ATTACHMENT 3
ENCLOSURE 1

HIGH DENSITY SPENT FUEL STORAGE SYSTEM

FRICTION TESTS
SLIDER PAD- SUPPORT BASE MATERIALS

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April 1981

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NUCLEAR FUEL AND SERVICES DIVISION • GENERAL ELECTRIC COMPANY
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ABSTRACT

A program was developed and implemented during which materials were identified and tested for use as slider pads and support bases in a spent nuclear fuel storage system. Breakaway (static) coefficient of friction values were determined when various material combinations were caused to slide against each other in a controlled water-lubricated environment. It was required that the slider pad-support base system be capable of operating, after being at rest under load in 100° 125° F water, for up to 40 years while subject to neutron and gamma radiation.

Various test data and specific test results are on file at the Spent Fuel Services Operation, General Electric Company, San Jose, Ca. These data are proprietary to the General Electric Company and are not contained in this report.

PRELIMINARY INVESTIGATION AND SCREENING

During the design phase of the high density spent nuclear fuel storage system, it was determined that a free standing module approach was practical if materials could be found to serve as slider pads and support bases so as to allow the storage module to slide upon the support base if subjected to seismic related horizontal forces. In order to qualify for use in the fuel storage system, the material(s) had to have previously been used (or approved for use) in underwater applications while being subjected to neutron and gamma radiation for prolonged periods of time and at the same time not be subject to galvanic corrosion when in contact with each other. In addition, the coefficient of friction of the materal(s) had to satisfy the requirements established by design engineering.

Literature searches and personal contacts were made to determine the extent and availability of existing friction data for materials which could be applied to the fuel storage application. It was found that the United States Department of the Interior performed sliding friction tests on metals for application where the mating surfaces slide over one another under high normal pressures after having been immersed in water for extended periods of time. In a report from the Canadian AECL, Chalk River, Ontario, a program is described which was undertaken to test and develop materials with good resistance to galling, wear, and corrosion for use as nuclear reactor components. The tests included measuring and recording the starting and running friction values. In a paper by S. Kato and N. Sato, it is stated that when two surfaces are in stationary contact under boundary lubrication, the static (breakaway) frictional force gradually increases with an increase of contact time or stick period. The paper suggests that the static or breakaway frictional force will not continue to increase with time after about 10,000 seconds (2.78 hours).

As a result of the intial investigation, several materials were identified that seemed to have the necessary corrosion resistance and prior use requirements, but breakaway coefficient of friction data were not available. A limited test program was begun to obtain "ball park" friction data so that only those materials which appeared to meet all of the pre-established acceptance criteria would undergo final qualification tests. During this period the candidate materials were caused to slide against type 304 SST in a water lubricated environment using "standard" equipment to measure the coefficients of friction. It was desirable to use type 304 SST as one part of the slider - support base system using standard machine finish surfaces.

QUALIFICATION TESTS

During seismic activity, the fuel storage container, and hence the attached slider pad, can move in any direction relative to the stationary support base. Such movement could be cyclic and the direction of movement could change at any time. This random type of movement cannot be easily simulated with the equipment used during the previous screening tests since the relative motion between the test materials was unidirectional. A test fixture was designed and built which would slide a test block (slider pad material) against test plates (support base material) in a back and forth cyclic motion. Each complete cycle, from top to bottom and back to top, provided two (2) breakaway friction values. This continuous cyclic motion may more closely duplicate seismic-related horizontal movement than would other test methods. The test fixture also allowed the test plates to be positioned so as to evaluate various surface finishes. A hydraulically actuated test machine was used for all cyclic testing. One test plate was bolted to the test fixture and a second test plate was bolted to a movable mounting plate which connected to a horizontal hydraulic cylinder such that a load normal to the sliding surfaces could be applied. A test block was attached to the test machine vertical actuator rod and caused to slide between the two (2) test plates. The test fixture frame, and thus the test plates, was attached to a load cell, which in turn was attached to the frame of the test machine. The force required to move the slider block between the test plates was measured by use of the load cell. Demineralized water was circulated through the test fixture. The configuration and surface finish of the slider block and the test plates were closely controlled. The surface finish of the various test pieces was measured using a Brush Surfindicator Model MS 1300.01.

PROCEDURE and TEST SETUP

The following test procedure was used:

1. The inside of the test fixture, the slider plates and the slider block were cleaned with alcohol, then with reagent grade acetone.
2. The dimensions of the slider block were taken and the contact surface area calculated to determine the hydraulic pressure setting for the normal force actuator.
3. The slider block and the test plates were mounted into the test fixture.
4. Cover plates were attached to the test fixture, the water connections were made, and demineralized water was circulated through the test fixture.
5. The normal pressure was applied to the test pieces and held for a specified time.

6. The normal pressure was increased to a specified level after which the slider block was caused to move and the breakaway forces were recorded as a function of time on an X-Y recorder. Most tests were continued for 200 cycles which provided 400 data points.

In addition to the various material combinations, the following test variables were closely monitored.

1. Magnitude and time the normal contact pressure was held before sliding started.
2. Magnitude of normal contact pressure during sliding.
3. Surface finishes of the test pieces.
4. Number of test cycles (sliding distance).

To determine if the breakaway coefficient of friction would be influenced due to time under load before first movement, the slider block was held stationary in contact with the test plates for specified times under pre-established mean contact pressures before sliding occurred. In general, when the test data indicated that specific material combinations may have the necessary frictional characteristics for use in the fuel storage system after the first hold time under load, additional tests were performed using different hold times.

DATA EVALUATION

Analyses were performed using data from each test to determine a realistic breakaway coefficient of friction (μ) when the slider block slides against the slider plates subject to the physical conditions maintained during the tests. Analyses were also performed to determine if hold time, normal pressures and slider plate surface finishes had any effect on the coefficients of friction. All mathematical analyses and statistical comparisons were made at the 95% confidence level. The manner in which the test data were mathematically evaluated is significant. Analyses indicated that data from none of the tests could be considered as coming from a normal population. It was, therefore, not proper to use mathematical techniques intended for the evaluation of a normal distribution such as $\overline{X}$ plus or minus some number of standard deviations. If one were interested in constructing a confidence interval for the population mean, the deviation from normality is not such a serious consideration, unless the deviation from normality is pronounced or unless the sample size is very small. This is a result of the central limit theorem of statistics. The problem at hand, however, was not to construct a confidence interval of the mean, but to (1) evaluate the differences which may exist between the data from each of the various tests, and (2) construct or determine a prediction interval defining a boundary which could be considered to reasonably contain a certain proportion of future coefficients of friction when sliding occurs, or to verify that future observations could be reasonably expected to come from the population defined by the test data. A procedure was used to construct the desired interval which assumes only that the data have no discontinuities. The limits using such methods would be wider (more conservative) than those where normality can be assumed.

Data evaluations included the following: 1) Comparing first movement data with middle of test data and with end of test data, and 2) comparing data from first hold period with data from subsequent hold periods. Two types of statistical comparisons were made, the first compared average performance (mean) and the second compared the diversion or spread (standard deviation) of the data from the average performance. If a statistically significant difference was noted between data sets, it could be assumed that the difference may not have been due to chance alone, but that an assignable cause, such as hold time, or surface finish of the test plates may have resulted in the difference. If no significant difference was noted, it could be assumed that the difference may have been due to chance alone.

SUMMARY

Based upon the several evaluations and comparisons of the test data, it was concluded that five (5) materials, when sliding against type 304 SST and subject to the conditions established during the tests, met the criteria established by design engineering and could be used as slider pads in the spent nuclear fuel system. No statistical significances were found which would indicate that a further increase in hold time would result in a change in the friction coefficient. The evaluations of data from these five (5) materials also indicated that the average coefficient of friction was consistently repeatable between tests and within tests.

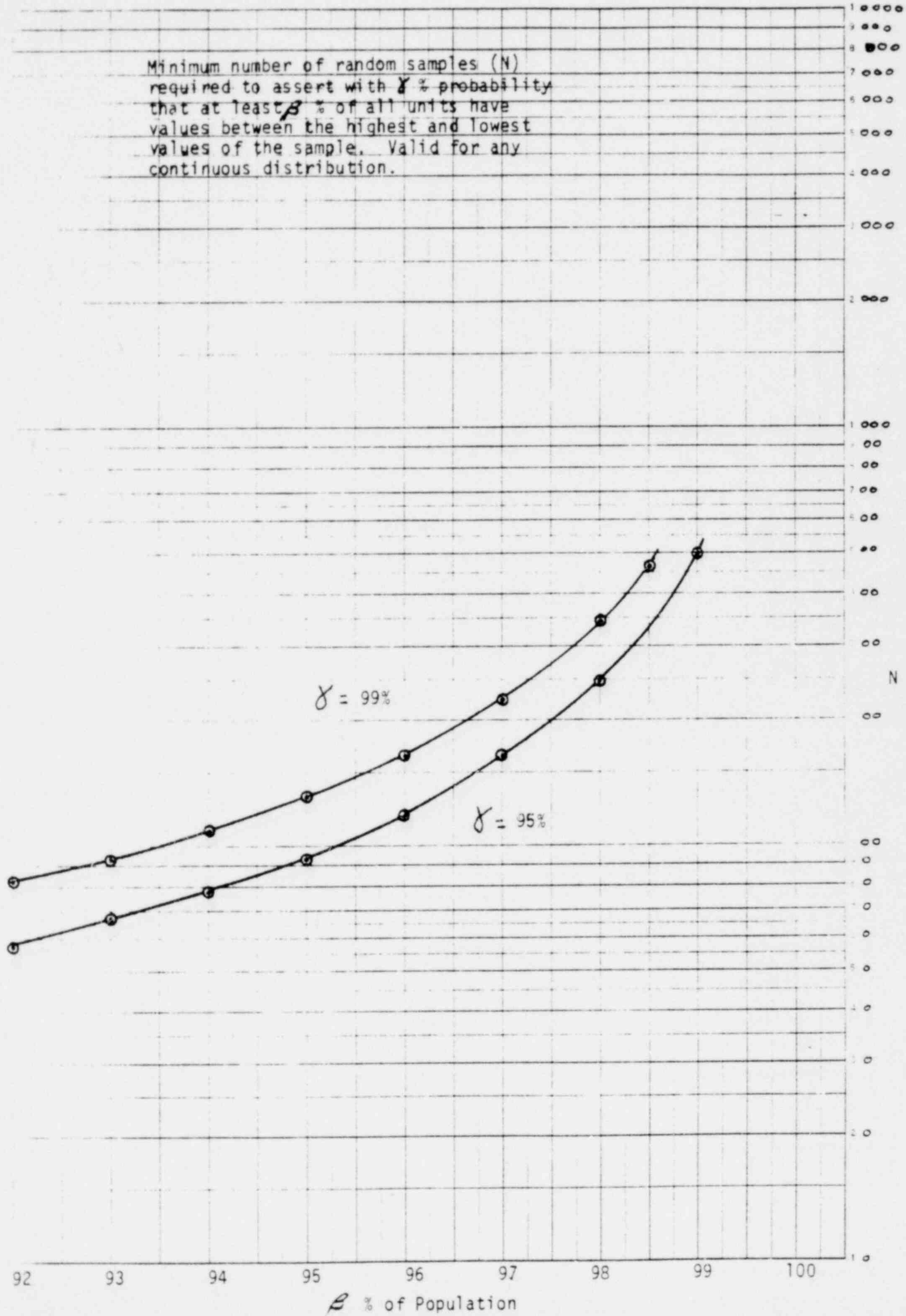
The following is an alternate explanation of the experimental data which was provided by a consultant who is an acknowledged expert on friction. All the reported sliding tests were in fact carried out under essentially identical conditions, and the differences in friction may have resulted in chance differences in surface cleanliness, etc. The non-normality of the test data is attributable to non-normality of other influences. Throwing all the friction coefficient data "into one pot", one can state that for surface preparation techniques, speeds and pressure similar to those used in the tests, all the friction coefficient values seem to lie within the desired region, which is quite satisfactory.

Using nonparametric techniques to establish a prediction interval, it can be asserted with 95% probability that at least 95% of all friction factors which may be encountered in the proposed application will lie within the desired range.

APPENDIX

The following curve is based on the theory of non-parametric tolerance limits and was prepared from "Non-Parametric Tolerance Limits" by R.B. Murphy, Annals of Mathematical Statistics, Vol. 19, 1949. The user of the curve can make the following determination: How sure can one be that the limits found by drawing inferences from the sample actually include the true limits? By increasing the sample size, the probability γ, can be increased. More specifically, one can assert with a probability γ that at least β percent of the population lies in a range established by the extreme values of the sample.

A special feature of this method is that it is distribution-free. The characteristic need not be distributed normally, or in any other specific manner as long as it is distributed continuously. When the characteristic actually does follow a normal distribution, more precise statements about the limits can be made using a table of normal tolerance limits. The above techniques for establishing population limits should not be confused with those for estimating parameters of the distribution, such as the average or standard deviation. Statistical methods provide different rationale for selecting the proper sample size for such problems.



Minimum number of random samples (N) required to assert with γ % probability that at least β % of all units have values between the highest and lowest values of the sample. Valid for any continuous distribution.
γ = 99%
γ = 95%
N
92
93
94
95
96
97
98
99
100
β % of Population

ATTACHMENT 3
ENCLOSURE 2

ERNEST RABINOWICZ
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November 23, 1977

RECEIVED
NOV 28 1977
D. R. SPONSELLER

David R. Sponseller
Project Engineer
General Electric Company
175 Curtner Avenue - M/C 859
San Jose, CA 95125

Dear Mr. Sponseller:

I herewith am sending you two copies of my report, in which I have incorporated the changes recommended by your people and have added an appendix.

Sincerely,

Ernest Rabinowicz

Ernest Rabinowicz

Enclosure

3 D V5455 REV0

X

David Sponseller 1/3/78

sm-h

ERNEST RABINOWICZ
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REVISED BY COVER LETTER OF 11/23/77

G.E. P.O. 529-CC084X

September 26, 1977

RECEIVED
NOV 28 1977
D. R. SPONSELLER

Report to General Electric Nuclear Energy Programs Division

Attn: Mr. D. R. Sponseller

Friction coefficient value for a high density fuel storage system

Abstract

Friction coefficient values obtained earlier in a study of a 304 steel - 304 steel water lubricated sliding systems have been used to estimate friction coefficient values likely to be encountered in a high density fuel storage system currently being designed by the General Electric Company. The mean friction coefficient anticipated is .523, while the lowest friction coefficient likely to be encountered, (1.69 standard deviations below the mean) is .349.

Ernest Rabinowicz
Sept 26, 1977

Introduction

This study was undertaken to derive a realistic minimum friction coefficient value for a high density fuel storage system being designed at GE. In this system, it is desired to resist horizontal shear forces due to seismic action through friction to the spent fuel pool floor. The two sliding materials are 304 stainless steel, the 'lubricant' is demineralized water at 70-150°F (21 - 66°C), and the nominal interfacial pressure is 700 - 2000 psi (1).

Some months ago the writer undertook an experimental study of the friction to be anticipated in a high density fuel storage system being constructed by Boston Edison (2). Since the Boston Edison conditions closely resembled those of the GE application, it was decided to carry out no additional testing but to use the Boston Edison data; to apply correcting factors to make them applicable to the GE conditions; and then to use the recomputed friction values to estimate the lowest friction coefficient likely to be encountered by GE.

In the tests carried out for Boston Edison it was found that variables such as temperature and apparent pressure had little demonstrable effect on the friction coefficient. Surface roughness appeared to have some effect, in that very rough surfaces gave a slightly lower value for mean friction coefficient and a distinctly lower standard deviation, indicating that the lowest value of friction coefficient (i.e. the mean friction coefficient minus one or two standard deviations) was larger for rough surfaces than for smooth ones. All these results are in good agreement with what is known about the friction coefficient of very poorly lubricated metallic surfaces.

The only important systematic effect encountered in the Boston Edison tests was that the friction coefficient was a function of the sliding velocity, with the friction increasing as the velocity decreased (the typical negative characteristic, responsible for frictional oscillations). In the Boston Edison case, the tests were carried out at speeds of .04 and 4 in/sec, bracketing the sliding speeds believed to be of interest. In addition, a number of static friction coefficient values, after times of stick covering a rather wide range, were determined.

In the GE case considered here there are no sliding velocity requirements as such, but rather it is believed that the horizontal shear forces increase from zero to peak in a time interval which is in the range .09 to .18 seconds (3). This information must now be converted to equivalent sliding velocities. In a paper published some years ago (4), the writer suggested that the static friction coefficient f_s corresponding to a time of stick t_1, would be the same as the kinetic friction coefficient f_K at a sliding velocity v_1, provided that

$$v_1 = \frac{d}{t_1}$$

where d is the diameter of the junction formed between the two sliding surfaces.

Later work (5) has shown that d is given by the relationship

$$d = \frac{60,000\ W_{ab}}{p}$$

where W_{ab} is the surface energy of adhesion of the contacting materials (in this case a value of twice the intrinsic surface energy or 3400 erg/cm^2 seems reasonable), while p is the penetration hardness of the 304 stainless steel (in this case about 2.5×10^{10} dyne/cm^2). This yields a value for d of 8.2×10^{-3} cm, or 3.2×10^{-3} inches. The writer estimates that an error of $\pm$ a factor of two is associated with this calculation, so that junction diameters of anywhere in the range 1.6×10^{-3} inches to 6.4×10^{-3} inches are possible. A detailed discussion of this calculation is contained in Appendix I.

In the GE case, the highest sliding velocity (and hence the lowest friction coefficient) would be encountered when surfaces with junctions of the largest possible size (6.4×10^{-3} inches) meet shear forces which increase in the lowest possible time (.09 seconds); the equivalent sliding velocity v_1 would be 7.1×10^{-2} in/sec. The Boston Edison friction test data must therefore be converted to this sliding velocity.

In the Boston Edison tests, for the first eight series of tests, half were carried out at the higher speed of 4 in/sec, and half at the lower speed, of .04 in/sec. The mean friction coefficient was found to be .37 at 4 in/sec, and .55 at .04 in/sec. The ratio of friction coefficients is 1.49. These experimental data agree quite closely with results obtained by the writer many years ago using an unlubricated plain steel on plain steel sliding system (figure 1). This earlier series of tests suggests that the plot of friction coefficient against log sliding velocity tends to be a straight line; it has therefore been assumed that it is precisely a straight line.

Figure 2 represents the friction coefficient values for the two applications. It will be seen that the friction at .071 in/sec is a factor of 1.42 greater than at 4 in/sec, while being a factor of 1.05 smaller than at .04 in/sec. Accordingly, to convert the friction values of the Boston Edison tests to the GE case, multiply the high speed and low speed friction coefficient values by the corresponding correction factor.

This takes care of the one hundred kinetic friction coefficient values, and leaves the question of what to do about the remaining 99 static friction values. They cover a variety of times of stick, geometries, roughness and rates of application of the shear force, and it is suspected that the GE fuel storage system may also encounter a variety of these variables since it is not a closely controlled laboratory situation. Secondly, the static and kinetic values have very similar means and standard deviations. It has therefore been decided simply to leave these values as they are.

Experimental friction values adjusted for GE case

Test 1. 304 steel on 304 steel. Room temperature. Hemispherically ended slider. Roughness 29 microinches rms. Distilled water lubricant. Sliding speed = 4 in/sec. Friction coefficients have been multiplied by 1.42.
f values:- 0.54, 0.64, 0.58, 0.50, 0.50, 0.53, 0.53, 0.48, 0.47, 0.47

Mean friction coefficient = 0.52.

Test 2. 304 steel on 304 steel. Room temperature. Hemispherically ended slider. Roughness 29 microinches rms. Distilled water lubricant. Sliding spead = 0.04 in/sec. Friction coefficients have been divided by 1.05
f values :- 0.35, 0.44, 0.59, 0.62, 0.61, 0.61, 0.61, 0.58, 0.63, 0.59

Mean friction coefficient = 0.56.

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. Friction coefficient values have been multiplied by 1.42.
f values:- 0.50, 0.60, 0.62, 0.55, 0.65, 0.71, 0.70, 0.70, 0.58, 0.55

Mean friction coefficient = 0.62

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. Friction coefficient values have been divided by 1.05.
f values:- 0.44, 0.50, 0.49, 0.61, 0.62, 0.68, 0.72, 0.57, 0.64, 0.78

Mean friction coefficient = 0.60

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

<u>Test 5</u>. 304 steel on 304 steel. Room temperature. Slider end diameter 0.09". Roughness 27 microinches rms. Distilled water lubricant. Sliding speed 3.9"/sec. Friction coefficient values have been multiplied by 1.42.

f values:- 0.51, 0.38, 0.45, 0.30, 0.36, 0.30, 0.44, 0.38, 0.47, 0.54

Mean friction coefficient = <u>0.41</u>.

<u>Test 6</u>. 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. Friction coefficient values have been divided by 1.05

f values:- 0.39, 0.41, 0.47, 0.48, 0.43, 0.45, 0.48, 0.50, 0.50, 0.47

Mean friction coefficient = <u>0.46</u>.

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

<u>Test 7</u>. 304 steel on 304 steel. 71-79C. Slider end diameter 0.09". Roughness 27 microinches rms. Distilled water lubricant. Sliding speed 3.8"/sec. Friction coefficient values have been multiplied by 1.42.

f values:- 0.72, 0.72, 0.55, 0.57, 0.57, 0.58, 0.51, 0.38, 0.43, 0.54

Mean friction coefficient = <u>0.56</u>

<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. Friction coefficient values have been divided by 1.05

f values:- 0.40, 0.36, 0.50, 0.42, 0.44, 0.42, 0.57, 0.45, 0.65, 0.41

Mean friction coefficient = <u>0.46</u>

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

Test 9. 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. Friction coefficient values have been divided by 1.05.

f values:- 0.44, 0.50, 0.49, 0.50, 0.50, 0.47, 0.53, 0.54, 0.58, 0.51

Mean friction coefficient = 0.51

Test 10. Same as test 9 but iron oxide particles to a depth of 0.25". Friction coefficient values have been divided by 1.05

f values:- 0.58, 0.55, 0.54, 0.60, 0.51, 0.50, 0.51, 0.54, 0.53, 0.55

Mean friction coefficient = 0.54.

Static friction test I. 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 of stick	Friction coefficient values	
1-sec	.23, .33, .44, .23, .70	.62, .56, .61, .68, .68, .64
10	.39, .39, .42, .32, .50	.61, .54, .61, .68, .66, .67
100	.36, .51, .37, .47, .50	.59, .54, .62, .67, .69, .68
1,000	.33 .46, .35, .48, .60	.61, .63, .69, .60
10,000	.29	.58, .72
50,000	.59	

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

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

All the adjusted friction coefficient values obtained are tabulated in Table 1, and a histogram and normal distribution which matches the distribution are given in figure 3. The χ^2 value between the histogram and the curve (for 9 degrees of freedom) is 10.3 giving a P value of .25, which suggests that the data are consistent with a normal distribution, and thus it is appropriate to use the properties of the normal distribution (e.g. the proportion of the curve lying outside $\bar{f} \pm 1.69\sigma$) in analysing the data.

Discussion

The question in the GE case is that of arriving at a realistic value for the least static coefficient of friction which might be encountered. Normally, this would be represented by the mean friction coefficient minus three or four standard deviations. As stated in the writer's Boston Edison report, there was a tremendous amount of averaging in the actual application as opposed to the experimental test conditions, since the total normal load and the total area of contact was of the order of 1000 times greater. Because the low experimental friction valuesall seemed attributable to very small patches on the 304 steel surfaces, a mean friction coefficient minus two standard deviations seemed quite adequate. However, in the Boston Edison situation, both maximum and minimum friction coefficients were of interest, and the $(\bar{f} \pm 2\sigma)$ criteria gave 95.5% assurance of identifying these values, as against a 4.5% probability of failing to do so. In the GE case, only the lower tail of the normal distribution is of interest, and to impose the same requirement of a 95.5% assurance of having identified the minimum value, the $(\bar{f} - 1.69\ \sigma)$ point must be found. In this case, this gives a minimum friction value of .349.

It should be mentioned that in this analysis all the friction data were cmobined into one population, whereas in the Boston Edison study the high and low frict.on values were considered separately. This was done because the earlier study contained two essentially dissimilar sets of friction coefficients, obtained at two widely different sliding speeds, whereas in the present study the results have been adjusted to the same sliding speed.

How reliable is the friction coefficient value we have derived? It should be clear that essentially random errors of about .005 or .010 produced by instrumental factors like recorder reading error and zero drift uncertainties produce negligible effect when combined with the statistical fluctuation of more than ten times the magnitude. Systematic errors due to having measured or computed the wrong quantities have all been chosen so as to give a conservative result. For example, an exceptionally large value of sliding velocity v was used in the calculations, since the maximum possible junction size and the minimum possible time of appli ation of the shear force was considered. If a value of v smaller by a factor of two had been used, kinetic friction coefficient values larger by about .04 would have resulted, which would in the end have led to overall $(\bar{f} - 1.69\ \sigma)$ values larger by about .02.

In the case of the static friction coefficient values, if there is a systematic error it is that the friction coefficient was measured after short periods of sticking (16 hours, or less), whereas in the application the times are likely to be in the months range. Although it is hard to estimate the effect of this, the writer's opinion is that this factor also will increase the overall $(\bar{f} - 1.69\ \sigma)$ value by about .01 or .02. As indicated in the Boston Edison report, this may by now be a minority view. The majority would argue that no substantial correction because of the difference in the times of stick is warranted.

The only possible source of error that remains is that due to contamination. Depending on how the 304 surfaces were made there may be some contaminants left on the surfaces which will give initially low friction coefficient values, perhaps as low as .05 below those given in the tests. (For example, when running the tests for Boston Edison the author carried out some preliminary runs using 304 steel specimensjust as they were found in the laboratory, without any preliminary cleaning, and this gave friction coefficient values up to a value of .05 lower than the values obtained later after the specimens were cleaned by abrasion.) However, this is a situation which improves with time, i.e. at the high temperatures, the contaminants will tend to move to the water-air interface at the top of the fuel storage system.

In any case, this source of error can be greatly reduced if care is taken that the 304 steel pads of the fuel storage racks are thoroughly cleaned, preferably using coarse, clean abrasive paper, before they are introduced into the fuel storage system. (The advantage of using rough surfaces is that the lowest value of friction coefficient is increased even though the mean value is somewhat reduced. Refer to static friction tests 1 and 2. In test 1, using a smooth surface, the mean friction is .53, but the lowest friction is .23. In test 2 using a rough surface, the mean friction is .49 and the lowest friction is .43).

Conclusions

The recommended minimum coefficient of friction to be used for design in the GE application is 0.349.

Acknowledgements

I wish to thank Mr. David R. Sponseller and Mr. Wallace Wheadon of GE, as well as Dr. John Reed of EDAC, for helpful inputs. Dr. Mukti Das of the Boston Edison Company provided much useful information with regards to the experimental work.

Table I. The friction coefficient values

	20	30	40	50	60	70
0		2	1	15	6	4
1			2	10	8	1
2		1	3	4	6	4
3	2	2	6	5	3	
4			6	10	4	2
5		2	8	6	2	
6		5	5	2	1	
7		1	8	6	2	
8		3	6	8	5	1
9	1	3	11	4	2	

Note: This table indicated that there were 11 friction coefficient values of .49 (the intersection of the 9 row and the 40 column), as well as 15 values of .50 (the intersection of the 0 row and the 50 column).

References

(1) Telex, D. R. Sponseller of GE to Dr. Ernest Rabinowicz, 8/8/77.

(2) E. Rabinowicz, "Friction coefficients of water-lubricated stainless steels for a spent fuel rack assembly," unpublished report to the Boston Edison Company dated Nov. 5, 1976.

(3) Letter, Subject "G.E. P.O. 529-CC084X," D. R. Sponseller of G.E. to Dr. Ernest Rabinowicz, 8/12/77, with attached preliminary drawing, C5442E-103, dated 8/18/77.

(4) E. Rabinowicz, "The intrinsic variables affecting the stick-slip process," Proc. Phys. Soc., 71, 668-675, 1958.

(5) E. Rabinowicz, "Friction and Wear of Materials," John Wiley & Sons, N.Y., 1965, pp 151-158.

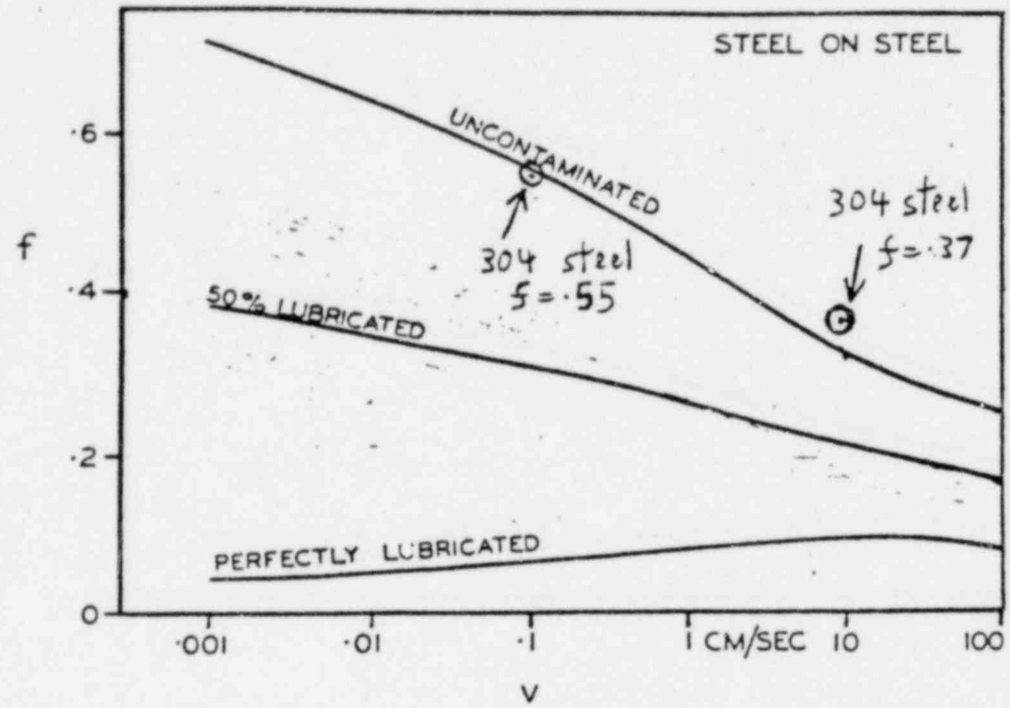

Figure 1. Plot dating to 1958 (reference 4) showing the friction-velocity functior for 1020 steel sliding on 1020 steel at various stages of lubrication. The data obtained with water-lubricated 304 steel fits the line denoting unlubricated sliding very well.

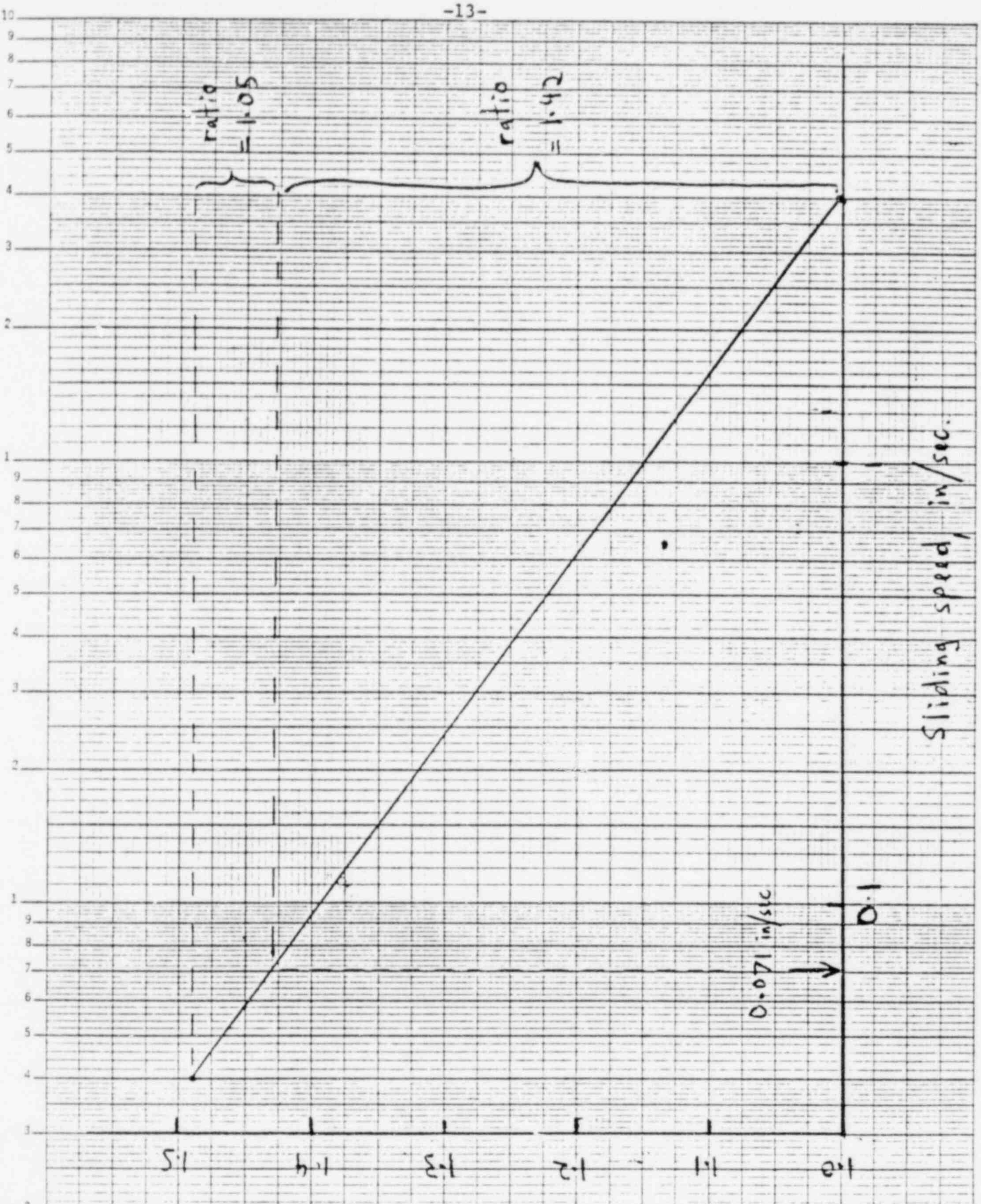

Figure 2. Schematic illustration of the friction-velocity relationships for stainless steel, water-lubricated surfaces.

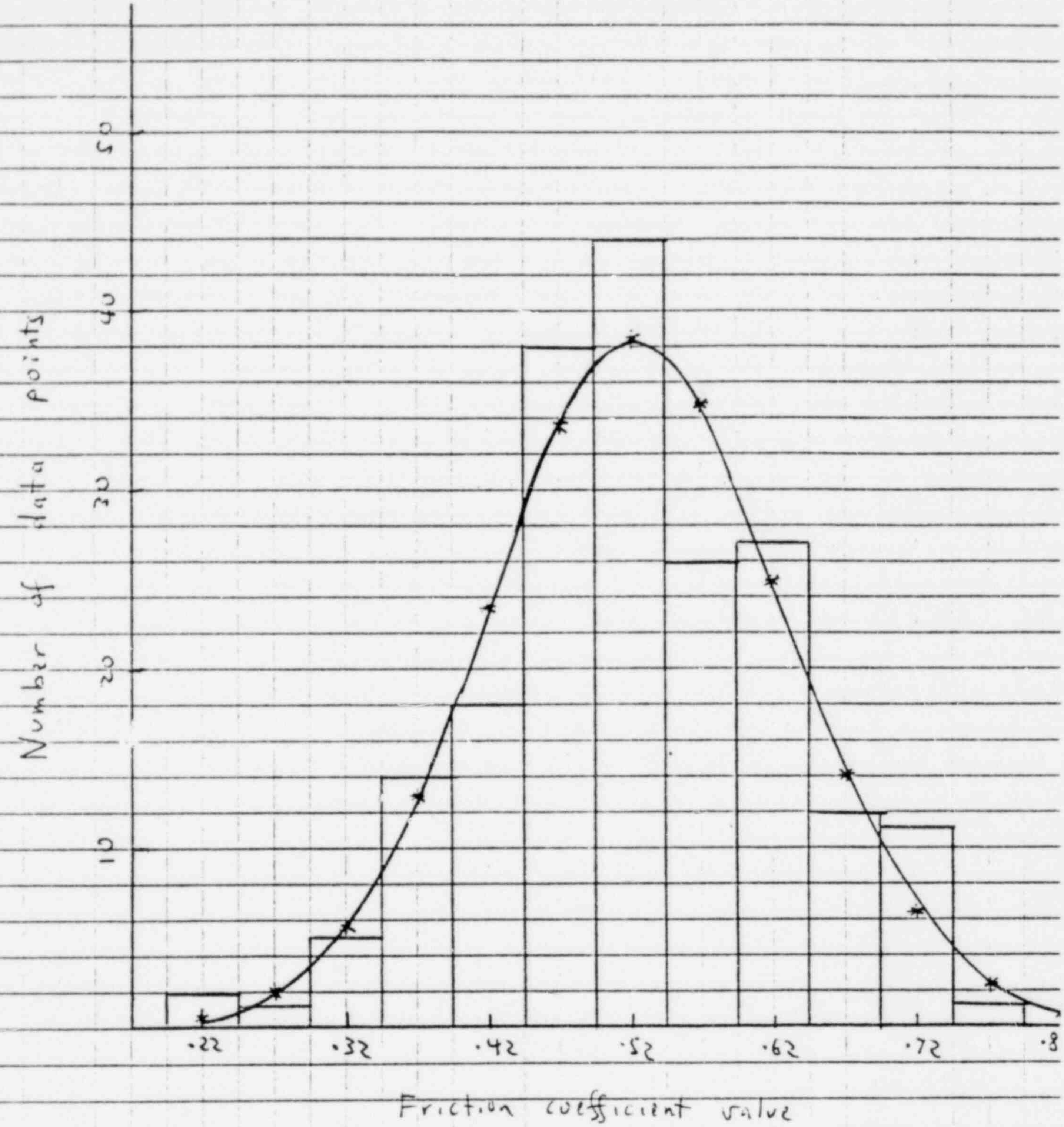

Figure 3. Histogram of the 199 friction coefficient values, also the corresponding normal distribution. The mean friction coefficient is .523, while the standard deviation is .103.

Appendix I. The size of junctions

On page 3 of the report, a value of 6.4×10^{-3} inches is adopted for the size of junctions to be anticipated in the HDSS. In this appendix a more extensive discussion of the reason for adopting this particular value is given.

Methods for determining the diameters of junctions were first developed in the 1950's. A summary is contained in Table 3.1 of reference 5, reproduced below.

Table 3.1 Estimates of Junction Diameter

Combination	Load	Lubricant	Method	Junction Diameter	Reference
Copper on steel	1 kg	None	f_s − distance	7μ	Rabinowicz, 1951
Steel on copper	1 kg	None	f_s − distance	6μ	Rabinowicz, 1951
Copper on copper	1 kg	Cetane	f_s − distance	8μ	Rabinowicz, 1951
Copper on steel	2 kg	None	Particle size	31μ	Rabinowicz, 1953
Copper on copper	0.1 kg	None	f_k autocorrelation	10μ	Rabinowicz, 1956
Copper on copper	0.1 kg	None	f_k fluctuations	5μ	Rabinowicz, 1956
Steel on steel	50 kg	Contaminated	$f_s - t$ vs. $f_k - v$	10μ	Rabinowicz, 1958
Copper on copper	Any	None	$24000\ \gamma/p$	26μ	Eq. 3.15
Steel on steel	Any	None	$24000\ \gamma/p$	13μ	Eq. 3.15

It will be seen that the values shown range from 0.2×10^{-3} inches to 1.2×10^{3} inches.

A little later, the surface energy theory of wear particle formation was developed. According to this theory, during sliding at moderate loads, (1 kg or less), junctions are formed, at some of them adherent wear particles are generated with diameters equal to the junction diameter, then these adherent wear particles tend to grow in size, until their diameter reaches a value given by the equation

$$\text{diameter} = 60{,}000\ W_{ab}/p \qquad \text{A1}$$

At this point the particle leaves the sliding surface.

The current status of the adhesive wear theory in general is discussed in a recent paper (A1).

Unfortunately, this theory has not yet given good values for the sizes of adherent particles and hence of junctions. But empirical data suggests that the adherent particles, and hence the junctions, have about 1/3 the diameter of loose wear particles. Accordingly, an appropriate value for the junction diameter d_j is given by the equation

$$d_j = 20{,}000\ W_{ab}/p \qquad \text{A2}$$

This equation is given on p 4.11 of reference A2.

Now W_{ab}, the energy of adhesion, may be written in the form

$$W_{ab} = \gamma_a + \gamma_b - \gamma_{ab} \qquad A_3$$

where γ_a and γ_b are the surface energies of the two sliding metals a and b respectively, and γ_{ab} is the interfacial energy. In this case, a and b are both stainless steel, and hence γ_{ab} is equal to zero, and γ_a as well as γ_b may be taken to have the same surface energy as iron, the main constituent of stainless steel, namely 1700 erg/cm^2 (see Table 2.1 on p 2.3 of reference A2). If p is made equal to 250 kg/mm^2, (and this value is based on experimental hardness measurements of various samples of 304-grade stainless steel in the Surface Laboratory at MIT) then by substitution in eqn. A2 it is found that d_j is 3.2×10^{-3} inches.

Now this value of d_j applies primarily to lightly loaded surfaces, typically with apparent pressures of about 100 psi or less, and total loads of but a few pounds. When the pressures are higher, and especially when a large total load is used, then the junction size is subject to change. According to one school of thought the average junction size increases proportionately to the tenth root of the apparent pressure (ref. A3), while according to another view there is no change in average junction size, at any rate until pressures exceeding 10,000 psi are reached (ref. A4). This second view, based on more recent and sophisticated experiments, is more likely to be correct.

In this case, it seems safest to allow for an increase in junction size by a factor of two over and above the value given by equation A3, which brings it up to a value of 6.4×10^{-3} inches. All in all, this seems to be a realistic value, and at the same time it is, to the extent that it is in error, likely to be an overestimate. In the present situation that makes it a conservative assumption.

Note that the other possible source of error in the calculation for junction diameter lies in the fact that the influence of the water has been ignored. This might reduce the surface energy of the steel by as much as a factor of two from the value of 1700 erg/cm^2, thus reducing the junction size by a factor of two. Considering both this factor and the influence of pressure considered above, the possible junction size values may vary by as much as a function of two about the value of 3.2×10^{-3} inches computed above by the use of eqn. A2, as is pointed out on page 2 of the main report.

References to Appendix I

A1) E. Rabinowicz, "The dependence of the adhesive wear coefficient on the surface energy of adhesion," pp 36-40 of "Wear of Materials - 1977" ASME, N.Y., 1977.

A2) E. Rabinowicz, "Study Guide to Friction, Wear and Lubrication, a Self-Study Subject," Center for Advanced Engineering Study, M.I.T., Cambridge, Massachusetts, 1974.

A3) E. Rabinowicz, "A quantitative study of the wear process," Proc. Phys. Soc. (London), 66B, 929-936, 1953.

A4) J.B.P. Williamson, "Topography of solid surfaces," pp 85-113 of "Interdisciplinary Approach to Friction and Wear," NASA SP-181, Washington, D.C., 1968.

Appendix II

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, mechanical reliability, electric contacts, 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, Electroplating, and Materials Processing.

Publications

Books

'Friction and Wear of Materials,' Wiley, New York, 1965.

'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
- 'Tribological Phenomena,' Encyclopaedia Brittanica
- 'Friction' and 'Wear,' McGraw-Hill Encyclopedia of Science and Technology

Reference Work Listings

Who's Who in America

American Men and Women in Science