RI 8124

Bureau of Mines Report of Investigations/1976

Effect of Environment on Friction and Wear Between Quartz and Steel

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 8124

Effect of Environment on Friction and Wear Between Quartz and Steel

By Daryl R. Tweeton, Twin Cities Mining Research Center,
Twin Cities, Minn.

UNITED STATES DEPARTMENT OF THE INTERIOR
Thomas S. Kleppe, Secretary
BUREAU OF MINES
Thomas V. Falkie, Director

This publication has been cataloged as follows:

Tweeton, Daryl R

Effect of environment on friction and wear between quartz and Steel. [Washington] U.S. Bureau of Mines [1976]

25 p. illus., tables. (U.S. Bureau of Mines. Report of investigations 8124)

Includes bibliography.

1. Steel–Surface properties. 2. Quartz–Surface properties. I. U.S. Bureau of Mines. II. Title. III. Title: Friction and wear between quartz and steel. (Series)

TN23.U7 no. 8124 622.06173

U.S. Dept. of the Int. Library

CONTENTS

	Page
Abstract	1
Introduction	1
Acknowledgments	3
Equipment and procedure	3
Results and discussion	5
Gas environments	5
Coefficient of friction	5
Temperature	11
Wear products	11
Roughness	12
Wear	14
Liquid environments	16
Coefficient of friction	19
Roughness	21
Wear	22
Summary	23
References	25

ILLUSTRATIONS

1.	Friction and wear testing machine	3
2.	Coefficient of friction--moist air, 6.8-kg load	5
3.	Coefficient of friction--moist air, 13.6-kg load	5
4.	Coefficient of friction--dry air, 6.8-kg load	5
5.	Coefficient of friction--dry air, 13.6-kg load	5
6.	Coefficient of friction--dry nitrogen, 6.8-kg load	6
7.	Coefficient of friction--dry nitrogen, 13.6-kg load	6
8.	Coefficient of friction--40-pct relative humidity air, 6.8-kg load	6
9.	Coefficient of friction--40-pct relative humidity air, 13.6-kg load	6
10.	Average coefficients of friction--gas environments, 6.8-kg load	8
11.	Average coefficients of friction--gas environments, 13.6 kg load	8
12.	Coefficient of friction in air as relative humidity and speed are varied	9
13.	Photomicrograph of wear product powder	12
14.	Photomicrograph of quartz surface outside wear scar	14
15.	Photomicrograph of quartz surface inside wear scar	14
16.	Photomicrograph of steel wearing area	15
17.	Wear scar widths of quartz blocks--gas environments, 6.8-kg load	17
18.	Wear scar widths of quartz blocks--gas environments, 13.6-kg load	17
19.	Weight loss of steel rings--gas environments, 6.8-kg load	18
20.	Weight loss of steel rings--gas environments, 13.6-kg load	18
21.	Coefficient of friction--liquid environments, 6.8-kg load	19
22.	Coefficient of friction--liquid environments, 13.6-kg load	19

TABLES

Page

1. Average coefficients of friction in gases..... 7
2. Average AA roughness heights for quartz blocks and steel rings after sliding contact for 2,000 revolutions (220 m) in gases..... 13
3. Wear of quartz blocks and steel rings after sliding contact for 2,000 revolutions (220 m) in gases..... 16
4. Average coefficients of friction in liquids..... 20
5. Average AA roughness heights for quartz blocks and steel rings after sliding contact for 2,000 revolutions (220 m) in liquids.... 21
6. Wear of quartz blocks and steel rings after sliding contact for 2,000 revolutions (220 m) in liquids..... 22

EFFECT OF ENVIRONMENT ON FRICTION AND WEAR BETWEEN QUARTZ AND STEEL

by

Daryl R. Tweeton[1]

ABSTRACT

The Bureau of Mines conducted experiments to measure the influence of environment on the friction and wear of a steel-quartz system at several speeds and loads. In each test a quartz block was pressed against a rotating ring of low-carbon steel. Environments used were moist air, dry air, dry nitrogen, water, aqueous oleylammonium acetate ($C_{18}H_{35}NH_3^{+-}OCOCH_3$), and aqueous aluminum chloride ($AlCl_3$). The sliding speeds were 2.2, 13, and 33 cm/sec, and the loads were 6.8 and 13.6 kg. The coefficient of friction, the wear, and the roughness of the surfaces were measured, and the wear debris was examined.

The coefficient of friction was significantly lower in moist air at 2.2 cm/sec than for any other combination of environment and speed employed, and was generally an inverse function of the oxidizing ability of the environment. The coefficient of friction increased somewhat with increasing load. The wear of the steel rings was greatest in dry air at all speeds and loads. The wear of the quartz blocks at 180 rpm was greatest in dry air, but at 12 rpm it was greatest in nitrogen. Friction and wear in aqueous oleylammonium acetate and in aqueous aluminum chloride were similar to effect in water alone.

INTRODUCTION

Friction and wear are important in mining. In drilling and cutting rock, for example, it is desirable to minimize the wear of tools and any friction not contributing to rock fragmentation. Conversely, it is desirable to maximize fragmentation of the rock, which is a form of wear in certain types of cutting and drilling.

Friction and wear can be influenced by many factors besides the nature of the rubbing surfaces. The factors considered in this study were environment, speed of rubbing, the force (normal load) with which one surface was pressed against the other, and duration of rubbing. The effect of environment was emphasized.

---

[1]Research physicist.

Several practical applications of the effect of environment have been made by other experimenters. In 1944, Rehbinder, Shreiner, and Zhigach (6)[2] reported that adding certain chemicals to flushing fluids used in drilling rock increased the penetration rate. The best additive varied with the type of rock, so the additives seemed to affect the rock itself rather than merely improving flushing or cooling. The increases in drilling rate were attributed to a softening of the rock, called the Rehbinder effect. More recently, the Bureau of Mines found that certain additives enhanced penetration rates when drilling quartzite (8) and copper ore conglomerate (9) with diamond-tipped coring bits. Effects of speed and load (thrust) also were investigated.

Westwood, Macmillan, and Kalyoncu (10) found that using additives which gave a zero zeta potential on soda-lime glass, quartz, or various other nonmetals enhanced drilling rates of a diamond-tipped drill in these materials, but retarded drilling rates of a spade bit. Westwood attributed this to a hardening of the material by an additive. This hardening would reduce the amount of deformation the material would undergo before fracturing, which would increase the efficiency of drilling done by brittle fracture (with diamond-tipped drills), but would decrease the efficiency of drilling done by ploughing (with a spade bit). The additive concentrations giving a zero zeta potential were much lower than those used by Rehbinder, Shreiner, and Zhigach (6) or the Bureau of Mines (8-9), so a softening observed by Rehbinder and a hardening observed by Westwood were not necessarily contradictory.

The effects of various gases on metal-metal friction and wear have been investigated by many experimenters. For most metals, friction is lower and wear is higher in environments containing oxygen than in inert gases, though there are numerous exceptions (4, 11).

The number of investigations of metal-nonmetal friction and wear is smaller than the number involving metal-metal systems. Metal-nonmetal friction and wear in dry air and dry argon were included in a study by Wolkowitz and Ranish (11), who used equipment similar to that of the present project. Basalt and rhyolite blocks were pressed against rotating steel rings. The investigators stated that the effect of the atmosphere on the coefficient of friction was unclear for these materials. However, their data indicate that, for conditions closest to those of the present project, the coefficient of friction was higher in air than in argon.

The influence of environment on metal-nonmetal friction was also demonstrated by Roepke and Peng (7). They primarily studied friction in ultrahigh vacuum, but also showed that friction between sapphire and stainless steel and between sapphire and various rock surfaces was higher in dry nitrogen than in air. They used a normal load of 100 g at a speed of 0.031 mm/sec.

The fact that friction and wear could be influenced by environment and the other factors previously listed was shown by past studies. However, large gaps remained in the knowledge of metal-nonmetal friction and wear for

[2]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

conditions close to those encountered in mining. Therefore, the Bureau's Twin Cities Mining Research Center conducted the present study to help eliminate some of those gaps. The effects of environment were emphasized, but speed, load, and duration of sliding were considered also. Because of time limits, only one pair of materials was studied, steel-quartz. This pair was chosen because steel is the most common metal in mining tools, and the hardest common rocks contain quartz. Quartz was used rather than a rock like granite because inhomogeneities in rock would introduce uncontrolled variables. In addition, Westwood, Macmillan, and Kalyoncu (10) found that it was the action of additives on the quartz that governed the effectiveness when drilling granite.

Further discussions of the findings from previous experiments will be presented along with the findings of the present project. Metal-metal as well as metal-nonmetal friction studies will be discussed because some steel was transferred to the quartz surface.

ACKNOWLEDGMENTS

The research described in this report was performed under the sponsorship of the National Research Council--Bureau of Mines Postdoctoral Research Associateship program.

EQUIPMENT AND PROCEDURE

A Dow Corning Alpha LFW-1[3] friction and wear testing machine was used to press a quartz block against a rotating steel ring (fig. 1), giving line contact friction initially. The blocks were cut from quartz crystals and had random crystal axis orientations. The block holder did not allow the orientation of the block to be adjusted. Two sizes of blocks were uses: 6.35 mm wide in gas environments and 3.85 mm wide in liquids. This was done to reduce costs by allowing surplus blocks from other experiments to be used and did not interfere with any important goal, because the object of the tests in liquids was to compare the effects of pure water containing additives with the effects of pure water, not with the effects of gases. The wider blocks were 10 mm high and 16 mm long; the narrower blocks were 7.8 mm high and 20 mm long. The rings were of SAE 4620 steel, containing

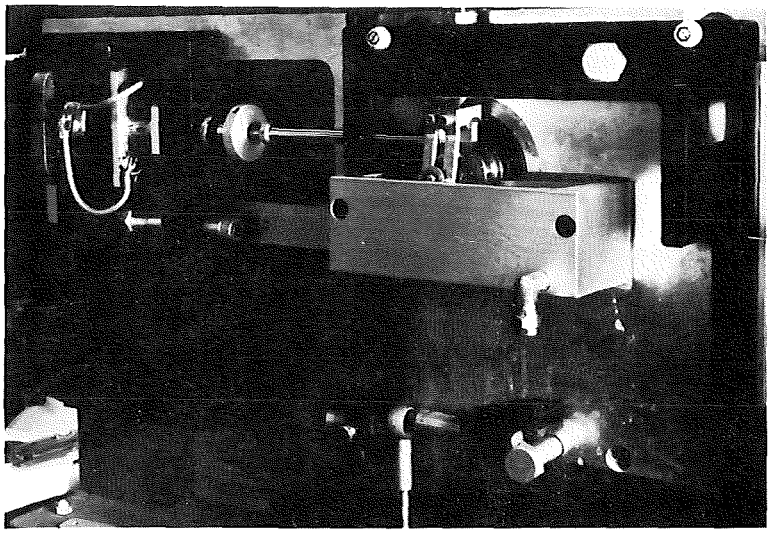

FIGURE 1. - Friction and wear testing machine.

[3]Reference to specific brands is made for identification only and does not imply endorsement by the Bureau of Mines.

0.20 pct carbon, 1.2 to 1.4 pct manganese, and 0.15 to 0.25 pct molybdenum. They were case-hardened to a Rockwell hardness of Rhn 58 to 63 and complied with ASTM Standard D 2714-68. They had a diameter of 35 mm and a width of 8.2 mm, so the length of the line contact equaled the width of the block.

Before use, the rings and blocks were cleaned. Rings were degreased three times in trichloroethylene in an ultrasonic cleaner, with each cleaning no shorter than one-half hour. They were then baked overnight at 100° C and stored in a desiccator until used.

The tangential (frictional) force on the block was determined by measuring the force on the restraining rod of the block holder with a calibrated strain gage connected to an amplifier and recorder. With a known normal load, the coefficient of friction (tangential force/normal load) could be determined continuously during the 2,000 revolutions of each test. The normal loads, applied by a weight acting through levers, were 6.8 kg and 13.6 kg. The rotation speeds were 12, 72, and 180 rpm, which correspond to 2.2, 13, and 33 cm/sec, respectively.

As stated before, tests were conducted in both gas and liquid environments. The gas environments included moist air, dry air, and dry nitrogen. A Lucite environmental chamber with rubber seals enclosed the block and ring during the tests using these gases. Moist air was obtained by having a tray filled with water in the environmental chamber, giving a relative humidity greater than 98 pct. Dry air (less than 1 pct relative humidity) was obtained by filling the tray in the environmental chamber with magnesium perchlorate. The relative humidity was determined with a meter that measured the resistance of certain salts in a probe. The nitrogen gas environment was created by allowing compressed nitrogen gas to flow into the chamber, flushing for one-half hour before each test. Rings and blocks were allowed to remain in the chamber for one-half hour before each test.

To obtain some indication of the temperatures generated by the friction, a radiometer was used to measure the infrared emissions (6.5 to 20 μm) from near the quartz-steel interface for one test at each load and speed. The environmental chamber had to be removed during these tests to avoid blocking the infrared rays from passing to the radiometer. Therefore, these tests were performed in room air, at 40 pct relative humidity.

The liquid environments consisted of two cationic additives, aqueous oleylammonium acetate, and aqueous aluminum chloride, and also distilled water. The environmental chamber was replaced by a metal cup which fit closely under the ring and was nearly filled with liquid. The bottom of the ring was thus immersed in the liquid. The wetted ring carried the liquid up to the quartz-steel interface as the ring rotated. The object of the studies with liquids was to determine if the chemical properties of the additives affected friction and wear under these conditions.

RESULTS AND DISCUSSION

Gas Environments

Coefficient of Friction

The average coefficient of friction, as a function of length of sliding, for each combination of speed and load using moist air, dry air, dry nitrogen, and room air is shown in figures 2-3, 4-5, 6-7, and 8-9, respectively.

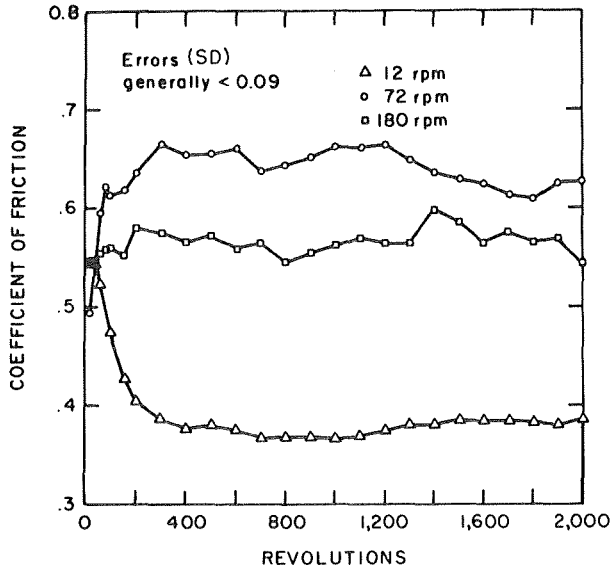

FIGURE 2. - Coefficient of friction—moist air, 6.8-kg load.

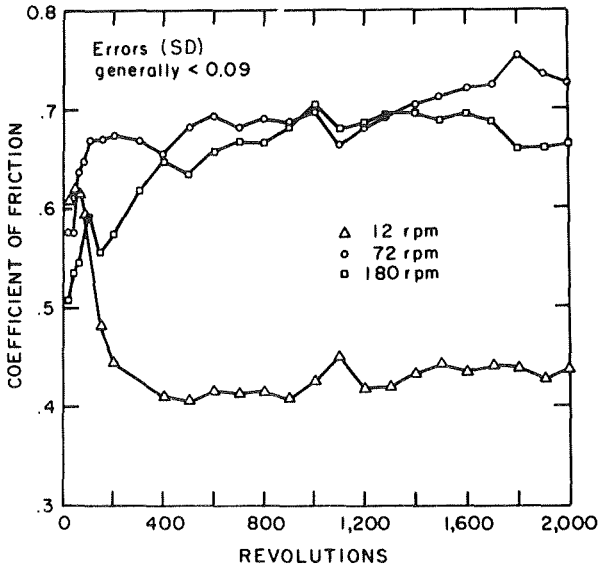

FIGURE 3. - Coefficient of friction—moist air, 13.6-kg load.

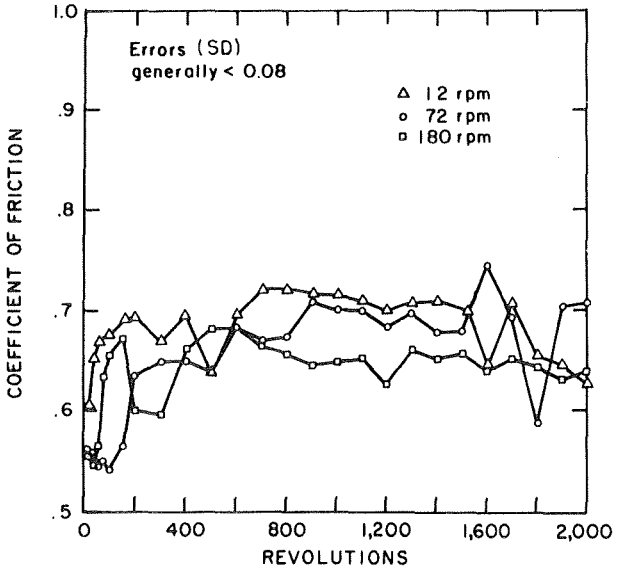

FIGURE 4. - Coefficient of friction—dry air, 6.8-kg load.

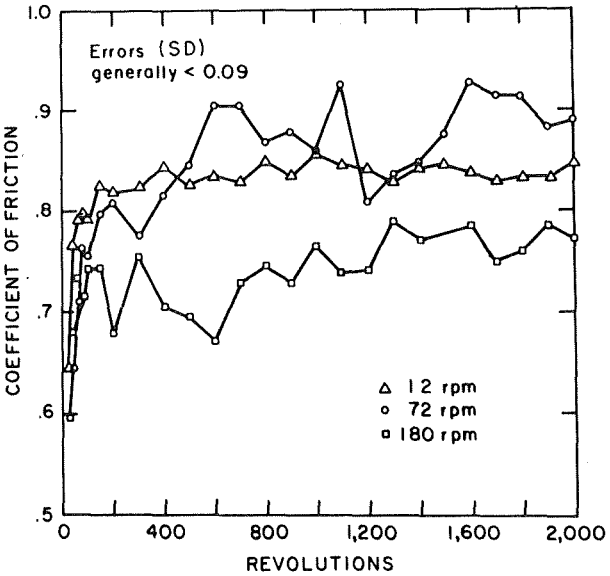

FIGURE 5. - Coefficient of friction—dry air, 13.6-kg load.

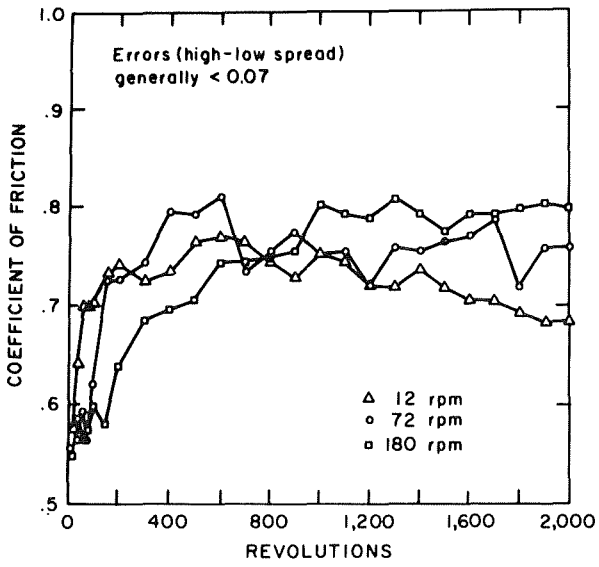

FIGURE 6. - Coefficient of friction–dry nitrogen, 6.8-kg load.

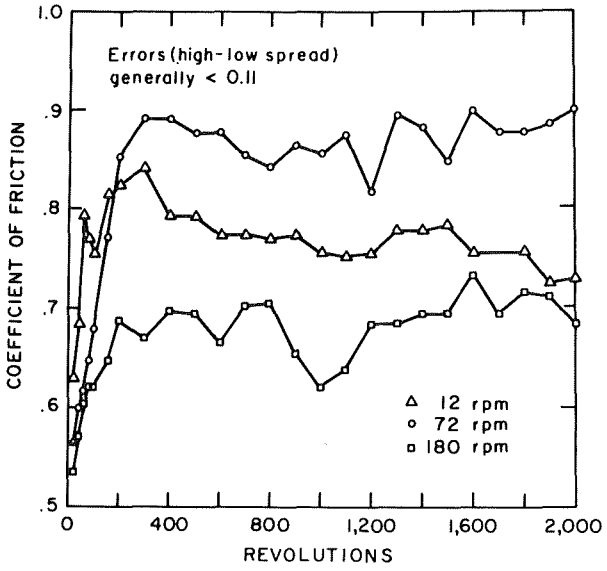

FIGURE 7. - Coefficient of friction–dry nitrogen, 13.6-kg load.

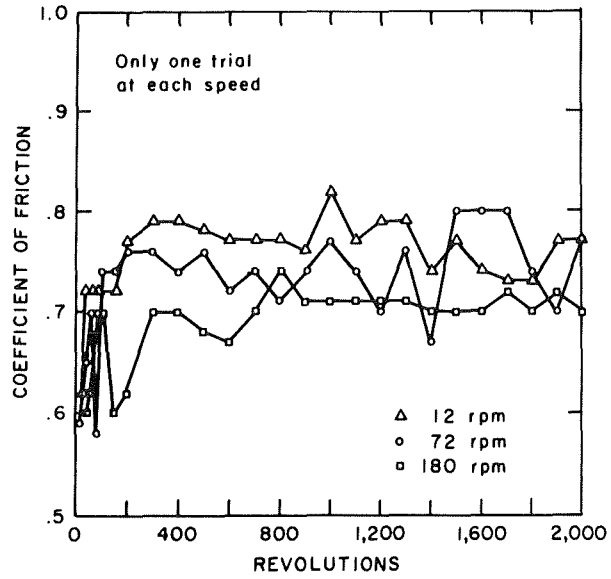

FIGURE 8. - Coefficient of friction–40-pct relative humidity air, 6.8-kg load.

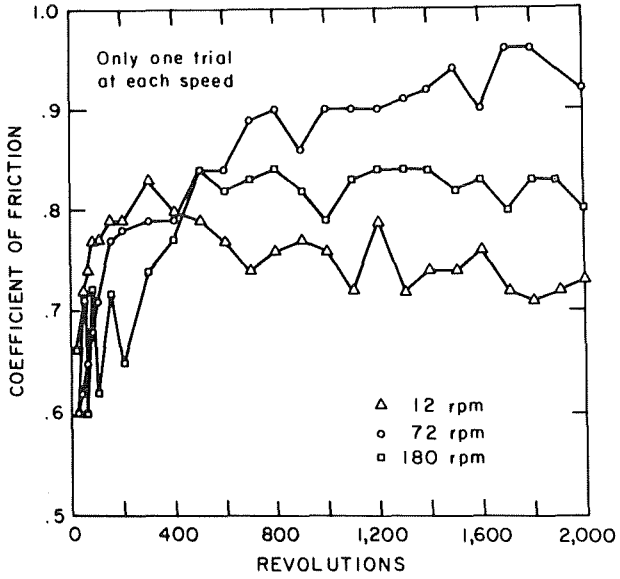

FIGURE 9. - Coefficient of friction–40-pct relative humidity air, 13.6-kg load.

Each point for moist air represents five to eight trials, for dry air three to four trials, for dry nitrogen two to three trials, and for room air only one trial. Coefficients of friction were plotted only for 20, 40, 60, 80, 100, 150, and 200 revolutions, and then for every 100 revolutions thereafter until 2,000 total revolutions, because the friction varied slowly enough that no more information would be displayed by plotting more points.

The coefficients of friction were reasonably constant after 400 revolutions, so to obtain an average equilibrium coefficient of friction for each load and speed, the average of the plotted points from 400 to 2,000 revolutions was calculated. These averages are listed in table 1. The errors are the standard deviations (SD) found when averaging over all trials and for each 100-revolution interval from 400 to 2,000 revolutions. Thus, these errors include contributions both from differences between trials and from fluctuations during trials. The former source of error was generally larger than the latter. No errors are shown for room air because one trial does not allow a valid error estimate to be made. To make the effect of environment on the average coefficients of friction more apparent, the contents of table 1 are plotted in figures 10 and 11.

TABLE 1. - Average coefficients of friction in gases

Environment	Normal load, kg	Coefficient of friction at specified speed		
		12 rpm (2.2 cm/sec)	72 rpm (13 cm/sec)	180 rpm (33 cm/sec)
Moist air.....	6.8	0.38±0.04	0.64±0.06	0.57±0.08
	13.6	.43± .06	.70± .06	.68± .09
Dry air.....	6.8	.69± .08	.68± .05	.65± .04
	13.6	.84± .04	.88± .12	.75± .06
Dry nitrogen.....	6.8	.73± .03	.76± .03	.77± .09
	13.6	.76± .04	.87± .05	.68± .06
40-pct relative humidity air.....	6.8	.77	.74	.70
	13.6	.75	.90	.82

Table 1 and figure 10 show that with a 6.8-kg load, the coefficient of friction was highest in the least oxidizing environment, dry nitrogen, and was lowest in the most oxidizing environment, moist air. As shown in figure 11, this generalization was not always valid with a 13.6-kg load, since the coefficient of friction was somewhat smaller in dry nitrogen than in dry air. It may be that an oxide layer was less effective in reducing friction with the heavier load because the oxide layer was penetrated more. The coefficient of friction tended to be higher with the heavier load.

The relationship between speed and coefficient of friction in moist air was different from that found in other environments. In moist air, the average coefficient of friction was significantly smaller at 12 rpm than at 72 or 180 rpm with a t-test confidence level well over 99 pct. In dry air or dry nitrogen, however, the effect of speed was much less. Also, figures 2 and 3 show that the coefficient of friction in moist air at 20 to 400 revolutions was different at 12 rpm than at the faster speeds. At 12 rpm in moist air, the coefficient of friction was initially quite high, and stayed nearly constant for about 50 revolutions. At higher speeds in moist air, the coefficients of friction were lower initially, but increased rapidly to an equilibrium value by 300 revolutions or less. The same type of pattern, an

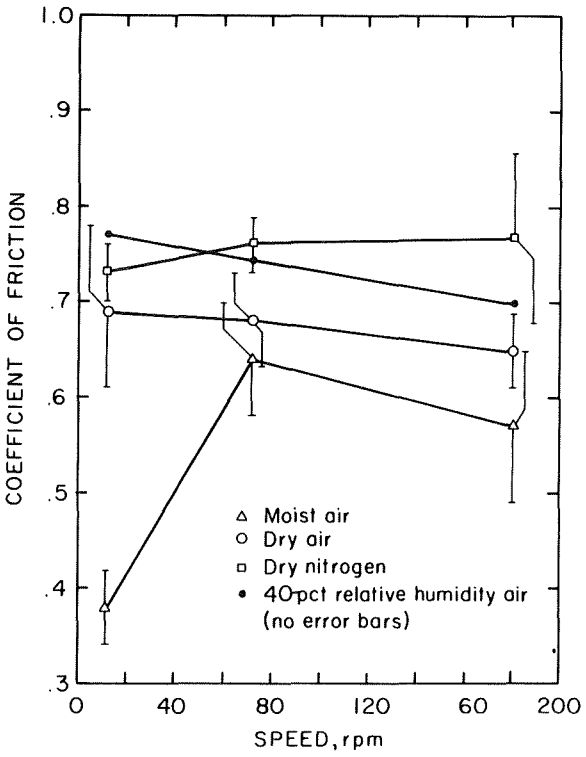

FIGURE 10. - Average coefficients of friction—gas environments, 6.8-kg load.

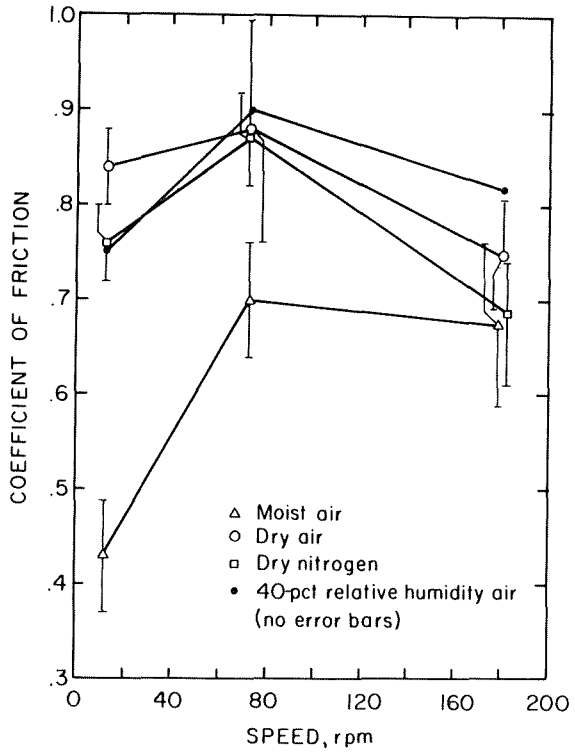

FIGURE 11. - Average coefficients of friction—gas environments, 13.6-kg load.

increasing coefficient of friction during the first few hundred revolutions, was observed for all speeds and loads in dry air and nitrogen.

The increases in friction during the first few hundred revolutions can be explained by assuming there was a surface layer which was worn away during that time. Despite being cleaned before use, some adsorbed water, oxides, or hydroxides would be on the rings and blocks. The increase in friction could also be due to metal being transferred to the block.

The decrease in friction during the first few hundred revolutions in moist air at 12 rpm may have been due to the increase in apparent contact area as quartz was worn away, which would decrease local heating and increase water vapor adsorption. The low equilibrium coefficient of friction may have been caused by a coating on the ring which had time to reform during each revolution only at the slowest speed and whose formation was aided by water vapor.

Previous experimenters have also observed that moisture can affect friction, usually lowering it but sometimes increasing it. Buckley (1), in a summary of nonmetal friction and wear, stated that aluminum oxide, magnesium oxide, and quartz were all lubricated by moisture in air. Krause (4) reported that the coefficient of friction for counterrotating cylinders of unalloyed carbon steel (0.44 pct carbon, 0.61 pct manganese, 0.03 pct phosphorus, and 0.016 pct sulfur) with a relative slip of 5 mm/sec was greater than 0.7

in dry air, but was between 0.4 and 0.5 in moist air. However, for manganese steel (1.25 pct carbon, 13.07 pct manganese, and 0.44 pct phosphorus), the coefficient of friction increased with increasing humidity.

The coefficient of friction for quartz-steel was expected to be smaller in moist air than in dry air. However, with 12 rpm, the difference between friction in moist air and friction in 40-pct relative humidity air was larger than expected. If moisture does reduce friction, then it seems reasonable that the friction obtained in moist air should be significantly closer to the friction obtained in 40-pct relative humidity air than to the friction obtained in dry air. This was not observed, however. Similarly, with moist air, the difference between 12-rpm friction and 72-rpm friction was larger than expected, especially since friction was not higher at 180 rpm than at 72 rpm.

Because the reduction in friction by moisture was so unexpectedly specific to the lowest speed and moist air, it seemed advisable to establish more firmly that the reduction of the friction was related to the environment and speed. Otherwise it could be suspected that by chance a block-ring pair which gave unusually low friction for some unknown reason (for example, one which had contaminated wear surfaces) had been used for each low-speed test in moist air. Accordingly, one block-ring pair was used for a long test in which the normal load was 6.8 kg, and both the relative humidity of the air and the speed of sliding were varied. The resulting coefficients of friction are shown in figure 12.

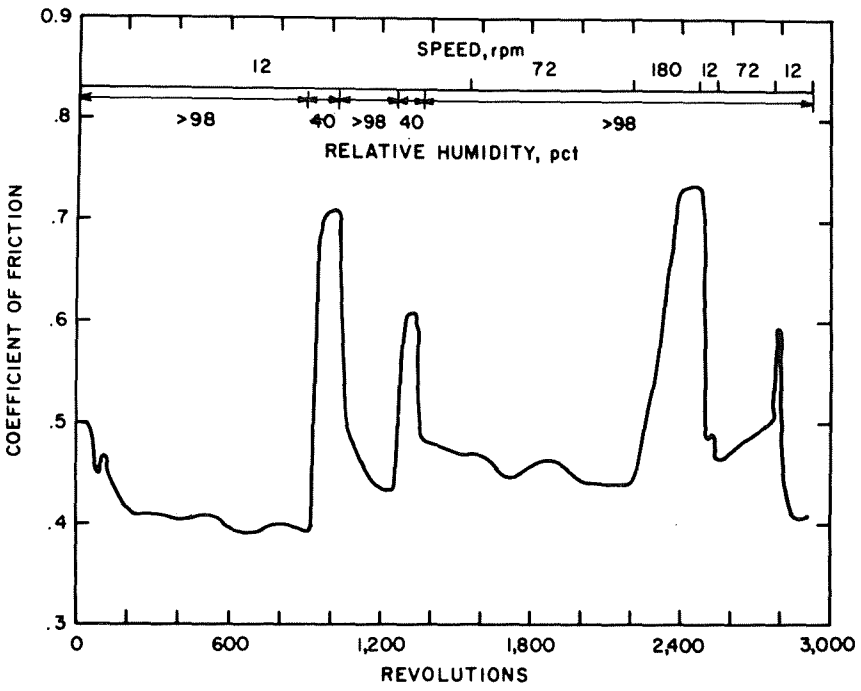

FIGURE 12. - Coefficient of friction in air as relative humidity and speed are varied.

The test was started with the tray in the environmental chamber filled with distilled water and with the chamber closed, which gave air of greater than 98-pct relative humidity, just as for the previous tests in moist air. The steel ring was rotated at 12 rpm for 900 revolutions, which was long enough to demonstrate that this test was giving results consistent with those of previous corresponding tests. As can be seen in figure 12,

the equilibrium coefficient of friction was 0.40, which was consistent with the 0.38±0.04 calculated for the average of the previous corresponding tests. The chamber was then opened, allowing the friction to occur in 40-pct relative humidity room air. The coefficient of friction quickly rose to 0.71, consistent with previous tests in room air (fig. 8). The chamber was then sealed to produce moist air, and the coefficient of friction was observed to decrease. This cycle was repeated again. For the second cycle, sliding was not continued long enough to establish equilibrium, only long enough to establish that a pattern similar to the first one was being obtained. This was positive evidence that changing from the moist air (98 pct relative humidity) to the drier air (40 pct relative humidity) did affect the coefficient of friction. The speed of sliding was then varied while the chamber remained closed. Shortly after the chamber had been closed, while the coefficient of friction was still declining, the rotational speed was increased to 72 rpm. The coefficient of friction was expected to rise, but it continued to fall to 0.44. After the speed was increased to 180 rpm, the coefficient of friction rose rapidly to 0.73, which was higher than the average for the previous tests in moist air at 180 rpm. Decreasing the speed to 12 rpm resulted in the coefficient of friction decreasing rapidly to 0.49. The speed was increased to 72 rpm, and again the coefficient of friction continued to decrease for a time. It then started to increase, however, and was still increasing when the speed was lowered to 12 rpm to determine if the coefficient of friction eventually would go down to the original 0.40. It increased briefly, then decreased to near the original value. The test was terminated at this point.

This test demonstrated that both the relative humidity of the air and the speed of sliding affected the friction. The effect of relative humidity was what would be predicted on the basis of previous tests. This was not always true for the effect of speed, however. The coefficient of friction for 12 rpm could be considered consistent with previous tests, since equilibrium had not been established at 1,500 or 2,550 revolutions in this test. Also, the low coefficient of friction for 72 rpm at 2,670 revolutions could be attributed to not having attained equilibrium. However, there was no definite explanation of the fact that the coefficient of friction for 72 rpm was unexpectedly low at 2,000 to 2,200 revolutions and for 180 rpm was unexpectedly high at 2,400 revolutions. It does seem reasonable that the previous history of the wear surfaces could affect the coefficient of friction. Indeed, figures 2 through 9 demonstrate that the duration of sliding affects the coefficient of friction. There are various mechanisms by which the history of the wear surfaces could influence the coefficient of friction; the transfer of metal to the quartz surface is one. Accordingly, the same coefficient of friction for a given speed should not be expected when the speed has been varied as when the speed is held constant for the entire test. In any case, the fact that relative humidity and speed can have a large effect on quartz-steel friction was amply demonstrated.

Temperature

The increases in temperature, ΔT (° C), indicated by the radiometer during trials in 40-pct relative humidity air follow:

Load	12 rpm	72 rpm	180 rpm
6.8 kg.....	7°	21°	39°
13.6 kg.....	11°	40°	73°

The initial temperature was 22° C. The indicated ΔT's should be proportional, but not equal, to the temperature increases of the rubbing surfaces. This is because the radiometer viewed regions of the blocks and rings that were close to, but not part of, the rubbing surfaces.

Wear Products

The nature of the wear products--that is, the fine powder worn from the blocks and rings during the friction tests and collected as it fell--depended on the environment and load. In moist air, with a load of 6.8 kg, the wear product was generally reddish, and adhered to the ring so much that at the end of some trials the wear surface of the ring was coated. With a normal load of 13.6 kg, however, the wear product was generally black and did not adhere to the ring nearly as much as the reddish powder did. Occasionally, black or partly black powder was produced with a 6.8-kg load at 12 and 72 rpm, and occasionally, reddish or partly reddish powder was produced with a 13.6-kg load at 12 and 72 rpm. When a ring with black powder was left in moist air for about half an hour, the powder became partly reddish. In dry air, black powder was generally observed with both loads, although reddish powder was usually produced with a 6.8-kg load at 12 rpm. Only black powder was formed in nitrogen.

The reddish powder was probably a mixture of hematite (Fe_2O_3) and quartz, and the black powder was probably a mixture of magnetite (Fe_3O_4) and quartz. Infrared analyses were consistent with this explanation, and indicated that very little hydroxide was present in either powder. The black powder was attracted by a magnet, but the reddish powder was not. X-ray diffraction analysis of the reddish powder yielded sharp quartz lines, but gave broad lines at the scattering angles where a sample of chemically pure hematite gave sharp lines. The black powder yielded only quartz lines.

Probably magnetite was formed first under all conditions, but quickly oxidixed to hematite in moist air at a 6.8-kg load. Oxidation of magnetite to hematite apparently was retarded by the lack of moisture in the dry air and nitrogen. The oxidation of iron to magnetite in nitrogen would require only a trace of oxygen, which was undoubtedly present.

The retardation of oxidation in moist air with a 13.6-kg load is more difficult to explain. Presumably, it is related to the higher temperatures at which the particles of magnetite were formed at the heavier load. However, the radiometer indicated that the surface temperature close to the friction

area was lower with 13.6 kg at 12 rpm, when black powder was usually produced, than with 6.8 kg at 72 and 180 rpm, when red powder was usually produced.

The size distributions of powders from tests in moist air were measured with a Coulter counter. For all loads and speeds, half of the powder was smaller than 2 μm in diameter. This was corroborated by a scanning electron photomicrograph of a speck of black powder from a test in moist air, shown in figure 13. The speck has a 60-μm diameter, but high magnification shows it is an agglomeration of many 1-μm or smaller particles.

Roughness

Profilometer traces were taken across the wear surfaces of rings and blocks before and after the friction tests. Traces representing both the profile itself and the arithmetic average (AA) roughness height were obtained. The AA roughness height is the arithmetical average of the absolute values of the vertical deviations from the centerline averaged over the roughness width cutoff, which was 0.76 mm for these traces. The AA roughness height is about 11 pct smaller than the root-mean-square roughness height. (These terms are discussed more fully in ASA Standard B46.1-1962.) The trace representing the AA roughness height was a continuous line, with each point on the line representing the AA roughness height for the last 0.76 mm the profilometer traversed. To simplify comparisons, it was desired to have one number to characterize the roughness for each ring or block, an "average arithmetic average roughness," which will be referred to as the average AA roughness. To calculate this, 10 values of the AA roughness height, spaced every 0.5 mm, were averaged, which gave an average AA roughness height for the middle 4.5 mm of the wear surface.

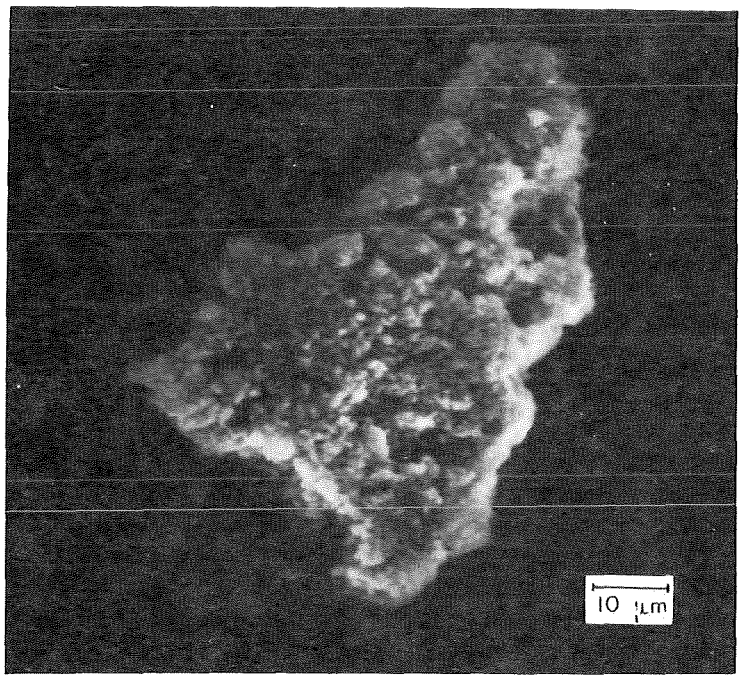

FIGURE 13. - Photomicrograph (X 1,000) of wear product powder.

The average AA roughness for the rings before use was 2.4 μm ±0.6. The blocks showed more variation, and had an average AA roughness before use of 3.3 μm ±1.9. Comparing traces taken before the friction tests with those taken after the friction tests showed that differences in initial roughness did not affect the final roughness.

The roughness measurements taken after the friction tests showed considerable scatter, but the

roughness of the blocks tended to increase with increasing speed and load, at least in air, and the roughness of the rings increased somewhat with increasing speed. The average AA roughnesses are shown in table 2. The errors listed are the standard deviations for all points used in determining the averages. Comparing the roughness in table 2 with the 2.4 μm ±0.6 roughness for rings and 3.3 μm ±1.9 roughness for blocks obtained before the friction tests shows that generally the rings were smoothed by sliding. The blocks, however, were usually made rougher. Only for a 6.8-kg load at 12 and 72 rpm in moist air was there a smoothing effect. It appears that a decrease in oxidation of the ring led to an increase in the roughness of the block.

TABLE 2. - Average AA roughness heights for quartz blocks and steel rings after sliding contact for 2,000 revolutions (220 m) in gases

Environment and material	Normal load, kg	Average AA roughness height for specified speeds, μm		
		12 rpm (2.2 cm/sec)	72 rpm (13 cm/sec)	180 rpm (33 cm/sec)
Moist air:				
Quartz.....	6.8	1.2±0.3	1.7±0.2	7.2±2.3
	13.6	3.2±2.0	7.5± .4	8.4±1.8
Steel.....	6.8	1.5± .3	1.3± .1	2.1± .6
	13.6	.8± .1	1.6± .1	2.3± .1
Dry air:				
Quartz.....	6.8	4.4±1.8	6.8±3.6	7.0±2.1
	13.6	6.7±3.4	9.4±4.3	9.4±2.1
Steel.....	6.8	1.3± .5	1.3± .2	1.6± .5
	13.6	.5± .2	.9± .2	3.2±1.0
Dry nitrogen:				
Quartz.....	6.8	8.8±2.4	9.5±3.3	7.4±2.8
	13.6	12.4±4.6	8.2±2.5	10.8±3.1
Steel.....	6.8	1.1± .4	1.4± .2	1.7± .4
	13.6	1.0± .2	1.2± .2	1.5± .5

Comparing the traces showing the profiles of the wear surface of the blocks with those of the rings showed that the wear did not lead to close conformation of the contacting surfaces.

Scanning electron photomicrographs were taken of some of the rings and blocks used in the moist air tests. Figures 14 and 15 are photomicrographs of a block used in a friction test in moist air with a 6.8-kg load at 12 rpm, showing the quartz surface outside and inside the wear scar, respectively. The smoothing effect of the low-speed wear is apparent. The photomicrographs of the rings confirmed that they remained quite smooth after the friction tests. Figure 16 shows a ring which was used in a friction test in moist air with a 6.8-kg load at 72 rpm. Small wear tracks can be seen, with a few being somewhat jagged, but there are no large pits or gouges. There was red powder on the surface of this ring.

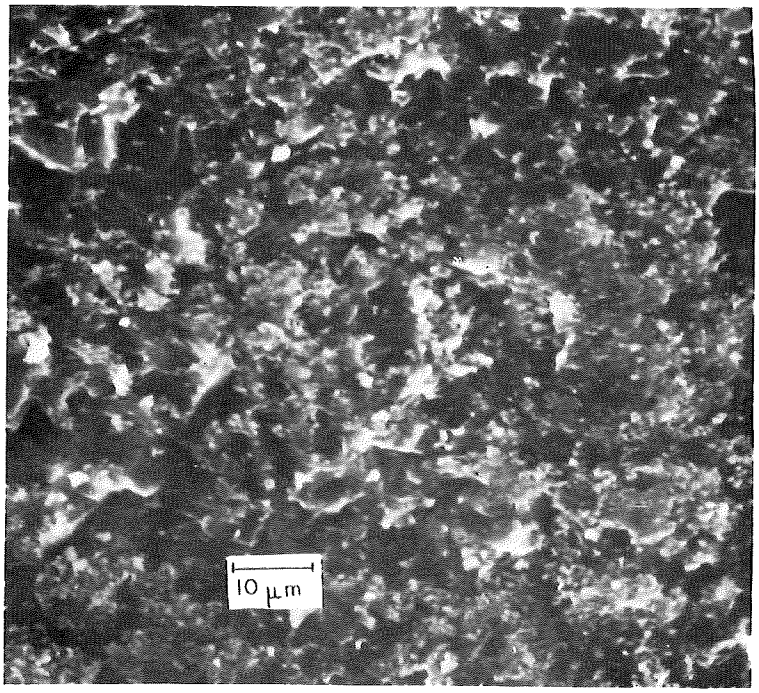

FIGURE 14. - Photomicrograph (X 1,000) of quartz surface outside wear scar.

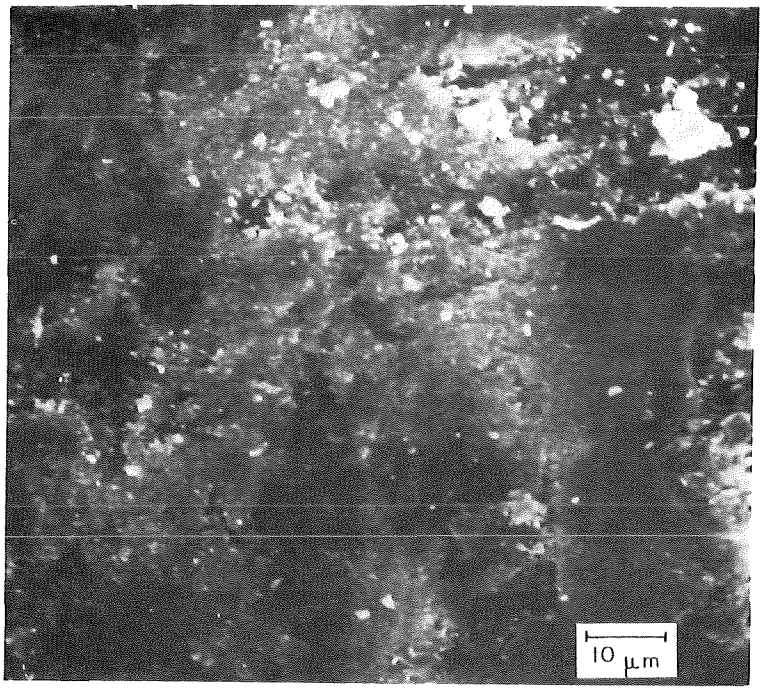

FIGURE 15. - Photomicrograph (X 1,000) of quartz surface inside wear scar.

Wear

The wear of the steel rings was measured by weighing them before and after the friction tests with an accuracy of 0.1 mg. The pretest weighing was at room temperature. Before a posttest weighing, the ring was allowed to cool to room temperature in the desiccator where it had been stored prior to the test. Loose powder was brushed off.

The wear of the quartz blocks was determined by measuring the width of the wear scar; that is, the distance across the wear scar in the direction of motion of the ring. (The weight loss was not a reliable wear indicator because some chipping often occurred at high speeds.) The block volume displaced by friction with a ring was proportional to $R^2 \sin^{-1} (W/2R) - (RW/2)\sqrt{1-(W/2R)^2}$, where W is the wear scar width and R is the radius of the ring, 17.5 mm. Since R was constant and W was small compared with 2R, the displaced volume was approximately proportional to W cubed.[4] A measuring microscope, accurate to 0.01 mm, was used to measure the width of the wear scar near both edges and at the center of the block. The cube root of the average of the cubes of these

[4] $R^2 \sin^{-1} (W/2R) \simeq R^2[(W/2R) + (W/2R)^3/6] = RW/2 + W^3/48R$. $(RW/2)\sqrt{1 - (W/2R)^2} \simeq (RW/2)[1 - (W/2R)^2/2] = RW/2 - W^3/16R$. $\therefore$ volume displaced is approximately proportional to $(W^3/R)(1/48 + 1/16)$.

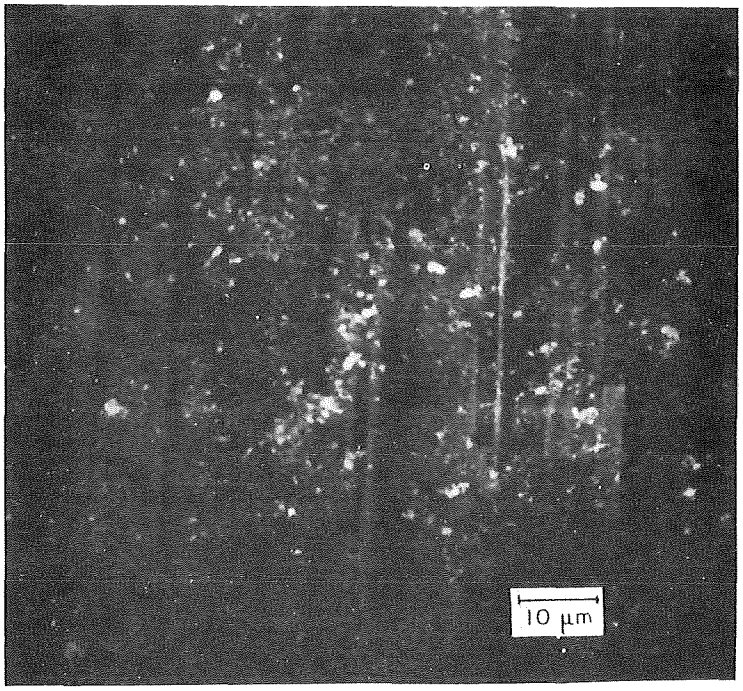

FIGURE 16. - Photomicrograph (X 1,000) of steel wearing area.

measurements was taken as the appropriately weighed mean scar width for each block.

The mean scar widths of the blocks and the mean weight losses of the rings are listed in table 3 and are plotted in figures 17-20. The errors shown are the standard deviations.

The environment significantly affected the wear of both quartz and steel. For every load and speed, the wear of the steel was greatest in dry air. The effect of speed on steel wear usually was not large, but with a 13.6-kg load in dry air, the wear was significantly higher with 12 rpm than with 72 or 180 rpm. The wear of the quartz was higher in dry air than in moist air. The quartz wear increased with speed in air, but decreased with speed in nitrogen at both loads. As expected, wear was always greater with the heavier load.

To explore the effect of the duration of sliding on wear, wear measurements were made after 1,000 revolutions and repeated after 2,000 revolutions in some of the friction tests in moist air. Though there was considerable scatter in the data, some qualitative observations were possible. Work hardening of the steel ring did not seem to occur at 72 or 180 rpm, since the wear of the ring was at least as great during the second 1,000 revolutions as during the first. Results of ring wear measurements for 12 rpm were inconclusive. The wear of the blocks, for these comparisons, was calculated by taking the cube of the wear scar width and also, for those blocks that did not chip, by using the weight loss. The fractions of wear occurring during the first 1,000 revolutions calculated by the two methods were reasonably consistent; the weight loss method yielded a 5- to 10-pct higher value. At 72 rpm, the wear during the first 1,000 revolutions was 0.6 to 0.7 of the total wear, using the wear scar width method. At 12 and 180 rpm, it was about half of the total. Thus, to summarize, the average wear rate during the first 1,000 revolutions was not greatly different from the average wear rate during the second 1,000 revolutions. At 72 rpm, the wear rate of the steel ring increased while that of the quartz block decreased somewhat, as a function of the duration of sliding. One possible cause is metal being transferred from the ring to the block, resulting in the friction becoming partly metal to metal.

TABLE 3. - Wear of quartz blocks and steel rings after sliding contact for 2,000 revolutions (220 m) in gases

Environment and material	Normal load, kg	Wear scar width of quartz blocks in millimeters; weight loss of steel rings in milligrams		
		12 rpm (2.2 cm/sec)	72 rpm (13 cm/sec)	180 rpm (33 cm/sec)
Moist air:				
Quartz.....	6.8	1.2±0.2	1.5±0.2	2.4±0.7
	13.6	1.3± .1	2.3± .3	4.3± .4
Steel.....	6.8	.7± .3	1.5± .4	1.3± .4
	13.6	1.6± .3	2.6± .6	3.3± .3
Dry air:				
Quartz.....	6.8	1.8± .3	2.6± .3	3.8± .4
	13.6	2.5± .6	3.5± .4	4.5± .5
Steel.....	6.8	2.9± .3	2.2± .5	2.6± .6
	13.6	10.6±1.1	4.3± .8	4.3±1.5
Dry nitrogen:				
Quartz.....	6.8	2.8± .3	2.4± .2	2.1± .4
	13.6	3.4± .3	3.0± .8	2.4± .2
Steel.....	6.8	1.1± .3	.6± .1	.7± .4
	13.6	2.1± .2	3.2± .6	1.7±1.1
Air, 40-pct relative humidity:				
Quartz.....	6.8	1.5	2.0	3.3
	13.6	1.4	3.2	4.5
Steel.....	6.8	2.5	1.1	1.3
	13.6	6.9	3.2	3.8

Liquid Environments

A series of friction and wear tests were performed in which the contact between the ring and block was in a liquid. Tests were conducted using the cationic additives aqueous aluminum chloride ($AlCl_3$) and aqueous oleylammonium acetate ($C_{18}H_{35}NH_3^+ \ ^-OCOCH_3$), and also, for comparison, distilled water. Three trials were performed with each of the three liquid environments at each speed and load. As will be demonstrated, neither wear nor coefficient of friction obtained when using either additive was significantly different from that obtained when using water alone.

The concentration of each additive was adjusted to yield a zero zeta potential, which is often referred to as the zero point of charge (ZPC). The ZPC was chosen because other investigators (10) found that cationic additives aided drilling with diamond-tipped bits the most at the ZPC. The appropriate concentrations were found by measuring streaming potentials in minus 28-, plus 35-mesh Wausau quartzite. The concentrations giving a ZPC were 2×10^{-6} M aluminum chloride and 2×10^{-6} M oleylammonium acetate.

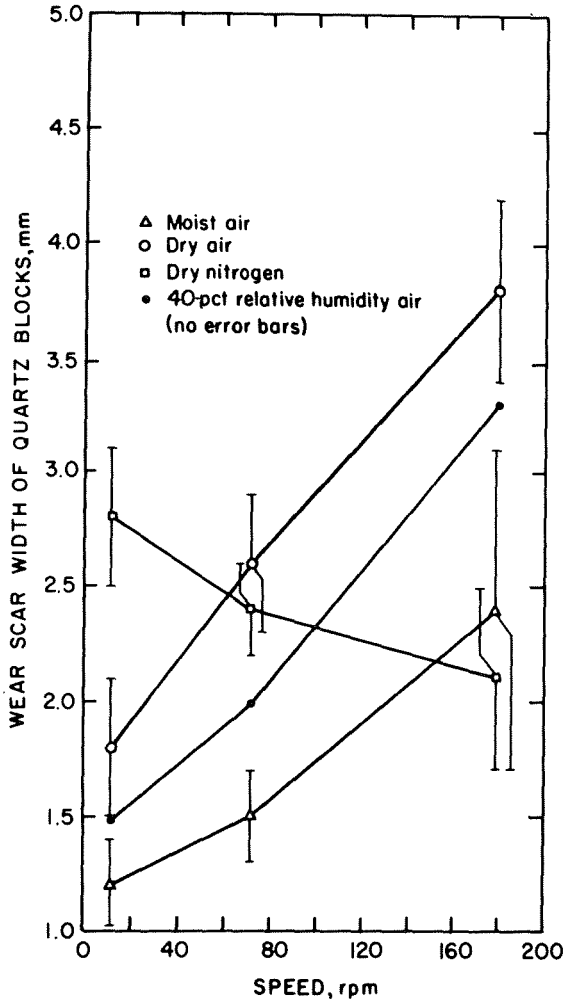

FIGURE 17. - Wear scar widths of quartz blocks—gas environments, 6.8-kg load.

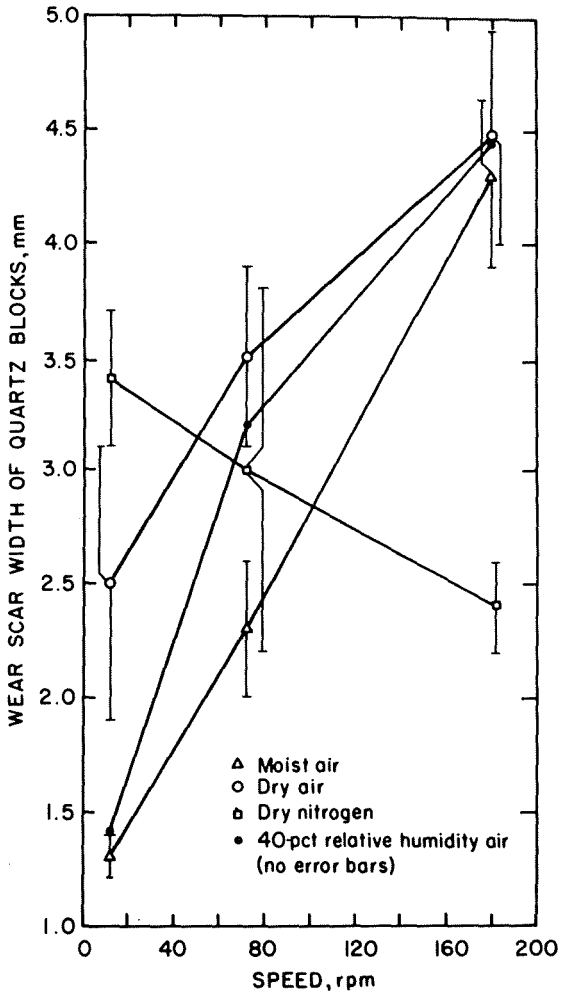

FIGURE 18. - Wear scar widths of quartz blocks—gas environments, 13.6-kg load.

No error estimates were made, but results from a previous experiment were available for comparison. Engelmann, Terichow, and Selim (2) had used the same streaming potential cell to measure the streaming potential for aluminum chloride and oleylammonium acetate streaming through minus 20-, plus 48-mesh charcoal granite. Their data indicated that the ZPC concentrations were 2×10^{-6} M aluminum chloride and 1×10^{-5} M oleylammonium acetate.

It was not determined whether the difference in results for oleylammonium acetate was caused by the additional constituents of granite as compared to quartzite, or by other factors such as the purer water available for the present experiment. In any event, the Engelmann experiment showed that both additives were effective in reducing the pendulum hardness of granite over a fairly wide range of concentrations. Oleylammonium acetate was nearly as effective at 3×10^{-6} M at 1×10^{-5} M, and was quite effective at 1×10^{-6} M.

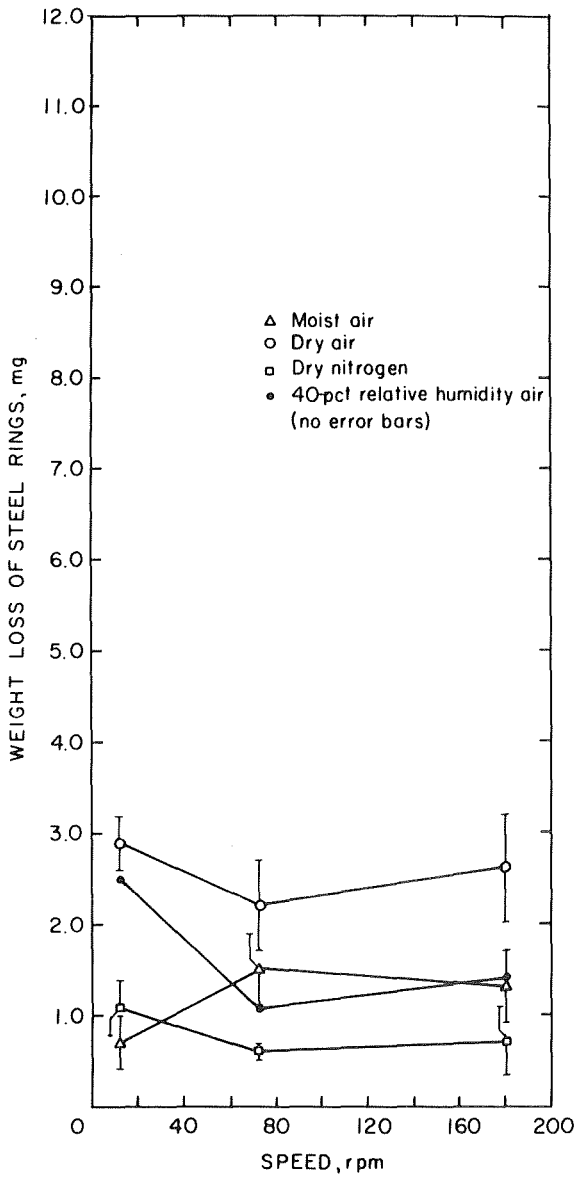

FIGURE 19. - Weight loss of steel rings—gas environments, 6.8-kg load.

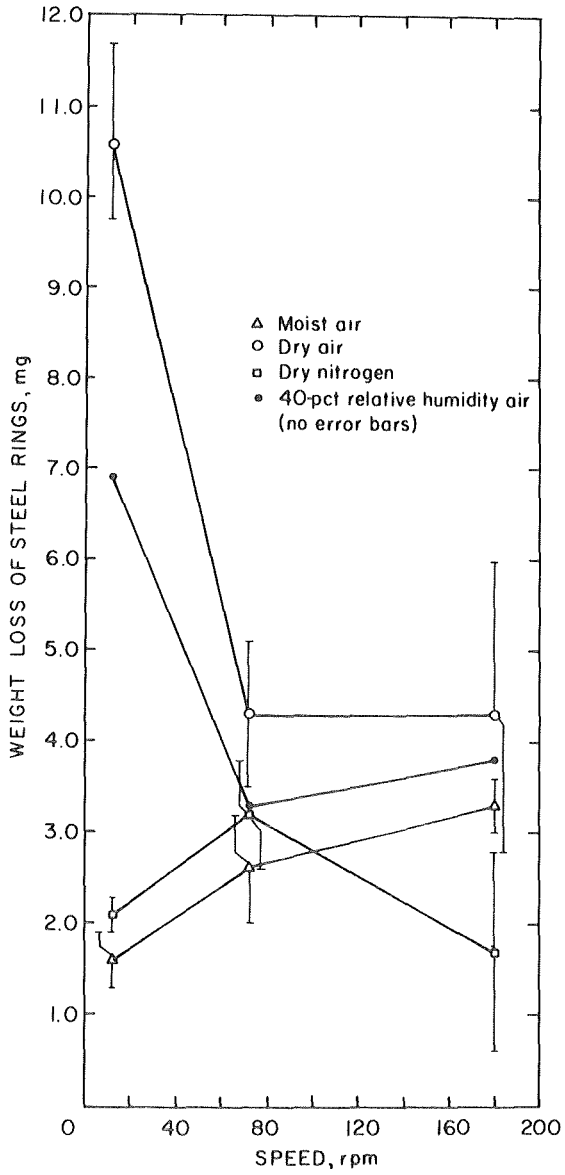

FIGURE 20. - Weight loss of steel rings—gas environments, 13.6-kg load.

Thus it appears that the concentrations for the present experiment should be within the effective range. The streaming potential cell, based on a design by Fuerstenau (3), is fully described in reference 2.

These particular additives were chosen for the present experiment because the ZPC concentrations were so dilute that the physical properties of the solutions, in particular the viscosity and surface tension, were not significantly different from those of water alone. Thus, any effect of additives would be due to altering the surfaces, rather than increasing the separation

of the surfaces as conventional lubricating oils do. Since it was already known that physical properties like viscosity could affect friction and wear, it was desired to eliminate such variables.

Coefficient of Friction

Figures 21 and 22 are graphs of the coefficients of friction as functions of length of sliding. As in figures 2 to 9, the coefficients of friction were plotted for 20, 40, 60, 80, 100, 150, and 200 revolutions and then for every 100 revolutions thereafter until 2,000 total revolutions. Because the additives did not effect the friction, the coefficients of friction in three liquids were averaged, rather than being graphed separately for each liquid. Thus each point represents nine trials.

To demonstrate that the additives did not significantly alter the friction, an average equilibrium coefficient of friction for each liquid is listed in table 4. It was desired that these averages and their standard deviations reflect both the differences between trials and the fluctuations during trials after the rapid changes in the first few hundred revolutions. Therefore, each average and its standard deviation were calculated from the 45 values generated by determining the coefficient of friction from 600 to 2,000 revolutions at 100-revolution intervals for the three trials with each liquid. This procedure was similar to that used for calculating the averages in table 1, except that the averaging was performed over 600 to 2,000 revolutions rather than 400 to 2,000 revolutions because obtaining a relatively constant coefficient of friction required more revolutions in liquids than in gases. For some cases, the friction continued to rise after 600 revolutions.

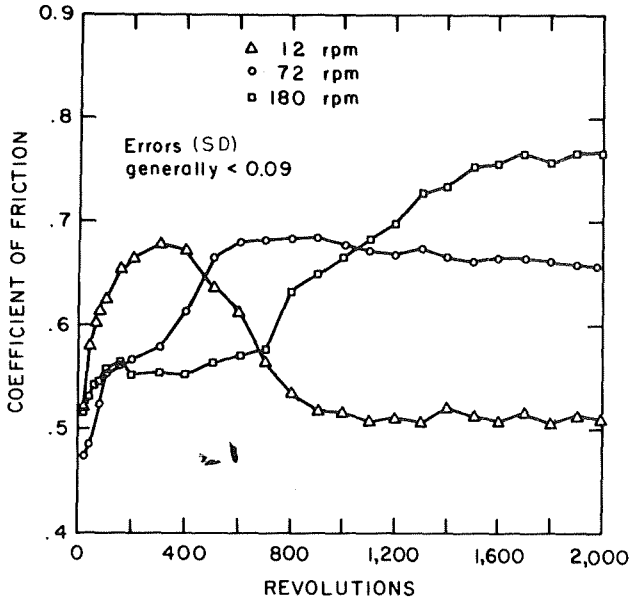

FIGURE 21. - Coefficient of friction–liquid environments, 6.8-kg load.

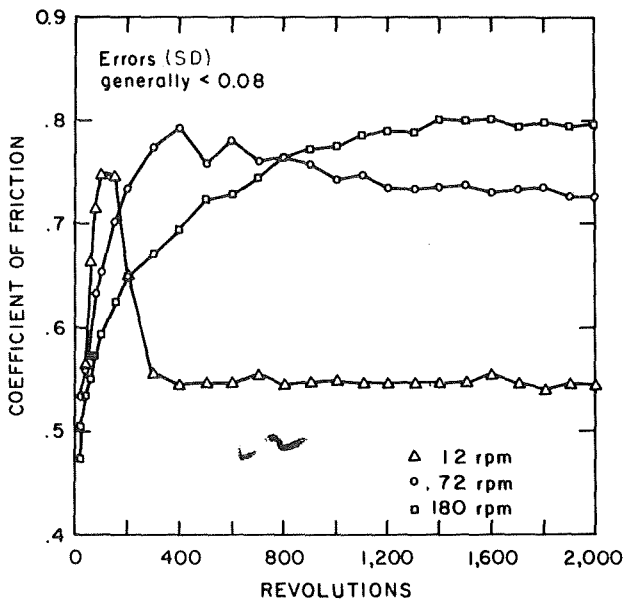

FIGURE 22. - Coefficient of friction–liquid environments, 13.6-kg load.

Table 4 also gives the average over all three liquids and the corresponding standard deviations.

TABLE 4. - Average coefficients of friction in liquids

Environment	Normal load, kg	Coefficient of friction at specified speed		
		12 rpm (2.2 cm/sec)	72 rpm (13 cm/sec)	180 rpm (33 cm/sec)
Distilled water.....	6.8	0.49±0.08	0.65±0.07	0.72±0.10
	13.6	.55± .02	.75± .03	.80± .06
Oleylammonium acetate.....	6.8	.53± .05	.72± .09	.62± .11
	13.6	.54± .03	.74± .05	.83± .04
Aluminum chloride.....	6.8	.57± .05	.67± .09	.78± .13
	13.6	.55± .02	.72± .02	.73± .08
Average for liquids.....	6.8	.53± .07	.68± .09	.71± .13
	13.6	.54± .02	.74± .04	.79± .07

Table 4 indicates that the additives did not significantly alter the friction. There were no systematic differences between the coefficient of friction in water and oleylammonium acetate or aluminum chloride larger than the errors.

A paired t-test also was performed to calculate the probability that the additives affected friction. The values used in the t-test were the average coefficients of friction for each trial averaged over 600 to 2,000 revolutions in 100-revolution intervals. Thus, there were three pairs of values at each load and speed. The paired t-test was taken over all loads and speeds, so there were 18 pairs of values for checking the effect of each additive. The confidence level for an effect on friction was less than 50 pct for both additives.

Because the additives did not affect friction, graphs showing the effect of environment, corresponding to figures 10 and 11, were not made for tests in liquids.

The coefficients of friction in liquids seemed quite large. In particular, the coefficient of friction at 12 rpm was larger in liquids than in moist air. To check whether this was caused by the difference in environment or by the narrower blocks used in liquids, a wide block left over from the tests in gases was run for 1,000 revolutions in moist air and then for 1,000 revolutions in water. The equilibrium coefficient of friction was 0.37 in moist air and 0.49 in water. Thus, at 12 rpm, moist air yielded a lower coefficient of friction than water. This suggests that the lubricating ability of the moist air resulted from enhancing oxidation rather than from the lubricity of the water molecules themselves. Caution should be used when comparing the friction tests in liquids with those in gases, however. The width of the block did have an effect at higher speeds. At 180 rpm, the equilibrium coefficient of friction in water was about 0.10 lower with a wide

block than with a narrow block. This was because the coefficient of friction kept rising for more revolutions with the narrow block.

Though this experiment did not show that additives giving a zero zeta potential on quartz affected quartz-steel friction, other experimenters have found a correlation for other systems. Macmillan, Huntington, and Westwood (5) slid a Victers diamond pyramid with a load of 20 g on MgO in water, n-hexadecane, dimethyl formamide (DMF), dimethyl sulfoxide (DMSO), DMF-DMSO solutions, and buffered aqueous 10^{-2} N NaCl solutions, and also slid an Al_2O_3 ball with a load of 300 g on soda-lime glass in water, pure n-alcohols, and hexanol-octanol solutions. The coefficient of friction was least when the concentration of pH of the liquids was adjusted to yield a zero zeta potential on the MgO or soda-lime glass. These investigators had found previously that MgO, soda-lime glass, and certain other nonmetals were hardest in cationic additives when the zeta potential was zero. They attributed the decrease in friction to the increase in hardness.

Roughness

Profiles of the wear surfaces were measured just as for the tests in gases. The average AA roughness heights, calculated by the same method used for the tests in gases, are shown in table 5. A complete set was taken for water, but only one speed and load were taken for each of the additive solutions because no differences due to additives were expected, based on the friction measurements. The scatter of data is very large for the quartz blocks, but the wear scars tend to be smoother than those from friction tests in gases. The roughness of the steel rings is similar to what was found in the tests in gases.

TABLE 5. - Average AA roughness heights for quartz blocks and steel rings after sliding contact for 2,000 revolutions (220 m) in liquids

Environment and material	Normal load, kg	Average AA roughness height for specified speed, μm		
		12 rpm (2.2 cm/sec)	72 rpm (13 cm/sec)	180 rpm (33 cm/sec)
Water:				
Quartz	6.8	0.7±0.3	1.3±1.7	2.0±1.6
	13.6	1.4±1.0	1.3±1.0	2.3±1.2
Steel	6.8	.9± .2	1.2± .3	.9± .2
	13.6	1.2± .2	1.5± .4	1.1± .2
Oleylammonium acetate:				
Quartz	6.8	ND	.6± .3	ND
Steel	6.8	ND	1.5± .2	ND
Aluminum chloride:				
Quartz	13.6	2.1±1.0	ND	ND
Steel	13.6	1.1± .3	ND	ND

ND--Not determined.

Wear

The wear, as measured by the average wear scar widths of the quartz blocks and weight of the steel rings, is listed in table 6. The listed errors are the standard deviations or 0.1, whichever was larger.

TABLE 6. - Wear of quartz blocks and steel rings after sliding contact for 2,000 revolutions (220 m) in liquids

Environment and material	Normal load, kg	Wear scar width of quartz blocks in millimeters, weight loss of steel rings in milligrams		
		12 rpm (2.2 cm/sec)	72 rpm (13 cm/sec)	180 rpm (33 cm/sec)
Water:				
Quartz.....	6.8	2.8±0.2	3.4±0.5	3.4±0.3
	13.6	2.4± .2	3.3± .2	3.6± .1
Steel.....	6.8	1.5± .2	1.5± .5	.8± .3
	13.6	2.0± .7	.7± .1	1.2± .3
Oleylammonium acetate:				
Quartz.....	6.8	3.0± .2	3.8± .6	3.5± .1
	13.6	2.3± .5	3.3± .1	3.6± .2
Steel.....	6.8	1.4± .3	1.0± .3	.8± .3
	13.6	1.5± .2	1.0± .3	1.1± .2
Aluminum chloride:				
Quartz.....	6.8	2.9± .1	3.0± .2	3.3± .2
	13.6	2.4± .4	3.0± .2	3.7± .3
Steel.....	6.8	1.0± .5	.9± .2	.5± .1
	13.6	1.3± .3	1.3± .2	1.1± .1
Average for liquids:				
Quartz.....	6.8	2.9± .2	3.3± .4	3.4± .2
	13.6	2.4± .3	3.2± .2	3.6± .2
Steel.....	6.8	1.3± .4	1.2± .3	.7± .2
	13.6	1.6± .5	1.0± .3	1.2± .1

It is clear that neither additive significantly altered the wear of the quartz. However, table 6 suggests that aluminum chloride reduced the wear of the steel. The additives were not expected to affect the steel directly, but could influence the steel wear by affecting the quartz abrasiveness. Accordingly, a paired t-test was performed to calculate the confidence level for the steel wear in the aluminum chloride solution being significantly different from the wear in water alone. The results from each trial were used, giving three pairs of values for each speed and load. The paired t-test was performed over all speeds and loads, giving 18 pairs of values. The confidence level was less than 90 pct, so the hypothesis that aluminum chloride affected the steel wear was rejected.

An additional reason for rejecting the hypothesis is that the two additives should have similar effects, if a ZPC is the important factor. However, the steel wear in oleylammonium acetate was close to that in water alone.

Because the additives did not significantly affect the wear of either quartz or steel, graphs showing the effect of environment, corresponding to figures 17 to 20, were not made. For the same reason, the effects of speed and load are best indicated by the averages for liquids at the bottom of table 6. The quartz wear increased but the steel wear decreased with increasing speed. The effect of load was not systematic. This was very different from the tests in gases, where a heavier load always gave greater wear.

SUMMARY

The effects of gas and liquid environments, speed of sliding, load, and duration of sliding on the friction and wear of quartz-steel were investigated by rotating steel rings against quartz blocks. The gas environments included moist air, dry air, and dry nitrogen. The liquid environments were aqueous aluminum chloride, aqueous oleylammonium acetate, and also, for comparison, distilled water. The concentrations of the solutions were those giving a zero zeta potential on quartz. The loads were 6.8 and 13.6 kg. The speeds were 12, 72, and 180 rpm, which correspond to 2.2, 13, and 33 cm/sec.

The coefficient of friction in gases was affected by the environment, speed, load, and duration of sliding. The friction was usually lowest in moist air, and highest in dry nitrogen. It was significantly lower in moist air at 12 rpm than with any other combination of environment and speed. In other environments, the effect of speed on friction was not large; friction was usually slightly higher at 72 rpm than at 12 or 180 rpm. The coefficient of friction in air was nearly always higher with a 13.6-kg than a 6.8-kg load. The friction usually increased during the first few hundred revolutions and then reached a nearly constant equilibrium value. In contrast, in moist air at 12 rpm, the friction decreased during the first few hundred revolutions to a lower equilibrium value.

The wear of the quartz blocks and steel rings in gases was affected by environment, speed, and load. The effect of speed depended on the environment; quartz wear increased with higher speed in air, but decreased with higher speed in nitrogen. The wear of the steel rings was significantly higher in dry air at 12 rpm with a 13.6-kg load than with any other combination of environment, speed, and load. The steel wear was always highest in dry air. The wear of both quartz and steel was always higher with the higher load.

Friction and wear in aqueous oleylammonium acetate and in aqueous aluminum chloride were similar to effects in water alone. The effect of speed and load on friction and wear was smaller in water than in gases. At 12 rpm, friction was lower in moist air than in water. However, at higher speeds, friction was somewhat lower in water than in gases.

The goal of this study was to help fill in some gaps in the knowledge of friction and wear, rather than to devise specific methods for increasing the efficiency of any particular mining subsystem. Nevertheless, certain inferences relating to practical applications can be made. Reducing wear or friction by controlling the zeta potential does not appear promising. If possible, slow speeds should be avoided because steel wear decreased but quartz wear increased with speed in air.

Practical applications of the effects of gas environments are possible for systems which are sufficiently enclosed that the environment at the rock-metal interface is controlled. Such systems include certain types of drilling, where the flushing medium controls the environment around the bit and for some distance around the stem. Also included are certain types of crushers, which are already enclosed to trap dust and could be more tightly enclosed without difficulty. In such systems, saturating the air with moisture could reduce steel wear. If it is desired to avoid moistening material being drilled or crushed, nitrogen could also reduce the steel wear, although escape of the nitrogen would have to be limited for this approach to be practical. The reduction in friction by moist air suggests that, in cases where lubrication by a liquid is not possible, lubrication by moist air could be beneficial, especially at low speeds.

REFERENCES[4]

1. Buckley, D. H. Friction and Wear Behavior of Glasses and Ceramics. NASA Tech. Memorandum TM X-68255, August 1973, 36 pp.

2. Engelmann, W. H., O. Terichow, and A. A. Selim. Zeta Potential and Pendulum Sclerometer Studies of Granite in a Solution Environment. BuMines RI 7048, 1967, 16 pp.

3. Fuerstenau, D. W. Measuring Zeta Potentials by Streaming Potential Techniques. Trans. AIME, v. 205, 1956, pp. 834-835.

4. Krause, H. Tribochemical Reactions in the Friction and Wearing Process of Iron. Wear, v. 18, No. 5, 1971, pp. 403-412.

5. Macmillan, N. H., R. D. Huntington, and A. R. C. Westwood. Chemomechanical Control of Sliding Friction Behavior in Nonmetals. Martin-Marietta Laboratories Tech. Rept. 73-16c, 1973, 28 pp.

6. Rehbinder, P. A., L. A. Shreiner, and K. F. Zhigach. (Hardness Reducers in Drilling.) Akad. Nauk Ukr. SSR, Moscow, 1944; translated by CSIRO, Melborne, Australia, 1948, 163 pp.

7. Roepke, W. W., and S. S. Peng. Surface Friction of Rock in Terrestrial and Simulated Lunar Environments. BuMines Contract R-09-040-001, NASA-OART, 1975, 34 pp.

8. Strebig, K. C., A. A. Selim, and C. W. Schultz. Effect of Organic Additives on Impregnated Diamond Drilling. BuMines RI 7494, 1971, 31 pp.

9. Unger, H. F., B. S. Snowden, and W. H. Engelmann. Diamond Drilling With Surfactants in Upper Michigan Conglomerate Using Surface-Set Bits. Pres. at 6th Conf. on Drilling and Rock Mechanics, Soc. Petrol. Eng., AIME, Austin, Tex., Jan. 22-23, 1970, SPE Preprint 4236, 12 pp.

10. Westwood, A. R. C., N. H. Macmillan, and R. S. Kalyoncu. Chemomechanical Phenomena in Hard Rock Drilling. Trans. AIME, v. 256, 1974, pp. 106-111.

11. Wolkowitz, W., and B. E. Ranish. Friction and Wear Between Unlubricated Metal and Nonmetal Surfaces. Grumman Res. Depart. Memorandum RM-239, September 1964, 41 pp.

[4]Titles enclosed in parentheses are translations from the language in which the item was published.

INT.-BU.OF MINES,PGH.,PA. 21039

☆U.S. GOVERNMENT PRINTING OFFICE:1976-603-755/85