the oil. Another advantage of an oil-free instrument is the freedom from cleaning and oiling periodically during shelf storage. Materials included in the investigation were plastics, plastics with fillers, impregnated metals, and impregnated carbon. Friction tests were made with an inclined-plane type of static-friction apparatus, and with shafts rotating in loaded journal bearings, at temperatures from -55° to $+70^{\circ}$ C. With bearings of typical materials stored on steel shafts, the effect of shelf storage on static friction was investigated. Wear tests were made with loaded bearings on $\frac{1}{4}$ -inch-diameter rotating shafts made of different types of steel. With oscillating $\frac{1}{4}$ -inch-diameter shafts and 1,000-gram loads, wear data were obtained on bearings of the more promising materials. Using an endstone wear testing machine, wear data were obtained for end-thrust bearings made of typical bearing materials. The performance of oil-free bearings in 18 timepieces was investigated.

1. Introduction

It is essential that aircraft instruments and devices operate satisfactorily over a wide temperature range. At subzero temperatures, increased viscosity and congealing of lubricating oils result in high friction with lubricated bearings. In aircraft clocks, similar jeweled instruments, and some mechanical fuzing devices, the power supplied for normal operation is not sufficient to overcome the excessively high friction at low temperatures. Some devices may be made to operate at low temperatures by having a surplus of power supplied, but this is not feasible in timepiece mechanisms. The nonspreading watch and clock oils conventionally used for lubricating jewel (sapphire) bearings are not satisfactory at -50° C, and at ordinary temperatures the necessity of periodic cleaning and oiling during shelf storage and during service is not desirable.

Because of the unsatisfactory performance of lubricated aircraft clocks at low temperatures, a project¹ was initiated to investigate materials that may be suitable for use as oil-free bearings in timepieces, between -55° and $+70^{\circ}$ C, to replace jewels that require lubrication. In addition to the primary objective of satisfactory operation at low temperature, another important advantage of an oil-free timepiece is freedom from cleaning and oiling periodically during shelf storage.

Bearing materials included in the investigation were plastics, plastics with fillers, impregnated metals, and impregnated carbon. Corrosion-resistant shaft materials were investigated. The work consisted of investigations of the friction and the wear characteristics of the materials, and trial of the more promising materials in timepieces.

¹ This project was initiated in October 1951, and was sponsored by the Bureau of Aeronautics, Department of the Navy.

2. Bearing Materials

The bearing materials tested are identified by sample number and composition in table 1. The percentages given are approximate; they are computed either from the densities of the samples and the densities of the ingredients, or from the composition of the suspension or dispersion as given by the manufacturer in conjunction with the known amount of fillers added. In some cases the samples from commercial firms are specially prepared materials; in other cases they are products that the manufacturers considered promising for the application.

For convenience, the abbreviations PTFE and PTFCE are used in this paper to symbolize polytetrafluoroethylene and polytrifluorochloroethylene, respectively.

2.1. Plastics

The low-friction characteristics of PTFE (polytetrafluoroethylene) were largely responsible for the inception of this project. This resin [1]² is waxy in appearance, and white or gray in color, except that thin sheets are transparent. It is a crystalline solid with good stability from -320° to $+500^{\circ}$ F, and is chemically inert to known reagents and solvents except molten alkaline metals and gaseous fluorine under pressure. Its relative softness and poor heat conductivity limit its suitability as a bearing material to applications involving low speeds and low unit pressures.

The PTFCE (polytrifluorochloroethylene) used in this investigation is a relatively hard thermoplastic, with good stability from -320° to $+375^{\circ}$ F. It is chemically inert to most organic solvents and reagents. It may vary from the amorphous to the crystalline state, depending largely on the rate of cooling in its preparation [2]. The amorphous material is transparent; and crystalline material is

Figures in brackets indicate the literature references at the end of this paper.

TABLE 1.—Bearing material

Sample	Material
101	Polytetrafluoroethylene (symbolized by PTFE).
102	Polytrifluoroethylene (symbolized by PTFCE).
103	Nylon, molded.
103a	Nylon, sintered and machined.
103b	Nylon, resintered after machining.
104	Polyethylene, high density, experimental.
201	No. 101+fiber glass+pigment.
202	No. 101+73% (40% vol) molybdenum powder.
202a	No. 101+85% (58% vol) molybdenum powder (0.5 to 5 μ).
202b	No. 101+82% (54% vol) molybdenum powder (0.5 to 5 μ).
202c	No. 101+85% (31% vol) molybdenum powder (0.5 to 5 μ).
203	No. 101+70% (33% vol) silver precipitated flowers.
204	No. 101+graphite.
204a	No. 101+graphite.
205	No. 101+copper powder.
206	No. 101+molybdenum disulfide.
206a	No. 101+61% (42% vol) molybdenum disulfide.
207	No. 102+graphite.
208	No. 101+50% (50% vol) tungsten powder (0.5 to 5 μ).
208a	No. 101+78% (29% vol) tungsten powder (0.5 to 5 μ).
209	No. 101+glass+molybdenum disulfide.
210	No. 101+glass.
211	No. 101+18% TiO ₂ +4% polymethylsiloxane.
212	No. 101+18% TiO ₂ +11% chlorinated biphenyl.
213	No. 102+molybdenum disulfide.
214	No. 102+14% (37% vol) No. 101+84% (28% vol) Mo (0.5 to 5 μ).
216	No. 102+60% No. 101, fused at 500° F.
216a	No. 102+60% No. 101, fused at 650° F.
218	First sample of No. 222, fused and molded again at NBB.
217	No. 101+28% (18% vol) titanium dioxide.
218	No. 102+61% No. 101+10% glass, fused 500° F, 13,000 psi.
218a	No. 102+51% No. 101+10% glass, fused 500° F, 3,000 psi.
219	No. 102+51% No. 101+13% chromium tetrahydrate.
220	No. 101+70% (34% vol) Mo+8% chromium tetrahydrate.
220a	No. 101+33% (20% vol) Mo+16% chromium tetrahydrate.
221	No. 101+glass+red pigment.
222	No. 101+glass+other fillers.
223	No. 101+glass+orange filler.
224	No. 101+glass+dark gray filler.
225	No. 101+glass+light-gray filler.
226	No. 101+gray filler.
227	No. 101+50% (52% vol) tin, fused 850° F, 5,000 psi.
227a	No. 101+80% (52% vol) tin, fused 700° F, 10,000 psi.
228	No. 101+13% glass, 0.05 μ avg diam of fibers.
229	No. 101+13% glass, 2 μ avg diam of fibers.
230	No. 101+25% dental silicate.
231	No. 101+67% (33% vol) copper powder.
232	No. 101+36% silicon powder (2 to 10 μ).
233	No. 102+57% No. 101, fused at 600° F.
234	No. 102+67% No. 101, fused at 600° F.
234a	No. 102+40% No. 101, fused at 500° F.
235	No. 101+25% dental silicate.
236	No. 102+40% No. 101, fused at 600° F.
237	No. 102+20% No. 101, fused at 600° F.
237a	No. 102+30% No. 101, fused at 600° F.
237b	No. 102+40% No. 101, fused at 600° F.
237c	No. 102+10% No. 101, fused at 600° F.
238	No. 101+63% (28% vol) molybdenum powder (0.5 to 5 μ).
238a	No. 101+30% (30% vol) molybdenum powder (0.5 to 5 μ).
238b	No. 101+73% (42% vol) molybdenum powder (0.5 to 5 μ).
301	Sintered porous bronze+polytetrafluoroethylene.
302	Sintered porous bronze+graphite.
303	Sintered porous bronze+molybdenum disulfide.
304	Sintered porous bronze+molybdenum disulfide.
401	Carbon+graphite+silver.
402	Electrographitic carbon+silver.
403	Carbon+graphite+babbit.
404	Electrographitic carbon+babbit.
501	Silver amalgam.
601	Pyrax glass, lapped and polished.
602	Stainless steel (420), hardened, honed and polished.
603	Hard-coated 61S aluminum alloy.
604	Sapphire, lapped and polished.
605	Bearing bronze; copper, 83%; lead, 8%; tin, 8%.
606	Tungsten+molybdenum disulfide+plastic coating on brass.
607	Brass, ordinary.
608	Boron carbide, special superfine quality.
609	No. 102+20% small flake graphite, coating, fused on brass.
610	Diamond, polished.
611	No. 101+green pigment, 1-coat enamel, fused on brass.
612	Polytetrafluoroethylene, clear finish, fused on brass.

translucent, and is harder than the amorphous and more resistant to cold flow and heat distortion. Neither form has the low-friction characteristics of PTFE at ordinary temperatures.

The nylon material used in these tests was of the hardest type, and has been used to some extent for bearings and gears in certain applications. This material normally contains water; the amount of water varies with the ambient temperature, humidity, and time of exposure, but frequently is between 1 and 4 percent. The friction is not exceptionally low.

The high-density polyethylene tested was a relatively new type of polyethylene plastic produced by a commercial firm for experimental purposes. It is characterized by higher molding temperatures and greater strengths than those of ordinary polyethylene.

2.2. Plastics With Fillers

Because of the relative softness of PTFE, it is logical to expect that its load-carrying ability and its wear resistance might be improved by the addition of suitable fillers. Accordingly, several fillers were tried in combination with this plastic, including graphite, molybdenum disulfide, fiber glass, dental silicate, silicon, titanium dioxide, silver, copper, tungsten, and molybdenum.

Samples 202, 202a, 202b, 202c, 203, 204, 106a, 208, 208a, 214, 217, 227, 227a, 230, 231, and 232 were prepared (at the Bureau) by adding the filler in powder form to PTFE clear finish-type suspension (in water) and stirring to make a uniform paste. In general, after drying to the consistency of a very stiff paste, these samples were molded into cylinders, which were then more completely dried on a hotplate or by heating in the mold. To fuse the PTFE, the samples were dried and then heated to about 700° F at a pressure of about 10,000 psi in a heavy-walled steel tube with a loose-fitting steel rod at each end. Samples 211, 212, 228, 229, and 235 were prepared in a similar manner, except that they were thoroughly mixed in a blender after the addition of acetone in quantities sufficient to provide suitable fluidity for the blending action. After blending the samples, much of the acetone was removed by decanting, some was removed by pressing with absorbent paper and by compressing in the hands in the manner used for forming snowballs, and then the mixtures were dried by heating as above. Samples 238, 238a, and 238b were prepared as above, except that PTFE aqueous dispersion, designated by the manufacturer as TD-3, was used instead of the PTFE clear finish-type suspension; and samples 220 and 220a were prepared in a similar manner with PTFE one-coat enamel-type suspension instead of the clear finish-type suspension.

PTFCE was tried also as a resin binder with different fillers, such as graphite, molybdenum disulfide, and PTFE. Sample 215 was prepared by mixing PTFE clear finish-type suspension with PTFCE dispersion (in xylol) and then blending after dilution with acetone. After the drying operation, this sample was heated in the heavy-walled tube to about 500° F at a pressure of about 5,000 psi to fuse

the PTFCE. A trial at higher temperatures, to fuse the PTFE also, resulted in an inferior product because of decomposition of the PTFCE (sample 215a at 650° F). Samples 234 and 234a were prepared by adding PTFCE powder to PTFE clear finish and blending after the addition of acetone. In preparing sample 236, PTFCE powder was added to TD-3 dispersion (PTFE) and the mixture was diluted with acetone. In preparing samples 237, 237a, 237b, and 237c, the PTFCE powder was dispersed in acetone, and the dispersion was blended with TD-3 dispersion. Samples 214, 218, 218a, and 219 were prepared by methods similar to the above, except that they contained other fillers in addition to the PTFCE. Samples 214 and 233 were prepared by mixing in paste form, without the addition of acetone.

Samples 201, 204a, 205, 206, 207, 209, 210, 213, and 216 were commercial preparations of PTFE containing fillers. Examination of these with a 20-power stereomicroscope disclosed pockets of pure plastic much larger than some of the journals in tinpieces. Sample 221 was similar to sample 201, except that it was mixed by the dispersion method instead of the micropulverizing method. This resulted in a more uniform mixture of the PTFE in sample 221 than in 201, but examination with a 20-power stereomicroscope revealed that the mixture was not as uniform as is desirable for bearings with a 0.005-in. bore. A few small pockets of glass without any binder were found in sample 221. The uniformity of mixture in samples 222 to 226 was similar to that of sample 221, and it is believed that these commercial samples also were prepared by the dispersion method.

2.3. Impregnated Bronze

Porous bronze (not oil-impregnated) was impregnated with PTFE suspensoid by subjecting a dry degreased specimen of porous bronze to a vacuum of about 15 mm of mercury for about 10 min. Then PTFE suspension was introduced to cover the specimen before the vacuum was released. The excess suspensoid was wiped from the surface, and the specimen was dried by heating to 400° F. The cycle was repeated several times before finally fusing the plastic at about 700° F. However, stereomicroscopic examination of the broken edge of a 0.19-in. plate showed that the pores near the center were not filled with plastic, the impregnation being complete only near the surface.

Sample 302 of porous bronze, impregnated with graphite, and samples 303 and 304, impregnated with molybdenum disulfide, were obtained commercially. Samples 302 and 303 were prepared by the hot-press method.

2.4. Impregnated Carbon

Samples 401 and 403 were molded carbon-graphite mixtures that had been impregnated with molten silver and with molten babbitt, respectively, by a vacuum-pressure process. Likewise, samples 402 and 404 were electrographitic carbon impregnated with silver and with babbitt, respectively.

2.5. Miscellaneous

The silver amalgam (sample 501) was made from precipitated flowers of silver mixed with mercury with a mortar and pestle. The amalgam was compressed in a steel cylinder at about 10,000 psi to drive out excess mercury. This material was very brittle, and the edges of the hole chipped during the boring and reaming operation. An amalgam of dental-alloy filings (about 70 percent of silver in the alloy) was made similar to the above. This material was less brittle than the silver amalgam, but was not a satisfactory oil-free bearing material; hence the investigation of this type of material was soon discontinued.

Samples 601 (glass), 602 (420 stainless steel), and 604 (sapphire) were used mostly with lubricants for reference purposes. Sample 603 was an electrically anodized coating (essentially a sapphire coating) on an aluminum alloy. Sample 605 was a bearing bronze (in composition similar to SAE Nos. 64 and 660 copper-base casting alloy), and sample 607 was ordinary yellow brass. Sample 606 was a commercial coating material consisting of tungsten, molybdenum disulfide, and a plastic; the coating was applied to the bore of a brass bearing and baked 3 hrs at 400° F, in accordance with the instructions supplied with it. Boron carbide (sample 608) has a hardness between those of sapphire and of diamond (sample 610). Samples 609, 611, and 612 were coatings of PTFCE plus graphite, PTFE one-coat enamel, and PTFE clear finish, respectively, fused on brass.

3. Shaft Materials

The shaft materials tested during this investigation are listed in table 2. The sample number in each case is the same as that used as type designations by the American Iron and Steel Institute (AISI), except for the cases of the cobalt alloy (C40) and the machinery steel (M), which are not listed by the manufacturer as meeting any AISI type.

The 303 steel was a free-machining chromium-nickel austenitic steel not capable of heat treatment, and commonly known as 18-8 steel. This was used chiefly for the wear-test shafts.

The 420 steel was a type used for cutlery, and may be heat-treated to a hardness of about 50 Rockwell C.

TABLE 2. Shaft materials

Sample	AISI type	Approximate composition				Hardness, RC
		Carbon	Manganese	Chromium	Nickel	
303	303	%	%	%	%	—
420	420	0.15 max	2.0 max	17 to 19	8 to 10	50
440C	440C	.41	1.0 max	13.7	* 0.11	56
D2	D2	.95 to 1.2	1.0 max	16 to 18	—	56
D3	D3	1.50	0.30	12.0	—	56
		2.10	.25	12.5	.60	60
O2	O2	0.30	1.00	—	—	60
C40 ^b	—	.16	2.0	20	16	78
M ^c	—	.3	(c)	(c)	(c)	94

^a From analysis; other values from SAE Handbook or from manufacturer's type analysis.

^b 40% cobalt, 7% molybdenum.

^c A machinery steel described by the manufacturer as a special chrome vanadium alloy with small amounts of nickel and molybdenum.

The 440C steel is described in various literature as having the greatest quenched hardness and wear resistance upon heat treatment of any corrosion- or heat-resistant steel.

The D2 steel was an air-hardening high-chromium tool steel having some corrosion resistance and good wear resistance in the hardened state. The D3 steel was similar, except that it was the oil-hardening type.

The O2 steel was an oil-hardening, nondeforming type, similar to that used for shafts in lubricated timepieces.

The cobalt-base alloy (C40) was a highly corrosion-resistant material of the type used for main-springs in watches.

The machinery steel (M) was furnished in the heat-treated condition and recommended as having good wear resistance.

4. Apparatus

The apparatus used in this investigation were selected or designed for making simple comparative tests of the friction and wear characteristics of oil-free bearing materials under conditions simulating those in service. Shafts $\frac{1}{8}$ in. in diameter were used for friction and wear measurements to give reasonable accuracy under various conditions of speed and load, and still be in the range of application of small oil-free bearings. Wear tests were made with $\frac{1}{8}$ -in.-diameter oscillating shafts as a compromise between ease of measuring the wear and the smallness of the oscillating shafts in timepieces. For shafts less than $\frac{1}{8}$ in. in diameter, timepieces were used for making comparative tests of the more promising materials.

4.1. Static-Friction Machines

An inclined-plane type of apparatus was used for making the static-friction tests. The tangent of the angle with the horizon when a rider on the incline starts to slide is used as a measure of f , the coefficient of friction.

An apparatus of this type available at the start of this project has been described previously [3]. It consists essentially of a hotplate mounted between two journals, with provision for slow tilting. The plate specimen is clamped to the plane surface of the hotplate, which provides for tests at and above room temperature. A pointer indicates the angle of tilt on a calibrated scale.

The rider specimen is loaded by a rectangular yoke, through a point contact. An electric circuit is arranged so that with a slight movement the rider contacts a needle and lights a small signal lamp.

The plate specimens are 7 by 2 by $\frac{1}{8}$ in., and the riders are 2 by 1 by $\frac{1}{2}$ in. The riders are undercut to leave a bearing surface 0.125 by 1 in. at each end, and have a cone-shaped depression in the center of the upper surface for contacting the point of the loading yoke.

A similar apparatus, without a hotplate, was constructed on a scale small enough to be operated

within an insulated control box at low temperatures. The insulated box was constructed of plywood with a 3-in. thickness of rock-wool insulation between the walls. The front of the box is removable to allow easy access, and windows are provided for readings during tests. An internal compartment contains a sirocco-type blower and space for dry ice or a heater, leaving an available working space 16 by 16 by 12 in.

4.2. Bearing-Friction Test Machines

A small friction-testing machine for use in the temperature-control box was constructed with two support ball bearings for mounting a test shaft with a journal for the test bearing at one end, and provision for driving at the other end. This outboard-test-bearing type of machine facilitates the changing of test bearings and minimizes the damage to the bores of the test bearings when sliding on and off the shaft. Measurements of the frictional torque are obtained from the displacement of a pendulum mounted on the test bearing housing. The load consists of the bearing housing plus the weight of the pendulum and bearing. The pendulum consists of a rod, a small bob, and a pointer that measures displacement from the center line on a suitable scale. The pendulum is calibrated in a horizontal position with the housing on a smooth horizontal surface, as indicated in figure 1. The force, R , necessary to maintain it in a horizontal position is measured by a balance. If the weight of the pendulum acts at its center of gravity so that $Wb = Ra$, then $W = Ra/b$. When the shaft is rotating, the friction torque is given by $Wc = Rac/b$, and $a/b = d/c$. The friction torque, Wc , $= Rd$. The frictional torque may be found from the displacement reading multiplied by R , which is a constant for each pendulum. Likewise,

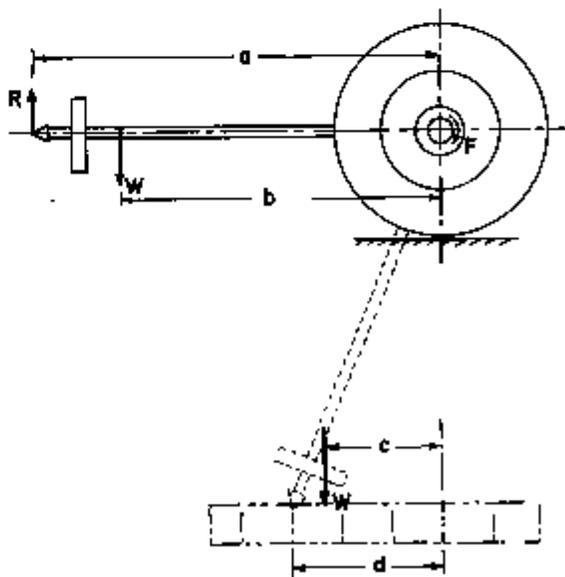


FIGURE 1. Diagrammatic sketch of friction torque measuring apparatus.

for a given load and shaft diameter, the coefficient of friction may be computed from the displacement multiplied by the appropriate constant.

4.3. Bearing-Wear Test Machines

Two multiple-shaft speed-reducing units were modified to provide apparatus for studying wear with sleeve bearings on rotating journals. Steel test journals, $\frac{1}{4}$ in. in diameter, were made and fitted to the ends of the six horizontal output shafts on each unit. Steel housings and weights suspended from flexible wire provide suitable loads on the bearings, and motorized drives are used to obtain the desired speeds. Four shafts of one of these machines are shown on the left half in figure 2. The bearing assembly has been removed from one of the shafts, and is shown disassembled on the table. The collar has been removed from the third shaft from the right to show the end of a test bearing in place.

The wear patterns along the entire lengths of the bearings indicated that the flexible wires attached to the steel housings were suitable for applying the load, and that swivel yokes were not necessary for uniform loading.

For studying wear of sleeve bearings on oscillating journals, oscillating-shaft machines were made by modifying oscillating display motors. One of the oscillating-shaft wear machines is shown in figure 2, clamped to the right end of the support of the above multiple shaft unit. A 2-lb weight attached with a wire plus the other moving parts provide a 1,000-g load on the pair of bearings, which are housed in a yoke made from $\frac{1}{8}$ -in. by $\frac{1}{2}$ -in. brass. One of the bearings may be seen directly above the upper end of the wire supporting the weight. The $\frac{1}{4}$ -in.-diameter steel shaft passes through two brass collars, which are soldered to the yoke of the oscillating bar; a setscrew in one of the collars engages the shaft so that it oscillates with the oscillating arm. Attached

to the outer end of the oscillating arm is a quadrant, which passes through a solenoid. A mercury-in-glass switch attached to the oscillating arm energizes the solenoid at the appropriate time to provide oscillating motion of the shaft-arm-quadrant assembly. Although the static load on the bearings is only 1,000 g, the load during the impulse from the solenoid is considerably greater. The oscillatory surface speed and the impulse loading of the shaft simulate the conditions common to balance-staff journals in timepieces.

An apparatus was designed and built for making thrust-bearing-wear tests with oscillating shafts. This apparatus, designated as an endstone-wear testing machine, is shown in figure 3. A motor-driven connecting rod oscillates a shaft back and forth with a motion of about 87° ; and this motion is doubled when transmitted to 4 vertical shafts, each of which has a $\frac{1}{8}$ -in.-diameter hole and setscrew at each end for attaching test-pin specimens. An endstone specimen in a 1,000-g weight supplies a load on each top pin; a specimen at each lower pin supports the 1,000-g weight plus the weight of the floating shaft and gear, or a total thrust load of 1,240 g. One of the 1,000-g weights has been removed and inverted to show the upper test pin and endstone specimen in the photograph. In operation, each weight is positioned coaxially with its test pin by means of four snug but free-fitting locating pins, and is prevented from rotating by means of a thin flexure spring. No vertical oscillation of the floating shaft was observed, and no effect of vertical forces from the gears was indicated in the test data.

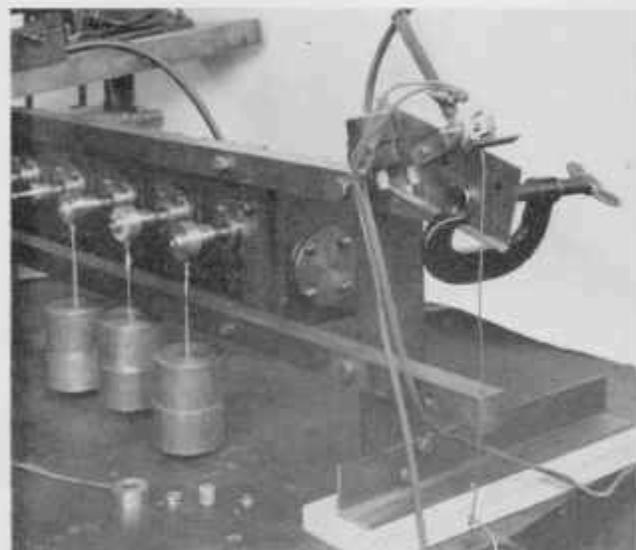


FIGURE 2. Journal-bearing wear-testing apparatus.



FIGURE 3. Thrust-bearing (endstone) wear-testing machine.

4.4. Timepieces

The timepieces used in a study of the suitability of the more promising bearing materials included aircraft clocks, ship clocks, navigation watches (type AN5740), ship chronometers, low-priced pocket watches (no jewels), and automobile electric clocks. Low-temperature tests of the timepieces were made in a commercial subzero chest in which thermostatically controlled temperatures down to -60°C were maintained.

5. Test Procedures

5.1. Static-Friction Tests

The coefficient of static friction between two solids depends largely on the physical and chemical properties of the surfaces [4]. Such factors as different surface finishes and the presence of surface films of oxides, oil, or dirt can seriously affect the reproducibility of friction data during a test program. As these factors vary in practice also, it was believed that in this project no purpose would be served by attempting to approach perfectly smooth and chemically clean surfaces. Instead, it seemed best to try to maintain a certain consistency in these variables, with a reasonable degree of cleanliness.

Accordingly, the surfaces for the static-friction tests were initially washed with soap and water, acetone, and ethyl alcohol; and thereafter, at frequent intervals between tests, wiped with industrial absorbent tissue soaked in ethyl alcohol. As far as possible, the original surface finishes of the specimens were left untouched throughout the tests, but there were a few exceptions, where refinishing was thought advisable.

For a particular set of conditions a friction measurement was taken by placing the rider on the plate and in contact with the needle, applying the load, retracting the needle about 0.004 in., and tilting the plate slowly until the signal lamp lit. This was repeated until a relatively constant value was obtained. Plate temperatures were measured by a thermocouple, and atmospheric temperatures inside the temperature-control box were determined with a liquid-in-glass thermometer.

5.2. Bearing-Friction Tests

Most of the important comparative friction data were obtained with the small outboard-test-bearing machine that was used in the temperature-control box. In general, the test bearings, 0.50 in. long, with bores slightly less than $\frac{1}{4}$ in., were pressed in a steel housing with a 0.500-in. bore, and then the bearing bore was reamed, burnished, or otherwise smoothly finished to the desired diameter. In these tests, benzene and tissue were used to clean the shafts and bearings, except that no solvent was used on the sintered nylon bearings. To minimize changes of the bearing surface during a test covering a range of temperature, the shaft was not rotated continuously but only for short periods before and while obtaining friction measurements. The air-circulating blower

was stopped while the torque was being read, so that the pendulum would not be influenced by the air currents. Observations of the torque were taken at intervals as the temperature near the bearing was reduced from room temperature to -70°C , and as the temperature was increased from room temperature to $+70^{\circ}\text{C}$, unless excessively high friction resulted before reaching these temperatures. A damping fluid was used around the lower end of the pendulum rod to minimize fluctuations.

In general, the test shafts were ground, honed, or lapped, and polished with 4/0 polishing paper to give a surface finish in the range of 1 to 3 μin .

5.3. Bearing-Storage Tests

For the storage test, three steel shafts, $\frac{1}{4}$ in. in diameter by $7\frac{1}{2}$ in. long, were supported at the ends, above and parallel to a steel plate, 5 in. by $7\frac{1}{2}$ in. Test bearings, $\frac{1}{2}$ -in outside diameter by $\frac{1}{2}$ in. long, were mounted in steel housings weighing 100 g each, and were reamed so that each bearing had a diametral clearance of 0.010 in. Brass collars with setscrews were used to space six bearings on each shaft so that each bearing had $\frac{1}{8}$ in. side play for axial movement. The shaft ends were clamped to the supports projecting upward from each end of the steel plate.

In making friction measurements for the beginning of the storage test, the above assembly was mounted on the static friction machine. The plate was tilted backward until all the bearings were touching the brass spacing collars, and then tilted forward until the pointer reading for the tangent of the angle was 0.05. Thereafter, the table was tilted to increase the reading 0.01 at the end of each minute, and a record was made for any bearing that moved axially during each increase in the angle of tilt. During the storage period the assembly was stored on a wooden shelf attached to a brick wall, with the plate tilted about 8 deg to insure that each bearing remained in contact with the appropriate brass spacing collar. The assembly was open to the room air but was protected overhead by another shelf and directly in front by a clear plastic shield, to safeguard against disturbance by falling plaster or wind-blown objects. After 10 months of storage the assembly was mounted on the static-friction machine again to determine the coefficient of starting friction after storage.

5.4. Bearing-Wear Tests

The modified multiple-shaft speed-reducing units were used to obtain the rates of wear with bearings on $\frac{1}{4}$ -in.-diameter journals that were rotated at various speeds, except that for the 1,800-rpm tests the journal was fitted directly to the shaft of an electric motor. The surface finish of the journals at the start of each test was from 1 to 4 μin ., except for some special tests with rougher finishes up to 16 μin . The bearings were cleaned, weighed, and pressed in steel housings from which suitable loads were suspended. If rapid wear was evidenced by particles of the bearing material accumulating under

the bearing within a few hours, the bearing was removed and weighed to determine the loss in weight. If no particles from wear were observed beneath the bearing, operation was continued several hundred hours before examination and weighing.

Wear data were obtained from typical oil-free materials on the $\frac{1}{8}$ -in. oscillating shafts of the modified oscillating display motors. The total angle of motion was about 1 radian (55° to 60°), with about 3 cps, corresponding approximately to simple harmonic motion with an amplitude of 0.5 radian. In each test, a pair of bearings, each 0.25-in. outside diameter by 0.125 in. long with 0.126-in. bore, was fitted to the brass yoke previously described (see fig. 2). The bearings were weighed before and after 60 days of operation. The surface finish of the journals at the start of each test was about 2 μ in.

Wear data were obtained with samples of typical materials on the endstone-wear testing machine shown in figure 3. The test pins were $\frac{1}{8}$ in. in diameter, with $\frac{1}{8}$ -in. radius at the ends. Tolerance on the radius was ± 0.001 in., with a surface finish of about 2 μ in. The total angle of motion was about 3 radians (172° to 175°), with 1 cps, corresponding approximately to simple harmonic motion with an amplitude of 1.5 radians. A dial indicator having a ball point with a radius of about $\frac{1}{8}$ in. was mounted over a flat-surface plate and used to measure the depth of wear periodically. When the depth of wear was relatively small, the diameter of the worn spot was measured also with a microscope.

5.5. Timepiece-Bearing Tests

Most of the operation with timepieces was at room temperature (about 25° C). A laboratory oven with a thermostat was used for maintaining the high temperature (75° C), and the subzero chest was used for the low-temperature (mostly -60° C) tests of timepiece operation. The daily rates were determined by comparison with standard NBS time signals available in the laboratory.

At suitable intervals, the oil-free bearings and shafts in the timepieces were examined for evidences of wear and corrosion. Conventional stereomicroscopes and measuring microscopes (10 to 100 \times) were used for these examinations.

6. Results

6.1. Static-Friction Results

Some preliminary testing was done in order to study reproducibility and the effect of load variation. For the range of pressures from about 10 to 30 psi, the starting friction was practically independent of load, for the materials investigated. A constant load that gave a pressure of 17 psi on the loaded area was used for the subsequent static-friction experiments.

As the cooling of the temperature-control box normally was accomplished by the evaporation of dry ice, the atmosphere inside the box during the

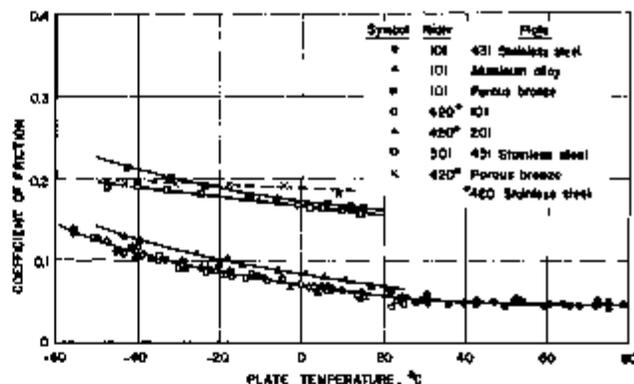


FIGURE 4. Effect of temperature on the coefficient of static friction.

low-temperature tests was composed mostly of gaseous carbon dioxide. In order to determine whether or not this influenced the results, some tests were run with a different cooling system. Alcohol was cooled externally by dry ice, and pumped through heat-exchanger elements over which the air in the box was circulated. Although this particular system did not cool the box below -25° C, the results obtained in this range with atmospheric air coincided very well with those from other tests conducted in the carbon dioxide atmosphere.

The effect of temperature on the static or starting friction for several combinations of different materials is shown in figure 4. The combinations that include PTFE (sample 101) or PTFE with fillers (sample 201) demonstrate an increase in friction with a decrease in temperature. For PTFE sliding on a 431 stainless-steel plate, and for 420 stainless steel sliding on PTFE and on plate 201 (PTFE+filler), the static friction versus temperature is represented by the lower curve in figure 4; the curve for PTFE sliding on aluminum is slightly higher. For PTFE sliding on dry porous bronze, and for porous bronze impregnated with PTFE (sample 301) sliding on stainless steel, the friction is much higher and is approximately the same as for stainless steel sliding on dry porous bronze. The porous bronze impregnated with PTFE did not have a film of PTFE over its surface, and evidently there was metal-to-metal contact between the bronze and the steel. With a coating of PTFE on the porous bronze, friction data (not shown in fig. 4) was similar to that for solid PTFE.

6.2. Bearing-Friction Results

a. Lubricated Bearings

For reference purposes, the coefficients of friction at speeds from 3 to 600 rpm were determined with a sapphire (not oriented) bearing ($\frac{1}{8}$ in. long) on a hardened 420 stainless-steel shaft, at 25° C, with a 643-g load. The diameter of the bore at the largest end was 0.2542 in. and at the smallest part of the bore near the center was 0.2524 in. The results of these tests are shown in figure 5. As would be

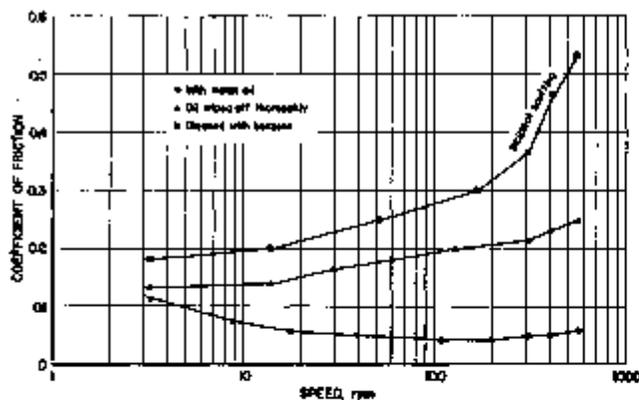


FIGURE 5. Friction versus speed for a polished sapphire bearing.

expected, when fully lubricated with a modern synthetic watch oil, at speeds above 15 rpm (1.0 fpm) the friction was relatively low. When the speed was decreased to about 3 rpm (0.2 fpm), evidently operation was in the thin-film region of lubrication, as there was little difference in friction with abundant oil supply and with a trace of oil left after wiping the shaft and bearing thoroughly with industrial absorbent paper. At higher speeds the inadequate oil supply resulted in higher friction. Removing the traces of oil by washing with benzene resulted in higher friction and incipient scuffing at the higher speeds; the score marks on the journal and the bearing bore were detected with a 20-power stereomicroscope after removing a brown deposit.

In general, when the lubricated jewels in a timepiece were replaced with oil-free bearings, the main-spring, metal bearings, and winding mechanism were lubricated with a low-temperature lubricant. Because of this, and for general information, friction data were obtained with a hardened 420 stainless-steel bearing on a hardened 420 stainless-steel shaft when lubricated with three low-temperature oils. These data, for a 2,200-g load, at 3 speeds, and for a range from -70° to $+60^{\circ}$ C, are given in table 3. The surface speed at 3 rpm with the $\frac{1}{4}$ -in.-diameter shaft more nearly simulates the surface speeds in timepieces; and, at this speed, the coefficient of

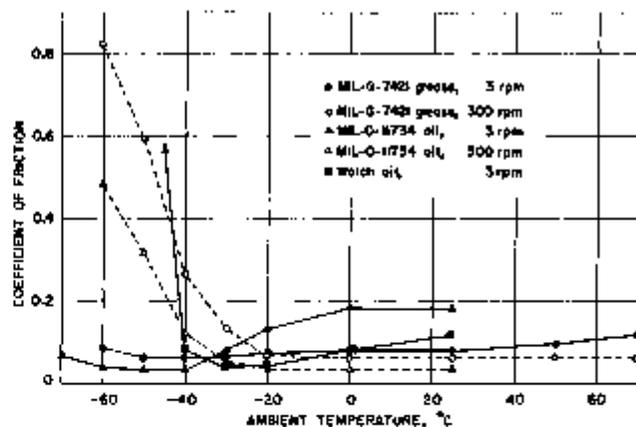


FIGURE 6. Friction versus temperature for a stainless-steel bearing.

friction decreases when the temperature is lowered sufficiently for the increasing viscosity to provide a thicker film of oil for lubrication. The relatively high friction at the higher temperatures indicates operation in the thin-film or boundary region of lubrication, in which oiliness is an important factor; and the lower friction with the special silicone fluid under these conditions indicates that it has greater oiliness than that of the other two synthetic oils. The MIL-O-11734 [5] and the MIL-L-17353 [6] lubricants are diester-type synthetic oils containing rust-inhibitor additives, designed for use in mechanical time fuzes and firearm mechanisms respectively. These two oils are not of the nonspreading type, such as watch oils, commonly used for jewel bearings; however, they do not have the extreme spreading tendency common to silicone fluids.

With the 420 stainless-steel bearing and shaft, with a 643-g load, friction data were obtained over a wide range of ambient temperature with MIL-O-11734 oil and MU-G-7421 (extreme low temperature) [7] grease at 3 and 300 rpm, and with watch oil at 3 rpm. These data are given in figure 6. The relatively high friction with MIL-O-11734 oil at 3 rpm at temperatures above -30° C indicates that this operation is in the thin-film or boundary region,

TABLE 3. Friction versus temperature for a honed-and-polished hardened 420 stainless-steel bearing, 0.2520-in. bore, cylindrical; with a hardened 420 stainless-steel shaft, 0.2504-in. diameter, with 2,200-g load; lubricated; at three speeds

Ambient temperature, °C	Coefficient of friction								
	MIL-O-11734 oil			MIL-L-17353 oil			Silicone fluid		
	3 rpm	15 rpm	300 rpm	3 rpm	15 rpm	300 rpm	3 rpm	15 rpm	300 rpm
+70	0.16	0.16	0.01	0.23	0.20	0.03	0.13	0.11	0.01
+60	.18	.15	0.01	.22	.20	.01	.10	.09	0.01
+50	.18	.16	0.01	.20	.20	0.01	.10	.09	0.01
+40	.18	.15	0.01	.20	.18	0.01	.10	.09	0.01
+30	.17	.17	0.01	.18	.15	0.01	.10	.05	0.01
+20	.11	0.01	0.01	.15	.08	0.01	.06	.01	0.01
+10	0.01	0.01	0.06	.12	0.01	0.01	.06	0.01	0.02
0	0.01	0.03	.27	0.01	0.01	.04	0.01	0.01	.04
-10	0.01	0.01	0.01	0.01	0.01	.09	0.01	0.01	0.01
-20	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

and the addition of an oiliness agent would be expected to lower the friction under these conditions.

In these and other friction tests, the surface finish of the shafts was kept in the range of 1 to 3 μ in. as measured by a profilometer.

b. Oil-Free Bearings

The effects of temperature on kinetic friction for different clearances with various materials were investigated with the small outboard-test-bearing machine with hardened stainless-steel shafts ranging in diameter from 0.2496 in. to 0.2520 in. These tests were run in the temperature-control box, at 300 rpm, with a 643-g load. These data from PTFE are given in figure 7. With a diametral clearance of 0.0024 in., the friction was nearly constant from -65° to $+70^{\circ}$ C. With a clearance of 0.0016 in. (at room temperature), the friction increased rapidly at about -50° C and at about $+50^{\circ}$ C, because of binding as the clearance decreased to zero. For the clearances investigated, the friction at 300 rpm was practically independent of clearance, and not greatly affected by temperature, except when binding occurred as a result of dimensional changes caused by the changes in temperature. The coefficient of expansion of PTFE is about 10 times greater than that of steel. At elevated temperatures, the restraint of the steel housing in preventing outward expansion of the plastic causes the bore to become smaller instead of larger. Conversely, as the temperature is lowered, release of the press fit tends to counterbalance the contraction of the bore of the plastic until the temperature is low enough for the bearing to become loose in the steel bore. To prevent movement of the plastic and the filled-plastic types of bearing in the steel housing at low temperatures, a small floating pin was inserted radially through the bearing housing into a matching hole extending $\frac{1}{8}$ in. into the bearing wall.

Typical data showing the effect of speed on friction for several materials are given in figure 8. These data were obtained at 25° C with a 643-g load, using a stainless-steel shaft having a 0.2504-in. diameter.

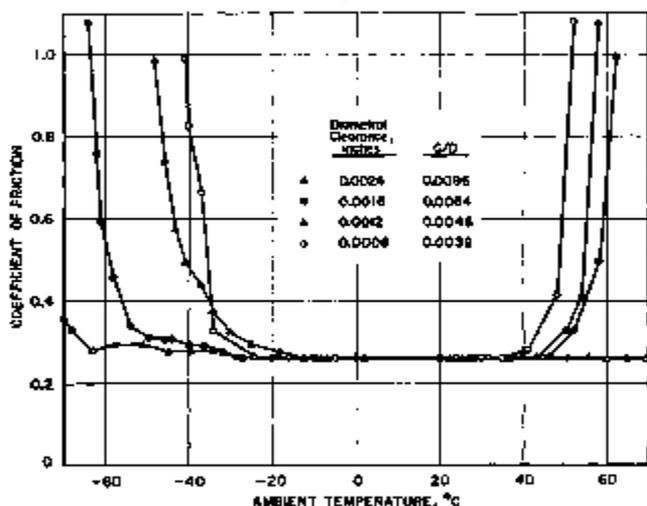


FIGURE 7. Friction versus temperature for a PTFE bearing, at 300 rpm, with various clearances at room temperature.

The test of the lapped-and-polished Pyrex-glass bearing lubricated with watch oil was made to obtain comparable data on a hard lubricated material similar to jewels (before the sapphire bearing was obtained). At 15 rpm, where the surface speed is about the maximum encountered in a timepiece bearing, the friction for PTFE is about 60 percent greater than with the lubricated glass, but at 2.5 rpm the friction of this plastic is the same as that of the lubricated glass.

The coefficients of friction at 25° C, using a 643-g load with $\frac{1}{8}$ -in.-diameter stainless-steel shafts at 3, 15, and 300 rpm, for many oil-free materials and for typical lubricated bearings, are given in table 4.

After it became evident that loads greater than 643 g could be tolerated (without excessive wear) with the $\frac{1}{8}$ -in.-bore oil-free bearings, friction data were obtained with a 2,200-g load, and these data are considered more important than the data obtained with the 643-g load. In these tests with the heavier load, friction data were obtained at speeds ranging from 2 to 600 rpm, and then the bearing was run in at 300 rpm to observe changes in friction. Friction data were obtained over the speed range after various amounts of run-in at 300 rpm, to investigate the effect of run-in at the relatively high load and speed. Typical data for these tests with samples 101 and 215 are given in figure 9, which also includes data (dotted curve) for a lubricated stainless steel bearing for comparative purposes. Because of excessive wear with sample 101 (PTFE) under these conditions, run-in with this material was limited to 1 hr and no data were obtained above

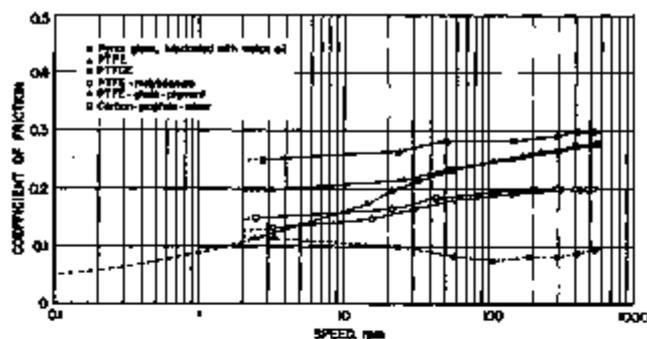


FIGURE 8. Friction versus speed for various bearing materials, with 643-g load.

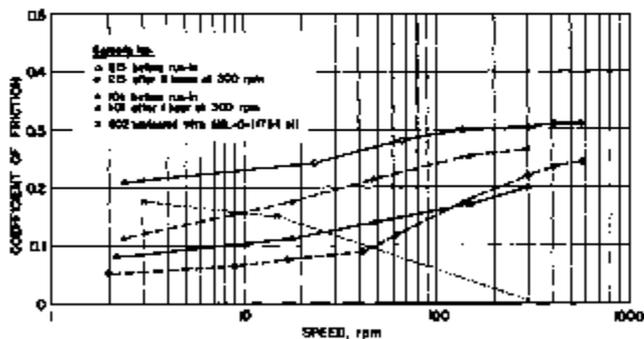


FIGURE 9. Friction versus speed for typical bearing materials, with 2,200-g load.

TABLE 4. Coefficient of friction for various bearing materials, with hardened 420 stainless-steel shafts, 1/4-in. diameter, at room temperature, with 643-g load

Sample	Coefficient of friction		
	3 rpm (0.2 fpm)	15 rpm (1.0 fpm)	300 rpm (20 fpm)
101	0.12	0.18	0.28
102	.25 to .27	.25 to .28	.29 to .45
103			.28 to .35
103a	.22	.20	.21 to .32
103b	.28	.20	.32 to .38
201	.20	.21	.26 to .32
202	.13	.15	.20
202a	.20	.21	.22
202b	.20	.21	.22
202c	.20	.21	.22
203	.27	.26	.23
204			.25
204a	.13	.15	.21
205	.13	.14	.23
206	.13	.18	.23
206a	.25	.28	.31
207	.16 to .25	.18 to .26	.24 to .29
208	.13	.20	.23
208a	.25	.25	.28
208b	.11	.13	.15
210	.11	.14	.17
211	.13	.19	.26
212	.16	.18	.23
213	.28	.30	.40
214	.16	.19	.23
215	.23	.22	.26
215a	.28	.26	.23
216	.13	.15	.19
217	.23	.23	.27
218	.28	.26	.26
218a	.26	.28	.27
219	.20	.23	.25
220	.30	.31	.33
220a	.23	.25	.30
221	.15	.16	.19
222	.12	.13	.17
223	.13	.19	.22
224	.13	.15	.20
225	.17	.18	.22
226	.13	.13	.25
227a	.15	.17	.20
228	.22	.23	.25
229	.23	.23	.25
401	.15	.16	.20 to .23
402	.28	.28	.27
403	.21	.22	.23
404	.27	.27	.26
501	.13	.13	.13
603 with MIL-G-7421 grease	.08	.06	.06
603 with MIL-O-11734 oil	.18	.15	.03
802 with watch oil	.12	.08	.04
803 with watch oil	.13	.08	.05
804 with watch oil	.12	.08	.05
804 oil wiped off	.13	.14	.21
804 clean	.18	.20	.38

300 rpm. Even so, rapid wear occurred and the friction increased about 50 percent during the run-in with this bearing. Before run-in, the friction with sample 215 was much higher than with sample 101; but after run-in, the friction with sample 215 was lower than with sample 101.

Friction data obtained with a hardened stainless-steel shaft at 3, 15, and 300 rpm, showing the effect of run-in and the effect of ambient temperature on friction, are given in table 5. With respect to time-pieces the coefficient of friction at 3 rpm (0.2 fpm)

is considered more significant than the data at higher speeds. Also, the friction after run-in is considered more significant than the initial friction.

For the four samples of PTFE+molybdenum metal powder (samples 202c, 238, 238a, and 238b), after several hours of operation at 300 rpm and then at 3 rpm, at 25° C, the coefficient of friction was in the range 0.18 to 0.26. After continued running at 3 rpm at -60° C the coefficient of friction at -60° C was 0.22 to 0.25. The concentration of molybdenum in these samples ranges from 50 to 75 percent (20 to 42 volume percent); for this range of concentration the coefficient of friction at 3 rpm was not greatly affected by temperature variations in this range from +25° C to -60° C. Likewise, the friction for sample 401 (carbon+graphite+silver) was not greatly affected by temperature.

For the high-density polyethylene (sample 104) and with unlubricated sapphire there was an increase in friction as the temperature was decreased below -20° C.

For the commercial bearing of sintered bronze+molybdenum disulfide (sample 304) the coefficient of friction increased from 0.17 to 0.44 during 12 min of operation at 3 rpm with the 2,200-g load. After turning the bearing 180° in its holder, in another test (not included in the table) with a 643-g load the coefficient of friction increased from 0.17 to 0.60 during 1 hr of operation at 3 rpm.

For the sample of bearing bronze (sample 605) the coefficient of friction increased from 0.13 to 0.44 during an hour of operation at 3 rpm with the 2,200-g load. After turning this bearing 180°, with a 643-g load, the coefficient of friction increased from 0.15 to 0.55 during 2 hr of operation at 3 rpm.

For the sample of commercial coating (sample 606), consisting of tungsten and molybdenum disulfide in a plastic, the coefficient of friction increased from 0.29 to 0.52 during an hour of operation at 3 rpm with a 2,200-g load.

It is of interest to note that under the conditions of these tests, the ordinary bearing bronze (83% copper, 8% tin, 8% lead) was somewhat superior to the bronze containing molybdenum disulfide and also to the commercial plastic coating material containing tungsten and molybdenum disulfide; but each of these samples was inferior to most of the other materials.

For sample 609 (graphite added to PTFCE) the friction was relatively high; above -20° C it was similar to the friction for PTFCE, and at lower temperatures the friction was greater than that of PTFCE.

For PTFCE bearings (at 3 rpm) the friction decreased with a decrease in temperature; but with PTFE or PTFCE containing PTFE as a filler the friction increased with a decrease in temperature in the temperature range from -20° to -60° C. This is illustrated in figure 10, with data for PTFCE, PTFE, and samples of PTFCE resin containing PTFE filler.

Data obtained in England [8], with the apparatus and method of test greatly different from that used at NBS, show no change in friction for PTFE in the range from -55° to -80° C. At temperatures down to -55° C the data are in general agreement with the data obtained at 3 rpm at NBS.

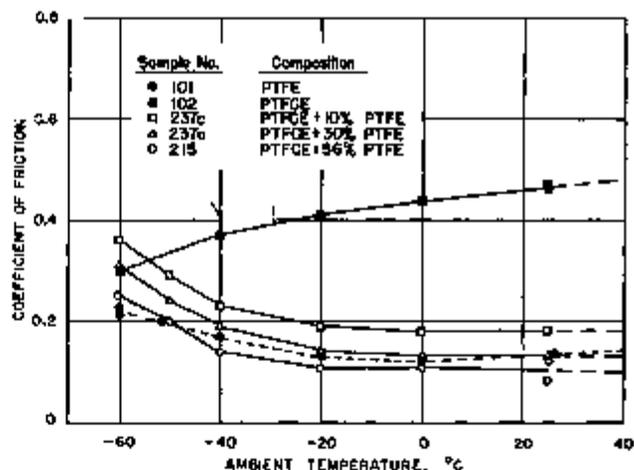


FIGURE 10. Friction versus temperature for PTFE, PTFCE, and PTFCE plus PTFE bearings.

TABLE 5. Effect of run-in and effect of temperature on the coefficient of friction for various bearing materials, with a hardened 480 stainless-steel shaft, $\frac{1}{2}$ -in. diameter

Sample	Bore condition	Load	Ambient temperature	Coefficient of friction			Sample	Bore condition	Load	Ambient temperature	Coefficient of friction		
				3 rpm	15 rpm	300 rpm					3 rpm	15 rpm	300 rpm
101	Reamed, C=0.008 in. After 1 hr at 300 rpm	g	25 °C	0.10	0.13	0.25	214	Reamed, C=0.008 in. After 7 hr at 300 rpm After 8 hr at 3 rpm After standing overnight	g	25 °C	0.08	0.13	0.22
			25 °C	.10	.18	.20				25 °C	.22	.25	.28
			0 °C	.10	.....	.....				25 °C	.19	.....	.....
			-20 °C	.10	.....	.....				25 °C	.16	.....	.....
			-40 °C	.19	.....	.....				0 °C	.16	.....	.....
			-60 °C	.13	.18	.20				-20 °C	.16	.....	.....
			-60 °C	.18	.....	.....				-40 °C	.16	.....	.....
			-60 °C	.22	.....	.....				-60 °C	.18	.28	.32
			-60 °C	.22	.....	.....				-60 °C	.22	.....	.....
			-60 °C	.22	.....	.....				-60 °C	.25	.....	.....
101	After speed range at -50 °C After 5 hr at 3 rpm at -60 °C After standing overnight Bearing turned 180° After 1 hr at 3 rpm	2,200	25 °C	.19	.....	.....	215	Reamed, C=0.008 in. After 7 hr at 300 rpm After 24 hr at 3 rpm After standing over weekend	2,200	25 °C	.05	.08	.24
			25 °C	.06	.08	.....				25 °C	.06	.10	.22
			25 °C	.14	.....	.....				25 °C	.16	.....	.....
			0 °C	.12	.....	.....				25 °C	.12	.....	.....
			-20 °C	.13	.....	.....				0 °C	.11	.....	.....
			-40 °C	.17	.....	.....				-20 °C	.14	.....	.....
			-60 °C	.20	.28	.....				-40 °C	.20	.25	.31
			-60 °C	.21	.....	.....				-60 °C	.20	.....	.....
			-60 °C	.23	.....	.....				-60 °C	.24	.....	.....
			-60 °C	.23	.....	.....				-60 °C	.24	.....	.....
102	Reamed, C=0.008 in. After speed range After 0.1 hr at 300 rpm After 7 hr at 3 rpm After standing overnight	2,200	25 °C	.19	.22	.35	218	Reamed, C=0.008 in. After 7 hr at 300 rpm After 24 hrs at 3 rpm After standing overnight	2,200	25 °C	.06	.17	.30
			25 °C	.43	.....	.38				25 °C	.09	.11	.22
			25 °C	.44	.....	.44				25 °C	.16	.....	.....
			25 °C	.48	.....	.....				25 °C	.18	.....	.....
			25 °C	.47	.....	.....				0 °C	.18	.....	.....
			0 °C	.44	.....	.....				-20 °C	.18	.....	.....
			-20 °C	.41	.....	.....				-40 °C	.16	.....	.....
			-40 °C	.37	.....	.....				-60 °C	.20	.25	.34
			-60 °C	.33	.31	.34				-60 °C	.22	.....	.....
			-60 °C	.30	.....	.....				-60 °C	.28	.....	.....
104	Reamed, C=0.008 in. After speed range After 3 hr at 3 rpm	2,200	25 °C	.10	.11	.16	20a	Reamed and burnished, C=0.002 in. After 5 hr at 300 rpm After 3 more hr at 300 rpm After 54 hr at 3 rpm After speed range After 2 more hr at 3 rpm	2,200	25 °C	.13	.15	.27
			25 °C	.13	.....	.....				25 °C	.07	.10	.25
			25 °C	.15	.....	.....				25 °C	.06	.09	.25
			0 °C	.13	.....	.....				25 °C	.11	.13	.26
			-20 °C	.15	.....	.....				25 °C	.08	.....	.....
			-40 °C	.22	.38	.38				0 °C	.09	.....	.....
			-60 °C	.22	.....	.....				-20 °C	.11	.....	.....
			-60 °C	.22	.....	.....				-40 °C	.18	.....	.....
			-60 °C	.30	.24	.24				-60 °C	.24	.28	.34
			-60 °C	.30	.....	.....				-60 °C	.25	.....	.....
202c	After speed range at -50 °C After 5 hr at 3 rpm at -60 °C After standing overnight	2,200	25 °C	.02	.06	.28	202c	After speed range at -50 °C After 3 hr at 3 rpm at -60 °C After standing overnight	2,200	25 °C	.10	.15	.24
			25 °C	.21	.25	.25				25 °C	.22	.....	.....
			25 °C	.22	.....	.....				25 °C	.22	.....	.....
			25 °C	.16	.....	.....				0 °C	.09	.....	.....
			0 °C	.16	.....	.....				-20 °C	.11	.....	.....
			-20 °C	.18	.....	.....				-40 °C	.18	.....	.....
			-40 °C	.20	.....	.....				-60 °C	.24	.28	.34
			-60 °C	.30	.24	.24				-60 °C	.25	.....	.....
			-60 °C	.32	.....	.....				-60 °C	.29	.....	.....
			-60 °C	.32	.....	.....				-60 °C	.32	.....	.....
-60 °C	.32	.....	.....	25 °C	.10	.15	.24						
-60 °C	.32	.....	.....	25 °C	.10	.....	.....				
-60 °C	.16	.18	.18										

TABLE 5. Effect of run-in and effect of temperature on the coefficient of friction for various bearing materials, with a hardened 420 stainless-steel shaft, 1/4-in. diameter—Continued

Sample	Bore condition	Load	Ambient temperature	Coefficient of friction			Sample	Bore condition	Load	Ambient temperature	Coefficient of friction		
				3 rpm	15 rpm	300 rpm					3 rpm	15 rpm	300 rpm
236	Reamed, C=0.008 in. After 7 hr at 300 rpm After 3 hr at 3 rpm After standing overnight After speed range at -50°C After 5 hr at 3 rpm at -60°C After standing overnight	2,200	25	0.10	0.11	0.27	236a	Reamed, C=0.006 in. After 8 hr at 300 rpm After 7 hr at 3 rpm After standing over weekend After speed range at -50°C After 6 hr at 3 rpm at -60°C After standing overnight	2,200	25	0.06	0.07	0.26
			25	.10	.12	.23				25	.29	.29	.27
			25	.12	---	---				25	.25	---	---
			25	.12	---	---				25	.25	---	---
			0	.12	---	---				25	.31	---	---
			-20	.16	---	---				0	.22	---	---
			-40	.23	---	---				-20	.22	---	---
			-60	.27	.30	.35				-40	.23	---	---
			-60	.29	---	---				-60	.25	.26	.28
			-60	.33	---	---				-60	.28	---	---
-60	.33	---	---	-60	.25	---	---						
25	.12	.15	.24	25	.18	.20	.23						
237	Reamed, C=0.006 in. After 6 hr at 300 rpm After 8 hr at 3 rpm After standing overnight After speed range at -60°C After 6 hr at 3 rpm at -60°C After standing overnight	2,200	25	.22	.27	.25	236b	Reamed, C=0.006 in. After 8 hr at 300 rpm After 8 hr at 3 rpm After standing overnight After speed range at -50°C After 6 hr at 3 rpm at -60°C After standing overnight	2,200	25	.10	.15	.17
			25	.12	.14	.24				25	.19	.21	.21
			25	.15	---	---				25	.18	---	---
			25	.14	---	---				25	.15	---	---
			0	.14	---	---				0	.15	---	---
			-20	.17	---	---				-20	.16	---	---
			-40	.23	---	---				-40	.18	---	---
			-50	.25	.30	.34				-60	.20	.21	.25
			-60	.34	---	---				-60	.22	---	---
			-60	.35	---	---				-60	.18	---	---
-60	.33	---	---	-60	.22	---	---						
25	.19	.30	.30	25	.22	.22	.20						
237a	Reamed, C=0.006 in. After 7 hr at 300 rpm After 7 hr at 3 rpm After standing overnight After speed range at -50°C After 6 hr at 3 rpm at -60°C After standing overnight	2,200	25	.13	.16	.23	304	Reamed, C=0.0018 in. After 0.1 hr at 3 rpm After 0.2 hr at 3 rpm Reamed and burnished, C=0.002 in. After 2 hr at 300 rpm After 4 more hr at 300 rpm After speed range at -50°C After 5 hr at 3 rpm at -60°C After standing overnight	2,200	25	.17	---	---
			25	.11	.13	.24				25	.23	---	---
			25	.15	---	---				25	.44	---	---
			25	.13	---	---				25	.16	.18	.23
			0	.13	---	---				25	.23	.25	.27
			-20	.14	---	---				25	.22	.24	.27
			-40	.19	---	---				0	.23	---	---
			-60	.24	.20	.33				-20	.24	---	---
			-60	.27	---	---				-40	.25	---	---
			-60	.31	---	---				-60	.27	.27	.27
-60	.33	---	---	-60	.25	---	---						
25	.13	.14	.20	-60	.23	---	---						
25	.13	.14	.20	25	.22	.23	.23						
237b	Reamed, C=0.006 in. After 8 hr at 300 rpm After 8 hr at 3 rpm After standing overnight After speed range at -60°C After 6 hr at 3 rpm at -60°C After standing overnight	2,200	25	.19	.22	.20	401	Polished sapphire, clean, C=0.002 in. After speed range at -50°C After 5 hr at 3 rpm at -60°C After standing overnight	0.43	25	.18	.22	---
			25	.13	.16	.25				0	.19	.23	---
			25	.13	---	---				-20	.20	.23	---
			25	.13	---	---				-40	.23	.30	---
			0	.13	---	---				-60	.25	.33	---
			-20	.15	---	---				-60	.28	.35	---
			-40	.20	---	---				25	.13	.15	---
			-60	.24	.27	.31				25	.20	---	---
			-60	.26	---	---				25	.44	---	---
			-60	.32	---	---				25	.20	---	---
-60	.34	---	---	25	.32	---	---						
25	.14	.17	.20	25	.20	---	---						
25	.14	.17	.20	25	.44	---	---						
237c	Reamed, C=0.006 in. After speed run After 8 hr at 300 rpm After speed run After standing over weekend After 8 hr at 3 rpm After speed range at -20°C After 6 hr at 3 rpm at -60°C After standing overnight	2,200	25	.15	.19	.32	605	Reamed, C=0.006 in. After 0.5 hr at 3 rpm After 1 hr at 3 rpm Reamed, C=0.006 in. After 0.5 hr at 3 rpm After 1 hr at 3 rpm Coating: thickness=0.003 in., C=0.002 in. After speed run After 0.1 hr at 300 rpm After 8 hr at 3 rpm After standing over holiday After speed range at -50°C After 6 hr at 3 rpm at -60°C After standing overnight	2,200	25	.41	.43	.46
			25	.21	.23	.35				25	.44	---	.30
			25	.19	.22	.30				25	.28	---	.26
			25	.16	---	---				25	.41	---	---
			25	.16	---	---				25	.41	---	---
			0	.18	---	---				25	.42	---	---
			-20	.19	---	---				0	.42	---	---
			-40	.22	---	---				-20	.41	---	---
			-50	.23	.33	.38				-40	.41	---	---
			-60	.28	---	---				-60	.43	.41	.39
-60	.32	---	---	-60	.42	---	---						
-60	.35	---	---	-60	.48	---	---						
25	.22	---	---	25	.48	---	---						
238	Reamed, C=0.006 in. After 5 hr at 300 rpm After 8 hr at 3 rpm After standing overnight After speed range at -50°C After 6 hr at 3 rpm at -60°C After standing overnight	2,200	25	.06	.13	.19	611	Coating: thickness=0.001 in., C=0.006 in. After speed run After 0.1 hr at 300 rpm After 8 hr at 3 rpm After standing overnight After speed range at -50°C After 6 hr at 3 rpm at -60°C After standing overnight	2,200	25	.03	.05	.21
			25	.21	.23	.25				25	.31	---	.18
			25	.26	---	---				25	.33	---	.17
			25	.18	---	---				25	.16	---	---
			0	.18	---	---				25	.33	---	---
			-20	.13	---	---				0	.33	---	---
			-40	.20	---	---				-20	.13	---	---
			-60	.24	.22	.25				-40	.15	---	---
			-60	.22	---	---				-60	.18	.22	.24
			-60	.22	---	---				-60	.20	---	---
-60	.23	---	---	-60	.18	---	---						
25	.19	.19	.20	-70	.18	---	---						
25	.19	.19	.20	25	.13	---	---						

c. Different Shaft Materials With Oil-Free Bearings

To investigate the effect of different shaft materials on friction, data were obtained with 4 typical bearing materials on each of 5 different shaft materials, at 25° C, with a 2,200-g load, during 8 hr of operation at 3 rpm. The data are given in table 6, in chronological order. With the bearing sample containing molybdenum (sample 202c), after 8 hr of operation the coefficient of friction was 0.07 with the cobalt alloy shaft (C40), 0.15 with the hardened 440C stainless-steel shaft, 0.33 with the relatively soft machinery steel (sample M), and 0.22 to 0.25 with the two shafts made of hardened high-chromium tool steels (samples D3 and D2). With each of the other three bearing materials, after 8 hr of operation at 3 rpm on each shaft, the friction was not greatly affected by the shaft material.

Check runs given in table 6 for bearings 101 and 215 give some indication of the reproducibility of the friction data under these conditions. However, in initial tests with bearing 101 and these new shafts there was a progressive increase in friction from 0.06 to 0.28, and a slight brownish glaze was observed on the bearing at its contact area. These test shafts were ground, lapped with diamond dust, and then polished with 4/0 polishing paper. They were cleaned by scrubbing and rinsing with benzene, but it is believed possible that traces of abrasives from the shafts may have been transferred to the bearing. Preliminary operation was continued with occasional cleaning of the bearing with a reamer and with benzene until a colored glaze no longer formed on the bearing and friction data became reasonably reproducible with check runs.

TABLE 6. Coefficient of friction for typical 1/4-in.-diam bearings, with various steel shafts, with 2,200-g load, at 3 rpm, at 25° C

These data are given in chronological order.

Sample		Coefficient of friction at 3 rpm, after—					
Bearing	Shaft	0 hr	1 hr	2 hr	4 hr	6 hr	8 hr
101	M	0.06	0.09	0.11	0.12	0.13	0.13
	D3	.10	.20	.23	.15	.15	.15
	440C	.10	.12	.14	.15	.15	.15
	D2	.10	.17	.17	.15	.15	.15
	M	.06	.11	.11	.12	.12	.13
202c	D2	.09	.11	.14	.16	.16	.13
	440C	.06	.07	.07	.09	.12	.15
	D3	.06	.10	.10	.12	.15	.22
	M	.07	.19	.27	.32	.32	.32
	D2	.08	.12	.15	.20	.23	.26
215	M	.08	.19	.17	.15	.14	.13
	D2	.16	.19	.18	.16	.13	.13
	440C	.22	.17	.15	.15	---	.17
	D3	.20	.20	.16	.13	.12	.11
	440C	.17	.18	.15	.14	.13	.13
401	D2	.16	.23	.25	.30	.34	.34
	440C	.20	.24	.24	.26	.26	.26
	D3	.20	.27	.28	.29	.30	.30
	M	.24	.29	.33	.36	.36	.34
215	C40	.04	.10	.11	.13	.14	.13
		.06	.09	.09	.06	.06	.07
		.06	.07	.08	.10	.11	.11
		.22	.25	.25	.27	.27	.27

6.3. Bearing-Storage Results

With the apparatus and procedure previously described, the effect of storage on starting friction and corrosion was investigated with 6 typical oil-free bearing materials on each of 3 different shafts. The shafts were an oil-hardening nondeforming tool steel (O2), an oil-hardening, high-carbon, high-chromium tool steel (D3), and 440C stainless steel; the average values of surface roughness as measured by a profilometer before starting the test were 3, 4, and 1 μin., respectively.

The data for the storage test are given in table 7.

TABLE 7. Effect of 10 months of storage on the coefficient of static friction, for various bearing and shaft materials

Bearing	Sample	Coefficient of static friction		Remarks
		New	After 10 months	
222	O2	0.09	0.15	No rust.
	D3	.12	.17	Do.
	440C	.11	.17	Do.
231	O2	.18	.17	Do.
	D3	.13	.17	Do.
	440C	.12	.17	Do.
237a	O2	.16	.23	Do.
	D3	.18	.23	Do.
	440C	.15	.23	Do.
238	O2	.18	1.7+	Journal badly rusted.
	D3	.12	1.7+	Journal rusted.
	440C	.14	0.90	Do.
401	O2	.17	.17	No rust.
	D3	.18	.20	Do.
	440C	.20	.18	Do.
605	O2	.16	.16	Do.
	D3	.09	.19	Do.
	440C	.10	.22	Do.

With bearing sample 231 on D3 and 440C shafts, and samples 222, 237a, and 238 on each shaft, the static friction increased during the 10 months of storage, the range of increase being from 28 to 77 percent. With sample 231 on shaft O2 and sample 401 on each shaft, within the accuracy of the data, there was no change in friction during storage. With the sample of bearing bronze (No. 605), included for comparative purposes, the increase in friction ranged from 60 to 120 percent. With sample 238 (PTFE+molybdenum) there was a very great increase in friction, resulting from corrosion on the shafts; in those areas (journals) of the shafts enclosed by this bearing material, the O2 journal was covered with rust and the journals of the other two shafts were spotted with rust. No corrosion was observed on any of the shafts in other bearing positions. There was considerable rust on the steel housings for bearings 238, and a slight amount of rust on the machined faces of the other bearing housings. On the faces in contact with bearings 238 the brass collars were discolored by corrosion. There was no abnormal discoloration on any of the other brass collars.

The sample 238 bearings used in these tests were machined and installed within 2 weeks after the preparation of this sample of material. Strong odors were emitted from the various samples of PTFE plus molybdenum for several weeks after fusing. Previous experience with new bearings in timepieces, and with pieces of steel in sample jars, indicated that freshly prepared samples of this type might cause corrosion. However, after aging several months, samples no longer caused corrosion of the steel in the jars with the samples. It is probable that storage at an elevated temperature would decrease the period of aging that seems necessary to eliminate the corrosive tendency of this type of material.

6.4. Bearing-Wear Results

a. Rotating Journals

Wear data were obtained with 2,000-g loads on bearings that were $\frac{1}{2}$ in. long with $\frac{1}{4}$ in. bores, corresponding to 35 psi on the projected area. Most of the data were obtained with 303 stainless-steel journals operating at 15 and 150 rpm, but some data were obtained with other types of steel used for the journals and some data were obtained at 700 and 1,800 rpm. These data are given in table 8, in terms of the number of hours of operation for 0.005 in. of radial wear on the loaded side, computed from the wear rates in milligrams per hour and the densities of the samples. An initial diametral clearance of 0.005 in. was assumed in making these computations; and the radial wear of 0.005 in. would increase this to 0.010 in. in the hours given in the table. These computed hours of operation for 0.005 in. of wear should be considered approximations, because the initial clearance in the tests varied from 0.005 in. and the bearing deformation resulting from the load was not considered.

TABLE 8. Rate of wear for various bearing materials, with $\frac{1}{4}$ -in.-diameter shafts, at room temperature, with 2,000-g load

Sample		Length of test at 150 rpm	Computed number of hours for 0.005-in. radial wear				Rating* at 150 rpm
Shaft	Bearing		15 rpm	150 rpm	700 rpm	1,800 rpm	
303	101	hr	hr	hr	hr	hr	5
	101	7	1,400	25	-----	-----	5
	102	31	1,340	116	-----	-----	4
	102	33	-----	134	-----	-----	4
	103	72	1,440	103	-----	-----	4
303	103a	95	1,160	99	-----	-----	6
	103b	-----	1,570	-----	-----	-----	4
303	201	332	85,400	12,700	-----	-----	2
	202	453	103,000+	100,000+	-----	-----	4
	202a	144	67,400	753	-----	-----	4
	202b	237	54,400	1,350	-----	-----	3
	202c	261	100,000+	1,050	-----	-----	3
303	204a	352	45,700	12,200	-----	-----	2
	205	436	2,230	910	-----	-----	4
	205	106	30,500	480	-----	-----	4
	205a	525	18,200	1,820	-----	-----	3
	207	76	2,050	182	-----	-----	4
303	209	260	8,000	1,260	-----	-----	5
	209a	307	9,890	1,820	-----	-----	3
	209	169	68,100	3,710	1,340	-----	3
	210	378	66,100	6,020	2,060	-----	3
211	190	19,100	119	-----	-----	4	

TABLE 8. Rate of wear for various bearing materials, with $\frac{1}{4}$ -in.-diameter shafts, at room temperature, with 2,000-g load—Continued

Sample		Length of test at 150 rpm	Computed number of hours for 0.005-in. radial wear				Rating* at 150 rpm
Shaft	Bearing		15 rpm	150 rpm	700 rpm	1,800 rpm	
303	212	hr	hr	hr	hr	hr	4
	213	184	5,700	236	-----	-----	3
	214	188	10,000	2,120	48	-----	3
	214	213	85,100	11,300	266	-----	2
	214	-----	-----	-----	93	-----	-----
440C	215	351	-----	1,880	-----	242	3
	215	210	-----	1,830	-----	415	3
C40	213	330	-----	3,810	-----	507	3
	215a	221	1,340	-----	-----	-----	4
303	216	361	100,000+	24,900	6,170	6,050	2
	216	-----	-----	-----	-----	-----	-----
440C	216	427	-----	30,400	-----	3,860	2
	216	324	-----	15,300	-----	1,900	2
303	217	312	18,900	2,070	-----	-----	3
	218	315	26,100	14,000	2,150	-----	2
	218a	334	22,600	12,200	-----	-----	2
303	219	629	21,900	11,000	21	-----	2
	220	335	100,000+	1,420	-----	-----	3
	220a	403	100,000+	2,000	-----	-----	3
	221	331	8,050	2,490	327	-----	3
	222	331	38,800	39,600	-----	-----	2
303	223	602	100,000+	12,000	5,120	1,720	2
	224	589	100,000+	46,800	2,300	2,110	2
	225	600	83,000	35,000	-----	-----	2
	225	331	20,700	27,000	41,500	6,720	2
D3	226	-----	-----	-----	-----	1,240	-----
	226	-----	-----	-----	-----	-----	-----
303	227a	29	112	35	-----	-----	5
	228	236	60,600	7,029	2,490	982	3
	229	107	60,800	10,100	2,100	704	2
	230	102	13,000	16,600	1,400	-----	2
	231	89	21,500	203	89	-----	4
303	232	102	4,450	1,660	166	-----	3
	233	102	3,860	4,150	553	-----	3
	234	477	-----	4,810	-----	222	3
	234a	578	-----	10,200	-----	1,010	2
	235	446	-----	11,400	-----	2,340	2
D3	236	-----	-----	-----	-----	-----	2
	236	-----	-----	-----	-----	-----	-----
D3	237	486	-----	1,010	-----	445	3
	237	525	-----	455	-----	237	4
303	238	700	-----	1,820	-----	-----	3
	238	1500	-----	1,010	-----	-----	3
303	239	700	-----	1,070	-----	-----	3
	239	1500	-----	725	-----	-----	4
	239	700	-----	1,520	-----	-----	3
	239	1500	-----	1,010	-----	-----	3
	237	486	-----	307	-----	589	4
303	237a	436	-----	415	-----	780	4
	237b	144	-----	507	-----	670	4
	237c	267	-----	2,220	-----	140	3
	237c	448	-----	876	-----	130	4
440C	237c	430	-----	1,220	-----	140	3
303	238	476	-----	26,800	-----	94	2
	238	600	-----	1,880	-----	1,510	3
D3	238	312	-----	3,750	-----	1,240	3
	238	310	100,000+	-----	-----	21	1
303	238a	478	-----	29,900	-----	30	2
	238b	380	-----	31,900	-----	42	2
303	304	1	-----	62	-----	-----	5
	304	-----	-----	-----	-----	-----	-----
303	401	597	14,800	13,300	234	-----	2
	402	405	19,400	8,220	-----	-----	3
	403	403	41,500	5,810	-----	-----	3
	404	338	5,740	313	-----	-----	4
303	605	4	-----	20	-----	-----	5
	606	0.8	-----	0.9	-----	-----	5
	606	256	-----	11,600	-----	513	2
	611	170	-----	3,220	-----	186	3
	612	143	-----	620	-----	-----	3

* 1: 100,000+ hr, excellent.
 2: 10,000 to 100,000 hr, very good.
 3: 1,000 to 10,000 hr, good.
 4: 100 to 1,000 hr, fair.
 5: 0 to 100 hr, poor.

In general, the duration of a test was short compared to the hours computed for 0.005-in. radial wear. Included in table 8 are the durations of the tests at 150 rpm. Special tests were made with sample 236 to get indications of the effect of duration of tests and the effect of journal roughness. In these special tests, three bearings (sample 236) with 0.005-in. initial clearance were tested on three 303 stainless-steel journals with roughness values of 2, 8, and 16 μ in., as measured with a profilometer. The wear was determined for 700 hr and then for 1,500 hr, after running an additional 800 hr. In this range of roughness, there was no trend for variation of wear with roughness; but there was a trend toward higher rate of wear with the longer period of operation. For these special tests the computed hours of operation for 0.005-in. wear on the loaded side ranged from 795 to 1,830 hr, which may be compared with 1,010 hr computed from a previous test with 486 hr of duration.

In table 8, ratings are given for the wear resistance of the bearing for each test at 150 rpm. Ratings 1 and 2 are given for computed hours of operation above 100,000 and 10,000, and are considered excellent and very good, respectively. Rating 3 is given for operation between 1,001 and 10,000 hr, and is considered good.

TABLE 9. Wear for various bearing materials, with $\frac{1}{2}$ -in. diameter shafts, at room temperature, with 1,000-g load; shafts oscillating, amplitude=0.5 radian, frequency=3 cps

Sample	Time run	Bearing loss in weight		Condition of journals at end of tests		Rating *	
		Front	Rear	Front	Rear		
303	80	Days	mg	mg			
		101	0.8	9.1	Very good	Scored	6
		306c	0	0.0	Good	Good	1
		306	0	0.4	Fair	Fair	3
		310	1	1	do	do	2
303	80	215	1	2	Very good	Very good	2
		319	2	2	Good	do	2
		321	1.0	0.6	Scored	Good	4
		322	0.1	2	Very good	do	2
		324	1	2	Good	Fair	2
303	80	234	1	1	Very good	Very good	1
		234a	1	0	Good	do	1
		237	4	4	Very good	do	3
		401	0	1.0	Fair	Fair	4
		403	1	0.2	Good	Good	2
440C	80	202c	3	4	Fair	Scored	4
		214	1	1	Good	Fair	2
		234a	1	1	Very good	Very good	1
		401	1	4	Good	Good	3
D3	80	202c	1.9	1.4	Scored	Scored	4
		214	2.5	1.6	do	do	4
		222	0.0	0.1	Good	Very good	1
		401	2	0.1	do	Good	2
C40	80	202a	0	3	Fair	do	3
		214	5	3	Good	do	3
		401	0	0	do	do	1
440C	10	303	5.8	5.8	Worn slightly	Worn slightly	5
		605	29.9	29.0	do	do	5
D3	10	303	12.1	16.3	do	do	5
		605	17.7	16.6	do	Worn and scored	5

*1: excellent; 2: very good; 3: good; 4: fair; 5: poor.

b. Oscillating Journals

Wear data were obtained with 1,000-g loads on typical paired bearings, each $\frac{1}{2}$ in. long with $\frac{1}{2}$ -in. bore, with various steel shafts in the modified oscillating display motors. The pressure during the impulse from the solenoid was considerably greater than the 70 psi corresponding to the 1,000-g static load. These data are given in table 9. In general, the loss in weight of the typical bearings and the condition of the journals after 60 days of operation are given. However, with porous bronze containing molybdenum disulfide (sample 303) and with bearing bronze (sample 605), the friction increased soon after starting the tests to the extent that a much higher voltage had to be applied to the solenoids to maintain operation and one solenoid burned out due to overloading. Because of this and excessive wear, tests with these two materials were stopped at the end of 10 days. It is of interest that the performance with these two bearing materials (samples 303 and 605) in this machine was very much inferior to any of the other oil-free materials that were tested on it. The rating numbers given in table 9 for each test are based on the bearing wear and the condition of the journals at the end of each test. The numbers 1 to 5 correspond to excellent, very good, good, fair, and poor, respectively.

c. Thrust Bearings With Oscillating Pins

With the endstone-wear testing machine, wear data were obtained with typical bearing materials and test pins made of typical shaft materials, with 1,000- and 1,240-g loads. The data obtained with the 440C test pins are given in table 10. For each measured depth of wear (see section 5.4 for method of measuring) the corresponding pressure (pounds per square inch) on the projected area was computed, and these data are included in table 10. At 0.0167 in. of wear the diameter of the wear mark, becomes the same as that of the pin (0.125 in.), so that for greater depths of wear the pressure does not increase. The average rates of wear per bearing, in inches per year, for each period are given in the table also.

With the diamond endstone there was no wear on the diamond or the pin that could be detected by ordinary means. No flat could be detected on the pin when examined with a 20-power stereomicroscope and when examined with a shadowgraph. No roughness was detected on the diamond, but examination with an interferometer indicated a depression about 17 μ in. deep near the center of the endstone after the 60-day test. On the basis of this test, diamond is rated as excellent for use as endstones.

With PTFE plus molybdenum (sample 202c) and with PTFE plus PTFE (sample 215) no measurable wear was detected during the last 20 days of operation, and hence these materials are rated very good for use as endstones.

With samples 222 and 401 the rate of wear was low during the last period of operation, and these materials may be rated as good. The relatively wide spread in the data for the carbon plus graphite

TABLE 10. Wear data for typical bearing materials, with endstone-wear machine, with 440C hardened steel shafts, 1/8-in. diameter with 1/16-in. radius at ends, at room temperature; shafts oscillating, amplitude=1.5 radians, frequency=1 cps

Sample	Time run	1,000-g load		1,240-g load		Average rate of wear ^b
		Depth of wear	Pressure ^a	Depth of wear	Pressure ^a	
101	Days	in.	psi	in.	psi	in./yr
	10	0.0075	325	0.0075	478	0.374
	20	.011	298	.020	383	.110
	40	.016	187	.015	247	.091
	60	.020	180	.020	223	.082
102	10	.005	575	.005	711	.132
	20	.009	323	.0075	478	.119
	40	.013	228	.011	330	.088
	60	.016	187	.014	283	.085
202c	10	.001	2,813	.001	3,490	.038
	20	.0015	1,875	.0015	2,326	.018
	40	.002	1,418	.002	1,758	.009
	60	.002	1,418	.002	1,758	.000
215	10	.0015	1,875	.002	1,758	.004
	20	.002	1,418	.002	1,758	.009
	40	.002	1,418	.002	1,758	.000
	60	.002	1,418	.002	1,758	.000
222	10	.0015	1,875	.0015	2,326	.038
	20	.0015	1,875	.002	1,758	.009
	40	.002	1,418	.002	1,758	.006
	60	.002	1,418	.0025	1,398	.006
401	10	.0015	1,875	.001	3,490	.046
	20	.002	1,418	.0015	2,326	.018
	40	.0025	828	.0015	2,326	.014
	60	.004	715	.0015	2,326	.005
604 (Sapphire)	10	.004*	715	-----	-----	.145 ^b
	20	.005	574	-----	-----	.035
	40	.007	412	-----	-----	.035
	60	.0095	311	-----	-----	.045
609	10	.010	282	.018	232	.475
	10	-----	-----	.0000	130,300	.000
610 (Diamond)	20	-----	-----	.0000	130,300	.000
	40	-----	-----	.0000	130,300	.000
	60	-----	-----	.0000	130,300	.000
611	4	.061	180	.027	233	2.85

^a Computed pressure on the projected area for each measured depth of wear; excepting diamond, in which case pressure was computed from the elastic deformation of the radius at the end of the steel pin.

^b Computed from average wear during each period of time run.

* Wear occurred on end of steel pin instead of on sapphire endstone.

plus silver (sample 401) is believed to be due to a lack of homogeneity in the mixture.

With sapphire (sample 604, unlubricated) a relatively large flat was worn on the end of the test pin, and the rate of wear given in table 10 is for this wear on the pin. However, the sapphire became roughened on part of the rubbing area, and was worn slightly.

With PTFE and with PTFCE the endstone-wear rate was high. With the coatings (samples 609 and 611) the tests were stopped after a few days of operation because of excessive wear.

Results obtained when samples 101, 202c, 215, and 401 were tested with pins made of 303 stainless steel, hardened D3 steel, and C40 alloy were similar to those obtained with 440C stainless-steel pins.

With 303 stainless-steel pins, specimens of tungsten plus molybdenum disulfide plus plastic coating (sample 606) on brass started wearing very rapidly, and the test was stopped at the end of the first day of operation. For comparison, a test with plain

brass (sample 607) gave less wear than the coated brass, although wear was excessively great in both cases. Although this coating is advertised as showing no wear when used as a thrust bearing under certain conditions, under the conditions used in these tests its wear resistance was inferior to that of brass.

6.5. Timepiece-Bearing Results

The performance of oil-free bearings was investigated in 18 timepieces, including chronometers, clocks, and watches.

For plastics and plastics with fillers, the coefficients of thermal expansion are such that with 1/8-in.-bore bearings subjected to a wide range of temperature, clearances much larger than those commonly used with metallic journal bearings are necessary. However, the percentage of clearance normally used for the relatively small journals in timepieces is such that the above condition presents no problem. Bearings of this type become loose in their housings at low temperature; in order to prevent axial displacement at low temperatures, these bearings were fitted in brass holders having the inner edges crimped inward slightly to retain the bearings.

In general, the amplitude of the motion of the balance wheels in the clocks and watches fitted with oil-free bearings was considerably less than the normal amplitude in oiled-jewel movements at ordinary temperatures. In most cases, heavier mainsprings were installed to increase the torque about 50 percent to provide more normal motion. However, in the chronometers the original mainsprings were not replaced, because they provided sufficient power for normal motion in these timepieces.

On the basis of the experience with timepieces, it appears that for ship chronometers in normal dial-up position the most severe wear is apt to occur at the upper balance-staff endstones, and for clocks operating in the normal 12:00-up position the most severe wear is apt to occur at the bearings for the balance-staff journals. Also, it is probable that the friction at these points is of major importance.

For watches and clocks, the friction and wear at the pallet stones also appears to be of major importance, and no material has been found to be more satisfactory than sapphire for this application. Unlubricated sapphire pallet stone appears to be satisfactory at ordinary temperatures, but at very low temperatures the addition of a film of a suitable low-temperature oil apparently gives less friction than clean sapphire.

Rusting is apt to occur in unlubricated timepieces, especially at the balance-staff pivots, unless precautions are taken to prevent it. Experience with timepieces in this investigation indicates vapor phase inhibitors, such as dicyclohexylammonium nitrite, are effective in preventing rust. Also, rusting may be prevented by the use of corrosion-resistant materials; no rust was observed with cobalt alloy (C40) pivots.

In general, at ordinary temperatures the timekeeping performance of timepieces with conventional

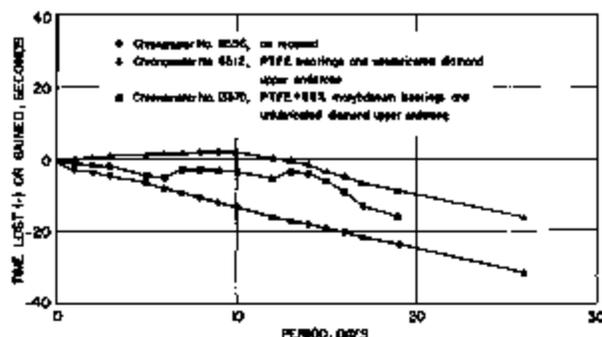


FIGURE 11. Representative time error for chronometers, at room temperature.

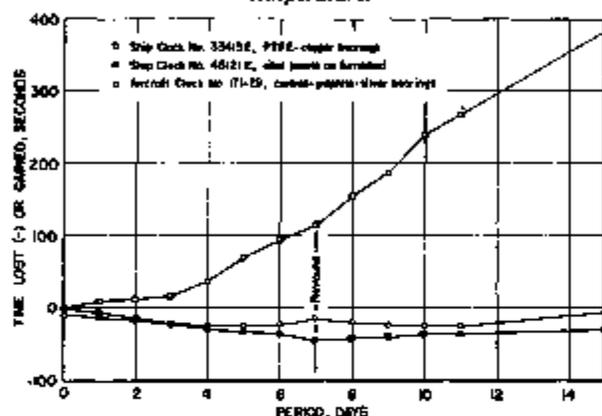


FIGURE 12. Isochronism curves for 8-day clocks.

lubricated jewels was somewhat superior to that of oil-free timepieces. The degree of this superiority is indicated in figure 11, which shows a plot of time errors for a conventional lubricated chronometer and for two chronometers containing oil-free bearings. However, with less accurate timepieces, the difference in accuracy is of less importance. Typical isochronism curves are given in figure 12, for a conventional ship clock, a similar clock fitted with PTFE-plus-copper bearings, and an aircraft clock fitted with carbon-graphite-silver bearings.

Representative data for the performance of six timepieces fitted with oil-free bearings at -60°C , $+25^{\circ}\text{C}$, and $+75^{\circ}\text{C}$ are given in table 11. The sapphire pallet stones in the watches and clocks and the mainsprings and other metal-to-metal working parts in these timepieces were lubricated with MIL-O-11734 oil. The size of the heavier mainsprings in the ship clocks was such that, because of the lesser free space in the mainspring barrels and the corresponding lesser number of turns in winding, they "ran down" in about 5 days instead of 8 days. This may account for the stoppage of one clock on the fifth day after winding, as it was nearly run down when it stopped. The range of temperature is beyond that ordinarily compensated for in timepieces, and lack of temperature compensation may account for some of the variation in rate with temperature for chronometer 13370 and clock 33413E. Considering the wide range in temperature, the rates for the other timepieces were not greatly affected by temperature variation.

TABLE 11. Timepiece performance at various ambient temperatures, with oil-free bearings, except for MIL-O-11734 oil on pallet stones, mainsprings, and other metal-to-metal parts

Timepiece	Oil-free bearings		Gain (+) or loss (-) in 24 hr		
	Sample	Number	-60°C	$+25^{\circ}\text{C}$	$+75^{\circ}\text{C}$
Ship chronometer No. 8512, dial up, wound daily.	101	10*	sec	sec	sec
			+17	-1	-45
			+10	-14	-20
			+7	0	-14
			+8	0	-13
Ship chronometer No. 13370, dial up, wound daily.	202c	10*	-118	+14	+36
			-148	0	+40
			-109	-14	-41
			-119	-1	-47
			-116	-14	-43
Navigation watch No. 965-41, 24:00 up, wound daily.	315	19	-7	+63	+56
			-7	+63	+66
			+51	+66	+60
			+37	+49	+66
			+37	+69	+55
Navigation watch No. 364-43, dial up, wound daily.	202	19	-69	+1	-10
			-39	-3	+20
			-5	-10	+26
			-3	-18	+17
			-31	-4	0
Ship clock No. 33413E, 12:00 up, 1 winding.	206	9	-311	+128	-143
			-334	+2	-35
			-344	-13	-101
			-330	-17	-200
			-334	-39	-200
Ship clock No. 46121E, 12:00 up, 1 winding.	401	9	+9	+82	+10
			+7	+21	+10
			+2	-2	+4
			+13	-15	0
			Stopped	-12	+2

* Including 1 diamond and 1 sapphire endstone, unlubricated.

Twelve timepieces fitted with various oil-free bearings were stored in a low-temperature cabinet maintained at -60°C . These were running at the start of this test but were not wound during the storage. After 30 days each timepiece was wound while remaining in the low-temperature cabinet; and if it did not start while winding, it was given quick twists in a manner ordinarily used for starting timepieces. The results of this low-temperature test are given in table 12. The low-priced watch No. 4-52

TABLE 12. Starting ability of timepieces, after winding, at -60°C , after 30 days of storage at -60°C

Timepiece	Oil-free bearings		Other parts	Starting ability
	Sample	Number		
Navigation watch 965-42	202	19	(*)	Started.
Ship chronometer 13370	202c	14	(b)	Do.
Ship clock 33413E	206	9	(*)	Do.
Aircraft clock 1	215	8	(*)	Do.
Navigation watch 965-41	215	19	(*)	Do.
Pocket watch 4-52	215	7	(a)	Would not start.
Aircraft clock 93-29	222	12	(*)	Started.
Aircraft clock 68-C-690	234a	12	(*)	Do.
Automobile electric clock K.A-494	234a	4	No oil	Do.
Ship chronometer 6512	237a	16	(b)	Do.
Aircraft clock 171-29	401	12	(*)	Do.
Ship clock 46121E	401	9	(*)	Would not run.

* MIL-O-11734 oil applied to pallet stones several months previously.
 (b) MIL-G-7421 grease in mainspring barrel to arbor bearing and inside fuse winding assembly.
 (c) MIL-O-11734 oil on pallet pin, pallet arbor, and mainspring assembly.

with oil at places noted in the table would not start, and ship clock No. 45121E would not continue running after starting several times. All the other timepieces continued running at -60°C after starting. In the watches and clocks having sapphire pallet stones, the stones had been lubricated with MIL-O-11734 oil several months previously, but this is not a nonspreading type as ordinarily used for this application in timepieces. Some time after the low-temperature starting test, the sapphire pallet stones were examined with a 20-power stereomicroscope; no oil appearing as a liquid could be detected, but various colors appearing on the surface of the sapphire indicated a boundary layer of lubricant was present.

It is believed that MIL-O-11734 oil applied to the sapphire pallet stones will provide boundary lubrication for a period of about 2 years. The oil may be applied to the pallet stones in a few minutes, without the disassembly and time that are required for oiling a timepiece throughout in the conventional manner. For current types of aircraft clocks, by removing the movement from the case the oil may be applied to the pallet stones easily in the conventional manner; or, after practice, with the movement in the case a small wire may be inserted through the regulator screw plug opening to apply the oil to the teeth of the escape wheel in less than a minute.

Near the end of this project, in aircraft clock No. 28169, 6 bearings and 2 endstones, sample 237a, were used to replace 8 sapphire jewels; and 7 PTFCE bearings (sample 102) were installed in other positions; namely, third, center, intermediate, and fourth wheel upper. In figure 10 it may be seen that the coefficients of friction for these two samples are practically the same at -60°C , and that the mean friction for the two samples remains about the same in the temperature range from -60° to $+25^{\circ}\text{C}$. This combination of bearings of these materials was tried to minimize the effect of temperature on the total friction in the clock. With the original mainspring (0.008 in. thick) the motion was poor; hence a stronger mainspring (0.011 in. thick) was installed to give more normal motion of the balance wheel. Operation at -60°C with the sapphire pallet stones unlubricated was not satisfactory. After the addition of MIL-O-11734 oil to the pallet stones, the motion at -60°C was only slightly less than at room temperature, although the clock lost several minutes per day at -60°C .

7. Conclusions

7.1. Plastics

The wear-test data and experience with PTFE in an aircraft clock and in a chronometer indicate that this material (without additives) is not suitable for general use as a bearing material because of its tendency to wear, but at very low surface speeds and low unit pressures its wear resistance may be adequate for special applications. The increase in friction at temperatures below -20°C detracts from its usefulness at low temperatures.

The high friction common to PTFCE at ordinary temperatures, and the rates of wear obtained with it in bearings, for a clock balance staff and an endstone for a chronometer balance staff, do not recommend its use as an oil-free bearing material for timepieces. However, its decrease in friction with decrease in temperature makes it useful for special applications at low speeds, such as that described in the last paragraph in section 6.5.

Nylon has been used as a bearing material in certain industrial applications. However, its friction is higher than that of some of the other materials investigated, and its relatively large variation in water content and change in size with change in ambient temperature and humidity are not desirable.

The high-density polyethylene is a relatively new type of polyethylene plastic, and was obtained near the end of the project. The friction with this material was somewhat greater than with PTFE, and the increase in friction with decrease in temperature was greater than that of PTFE. However, the rate of wear at 150 rpm with this polyethylene (sample 104) was less than that of any of the other unfilled plastics tested under similar conditions.

7.2. Plastics With Fillers

PTFCE containing 10 to 60 percent of PTFE as a filler is one of the most promising oil-free bearing materials developed during the project. A patent which is pending, covering this type of material, has been assigned to the U. S. Government. This material has some of the hardness characteristics of PTFCE, the frictional characteristics of PTFE, and wear resistance much greater than that of either of these plastics alone. Unfortunately, the fact that its frictional characteristics are similar to those of PTFE detracts from its usefulness at temperatures below -20°C .

With the samples of PTFCE containing graphite and molybdenum disulfide (samples 207 and 213, respectively), the friction and the wear were less than with PTFCE; but these dry lubricant additives did not decrease the friction and wear as much as did the PTFE filler.

PTFE containing molybdenum metal powder as a filler is a promising material also, and a patent (No. 2,715,617) covering this type of material has been assigned to the Government. It has good frictional characteristics and exceptionally good wear resistance under certain conditions.

The commercial preparation of PTFE containing fiber glass and pigment (sample 201) has good wear and friction characteristics when used as oil-free bearings with 0.25-in. bore. However, the relatively large size of some of the glass fibers and the lack of uniformity in the mixture prevent it from being suitable for bearings where the bore is only about 0.005 in.

The addition of graphite, copper powder, or molybdenum disulfide powder to PTFE (samples 204a, 205, and 206) has a similar effect in reducing wear in 0.25-in. bearings. However, these commer-

cial preparations have small pockets of pure plastic similar to those observed in the material with code No. 201.

In general, the addition of a filler to PTFE decreases the wear greatly, but the filler of silver precipitated flowers (sample 203) is an exception. The experience of high wear and high friction at low speeds with a bearing of this material is not understood. It is believed, from microscopic examination, that the silver particles are much less than 1μ in size but have a great tendency to occur in conglomerations larger than 5μ . Because of the conglomerations, it is possible that the PTFE does not surround and bind the individual silver particles; and the breakup of the conglomerations during testing may cause the high wear and high friction. In this connection, molybdenum metal powder is readily available in particle sizes from 0.5 to 5μ , and this range of particle size appears to be especially suitable for fillers in PTFE compositions for small oil-free bearings.

7.3. Impregnated Bronze

Stereomicroscopic examination of the porous bronzes showed some of the pores and the sections of solid bronze to be much larger than the diameters of common balance-staff journals, and this makes the use of impregnated porous bronze impractical for this application. Also, for larger journals, the friction and wear data obtained for porous bronze impregnated with PTFE and with molybdenum disulfide discourage its use for an oil-free bearing composition, under the conditions that were investigated.

7.4. Impregnated Carbon

In general, the metal-impregnated carbon materials that were tested have good friction and wear characteristics. An additional advantage is their low coefficient of thermal expansion, and in some applications their good electrical conductance may be useful. As suggested by the manufacturer, the carbon-graphite-silver material (sample 401) seemed more promising for use in timepieces than other samples (402, 403, and 404) produced by the same company. The spread in data obtained with this material on the endstone-wear testing machine indicates a lack of homogeneity in the sample; this and the relative coarseness of the structure discourage its use for very small bearings (less than $\frac{1}{16}$ -in. bore).

7.5. Miscellaneous

No material was found to be as satisfactory as diamond for use as a thrust-bearing material under conditions of high load such as occurs at the balance-shaft upper endstone in chronometers. By an X-ray

diffraction test for orientation, it was found that the faces of the diamond used in the endstone-wear testing machine and the diamond endstone in chronometer 13370 were within 4° of being parallel to an octahedron (111) face (cleavage plane). The face of the endstone in chronometer 6512 was found to differ about 22° from the octahedral (111) plane. It is considered that each of these diamond endstones was very satisfactory for its intended use as a thrust bearing, even without lubrication.

No material was found to be as satisfactory as sapphire for use as pallet stones in timepieces. Sapphire appeared to be suitable for use as unlubricated endstones when the load was relatively light, especially in timepieces normally operating in an upright position. Unlubricated (clean) sapphire hole bearings (jewels) caused rapid wear or rusting of the conventional balance-staff pivots in timepieces.

Boron carbide without lubrication did not appear to be suitable for use as pallet stones or as a journal-bearing material.

Under the conditions tested, ordinary brass and bearing bronze conventionally used for making small bushings did not appear suitable for this application without lubrication.

In journal bearings, a fused coating of PTFE plus graphite gave good resistance to wear but the friction was relatively high. A fused coating of PTFE one-coat enamel gave lower friction, but the resistance to wear was somewhat less than with the above coating. Both of these coatings (samples 609 and 611, respectively) wore rapidly when tested as thrust bearings. Because of the thickness of the coatings ordinarily used and the difficulty in making a uniform coating with a good bond on small parts, the use of coatings of this type does not seem practical for journals or bearings less than $\frac{1}{8}$ in. in diameter. However, work at the Naval Research Laboratory [9] indicates that PTFE coatings may be useful for some applications.

The silver amalgam (sample 501) gave exceptionally low friction at room temperature. However, this material was very brittle and the edges of the hole chipped badly during the boring and reaming operations. An amalgam of dental alloy filings was also tried; it was less brittle than the silver amalgam, but the bearing gave increasingly high friction at the start of a test and scuffing of the bearing soon occurred.

Other publications that may be of interest deal with dry bearings suitable for textile mills [10], and with the frictional characteristics of plastics with and without lubrication [11].

The experimental work (mostly static friction tests) during the early part of this investigation was conducted by John Young, who left the Government service in September 1952.

8. References

- [1] E. I. duPont de Nemours & Co., Tech. Serv. Bul. 13 (1949).
- [2] M. W. Kellogg Company, Tech. Bul. 2-10-50.
- [3] H. S. White and D. Zei, Static friction tests with various metal combinations and special lubricants, *J. Research NBS* **46**, 292 (1951) RP2198.
- [4] F. P. Bowden and D. Tabor, *The friction and lubrication of solids* (Oxford Univ. Press, London, 1950).
- [5] MIL-O-11734 Military Specification: Oil, lubricating, synthetic (for mechanical time fuses).
- [6] MIL-L-17353 Military Specification: Lubricating-oil, low temperature, special.
- [7] MIL-G-7421 Military Specification: Grease; extreme low temperature.
- [8] R. F. King and D. Tabor, The effect of temperature on the mechanical properties and the friction of plastics, *Proc. Phys. Soc. (London)* [B] **66**, 728 (1953).
- [9] R. C. Bowers, W. C. Clinton, and W. A. Zisman, Frictional behavior of polyethylene, polytetrafluoroethylene, and halogenated derivatives, *Lubrication Eng.* **9**, 204 (1953).
- [10] S. Ricklin and R. R. Miller, Filled Teflon for dry bearings, *Materials & Methods* **46**, 112 (October 1954).
- [11] W. C. Mills and L. B. Sargent, Jr., Frictional characteristics of plastics, *Lubrication Eng.* **11**, 313 (1955).

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