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Boston Edison Q 23.1.3

FRICTION COEFFICIENTS OF WATER-LUBRICATED STAINLESS STEELS FOR A SPENT FUEL RACK FACILITY

November 5, 1976

Summary

A series of experiments have been carried out on a pin-on-disk friction tester to determine the frictional characteristics of a 304 stainless steel on 304 stainless steel sliding combination in distilled water. Tests were carried out at two normal pressures, two sliding speeds, and two temperatures, and the effects of introducing iron oxide contaminant particles and varying the surface roughness were determined.

It was concluded that, provided that the initial surfaces are reasonably clean, a design based on friction coefficient values between 0.80 and 0.20 should cover all eventualities.

Ernest Rabinowicz

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DESIGNATED ORIGINAL

Certified By Melanie J. Miller

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November 5, 1976

Boston Edison Q 23.1.3

Report to Boston Edison Co. Attn:- Dr. Mukti L. Das

Friction coefficients of water-lubricated stainless steels

Introduction

It is my understanding that Boston Edison is in the process of designing a new spent fuel rack. In order to consider the feasibility of this design, it is necessary to know the friction coefficient to be anticipated between two of the components of the system, namely the bearing plates attached to the rack module and the spent fuel floor.

In order to determine the friction coefficient, it was decided to carry out testing using a standard method for measuring friction, that involving a pin-on-disk friction apparatus which has been in use for many years in the Surface Laboratory at M.I.T. With this apparatus, it is possible to reproduce the significant variables of the application, namely the contacting materials, the lubricant, the interfacial pressure, the temperature, surface roughness and the anticipated sliding velocity.

A few significant variables could not be well matched, in particular the amount of surface contamination (introduced during the various machining processes or during assembly) likely to be on the sliding surfaces at the beginning of the operation of the system. But experience with other similar sliding systems, and indeed experience gained in these tests, suggests that this initial contamination is worn off relatively quickly and thereafter relatively clean sliding conditions prevail.

Apparatus and experimental procedure

A schematic illustration of the pin-on-disk apparatus used in these tests is shown in figure 1. In this apparatus the top specimen, the pin, is held essentially stationary in a dynamometer while it is pressed against the rotating disk by a dead weight load. The angular speed of the disk is controlled by an infinitely-variable motor drive and pulley system, and the position of the pin is adjusted so as to produce the desired sliding speed. The friction force is measured using a strain gage ring, and recorded continuously with a Sanborn recorder.

For these tests, the bottom disk was replaced by a cup, so that the flat sliding specimen mounted in the cup could be immersed to a depth of 2 cm by distilled water. In some of the tests, this water was heated, by an immersion heater, to a temperature in the range 72 C - 78 C (162F - 172F). In other of the tests, fine iron oxide particles (F_2O_3) were introduced into the water to simulate the effect of corrosion products in the spent fuel tank.

A more complete discussion of the experimental procedure is to be found in Appendix I, which outlines the various experimental conditions used in the tests, and which was approved by Dr. Das.

Two sliding speeds were used in the tests. One of them, namely 4"/second, corresponds to the maximum sliding speed derived from Figure 6, entitled "Pilgrim - relative displacement of floor and mass,", of the report "A feasibility study report on the spent fuel rack modules for Yankee Atomic Electric Company Pilgrim Station 1," dated September 29, 1976, by A. J. Sturm and K. E. Neumeier of Programmed Remote System Corporation. The other speed, 0.04"/

second, was chosen to be two orders of magnitude slower than the top speed, so as to bracket all speeds likely to be encountered. During the slow speed tests, five determinations of the static friction coefficients, after the sliding specimens were kept at rest for one minute under the normal load of 2 kg, were also made.

A normal load of 2 kg was used in all the tests. In some of the tests a pin was used on whose end a circular flat of diameter 0.09" had been machined. This gave a mean contact pressure of 690 psi, closely similar to that of the application (770 psi when a force of 22,000 lb acts on a circular bearing plate of diameter 6 inches). In other cases the end of the pin was rounded off, and this produced much higher pressures, similar to those which arise in the application when the bearing plate and the spent fuel floor only contact over a few patches.

All the tests were of one hour duration, except for some of the high temperature tests which were shortened to 0.5 hours when it was discovered that prolonged exposure to high temperatures had an adverse effect on the dynamometer ring.

In addition, a more systematic series of static friction tests were carried out on surfaces which had been stationary for times of 1, 10, 100, 1000, 10,000 and 50,000 seconds. For these tests, the relative speed applied to induce sliding was 6×10^{-4} in/sec.

Most of the testing was done using flat specimens of surface roughness 22µ" CLA (27 µ" RMS) as measured with the Talysurf Profilometer. A few tests were carried out with much coarser surfaces, with surface roughness values of 260 µ" CLA (320 µ" RMS). In both cases the surfaces were obtained by abrasion against abrasive papers. The surfaces were introduced into the sliding system without further cleaning or surface treatment after the abrasion and surface roughness determination procedures.

Results

The results of the various tests are described in turn. During each sliding test ten friction coefficient values obtained at roughly uniform intervals of time were determined, and these are given, as is their mean, and in some cases comments about extreme friction values are also provided. For the slow speed tests, the five static friction coefficient values and their mean are also given.

In the case of the static friction tests, the various friction values, as well as the mean of the last batch of values, after enough sliding had been produced to wear off some small amount of surface contamination, are also given.

Test 1. 304 steel on 304 steel. Room temperature. Hemispherically ended slider. Roughness 29 microinches rms. Distilled water lubricant. Sliding speed = 4 in/sec.

f values:- 0.38, 0.45, 0.41, 0.35, 0.35, 0.37, 0.37, 0.34, 0.33, 0.33

Mean friction coefficient = 0.36

Test 2. 304 steel on 304 steel. Room temperature. Hemispherically ended slider. Roughness 29 microinches rms. Distilled water lubricant. Sliding speed = 0.04 in/sec.

f values:- 0.37, 0.46, 0.62, 0.65, 0.64, 0.64, 0.64, 0.61, 0.66, 0.62

Mean friction coefficient = 0.59. Peak friction value = 0.82

Static f:- 0.62, 0.58, 0.57, 0.63, 0.74, mean = 0.62

Test 3. 304 steel on 304 steel. 73C - 74C. Hemispherically ended slider. Roughness 29 microinches rms. Distilled water lubricated. Sliding speed 4 in/sec.

f values:- 0.35, 0.42, 0.44, 0.39, 0.46, 0.50, 0.49, 0.49, 0.41, 0.39

Mean friction coefficient = 0.43

Test 4. 304 steel on 304 steel. 72-76C. Hemispherically ended slider. Roughness 29 microinches rms. Distilled water lubricated. Sliding speed = 0.04 in/sec.

f values:- 0.46, 0.52, 0.51, 0.64, 0.65, 0.71, 0.76, 0.60, 0.67, 0.82

Mean friction coefficient = 0.63 Peak friction value = 0.91

Static f:- 0.64, 0.46, 0.57, 0.56, 0.74 mean = 0.59.

Test 5. 304 steel on 304 steel. Room temperature. Slider end diameter 0.09". Roughness 27 microinches rms. Distilled water lubricant. Sliding speed 3.9"/sec.

f values:- 0.36, 0.27, 0.32, 0.21, 0.25, 0.21, 0.31, 0.27, 0.33, 0.38

Mean friction coefficient = 0.29, minimum friction = 0.20.

Test 6. 304 steel on 304 steel. Room temperature. Sliding speed = 4.3×10^{-2}"/sec. Slider end diameter 0.09", distilled water, roughness 27 μ" rms.

f values:- 0.41, 0.43, 0.49, 0.50, 0.45, 0.47, 0.50, 0.53, 0.53, 0.49

Mean friction coefficient = 0.48, maximum friction = 0.61

Static f:- 0.51, 0.49, 0.52, 0.47, 0.49, mean = 0.50

Test 7. 304 steel on 304 steel. 71-79C. Slider end diameter 0.09". Roughness 27 microinches rms. Distilled water lubricant. Sliding speed 3.8"/sec.

f values:- 0.51, 0.51, 0.39, 0.40, 0.40, 0.41, 0.36, 0.27, 0.30, 0.38

Mean friction coefficient = 0.31

<u>Test 8</u>. 304 steel on 304 steel. 72-76 C. Slider end diameter 0.09". Roughness 27 microinches rms. Distilled water lubricant. Sliding speed 4.1×10^{-2}"/sec

f values:- 0.42, 0.38, 0.53, 0.44, 0.46, 0.44, 0.60, 0.47, 0.68, 0.43

Mean friction coefficient = <u>0.48</u>

Static f:- 0.36, 0.36, 0.45, 0.70, 0.55, mean = 0.48

<u>Test 9</u>. 304 steel on 304 steel. Room temperature. Slider end diameter 0.09". Roughness 27 microinches rms. Distilled water lubricant with fine iron oxide particles to a depth of .005". Sliding speed 4.2×10^{-2} in/sec.

f values:- 0.46, 0.53, 0.51, 0.52, 0.53, 0.49, 0.56, 0.57, 0.61, 0.54

Mean friction coefficient = <u>0.53</u>

<u>Test 10</u>. Same as test 9 but iron oxide particles to a depth of 0.25".

f values:- 0.61, 0.58, 0.57, 0.63, 0.54, 0.53, 0.54, 0.57, 0.56, 0.58

Mean friction coefficient = <u>0.57</u>. Maximum friction = 0.72

<u>Static friction test I</u>. 304 steel on 304 steel. Room temperature. Slider end diameter 0.09". Roughness 27 microinches rms. Distilled water lubricant. Initiating sliding speed = 6×10^{-4} in/sec.

Time	Friction coefficient values		Mean of last valu
1 sec	.23, .33, .44, .23, .70	.62, .56, .61, .68, .68, .64	.63
10	.39, .39, .42, .32, .50	.61, .54, .61, .68, .66, .67	.63
100	.36, .51, .37, .47, .50	.59, .54, .62, .67, .69, .68	.63
1,000	.33 .46, .35, .48, .60	.61, .63, .69, .60	.63
10,000	.29	.58, .72	.65
50,000	.59		

Static friction test II. Same as tatic friction test I, but surface roughness is 310 microinches rms.

Time	Friction coefficient values	Mean friction
1 sec	.44, .46, .48, .45, .49, .49, .54, .49	.48
10	.52 .46 .49 .48 .51 .53 .52 .60	.51
100	.45 .45 .43 .49 .50 .51 .45 .60	.49
1,000	.43 .49 .52 .51	.49
10,000	.50 .49 .46 .54	.50
50,000	.43	.43

Discussion

Looking at the frictional data themselves, we note that they seem pretty consistent. The typical batch of ten friction coefficient values shows just about the trend and amount of scatter I would have expected, with initial friction values somewhat low, but with overall scatter (as defined by the standard deviation) about 20% of the mean value.

The effect of the variables seems typical, also. Temperature had very little effect, because the stainless steel-stainless steel system is not affected by moderate changes of temperature, and the water is such a poor lubricant that temperature has little effect on its performance. Interfacial pressure also has little effect, in line with general experience with friction coefficient determinations. Sliding speed has a major effect, in that the friction is distinctly higher at lower sliding speeds; however the time of stick seems to have relatively little effect.

As anticipated, iron oxide particles introduced into the sliding system produced no noticeable change in friction, because they are too easily pushed aside during sliding. Surface roughness has some influence, in that the very rough surfaces gave somewhat lower friction. I would anticipate that very smooth surfaces (for example 1 or 2 μ" rms) would give distinctly higher friction values still.

What kind of friction coefficient values should Boston Edison expect? Before starting the project it was my feeling based on previous experience that friction coefficient values between 0.4 and 0.65 would be typical of this sliding system, and indeed the results obtained are in good agreement with this expectation. However, previous experience provided little guidance on the extreme values to be expected. These experiments described above suggest that f = 0.80 and f = 0.20, the extreme values reliably observed in these tests, might be regarded as the upper and lower limits respectively.

At first sight it seems that, by using the largest and smallest values observed in our tests as the extreme values to be anticipated in practice we are providing no margin of safety, but in practice a substantial margin of safety is inherent in our experiment, in which the friction is measured over a small area of about .006 in^2, whereas in the application the friction is averaged over the much larger area of 100 in^2. This tends to average the friction coefficient and to suppress extreme values.

What guidance do the results provide for those designing the Boston Edison spent fuel rack module system. The only helpful fact that emerges is that the rough surfaces (250 μ" rms) seem preferable. Both theory and practice suggest that the extremely high friction values are avoided, because the geometry discourages the formation of large, strong junctions. At the same time it is probably easier to scrape contaminants from the peaks of large sharp asperities, so that low friction coefficients are less likely to persist for any length of time.

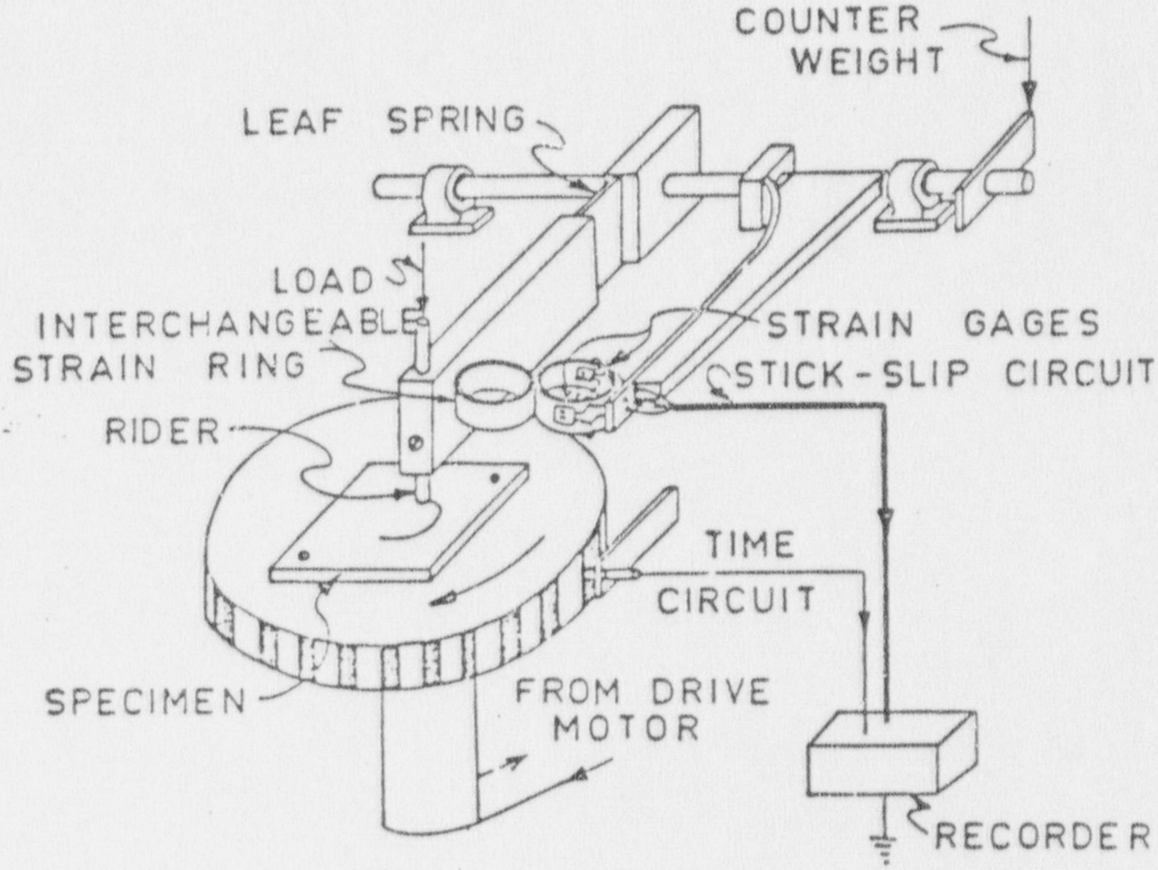

Figure 1. Schematic illustration of the pin-on-disk tester. For these tests, the flat specimen was in a cup-fixture which was immersed in distilled water, and for the high temperature tests an immersion tester was used.

Appendix 1. Operating procedure

The pin-on-disk tester

In the pin on disk tester, one of the sliding materials is in the form of a pin or cylinder, typically 1" long and 0.25" diameter, with an end which may be either flat, hemispherical or a trunkated cone. The other surface, the flat, is typically a plate of dimensions 2" x 2" x 1/4" mounted either on a flat surface, or in a cup if a liquid lubricant is to be used. The flat surface is rotated via a variable speed motor and a pulley system, thus producing sliding speeds anywhere in the range 3×10^{-3} to 3×10^{2} cm/sec. The normal load is typically a dead weight in the range 10 gm to 5 kg, while the friction force is measured by the strain gages mounted on the strain ring, and recorded continuously by a Sanborn recorder. Calibration is by deadweight, via string-and-pulley system, and is applied directly to the rider.

Pin on disk machines represent one of the most flexible ways of studying friction. Various machines of this type are described on pp 159 to 222 of the compilation "Friction and Wear Devices," 2nd Edition, American Society of Lubrication Engineers, Park Ridge, Ill. 1976.

The operation of the pin-on-disk tester has been discussed in a number of my published papers. The earliest and the most recent are the following:-

E. Rabinowicz, "The frictional properties of titanium and its alloys," Metal Progress 65, No. 2, 107-110, 1957.

E. Rabinowicz, "The boundary friction of very well lubricated surfaces," Lubrication Engineering, 10, 205-208, 1954.

E. Rabinowicz and P. A. March, "Friction and wear of rare earth metals in air," J. Less Common Metals, 30, 145-151, 1973.

E. Rabinowicz, "Friction and wear of self-lubricating metallic materials," J. Lubrication Technology, Trans. ASME F, 97, 217-220, 1975.

The pin on disk tester as well as other friction measuring apparatus, are discussed in section 4.17 of my book "Friction and Wear of Materials," John Wiley and Sons, NY, 1965.

In the tests to be carried out for Boston Edison, the basic variables to be used are the following.

Materials. 304 stainless steel. The flat specimen is to be a plate of dimensions 2" x 2" x 1/4", with a surface finish of 2 microinches ± a factor of two as determined in a Talysurf model 4 Profilometer. The surface finish is to be generated by hand lapping against emery paper. In addition, tests may be carried out at a surface finish of 250 microinches ± a factor of two, generated and measured in the same way. The Talysurf has been recalibrated this week against a standard surface.

The pin is 304 stainless steel of 1/4" diameter and approximately 1" in length. Two configurations are used. In one of them, the pin is terminated by a hemisphere of diameter 1/4", and this produces point contact. In the other case, the pin is terminated by a flat of diameter 0.09". When loaded by a dead weight load of 2 kg, this configuration produces the same surface stress as the actual pad of 6" diameter when loaded by 22,000 lb.

Lubricant. Distilled water, applied to a depth of about 1". Two lubricant temperatures are used, namely room temperature (70-80°F) and an elevated temperature (160-180°F).

Sliding speed. Two sliding speeds are used, namely 4"/sec, corresponding to the maximum speed anticipated in the application and 0.04"/sec, or 1% of the maximum speed. Sliding tests are to be of one hour duration. In the slow speed tests, the static friction after static load application for 1 minute are also to be measured.

Force measurement

The normal force is to be applied by dead weight loading, while the friction force is to be measured and continuously recorded, by a Sanborn model 150 recorder. Calibration of the whole apparatus, namely the friction dynamometer and the Sanborn recorder as a unit, are to be made before each day's runs by a dead-weight-and-pulley method.

Personnel

All the tests will be carried out by Professor Ernest Rabinowicz of M.I.T. Prof. Rabinowicz has used the pin-on-disk tester for over twenty years, and has carried out friction testing using this and other methods continuously for the past twenty-nine years. His technical biography is appended.

Ernest Rabinowicz Oct 26, 1976

Approved
[illegible signature]
10/27/76

Technical Biography of Ernest Rabinowicz

Education

Cambridge University, England 1944-1947 B.A. in Physics

Cambridge University, England 1947-1950 Ph.D. in Physical Chemistry

Thesis title "Autoradiographic study of frictional damage."

Positions

1950-1954	Research staff member, M.I.T.
1954-1961	Assistant Professor of Mechanical Engineering, M.I.T.
1961-1967	Associate Professor of Mechanical Engineering, M.I.T.
1967-	Professor of Mechanical Engineering, M.I.T.
1961 Summer	Consultant, IBM
1969 Spring	Visiting Professor, Haifa Technion
1970 Summer	Consultant, IBM

Professional Organizations

Member, American Physical Society

Member, American Society of Lubrication Engineers

Member, American Society of Mechanical Engineers

Fellow, Physical Society of London

Group Subscriber, Institution of Mechanical Engineers, London

Registered Professional Engineer, Commonwealth of Massachusetts

Awards

Hodson Award of the American Society of Lubrication Engineers for 1957.

Research Experience

His research has been in the fields of friction and wear, materials, mechanical reliability, the mechanisms of polishing and comminution, and the use of radioisotopes.

Teaching Experience

Courses taught have been in the fields of Friction and Wear, Applied Mechanics, Materials, Experimentation, and Materials Processing

Publications

Books

'Friction and Wear of Materials,' Wiley, New York, 196 .

'An Introduction to Experimentation,' Addison-Wesley, Reading, Mass., 1970.

(with N. H. Cook) 'Physical Measurement and Analysis,' Addison-Wesley, Reading, Mass., 1963.

(edited) 'Friction - Selected Reprints,' Amer. Inst. Phys., New York, 1964.

(with six other authors) 'Mechanical Behavior of Materials,' ed. F. A. McClintock and A. S. Argon, Addison-Wesley, Reading, Mass., 1966.

(with six other authors) 'An Introduction to the Mechanics of Solids,' ed. S. H. Crandall and N. C. Dahl, McGraw Hill, N.Y., 1959.

Videotape Lecture Series

"An Introduction to Experimentation, A Self-Study Subject," Center for Advanced Engineering Study, M.I.T., Cambridge, Mass., 1972.

"Friction, Lubrication, and Wear, a Self-Study Subject", Center for Advanced Engineering Study, M.I.T., Cambridge, Mass., 1974.

Other technical writing

One patent and eighty articles, including

Wear, Encyclopaedia Brittanica

Friction, Encyclopedia Americana

Tribology, Encyclopaedia Brittanica

Reference Work Listings

Who's Who in America

American Men and Women in Science

Appendix 2. Discussion of experimental errors

The design and mode of operation of the pin-on-disk friction apparatus are such that errors in the determination of the friction coefficient tend to be kept to reasonably small values. For example, measurements have shown that the dead weights totalling 2 kg, used for applying the normal load, actually had a weight of 2.006 kg, but this introduced no error because the same weight is used in calibrating the friction force measurement with the dynamometer.

What errors there are arise mainly from some zero drift in the experiment, arising partly from slight instability of the Sanborn recorder in its maximum gain position, and partly from slight drift in the performance of the strain gage ring, resulting from creep of the adhesive bonding the strain gages to the aluminum ring. To counteract this zero drift, we frequently unloaded the dynamometer, during a friction test, to determine the instantaneous zero position. All in all, I would anticipate that the error in the friction coefficient due to this zero drift would be less than 0.02 in all cases, and generally only 0.01 or less. For the typical friction coefficient of 0.5, these would amount to errors of 4% and 2% respectively.

A more serious error arises from the fact that the dynamic characteristic of our dynamometer tends to introduce vibration into the friction trace which are probably more extreme than the fluctuations in the friction coefficient, and we compensate for this by introducing a little damping into the electronic circuitry. The consequence is that there is no error in determining the average value of the friction coefficient, which constitutes almost all the friction values tabulated above, but there may be an error, which I estimate to be about 0.03, in the 'maximum friction' values as determined in the slow speed tests.

An additional source of error may exist in the high temperature tests, in which, towards the ends of the tests, the strain gage ring became substantially warm, and in consequence, took on a few of the characteristics of a resistance thermometer. Perhaps a random error of as much as 0.10 could have afflicted some of the friction values. This has serious consequences only in regard to test 4, in which the highest average friction value of 0.82 was measured, as well as the highest peak friction value of 0.91. If we suppose that these data points were afflicted with an error of up to 0.11, then we can state that there were many occasions in which friction coefficient values above 0.70 were measured, but it is not certain that the friction coefficient ever rose above 0.80.

Appendix 3. Effect of time of stick on static friction

In most sliding systems, the friction coefficient is increased if the surfaces are kept at rest for long periods of time before sliding is commenced. According to some workers, this effect continues as long as the time at rest is increased, while according to others, the friction coefficient ceases to increase after the time of stick reaches some time in the interval 100-10,000 seconds. (A good summary of the various points of view of this problem are to be found in the paper, "Some considerations on characteristics of static friction of machine tool slideway," S. Kato, N. Sato and T. Matsubayashi, J. Lubrication Technology, Trans ASME F, 94, 234-247, 1972).

In our situation, we hardly measured any increase of friction with increased time of stick. But let us make an extreme-case assumption that the static friction coefficient is 0.65 after 10,000 secs at rest, and increases by 5% for every factor of 10 increase of time from that point on. Then in 20 years (6×10^8 years), the time will have increased by nearly five factors of ten and the friction will have increased by about 24% to 0.80. Thus, an upper design limit of 0.80 seems adequate, even if we assume that the friction coefficient continues to increase. (Incidentally, I personally believe that the friction does continue to increase with time of stick and have published papers to that effect. According to the Kato paper referred to above, this is by now a minority position).

Appendix 4. Statistical analysis of friction coefficient values

A short statistical analysis of the friction data has been carried out in order to determine, by standard statistical techniques, the highest and lowest friction values which might reasonably be anticipated. As will be seen by examining the actual friction coefficient values, the friction coefficient values observed in this series of tests cover a wide range, since there is systematic variation of the friction with the degree of surface contamination and with the sliding speed (as well as considerable random variation caused by local variations in bond strengths between the various junctions found between the top and the bottom sliding surfaces). Accordingly, it seems sensible to perform separate analyses to determine the highest expected friction coefficient value and the lowest expected friction coefficient values.

A. Highest friction coefficient values

Here we consider all the friction runs which gave high friction values, namely tests 2, 4, 6, 8 and 10 (eliminating in each case the first two values, which might have been affected by contamination), as well as the second half of the results obtained in static friction test 1 and all the results of static friction test 2.

In this way we obtain 134 friction coefficient values, and their histogram is shown in figure 1. The normal distribution which best fits these data (i.e. by having the same number of data points, the same mean, and the same standard deviation) is superposed.

The mean friction coefficient value for these data is .563, and the standard deviation is .096.

The procedure for carrying out these computations is discussed on pps

47 to 51 of the book "An Introduction to Experimentation," E. Rabinowicz, Addison-Wesley, Reading, MA, 1970.

B. Low friction coefficient value

All the friction data given in the body of the report but not shown in figure 1 is plotted in figure 2. Again the corresponding normal distribution is superposed.

The mean friction coefficient value in this case is .380, and the standard deviation is .080.

Discussion

At this point we must decide how many standard deviations to go above and below the mean, in order to compute the highest and lowest anticipated friction value. Under normal circumstances, a value of three or four times the standard deviation would seem to be appropriate. In this case, I think a value of twice the normal distribution is more sensible, in that there is already a considerable degree of averaging in going from the tests with an area of .006 in^2 to the application with an area of 100 in^2. Nominally, a standard deviation of $(\bar{x} + 2\sigma)$ or $(\bar{x} - 2\sigma)$ is exceeded about once in every 40 occasions, but because of this area effect, in this case the likelihood of exceeding the extreme value is very small.

As regards the high friction value, $\bar{x} + 2\sigma$ is .755

As regards the low friction value, $\bar{x} - 2\sigma$ is .224.

Note, in deriving these values, we have allowed only for random fluctuations, not systematic effects. As regards the high friction value, there is the likelihood that the friction value may continue to rise with time of stick, and hence some small allowance for this, raising the friction coefficient to .80, may be appropriate. As regards the low friction value, an allowance for greater contamination appears to be prudent, thus lowering the friction coefficient to .20 or even a little further.

The method used in this analysis, of separating the experimental data into high friction and low friction values may strike the reader as being very artificial. If we simply lump all the 199 friction values together, the overall population has a mean of .503 and a standard deviation of .125. Thus the upper limit ($\bar{x} + 2\sigma$) would be .753, and the lower limit ($\bar{x} - 2\sigma$) amounts to .253. It will be seen that these values are almost the same as those yielded by the other analysis.

Max = .8
Min = .2
Mean = .5
Note: The Mean is more realistic in the area of slipping [illegible] [illegible]. See pg [illegible] for discussion on [illegible] effect.

Incidentally, we have also analysed the data shown in figures 1 and 2 by carrying out a χ^2 analysis (as outlined on pps 52 to 55 of the "An Introduction to Experimentation" text cited above). The data shown in figure 1 are quite unlikely to be a normal distribution, since χ^2 is 16.29 with 6 degrees of freedom, giving a P value of .014 only. The data of figure 2 gives a χ^2 value of 3.40 for four degrees of freedom and a P value of .49, and may well be part of a normal distribution. In this particular case, I don't believe the above analysis is invalidated by the finding that the experimental data shown in figure 1 are not normally distributed.

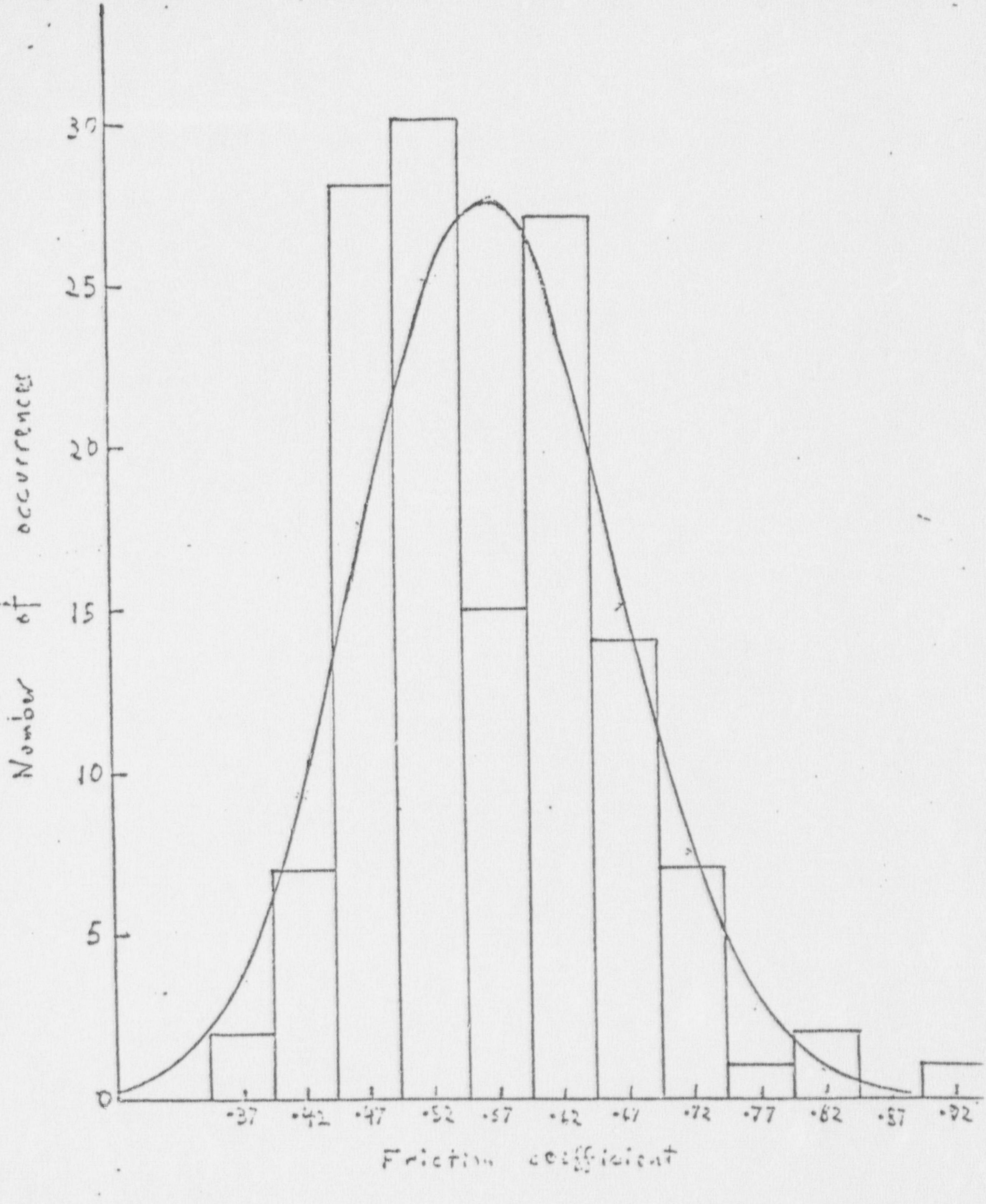

Fig 1. Histogram of 134 high f values..

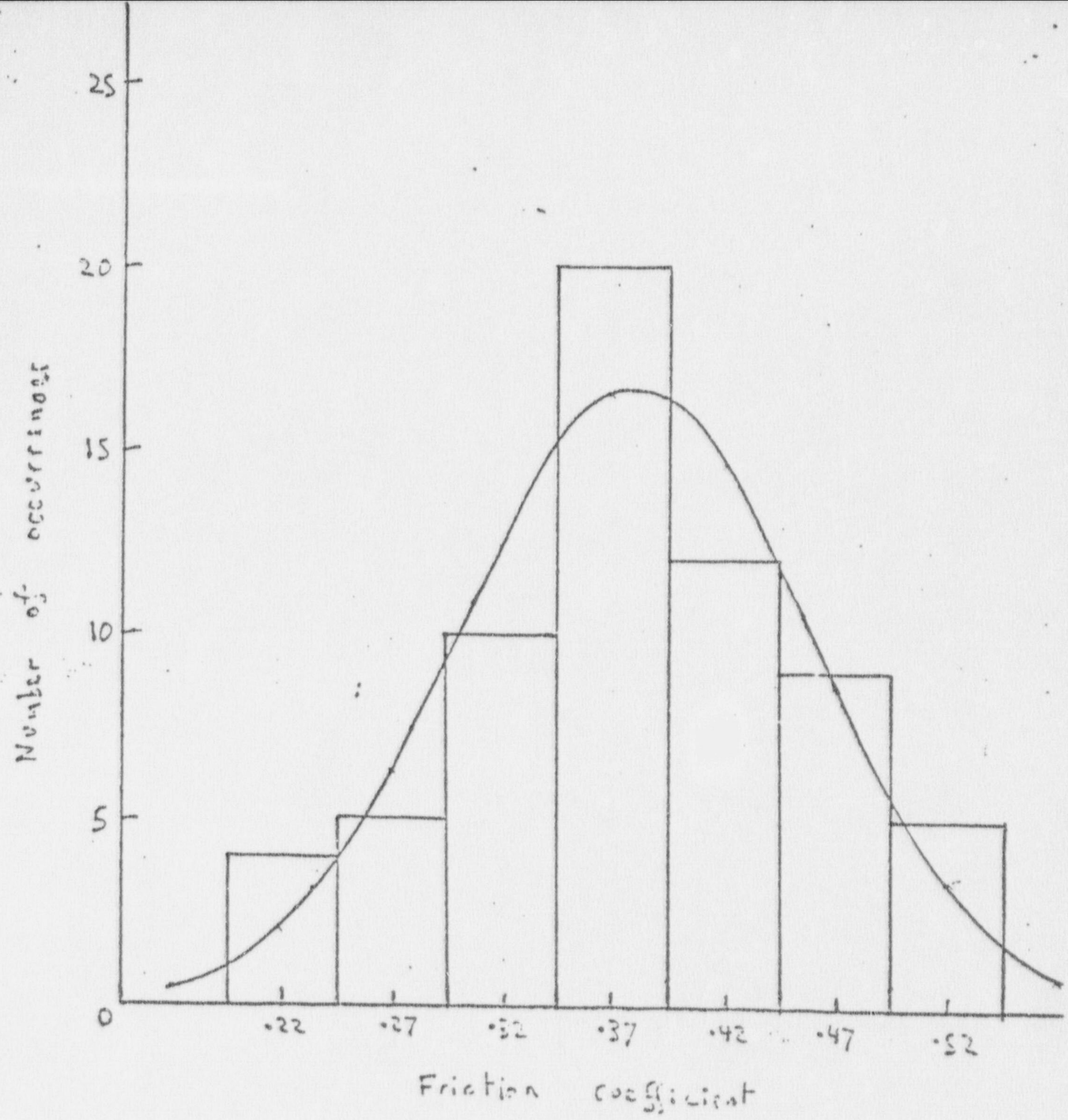

Fig 2. Histogram of 65 low friction values

Appendix 5. Questions submitted to me through Boston Edison

(Based on the main body of the report and the first three appendices).

Question 1.

We should be concerned only with static coefficients. Long term sliding which produces high coefficients are not germain to our problem. Test 6, Test 8, and Static Friction Tests I & II are the only ones which appear to be useable.

My comment

This may possibly be correct, though I should make clear that modern friction workers regard the distinction between static and kinetic friction coefficients as being rather artificial, since all friction coefficients are functions of other variables, such as speed, time, rate of increase of the shear force, and stiffness of the sliding system.

Question 2.

The use of a small rounded pin with high contact stresses and deformation are not valid. Data taken using this equipment should be disregarded. This includes Tests 1 through 4.

My comment

For an opposite opinion, I quote from p 98 of the classic book "Friction and Lubrication of Solids," F. P. Bowden and D. Tabor, Clarendon Press, Oxford, 1954. "It follows that the real area of contact A depends only on the load W and the hardness p and is almost independent of the apparent area of the surfaces. Consequently, the friction force F should be independent of the apparent area of the surfaces. This is Amonton's first law."

Question 3.

Using the data presented from the four tests which appear to be valid for our situation the maximum values for static friction are .52 in Test 6, .68 in Test 8, .72 in Static Friction Test I and .60 in Static Friction Test II. It appears to us that based on these tests and using a standard bell curve for data distribution we should have an effective coefficient no higher than .70.

My comment

I don't agree that only four tests are valid.

Final statement submitted to me

Since the required analysis is not sensitive to changes in friction between .7 and .8 Yankee agrees that the .8 value should be specified.

My comment

Fortunately the required analysis applies equally to friction coefficients of 0.7 and of 0.8, so that all is well.

Ernest Rabinowicz

Ernest Rabinowicz