SCREENING CONTACT MATERIALS FOR LOW SPEED SLIP RING ASSEMBLIES

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ABSTRACT

As part of a program to improve overall performance, a study was undertaken to evaluate forty potential replacement alloys for either the brush or ring members of a slip ring assembly. As in a previous study[1], a reciprocating crossed rod technique was employed to monitor friction coefficient, electrical noise, and relative wear. Tests were performed in air and two candidate fill fluids. Initially, all the alloys were tested as potential brush replacements. These tests were run with the brush alloys riding against a hard gold electroplate (typical of the current materials). Based on these initial results, seven of the alloys were selected as potential ring replacements. Each of the candidate ring alloys was then tested against ten potential brush materials. A numeric rating system was developed which considered changes in wear, noise, and friction. A number of the candidate alloys were selected for additional longer term testing in actual slip ring hardware.

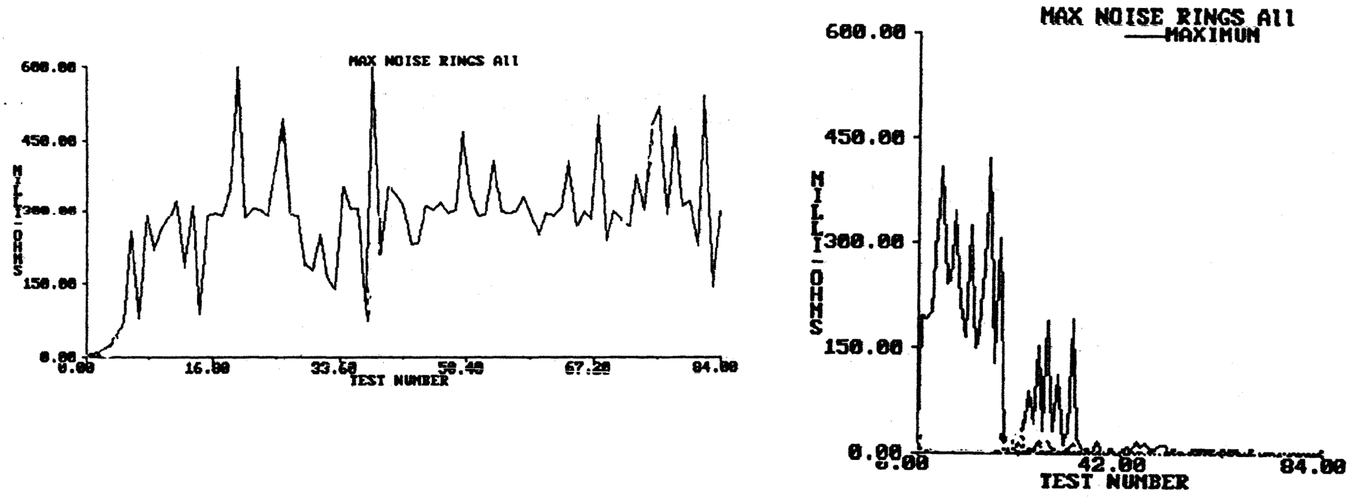
Keywords: Sliding contacts, Slip ring, Gold alloys.

INTRODUCTION

As part of an on-going improvement program, a multi-disciplinary team is continuing efforts to optimize the performance of a fluid immersed slip ring assembly. The team has established performance targets related to electrical noise, mechanical torque, and component wear. Initial results of this program have been reported previously at the 1990 Holm Conference.[1,2] The starting point for the program was based on an assembly using an Au alloy brush, an electroplated Au ring, and a commercially available fill fluid. This assembly was characterized by erratic performance.

The initial phase of the program evaluated over 100 potential fill fluids, and used a short term screening test to monitor friction coefficient, electrical noise. and wear. The screening was performed with a reciprocating cross-rod device instrumented to record electrical resistance and friction coefficient. Additionally, after each test, the contacts were examined for evidence of wear. Based on the screening test, the most promising fluids were tested with actual hardware in an automated test facility.[2] Figure 1 contains plots characterizing the electrical noise for both the original fill fluid and for one of the most promising of the candidate fill fluids.[3]

Based on the performance improvements achieved by optimizing the fill fluid, a similar program was initiated to examine the role of contact materials. All of the fluid screening was performed using a single Au alloy brush material running against electroplated Au rods. The alloy characterization was divided into three phases: 1) Use the cross-rod test to screen new brush materials run against the same Au-electroplated surfaces used for the fluid screening; 2) Based on the performance in Phase I, select a limited number of the candidate brush alloys, and again use the cross-rod instrument to evaluate these materials for use as unplated ring contacts; and 3) Develop a rating program to rank the relative performance of the various systems, and select the most promising combinations for testing as actual hardware in the R.J. Lee facility.[2] This paper is intended as an on-going progress report on the program. It will attempt to summarize the results for Phases I and II. The results for Phase III will be limited to introducing the rating systems. Data from the hardware tests will be reported at a later date.



a.) Commercial fill fluid

b.) Experimental fill fluid

Figure 1 .) Plots of the maximum recorded noise level found on any of the eighteen rings contained on a slip ring assembly.

EXPERIMENTAL

Materials

Table 1 lists the precious metal content and hardness for each of the alloys tested in the program. Each alloy was east from raw elements. For the initial brush screening program, the ingots were cast at .1875" diameter. After an initial homogenization anneal at 1400°F for 3 hours, the alloys were reduced to .010" wire. Since the alloys were experimental, no attempt was made to optimize the cold reduction/annealing schedules. Anneals were generally done at 1400°F. Initially each alloy was tested in the cold worked state. However, a number of the alloys were found to be age hardenable. The resultant hardnesses and aging schedules are listed in Table 1. For these samples, the aging was done from the cold worked state.

For the initial Phase I testing, both a Co and Ni hardened electroplated Au surfaces were-used for the mating contacts. The electroplates paralleled the surfaces used in the original screening program.'

For Phase II, the same .010" diameter brush materials were used. However, since the rods were .0625" diameter, a new .250" diameter casting was prepared for each alloy. Processing was similar to that used for the candidate brush materials.

Fluids

Each alloy system was tested in at least two fill fluids. One fluid represented the commercially used perfluorinated polyalkylether (PFPE). The second fluid contained a 1% additive of a brominated arylester in the commercial PFPE. (This combination was fluid #84 from Reference 1.) As a point of reference, many of the material pairs were also run in ambient air with no fill fluid (i.e.-unlubricated).

Testing Conditions

A block diagram of the reciprocating cross-rod device is shown in Figure 2. Since the circuit and construction details are given in Reference 1, the specifics will not be repeated here, In general, the tests were performed with a maximum clamped current of 10ma. The unit operates at 5.5 rpm and a stroke length of .5". For each test, a .0625" diameter rod is used to simulate the -ring material; It is held stationary. A smaller diameter (.010") wire is used to represent the brush material. The axis of the small wire is held at right angles to the rod. The small wire moves back and forth on the rod in a direction parallel to the axis of the rod. All tests were run for 30 minutes at 120°F. The normal force was set at 15 grams. The average friction coefficient and electrical noise values were measured for one minute at both the start and end of the test, and monitored for the entire 30 minutes.

After testing, both the wire and rod were examined

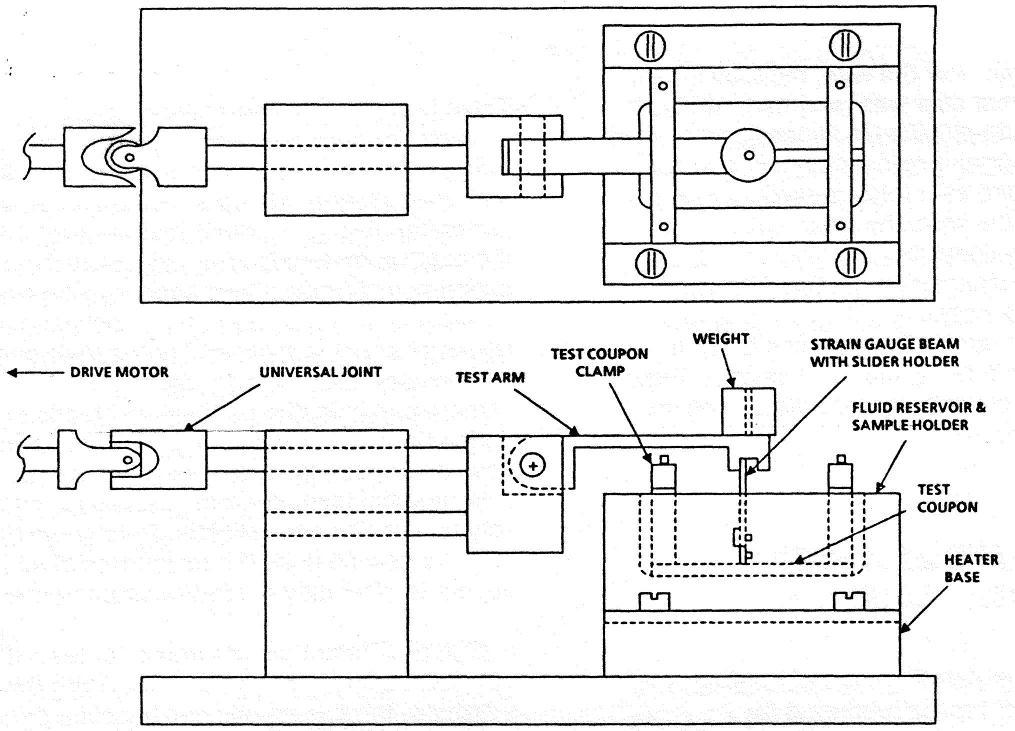
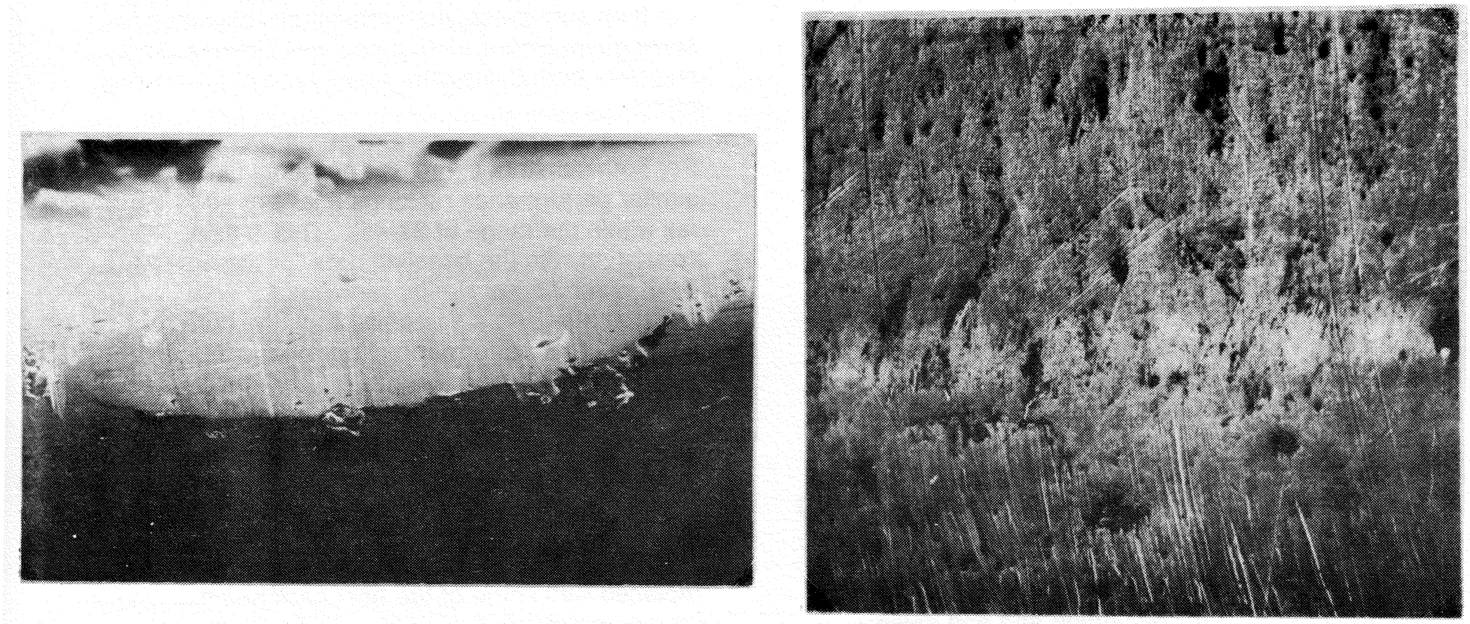


Figure 2.) Schematic diagram of crossed rod testing equipment.



a.) Wire wear (550x)
("rectangular wear area" = 7)

b.) Rod wear (150x)
(Subjective rating of "1")

Figure 3.) SEM photomicrographs illustrating two levels of wear typical of this program.

for evidence of wear. For the wire, the total length and width of any wear scar was recorded. Although the scar tended to be elliptical in shape, a calculated "rectangular area" (major axis length times minor axis length) was used as a relative ranking of wear performance. For the wire, the wear was concentrated at the contact spot. For the rod, the wear was evenly distributed along the .5" contact length. In all cases, only a slight burnishing was detected. This was qualitatively ranked using a scale of 1 to 5, with 5 being the most severe. Figure 3 contains SEM photo-micrographs illustrating the wear ranking procedures.

RESULTS AND DISCUSSION

Phase I

Table II contains test data for each of the Phase I alloys mated against the Co hardened Au electroplate. The table contains data for tests done in both the commercial and the experimental fill fluids. Table Ill contains similar data for the Phase I alloys tested against the Ni hardened Au electroplate. For completeness, Table IV contains data for some of the Phase I alloys tested against both of the Au electroplates, but in the absence of any fill fluid.

In comparing the data, it should be noted that samples 1-5 represent the original Au alloy brush material (Neyoro G). As shown by the variation in hardness, the samples represent different thermo-mechanical treatments for the brush. The data for the aged samples (l-3) is felt to be representative of lot to lot scatter. Therefore, the average of these three values could be considered the baseline for each segment of the study.

In an effort to quantify the relative performance, a subjective rating system was developed. The system attempted to put equal weighting on all three parameters (friction, noise, and wear). This was done by examining the measurements for the baseline data (test 1-3 in each fluid), and developing a subjective weighting factor for all six variables. For simplicity, the following factors were chosen, 10 times for the beginning and end friction measurements, 1 for beginning and end noise measurements (expressed in milliohms), 5 times for the rod wear, and one for the wire wear. Because of the subjective nature of this rating system, it was felt that a 10% scatter would not be unreasonable. Therefore, a minimum 20% improvement in the average baseline rating was felt to be significant.

Table V contains a comparison of the top 10 rated systems'for each type electroplate vs. the average rating for baseline samples l-3. For the Ni hardened system, the data demonstrates a 20% performance improvement for the new fill fluid with the existing materials. For this substrate, the experimental brush alloys appear to neutralize any differences in the overall ratings between the fluids. However, there is a general noted difference in the friction coefficient data for the two fluids. For the commercial fluid, the friction level tends to rise during the test. In actual use, this would correlate to an undesirable rise in the operating torque. For the experimental fluid, the torque tends to remain constant or decrease slightly. Relative to the Neyoro G in the new fill fluid, the experimental alloys appear to offer only borderline improvement.

A slightly different picture arises for tests done with the Co-hardened substrates. With this substrate, there is no obvious baseline difference between the two fill fluids. However, relative to the reference level, at least six of the experimental brushes exceed the 20% performance improvement target. It should also be noted that 9 of the top 10 systems utilized the new fluid. For the lower rated systems, the general rise in friction coefficient is also seen with the commercial fluid.

For both substrates, the ambient air tests tend to show much higher friction and wear values. This suggests both fluids offer some type of lubricating effect.

For both substrates, the use of the fill fluids result in similar performance rankings (i.e.- top 10 for both fall within the range of 37-45). This is also consistent with the baseline data for the new fill fluid, which shows similar rankings for both electroplates. As a screening tool, the data suggests that performance improvements can be achieved by altering the surface chemistry. This layer can be altered by changes in the bulk alloy composition or changes to the fill fluid.

Phase II

In Phase II, the electroplated Au substrates were replaced with some of the best performing experimental brush systems. Table VI contains the performance data for wrought rod/wrought brush combinations. Table VII contains the top 25 ranked systems from Table VI. (As a point of reference, Table VII also lists a single average ranking for the 12 baseline points contained in Table V and performance rankings for the three best unlubricated systems.)

Based on a baseline value of 54 for the Neyoro G vs. Au-electroplated systems, all twenty five of the wrought vs. wrought systems in Table VII exceed the 20% improvement target discussed earlier. Nine of the twenty five offer a 30% lower ranking (~37.8) and two are ranked 40% below the baseline level. For these systems, Neyoro G is found on 14 of the 25 highest ranked systems. Alloy 27 is found on seven systems,4 as a rod, and 3 as a brush). Alloys 24 and 31 are found six times. Of the fifty possible entries, no'other alloy appeared more than three times.

Phase III

Based dn the data contained in this paper, a number of systems were selected for additional hardware testing. Currently, the Phase I systems are under test at R.J. Lee. Unfortunately, the tests are not yet completed. Phase II systems, have also been selected, and these systems are currently under fabrication.

Finally, it should be noted that the ranking system used in this paper is somewhat arbitrary. Additional work is required to fully optimize the weighting factors. It is hoped that, as the longer term (1000 hours) hardware data becomes available, the resultant performance information will allow refinement of the ranking procedure.

CONCLUSIONS

Based on data generated from the reciprocating cross-rod instrument, a ranking system has been developed to screen both materials and fluids for potential use in submerged slip rings. The data shows that some performance improvement can be achieved by optimizing either the fill fluid or the contact materials. Additional improvements can be achieved by taking a systems view, and simultaneously optimizing both the fluid and contact materials.

Additionally, the data suggests:

1) In combination with the fill fluids used in this study, the wrought slip ring/wrought brush appears to offer great potential.

2) There is no obvious correlation between alloy composition or hardness and relative performance in this test.

3) The best ranked systems have Au contents between 50% and 90% and hardnesses between 280Hv and 380Hv.

4) Additional work is required to understand the potential surface interactions between the fill fluids and the contact materials.

ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance and guidance provided by the Naval Slip Ring committee. Mr. David File, Mr. Gary Anderson, Dr. John Williams and Mr. Harry Briendel are responsible for providing the technical oversight which allowed this cooperative effort to flourish. The progress in this program is a direct reflection of their untiring dedication. The authors also wish to thank Dr. Don Flom for his technical input. A special thanks is also given to Mr. Chuck Spangler of the R.J. Lee Group for all his assistance and perseverance in administerlng the automated test facility.

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2) C. Ackerman, H. Lentz et al, "Automated Torque and Resistance Measurement s of Sliding Electrical Contacts During Life Testing", Proc. 36th IEEE Holm Conference on Electrical Contacts, pp. 259-268, 1990.

3) Private Communication, C. Spangler of the R.J. Lee Group, 4/93.

Table I. Compostion and Hardness of the Experimental Alloys

Alloy	Composition					Hardness	Comments
Designation	Au	Pd	Ag	Pt	Other Elements	Hv	
1	71.5		4.5	8.5	Cu, Zn, Ir	361	commmercially heat treated
2	71.5		4.5	8.5	Cu, Zn, Ir	353	commmercially heat treated
3	71.5		4.5	8.5	Cu, Zn, Ir	331	commmercially heat treated
4	71.5		4.5	8.5	Cu, Zn, Ir	288	annealed
5	71.5		4.5	8.5	Cu, Zn, Ir	245	annealed
8			90		Cu	143	
9		95			Ru	240	
10				90	Ir	164	
11	82				Ni	328	
12	70	8			Ni	348	
13	80				Cu	201	
14	49	33	16		Ru	190	
15	65	33			Ru	207	
16	90				Cu	149	
17	63		15		Cu	246	
18	70	1	13.4	7.5	Cu, Zn	261	
19	68.5	4	12	2.5	Cu, Zn	299	
20	63	5	19		Cu, Zn	282	
21	65	3	23	0.5	Cu, Zn	247	
22	61.8	3	26		Cu, Zn	259	
23	62.5	3	15	1.4	Cu, Zn	305	
24	59	4	22.5		Cu, Zn	303	
52						354	Alloy 24- aged 550F,30 min.
53						365	Alloy 24- aged 600F,30 min.
25	56.5	5	25		Cu, Ni	284	
26	56	4	20		Cu, Zn	310	
27	51	7	27		Cu, Zn	286	
51						380	Alloy 27- aged 550F, 30 min.
28	50	10	20		Cu, Zn	292	
49						397	Alloy 28- aged 500F,30 min.
50						419	Alloy 28- aged 550F,30 min.
29	2	28	60		Cu, Zn	260	
30	25	15	51	0.8	Cu, Zn	228	
31	35	10.5	41	1	Cu, Zn	286	
32	70		24		Cu	222	
33	81	11		6	Sn, Fe	187	
34	72		13.7	3	Cu,Zn	261	
54						326	Alloy 34- aged 550F,30 min.
35	52	37.5			Sn, Zn, In	312	
36	51.5	38.5			In, Ga	383	
37	50	36.5			Cu, Sn, In, Ga	385	
48						433	Alloy 37- aged 550F, 30 min.
38	2	27.5	58.5		Cu, Zn	256	
39	80				Ni	392	
40		60	40			205	
41	84	13.5			Sn, In	218	
42		25			Ni, Cu, Zn, Mg	344	
43		25			Ni, Cu, Zn, Mg	357	
44	82		8	8	Zn, Re	182	
45	42				Cu, Zn, Ni	308	
46	75				Cu, Zn, Ni	394	
47		25			Ni, Cu, Zn, Mg	501	

TABLE II. Performance Data for Experimental Brushes versus Co hardened Au electroplate

			Commercial Fluid							Experimental Fluid					
Alloy #	Hardness		FRICTION		NOISE		WEAR			FRICTION		NOISE		WEAR	
			BEGIN	END	BEGIN	END	Rod	wire		BEGIN	END	BEGIN	END	Rod	Wire
1	361		0.17	0.18	10	8	3	8		0.15	0.17	26	13	2	0
2	353		0.17	0.25	10	8	3	17		0.17	0.23	20	12	1.5	13
3	331		0.17	0.25	9	8	3	17		0.17	0.17	18	12	2	8
4	288		0.17	0.27	12	10	3	7		0.17	0.18	16	13	1	6
5	245		0.18	0.27	13	8	3	11		0.17	0.18	22	13	1	6
8	143		0.2	0.22	7	6	3	52		0.2	0.2	9	9	1	25
9	240		0.2	0.22	12	10	3	25		0.2	0.17	16	18	1	20
10	164		0.2	0.27	13	10	3	12		0.22	0.15	13	30	1	17
11	328		0.18	0.43	12	10	2	8		0.15	0.18	43	12	2.5	2
12	348		0.2	0.43	10	8	3	19		0.17	0.17	33	12	2	8
13	201		0.2	0.33	111	10	1	17		0.18	0.17	13	13	1	15
14	190		0.27	0.33	10	10	3	24		0.2	0.18	13	10	1	21
15	207		0.17	0.33	11	8	3	11		0.18	0.17	13	12	1	14
16	149		0.18	0.25	7	8	1	13		0.22	0.23	12	9	1	14
17	246		0.17	0.23	12	10	3	9		0.18	0.2	16	10	2	5
18	261		0.17	0.3	>50	10	3	9		0.2	0.17	17	17	1	8
19	299		0.15	0.43	34	10	3	8		0.16	0.22	20	10	3	7
20	282		0.17	27	>50	8	4	11		0.2	0.2	13	10	1	6
21	247		0.17	0.33	20	10	4	17		0.22	0.18	14	13	1	9
22	259		0.17	0.23	42	8	3	14		0.22	0.22	14	14	1	10
23	305		0.17	0.33	30	10	3	7		0.17	0.23	14	11	2	6
24	303		0.17	0.27	>50	9	3	6		0.17	0.18	13	12	3	8
25	284		0.17	0.18	>50	>100	3	7		0.17	0.2	14	10	3	3
26	310		0.17	0.3	50	8	2	5		0.17	0.17	15	15	3	11
27	286		0.17	0.27	>50	7	3	10		0.17	0.17	14	14	1	7
28	292		0.18	0.25	>50	8	3	6		0.17	0.2	14	12	1	4
29	260		0.17	0.28	35	8	3	11		0.2	0.17	15	14	1	8
30	228		0.17	0.33	48	8	2	11		0.2	0.17	13	13	1	12
31	286		0.17	0.28	22	9	3	8		0.18	0.17	14	10	2	8
32	222		0.2	0.4	20	8	2	26		0.2	0.2	13	12	2	15
33	187		0.25	0.47	13	10	2	24		0.23	0.17	18	17	1	40
34	261		0.33	0.47	10	10	3	14		0.23	0.17	16	16	1	28
35	312		0.2	0.4	17	12	3	13		0.2	0.17	20	25	1	9
36	383		0.17	0.33	17	13	3.5	10		0.18	0.15	22	25	1	9
37	385		0.18	0.4	18	16	2	10		0.18	0.15	21	20	1	8
38	256		0.2	0.42	12	9	3	30		0.2	0.17	16	16	1	24
39	392		0.17	0.37	17	14	3	9		0.22	0.17	22	20	1	7
40	205		0.22	0.45	20	10	2	29		0.22	0.17	24	20	1	28
41	218		0.28	0.45	12	9	2	44		0.25	0.17	16	15	1	42
42	344		0.2	0.28	30	23	3	30		0.2	0.17	40	34	1	13
43	357		0.25	0.27	35	46	3.5	25		0.25	0.27	48	32	3	19
44	182		0.3	0.47	11	9	2	42		0.27	0.18	15	13	1	40
45	308		0.17	0.48	>50	14	3	8		0.2	0.23	20	15	3	10
46	394		0.17	0.57	19	12	3	12.5		0.18	0.23	19	14	3	5
47	501		0.25	0.53	28	14	4	13		0.22	0.25	25	16	3	5
48	433		0.17	0.17	>80	20	3	3.5		0.17	0.27	20	14	3	4
49	397		0.15	0.15	70	>100	3	0		0.17	0.2	14	12	3	10
50	419		0.18	0.4	48	7	3	3		0.17	0.17	14	12	3	8.5
51	380		0.15	0.35	25	8	3	4		0.2	0.25	13	10	2	4
52	354		0.15	0.3	30	9	3	4.5		0.2	0.2	13	11	2	4
53	365		0.25	0.32	27	8	3	7.5		0.2	0.22	13	10	2	2.5
54	326		0.17	0.32	30	10	1	6.5		0.18	0.23	13	10	3	10

TABLE III. Performance Data for the Experimental Brushes versus Ni hardened Au electroplate

			Commercial Fluid							Experimental Fluid					
Alloy #	Hardness		FRICTION		NOISE		WEAR			FRICTION		NOISE		WEAR	
			BEGIN	END	BEGIN	END	Rod	wire		BEGIN	END	BEGIN	END	Rod	Wire
1	361		0.2	0.37	13	10	3	24		0.18	0.17	15	13	2	7
2	353		0.17	0.37	15	10	3	24		0.18	0.17	16	16	1	9
3	331		0.2	0.35	14	11	2	15		0.2	0.17	16	16	1	8
4	288		0.22	0.37	15	10	3	37		0.22	0.17	18	16	1	18
5	245		0.23	0.37	14	11	3	45		0.23	0.17	16	17	1	25
8	143		0.33	0.27	7	8	1	78		0.28	0.22	11	11	1	67
9	240		0.27	0.33	16	14	2	35		0.28	0.17	20	33	1	40
10	164		0.3	0.37	14	12	3	54		0.22	0.17	26	30	1	55
11	328		0.23	0.33	16	12	3	10		0.2	0.17	18	18	1	7.5
12	348		0.2	0.33	23	10	3	15		0.22	0.17	16	16	1	10
13	201		0.33	0.4	10	9	4	30		0.23	0.2	13	14	1	25
14	190		0.27	0.45	12	9	3	45		0.25	0.18	20	15	1	42
15	207		0.27	0.43	15	10	3	36		0.25	0.17	18	18	1	36
16	149		0.32	0.38	10	10	2	38		0.28	0.2	13	13	1	54
17	246		0.22	0.37	13	10	2	26		0.22	0.18	16	13	1	17
18	261		0.22	0.43	14	10	2	31		0.22	0.17	18	16	1	27
19	299		0.17	0.37	13	10	2	21		0.22	0.17	16	15	1	23
20	282		0.2	0.4	13	9	2	25		0.2	0.17	15	14	1	23
21	247		0.23	0.42	13	10	2	27		0.23	0.2	15	14	1	32
22	259		0.27	0.4	9	9	2	21		0.2	0.2	15	13	1	36
23	305		0.18	0.37	14	9	2	29		0.2	0.17	16	16	1	19
24	303		0.2	0.4	13	8	2	2		0.22	0.17	4	12	1	19
25	284		0.22	0.38	14	10	2	20		0.2	0.17	16	15	1	15
26	310		0.2	0.33	13	10	2	22		0.2	0.17	15	14	1	14
27	286		0.18	0.23	25	12	1	25		0.2	0.17	15	16	1	20
28	292		0.17	0.2	30	12	1	25		0.18	0.17	15	14	1	17
29	260		0.22	0.18	10	10	1	33		0.18	0.17	15	15	1	21
30	228		0.22	0.18	11	11	1	31		0.2	0.2	15	15	1	26
31	286		0.22	0.17	13	12	1	20		0.2	0.15	16	13	1	20
32	222		0.23	0.23	10	9	1	24		0.23	0.2	15	13	1	40
33	187		0.25	0.47	13	10	2	24		0.23	0.17	18	17	1	40
34	261		0.33	0.47	10	10	3	14		0.23	0.17	16	16	1	28
35	312		0.2	0.4	17	12	3	13		0.2	0.17	20	25	1	9
36	383		0.17	0.33	17	13	3.5	10		0.18	0.15	22	25	1	9
37	385		0.18	0.4	18	16	2	10		0.18	0.15	21	20	1	8
38	256		0.2	0.42	12	9	3	30		0.2	0.17	16	16	1	24
39	392		0.17	0.37	17	14	3	9		0.22	0.17	22	20	1	7
40	205		0.22	0.45	20	10	2	29		0.22	0.17	24	20	1	28
41	218		0.28	0.45	12	9	2	44		0.25	0.17	16	15	1	42
42	344		0.2	0.28	30	23	3	30		0.2	0.17	40	34	1	13
43	357		0.25	0.27	35	46	3.5	25		0.25	0.27	48	32	3	19
44	182		0.3	0.47	11	9	2	42		0.27	0.18	15	13	1	40
45	308		0.2	0.35	20	14	1	16		0.22	0.18	20	17	1	10
46	394		0.2	0.38	18	14	2	18		0.2	0.2	19	17	1	8
47	501		0.18	0.37	23	18	2	10		0.22	0.2	25	19	1	10
48	433		0.17	0.32	22	14	1	6		0.17	0.18	22	19	1	9
49	397		0.18	0.32	14	10	1	7		0.18	0.17	14	13	1	7.5
50	419		0.22	0.32	12	9	1	8		0.17	0.17	15	12	1	9
51	380		0.18	0.32	13	10	1	13		0.2	0.17	16	12	1	11
52	354		0.18	0.32	14	10	1	10		0.18	0.17	14	13	1	9.5
53	365		0.17	0.3	16	10	1	9.5		0.18	0.15	14	13	1	8
54	326		0.18	0.33	16	10	1	17		0.2	0.17	15	14	1	19

Table IV. Performance Data for the Experimental Brushes tested in Air

			vs. Co Hardened Au substrate							vs. Ni Hardened Au substrate					
Alloy #	Hardness		FRICTION		NOISE		WEAR			FRICTION		NOISE		WEAR	
			BEGIN	END	BEGIN	END	Rod	Wire		BEGIN	END	BEGIN	END	Rod	Wire
18	261		0.33	0.33	13	11	1	24		0.25	0.35	13	16	2	18
19	299		0.3	0.45	14	12	2	27		0.27	0.43	14	14	3	9
20	282		0.28	0.43	14	10	2	27		0.33	0.43	17	15	3	9
21	247		0.4	0.55	12	10	2	27		0.25	0.4	15	15	2	27
22	259		0.33	0.53	11	13	2	120		0.3	0.4	13	14	3	9
23	305		0.28	0.5	12	13	4	27		0.28	0.37	14	22	3	7
24	303		0.3	0.45	12	12	3	36		0.25	0.4	11	13	3	6
25	284		0.28	0.45	12	10	3	19		0.25	0.43	13	12	3	6
26	310		0.28	0.6	11	11	4	36		0.3	0.4	13	13	2	7.5
27	286		0.3	0.53	12	12	4	33		0.28	0.35	13	14	3	15
28	292		0.3	0.5	14	10	3	15		0.27	0.35	14	18	1	9.5
29	260		0.33	0.55	11	11	1	33		0.27	0.38	11	14	1	7
30	228		0.33	0.53	12	12	4	29		0.33	0.4	13	0.2	1	13
31	286		0.33	0.5	12	12	2	16		0.28	0.37	13	14	1	9
32	222		0.38	0.57	12	12	2	35		0.33	0.43	13	12	2	15
33	187		0.48	0.5	13	13	2	45		0.48	0.5	13	13	2	45
34	261		0.38	0.43	12	11	3	25		0.38	0.43	12	11	3	25
35	312		0.22	0.42	16	14	3	12		0.22	0.42	16	14	3	12
36	383		0.32	0.45	17	16	3	10		0.32	0.45	17	16	3	10
37	385		0.27	0.4	17	15	3	13		0.27	0.4	17	15	3	13
38	256		0.37	0.48	12	10	3	38		0.37	0.48	12	10	3	38
39	392		0.27	0.43	17	11	3	10		0.27	0.43	17	11	3	10
40	205		0.43	0.62	19	12	3	52		0.43	0.62	19	12	3	52
41	218		0.4	0.55	13	12	1	42		0.4	0.55	13	12	1	42
42	344		0.3	0.43	30	22	3	17		0.3	0.43	30	22	3	17
43	357		0.28	0.28	60	56	4	39		0.28	0.28	60	56	4	39
44	182		0.53	0.58	13	12	3	42		0.53	0.58	13	12	3	42

TABLE V. Performance Ratings for the Ten Best Experimental Brush Materials

Co hardened Au Electroplate

Alloy test #	Au	Pd	Ag	Pt	Hardness	Fluid type	FRICTION		NOISE		WEAR		Rating
							Begin	End	Begin	End	Rod	Wire	
Baseline													
1	71.5		4.5	8.5	361	Commercial	0.17	0.18	10	8	3	8	44.5
2	71.5		4.5	8.5	353	Commercial	0.17	0.25	10	8	3	17	54.2
3	71.5		4.5	8.5	331	Commercial	0.17	0.25	9	8	3	17	53.2
avg. 1-3													**50.63**
1	71.5		4.5	8.5	361	Experimental	0.15	0.17	26	13	2	0	52.2
2	71.5		4.5	8.5	353	Experimental	0.17	0.23	20	12	1.5	13	56.5
3	71.5		4.5	8.5	331	Experimental	0.17	0.17	18	12	2	8	51.4
avg. 1-3													**53.37**
avg. both fluids													**52**
Experimental													
16	90				149	Commercial	0.18	0.25	7	8	1	13	37.3
20	63	5	19		282	Experimental	0.2	0.2	13	10	1	6	38
28	50	10	20		292	Experimental	0.17	0.2	14	12	1	4	38.7
53	59	4	22.5		365	Experimental	0.2	0.22	13	10	2	2.5	39.7
51	51	7	27		380	Experimental	0.2	0.25	13	10	2	4	41.5
52	59	4	22.5		354	Experimental	0.2	0.2	13	11	2	4	42
27	51	7	27		286	Experimental	0.17	0.17	14	14	1	7	43.4
16	90				149	Experimental	0.22	0.23	12	9	1	14	44.5
17	63		15		246	Experimental	0.18	0.2	16	10	2	5	4.8
21	65	3	23	0.5	247	Experimental	0.22	0.18	14	13	1	9	45

Ni hardened Au Electroplate

Alloy test #	Au	Pd	Ag	Pt	Hardness	Fluid type	FRICTION		NOISE		WEAR		Rating
							Begin	End	Begin	End	Rod	Wire	
Baseline													
1	71.5		4.5	8.5	361	Commercial	0.2	0.37	13	10	3	24	67.7
2	71.5		4.5	8.5	353	Commercial	0.17	0.37	15	10	3	24	69.4
3	71.5		4.5	8.5	331	Commercial	0.2	0.35	14	11	2	15	55.5
avg. 1-3													**64.2**
1	71.5		4.5	8.5	361	Experimental	0.18	0.17	15	13	2	7	48.5
2	71.5		4.5	8.5	353	Experimental	0.18	0.17	16	16	1	9	49.5
3	71.5		4.5	8.5	331	Experimental	0.2	0.17	16	16	1	8	48.7
avg. 1-3													**48.9**
avg. both fluids													**56.55**
Experimental													
24	59	4	22.5		303	Commercial	0.2	0.4	13	8	2	2	39
50	50	10	20		419	Commercial	0.22	0.32	12	9	1	8	39.4
49	50	10	20		397	Commercial	0.18	0.32	14	10	1	7	41
49	50	10	20		397	Experimental	0.18	0.17	14	13	1	7.5	43
53	59	4	22.5		365	Experimental	0.18	0.17	14	13	1	8	43.3
24	59	4	22.5		303	Experimental	0.22	0.17	4	12	1	19	43.9
52	59	4	22.5		354	Commercial	0.18	0.32	14	10	1	10	44
50	50	10	20		419	Experimental	0.17	0.17	15	12	1	9	44.4
52	59	4	22.5		354	Experimental	0.18	0.17	14	13	1	9.5	45
53	59	4	22.5		365	Commercial	0.17	0.3	16	10	1	9.5	45.2

Ratings = 10*(Begin + End Friction) + (Begin + End Noise) + 5*(Rod Wear) + (Wire Wear)

TABLE VI. Performance of Wrought Alloy Rings

			Commercial Fluid						Experimental Fluid						Air					
ROD	WIRE	Hardness	FRICTION		NOISE		WEAR		FRICTION		NOISE		WEAR		FRICTION		NOISE		WEAR	
		rod/wire	BEGIN	END	BEGIN	END	ROD	WIRE	BEGIN	END	BEGIN	END	ROD	WIRE	BEGIN	END	BEGIN	END	ROD	WIRE
17	25	244/284	0.23	0.28	100	10	1	56	0.20	0.23	90	12	1	25	0.40	0.57	12	9	3	18
17	52	244/354	0.20	0.25	100	15	1	40	0.20	0.22	100	13	1	18	0.40	0.53	14	11	2	17
17	24	244/303	0.27	0.28	16	10	2	58	0.20	0.27	60	13	1	28	0.38	0.53	20	9	1	10
17	20	244/282	0.23	0.30	70	111	1	55	0.20	0.23	70	16	1	28	0.43	0.57	12	8	3	22
17	49	244/397	0.22	0.23	70	70	2	35	0.23	0.22	15	12	2	11	0.40	0.55	12	10	3	18
17	28	244/290	0.25	0.30	22	8	1	42	0.20	0.22	80	13	1	29	0.42	0.50	15	12	2	22
17	27	244/286	0.20	0.23	80	15	1	38	0.23	0.23	100	16	1	49	0.37	0.48	25	17	3	16
17	51	244/380	0.20	0.28	100	100	2	21	0.22	0.27	80	12	1	35	0.40	0.50	19	14	2	18
17	31	244/286	0.23	0.28	22	10	2	26	0.22	0.22	70	15	2	14	0.38	0.50	23	14	3	10
17	29	244/260	0.20	0.27	54	34	1	55	0.20	0.23	80	12	1	13	0.40	0.50	16	18	3	16
28	25	305/284	0.23	0.28	13	10	1	10	0.25	0.28	10	7	1	17	0.33	0.43	14	10	2	12
28	52	305/354	0.20	0.30	13	13	1	14	0.22	0.20	13	8	1	15	0.33	0.37	14	12	2	10
28	24	305/303	0.20	0.27	64	10	1	9	0.22	0.22	12	8	1	13	0.37	0.47	16	9	1	24
28	20	305/282	0.23	0.37	13	9	1	20	0.23	0.22	15	10	1	16	0.35	0.40	14	12	3	12
28	49	305/397	0.20	0.28	16	9	1	15	0.18	0.25	10	5	1	11	0.37	0.42	23	12	2	14
28	28	305/290	0.40	0.66	16	16	1	18	0.22	0.22	10	9	1	17	0.37	0.43	16	10	2	22
28	27	305/286	0.22	0.27	16	11	2	16	0.22	0.22	13	9	1	13	0.33	0.38	28	14	1	12
28	51	305/380	0.20	0.28	13	9	2	12	0.20	0.22	15	7	1	11	0.33	0.43	13	10	2	20
28	31	305/286	0.20	0.25	13	12	1	9	0.22	0.22	10	11	1	12	0.40	0.43	18	12	1	18
28	29	305/260	0.20	0.27	10	8	1	65	0.23	0.23	12	9	1	14	0.33	0.40	18	14	1	12
27	25	286/284	0.22	0.27	14	10	1	14	0.23	0.22	13	10	1	12	0.30	0.35	19	16	2	12
27	52	286/354	0.20	0.23	11	8	1	11	0.23	0.23	11	9	2	15	0.30	0.33	26	12	3	8
27	24	286/303	0.25	0.25	14	10	1	13	0.25	0.27	13	6	1	18	0.23	0.23	14	12	1	8
27	20	286/282	0.23	0.25	12	8	1	8.5	0.22	0.23	10	9	2	17	0.25	0.33	20	15	1	15
27	49	286/397	0.20	0.22	16	10	3	8.5	0.17	0.18	14	10	2	15	0.32	0.37	28	11	3	6
27	28	286/290	0.23	0.23	13	10	1	11	0.23	0.22	9	10	2	10	0.33	0.35	13	13	2	10
27	27	286/286	0.23	0.25	14	9	1	12	0.23	0.23	10	9	1	16	0.30	0.38	65	10	1	14
27	51	286/380	0.20	0.22	14	9	1	6.5	0.20	0.23	17	10	1	13	0.27	0.30	24	14	2	6
27	31	286/286	0.25	0.23	10	9	2	10	0.25	0.23	9	8	1	11	0.38	0.37	12	10	2	16
27	29	286/260	0.23	0.27	12	8	1	15	0.22	0.20	12	10	1	15	0.30	0.37	21	15	2	8

TABLE VI. Performance of Wrought Alloy Rings

			Commercial Fluid						Experimental Fluid						Air					
ROD	WIRE	Hardness	FRICTION		NOISE		WEAR		FRICTION		NOISE		WEAR		FRICTION		NOISE		WEAR	
		rod/wire	BEGIN	END	BEGIN	END	ROD	WIRE	BEGIN	END	BEGIN	END	ROD	WIRE	BEGIN	END	BEGIN	END	ROD	WIRE
24	25	303/284	0.23	0.20	10	10	3	4.5	0.20	0.17	18	18	2	6	0.28	0.33	53	13	2	6
24	52	303/354	0.22	0.20	10	10	4	7.5	0.17	0.17	20	10	1	5	0.32	0.38	56	8	2	6
24	24	303/282	0.25	0.22	10	9	2	5	0.18	0.17	14	11	1	5	0.25	0.27	56	16	3	10
24	20	303/290	0.22	0.20	12	10	1	11	0.20	0.20	15	12	2	5	0.27	0.32	72	10	2	6
24	49	303/286	0.23	0.20	12	9	2	23	0.18	0.20	16	13	2	6	0.30	0.28	78	16	3	5
24	28	303/380	0.23	0.23	11	11	3	10	0.20	0.18	20	14	3	5.5	0.32	0.32	90	13	2	9
24	27	303/286	0.23	0.22	9	10	3	10	0.18	0.17	14	10	1	5	0.30	0.33	70	9	2	6
24	51	303/380	0.20	0.20	7	8	3	7.5	0.18	0.18	46	13	2	5	0.32	0.33	16	15	2	10
24	31	303/286	0.25	0.25	10	10	1	26	0.17	0.18	12	8	2	5.5	0.27	0.33	64	9	2	7
24	29	303/260	0.22	0.20	14	10	2	11	0.22	0.22	10	8	3	9	0.35	0.38	74	16	3	5
53	25	361/284	0.17	0.17	18	11	1	5	0.18	0.20	8	9	1	12	0.28	0.32	19	14	3	10
53	52	361/354	0.15	0.17	100	14	1	2.8	0.17	0.17	80	11	1	3.7	0.27	0.30	70	10	2	7
53	24	361/303	0.17	0.22	80	16	2	11	0.17	0.17	70	14	1	9.5	0.32	0.32	40	13	2	13
53	20	391/282	0.17	0.17	100	12	1	6	0.17	0.17	100	1	1	7.5	0.30	0.32	17	13	3	11
53	49	361/397	0.17	0.20	72	13	1	5	0.20	0.22	80	11	2	10	0.27	0.32	23	16	3	6
53	28	361/290	0.17	0.18	14	9	1	5	0.20	0.20	80	14	1	9.5	0.27	0.32	32	10	2	11
53	27	361/286	0.17	0.20	70	11	1	7	0.17	0.17	90	10	1	11	0.32	0.33	32	12	2	14
53	51	361/380	0.18	0.27	54	10	1	47	0.17	0.20	70	10	2	8	0.30	0.32	17	14	2	7
53	31	361/286	0.17	0.18	24	10	1	7	0.20	0.22	70	8	3	16	0.27	0.33	64	9	2	7
53	29	361/260	0.18	0.22	16	10	1	13.5	0.18	0.22	80	10	2	8.5	0.35	0.38	74	10	1	7
19	25	272/284	0.25	0.25	8	8	4	8	0.22	0.23	15	11	1	11	0.30	0.47	20	13	3	12
19	52	272/354	0.23	0.27	7	8	3	9	0.22	0.28	12	9	2	20	0.33	0.43	12	12	3	18
19	24	272/303	0.23	0.25	7	8	4	8.5	0.23	0.23	12	10	1	15	0.33	0.42	8	10	1	15
19	20	272/282	0.22	0.25	10	8	3	13	0.20	0.23	16	9	3	17	0.35	0.43	12	7	1	11
19	49	272/397	0.20	0.27	12	8	3	15	0.23	0.25	13	10	1	13	0.30	0.40	62	12	2	12
19	28	272/290	0.23	0.33	13	10	2	20	0.20	0.23	12	10	1	16	0.33	0.50	16	9	4	15
19	27	272/286	0.22	0.30	13	7	2	11	0.23	0.28	12	11	2	23	0.30	0.42	10	8	3	12
19	51	272/380	0.22	0.27	11	9	4	11	0.20	0.27	13	8	1	17	0.37	0.43	17	8	1	15
19	31	272/286	0.27	0.30	9	10	2	12	0.23	0.25	13	12	1	13	0.33	0.47	16	12	2	20
19	29	272/260	0.22	0.28	13	9	2	13	0.23	0.25	10	9	1	19	0.40	0.47	25	9	4	10

TABLE VI. Performance of Wrought Alloy Rings

			Commercial Fluid						Experimental Fluid						Air					
ROD	WIRE	Hardness	FRICTION		NOISE		WEAR		FRICTION		NOISE		WEAR		FRICTION		NOISE		WEAR	
		rod/wire	BEGIN	END	BEGIN	END	ROD	WIRE	BEGIN	END	BEGIN	END	ROD	WIRE	BEGIN	END	BEGIN	END	ROD	WIRE
NeyoroG-dht	25	300/284	0.22	0.22	9	10	3	3.8	0.22	0.17	10	10	2	9	0.30	0.33	10	12	3	9
hta		330/284	0.22	0.22	12	13	2	9	0.22	0.20	10	9	1	18	0.30	0.30	32	15	2	6
NeyoroG-dht	52	300/354	0.22	0.28	8	8	3	10	0.18	0.17	9	8	1	5	0.23	0.27	13	9	3	12
hta		330/354	0.22	0.22	10	10	3	5.5	0.22	0.18	9	10	1	12	0.23	0.30	15	18	2	8
NeyoroG-dht	24	300/303	0.25	0.27	8	10	3	7.5	0.22	0.18	9	8	1	13	0.37	0.40	82	52	3	6
hta		330/303	0.22	0.23	10	11	4	11	0.22	0.22	11	10	1	17	0.33	0.33	76	22	2	6
NeyoroG-dht	20	300/282	0.22	0.33	8	8	3	9	0.22	0.17	9	9	1	10	0.33	0.33	70	13	1	7
hta		330/282	0.28	0.25	9	10	1	34	0.22	0.20	9	8	1	21	0.32	0.30	50	62	3	10
NeyoroG-dht	49	300/397	0.20	0.20	9	9	3	3.5	0.20	0.18	11	10	2	7	0.33	0.37	40	16	3	7
hta		330/397	0.22	0.20	12	11	2	6.5	0.17	0.17	13	10	2	8	0.35	0.40	70	30	3	8
NeyoroG-dht	28	300/292	0.20	0.22	10	9	2	10	0.20	0.18	10	9	1	15	0.43	0.33	20	18	1	70
hta		330/292	0.20	0.22	10	9	2	16	0.20	0.17	10	10	1	18	0.38	0.32	18	18	1	56
NeyoroG-dht	27	300/380	0.20	0.25	12	10	3	9	0.18	0.18	8	8	1	13	0.73	0.50	24	19	1	200
hta		330/380	0.22	0.18	12	9	2	18	0.22	0.20	9	9	1	16	0.58	0.97	15	12	1	150
NeyoroG-dht	51	300/380	0.22	0.20	10	11	2	6	0.18	0.17	8	9	1	5	0.45	0.32	23	22	2	76
hta		330/380	0.23	0.23	10	10	3	4	0.20	0.18	10	8	1	13	0.37	0.30	20	20	1	42
NeyoroG-dht	31	300/286	0.22	0.25	8	10	2	7.5	0.20	0.17	8	8	1	14	0.40	0.30	18	16	1	48
hta		330/286	0.25	0.22	8	10	2	7.5	0.20	0.17	8	8	1	14	0.27	0.37	18	16	1	36
NeyoroG-dht	29	300/260	0.20	0.30	10	7	2	14	0.18	0.17	10	10	1	11	0.73	0.40	20	18	2	184
hta		330/260	0.18	0.17	10	8	1	15	0.20	0.17	10	10	1	26	0.60	0.43	18	15	2	150

TABLE VII. Performance Ratings for the Best 25 Wrought Pairs

ROD	WIRE	Hardness	TEST	FRICTION		NOISE		WEAR		RATING
		rod/wire	FLUID	BEGIN	END	BEGIN	END	ROD	WIRE	
NeyoroG-dht	51	300/380	Experimental	0.18	0.17	8	9	1	5	30.5
NeyoroG-dht	52	300/354	Experimental	0.18	0.17	9	8	1	5	30.5
28	49	305/397	Experimental	0.18	0.25	10	5	1	11	35.3
53	28	361/290	commercial	0.17	0.18	14	9	1	5	36.5
NeyoroG-dht	20	300/282	Experimental	0.22	0.17	9	9	1	10	36.9
24	27	303/286	Experimental	0.18	0.17	14	10	1	5	37.5
NeyoroG-dht	27	300/380	Experimental	0.18	0.18	8	8	1	13	37.6
53	25	361/284	Experimental	0.18	0.20	8	9	1	12	37.8
27	31	286/286	Experimental	0.25	0.23	9	8	1	11	37.8
27	20	286/282	commercial	0.23	0.25	12	8	1	8.5	38.3
24	24	303/282	Experimental	0.18	0.17	14	11	1	5	38.5
24	24	303/282	commercial	0.25	0.22	10	9	2	5	38.7
NeyoroG-dht	31	300/286	Experimental	0.20	0.17	8	8	1	14	38.7
27	51	286/380	commercial	0.20	0.22	14	9	1	6.5	38.7
NeyoroG-hta	31	330/286	Experimental	0.20	0.17	8	8	1	14	38.7
NeyoroG-dht	24	300/303	Experimental	0.22	0.18	9	8	1	13	39
NeyoroG-dht	29	300/260	Experimental	0.18	0.17	10	10	1	10.5	39
24	31	303/286	Experimental	0.17	0.18	12	8	2	5.5	39
27	52	286/354	commercial	0.20	0.23	11	8	1	11	39.3
NeyoroG-hta	27	330/380	Experimental	0.20	0.18	10	8	1	12.5	39.3
NeyoroG-hta	52	330/354	Experimental	0.22	0.18	9	10	1	12	40
NeyoroG-dht	31	300/286	commercial	0.22	0.25	8	10	2	7.5	40.2
NeyoroG-hta	31	330/286	commercial	0.25	0.22	8	10	2	7.5	40.2
NeyoroG-dht	49	300/397	commercial	0.20	0.20	9	9	3	3.5	40.5
NeyoroG-dht	51	300/380	commercial	0.22	0.20	10	11	2	6	41.2
Average rating for 12 lubricated baseline assemblies										**54.3**
Three best unlubricated systems										
19	20	272/282	air	0.35	0.43	12	7	1	11	42.8
27	24	286/303	air	0.23	0.23	14	12	1	8	43.6
19	24	272/303	air	0.33	0.42	8	10	1	15	45.5