**PARTICLE MIGRATION
THROUGH SEALED BEARINGS**

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Abstract

Tests were performed to determine the ability of various types of shielded bearings to isolate particulate from a clean environment in support of the Direct Optical Initiation (DOI) program. In the DOI firing system, a stronglink mechanism will share the same environment with a high-powered laser which needs uncontaminated optics to perform properly. Two commercially available shielded and sealed bearings were tested along with a sealed bearing designed at AlliedSignal Inc., Kansas City Division (KCD). The KCD-designed bearing proved to be the best barrier, but the torque required to function the bearing was magnitudes above the commercial bearings. The commercial sealed bearing was an effective barrier, allowing a small fraction of particles to migrate through, and had a relatively low running torque. The shielded bearing was not acceptable as a particle barrier.

Summary

Various types of shielded and sealed bearings were evaluated to determine their ability to prevent particulate migration from a contaminated area to a clean area in the Direct Optical Initiation (DOI) firing system. Tests were designed and developed to test the barrier effectiveness of bearings representing the DOI firing set, which has a stronglink mechanism sharing the same environment with a high-powered laser. Stronglink mechanisms inherently generate particulate debris which could be detrimental to the laser. The stronglink will rotate an optical element in the laser, thus enabling or safing the system. The only barrier between the stronglink and the laser environment will be the stronglink bearing/shaft system.

Commercially available shielded and sealed bearings were tested along with a sealed bearing designed at AlliedSignal Inc., Kansas City Division (KCD). Three different particulate media were

characterized and used to represent various types of particulate contamination. A vibration environment acted as the driving force to migrate the particles through the bearing.

The KCD-designed bearing proved to be the best barrier for the three media types, allowing only 78 to 200 particles through when there were approximately 3×10^9 available. This was the case for all three media. The commercial sealed bearing was an effective barrier for aluminum oxide and stainless steel particles. It was not at all effective for more dense tungsten particles. The shielded bearing was not acceptable as a particle barrier for any media.

Torque measurements were made to compare the three bearing types. The torque required to function the KCD-designed bearing was magnitudes above the commercial bearings. Running

torque for the KCD-designed bearing was measured at 2.27×10^{-2} in-oz (16,341 mgmm) compared to 2.067×10^{-3} in-oz (1490 mgmm) for the commercial sealed bearing and 3.27×10^{-4} in-oz (236 mgmm) for a standard bearing (using 2.64 oz (75 gram) axial load).

Discussion

Scope and Purpose

This work was performed to determine the ability of sealed and shielded bearings to isolate particulates of various sizes and types in the Direct Optical Initiation (DOI) firing system. DOI is unique in that it uses a high-powered laser to initiate the weapon. This system is unique because an electromechanical switch (stronglink) shares the same environment as the laser optical components. Past systems have had hermetically sealed stronglinks isolated from the rest of the firing set. The stronglinks use a mechanical discriminator requiring a proper unique signal to enable the system. The mechanical discriminator and other mechanisms of the stronglinks generate particulates which could be detrimental to the optical system. The stronglink switches rotate optical elements which disrupt the laser beam and are isolated from the optical elements only by a sealed bearing/shaft system. Isolation effectiveness of three bearing types, two commercially available and a sealed bearing designed at AlliedSignal Inc., Kansas City Division (KCD), were tested with three different particulate materials with known size distributions.

Torque data was also measured and recorded for the shielded/sealed bearing and compared with that of a standard, nonshielded bearing.

Activity

Background

The Direct Optical Initiation firing system relies on two stronglink switches to interrupt the optical energy generated by a high-power laser prior to the energy being focused into fibers. The interruption is accomplished by rotating an optical element of the laser and another optical element immediately at the laser output. The current definition has one stronglink sharing the same volume as the laser. A stronglink switch contains a mechanical discrimination mechanism that operates only with a proper unique signal. The mechanical discrimination mechanism, the solenoids, and other driver mechanisms inherently generate particulate debris. These particles present themselves in different forms such as metallic particles generated from components physically touching on particles of the dry film lubrication which have sloughed off.

A destructively tested (D-test) Dual Stronglink was postmortemed, and particles were vacuumed out of the stronglink and collected on a filter. The particles were counted and the material was analyzed using the electron probe microanalyzer (EPMA). There were 980 particles collected, with an average size of 2 μm (0.000080 inch). Fifty-five percent of the particles were stainless steel,

26 percent were molybdenum disulfide (a dry film lubricant), 15 percent were copper, and the remainder was composed of a small sample of other elements. Other stronglinks, the Trajectory Stronglink and Intent Switch, have seen similar types and sizes of particles indicating that particles will be generated. The prediction of the particles' location is not possible over the life of the component.

The stronglink switch in the DOI optical package will be isolated from the laser optical cavity by a bearing/shaft assembly in the current definition. Three types of bearings were evaluated to determine their ability to prevent particles from migrating into the optical cavity.

Bearing Selection

Three types of shielded/sealed bearings were selected for evaluation. Two are commercially available and one is a special KCD-designed sealed bearing. All bearings were flanged, with a ribbon retainer, and double-sealed, meaning there is a seal on both sides of the bearing. The size of the bearings are 0.125-inch inner diameter and 0.3125-inch outer diameter. This is a typical size for a stronglink bearing and was the size of the KCD-designed sealed bearing. The inner and outer races are toleranced to 0.0002 inch with a radial play of 0.0002 to 0.0008 inch. The bearings were tested dry, without any lubrication.

Two types of commercial bearings were tested. One is called a shielded bearing, and the other is a sealed bearing.

The shielded bearing has a precision stainless steel stamped detail held in place by a snap wire in the outer race. These shields are positioned accurately in the

outer race to maintain a close tolerance, within a few ten thousandths of an inch, to the inner race. Figure 1 is a picture of the shielded bearing and Figure 2 is a diagram of the bearing showing the shield.

Figure 1. Commercial Shielded Bearing

Figure 3 shows the commercial sealed bearing. The seal is accomplished by a thin fluoro-polymer-coated glass cloth washer fixed to the outer race by a snap ring. The seal maintains a rubbing contact with a polished shoulder on the inner race. Figure 4 is a diagram of the sealed bearing.

The Kansas City Division has designed a sealed bearing for possible use on the Dual Stronglink. Figure 5 shows the design, consisting of a commercial bearing which has been modified by cutting a groove on the inside diameter of the outer race and machining a step in the outer diameter of the inner race. Two washers on each end act as the shield. A PEEK (polyetheretherketone) washer is on the

Figure 2. Commercial Shielded Bearing Schematic

Figure 4. Commercial Sealed Bearing Schematic

Figure 3. Commercial Sealed Bearing

Figure 5. KCD-Designed Bearing Schematic

outer race and lays on top of a Teflon washer which rests on the inner race. Figure 6 shows the components and a finished bearing.

Particle Characterization

Aluminum oxide, stainless steel, and tungsten particles were selected to evaluate particle migration through the bearings. Aluminum oxide was used as a lightweight material to represent generic "dirt" or a dry film lubricant and was available as metallographic polishing media. Commercially available 316 stainless steel particles used for powder preform parts were selected to represent stainless steel particulate debris since most parts used on stronglink mechanisms

are stainless steel. Tungsten was selected because it is dense compared to the other two materials and therefore is likely to move more readily. This was also procured as a raw material used for powder preform product.

The particles were screened using a filter so that no particles larger than 35 μm would be tested. The screened particles were characterized using a JEOL 733 electron probe microanalyzer (EPMA). This instrument operates very similarly to a scanning electron microscope but is generally used for quantitative analysis of materials.

The EPMA includes a Particle Recognition and Characterization (PRC) program which is used to locate, size, and chemically

Figure 6. KCD-Designed Bearing and Components

analyze well-dispersed, low-aspect ratio particles. When the video signal is between the threshold values, a particle is said to be detected. The particle center is located, and a set of eight rotated diameters is measured. Values for the average diameter, maximum diameter, minimum diameter, crude area, and perimeter for each particle are calculated and stored. When the sizing is complete, the electron beam is repositioned at the particle center and an energy dispersive spectrum is acquired. After the particles are sized and classed chemically, multiple frame average sizes and diameter histograms are accumulated for each type as well as for unknown particles. This can be adjusted for certain particle classes, such as chemistry only and size value range.

The average diameter of the aluminum oxide particle was $2.57\text{ }\mu\text{m}$ (0.00010 inch) and ranged from $1.87\text{ }\mu\text{m}$ to $3.46\text{ }\mu\text{m}$ (0.00007 to 0.00014 inch). For the stainless steel, the particle size ranged from $4.96\text{ }\mu\text{m}$ (0.00020 inch) to $27.68\text{ }\mu\text{m}$ (0.00109 inch) with an average diameter of $15.64\text{ }\mu\text{m}$ (0.00062 inch). The tungsten particles were between $1.72\text{ }\mu\text{m}$ and $8.85\text{ }\mu\text{m}$ (0.00007 to 0.00035 inch) with an average diameter of $6.81\text{ }\mu\text{m}$ (0.00027 inch). Appendix A shows the summary sheets and sample data for all three materials noting the sizes and populations.

Particle Migration Testing

To determine the ability of seals or shields to prevent or minimize particle migration through the bearing, a fixture was designed and fabricated to isolate the bearing path. Figures 7 and 8 show the vibration test fixture. The test bearing is mounted in a middle plate which separates two cavities. A known volume of particles is placed in

Figure 7. Vibration Test Fixture

Figure 8. Vibration Test Fixture Exploded

the upper cavity. A conical, polyvinyl chloride, tapered plug was used to plug the inner diameter of the inner race. Flanged bearings were used to prevent particles

from going outside the outer race, and the flanges were also used to hold the bearing in place.

A 30-minute, 11.77-g RMS random vibration spectrum (Figure 9) used for testing the Trajectory Stronglink was used as the driving force on the particles. This spectrum was used because it enveloped most of the current program requirements and the DOI vibration requirements had not been identified.

In an effort to "over-test" the bearing shields, the quantity of particles used for migration testing was orders of magnitude higher than would be present in actual units. A specific volume (50 mm³) of particles was placed in the upper cavity. Based on the average diameter and assuming a 50 percent packing factor, there were 2.8×10^9 aluminum oxide, 12.5×10^6 stainless steel, and 1.5×10^8 tungsten particles placed in the upper cavity. Figure 10 shows a representative

Figure 9. Vibration Test Spectrum

Figure 10. Representative Sample of Particles (6.5X)

sample of particles used for testing.

After the vibration test, the fixture was disassembled and the lower cavity inspected for particles. A sampling setup with conductive adhesive tape was placed in the lower cavity, directly below the bearing. The conductive adhesive tape captured passed particles for analysis. Photographs were taken, and, in some cases, the particles were counted and characterized by the electron probe microanalyzer.

Test Results

The commercial shielded bearing was tested with aluminum oxide and found to allow particles smaller than $38\text{ }\mu\text{m}$ to pass through very easily. Figure 11 shows the particles that migrated through. This bearing was no longer tested due to the poor results with the aluminum oxide.

The commercial sealed bearing was much better as a particle barrier. Figure 12 shows one of the results of the aluminum oxide particles that migrated through the bearing. The particles were characterized on the EPMA which found 1201 particles between 3 and $19.5\text{ }\mu\text{m}$ composed mainly of aluminum oxide with a few iron particles present. Figure 13 shows the results of stainless steel particle migration. Since there were millions of particles available, the percent of particles which migrated is extremely small, in the order of 3×10^{-6} percent. The denser tungsten particles migrated through the seal extremely readily as is evident in Figure 14. Therefore, the glass cloth seal is not an effective seal against the denser tungsten particles.

Since a large quantity of particles is not present in a stronglink switch, it was decided to try to test the commercial sealed bearing using the stainless steel particles in a smaller quantity. The test used a measured quantity (0.0046 grams)

Figure 11. Aluminum Oxide Particles Migrated Through Commercial Shielded Bearing (6.5X)

Figure 12. Aluminum Oxide Particles Migrated Through Commercial Sealed Bearing (6.5X)

Figure 13. Stainless Steel Particles Migrated Through Commercial Sealed Bearing (6.5X)

Figure 14. Tungsten Particles Migrated Through Commercial Sealed Bearing (6.5X)

of stainless steel particles. The approximate weight per particle was calculated to be 1.6×10^{-8} grams, based on the density of 8 g/cm^3 and particle volume of $2 \times 10^{-9} \text{ cm}^3$. Therefore, there were approximately 287,000 particles in this test with the commercial sealed bearing. EPMA and PRC analysis determined that only 39 particles were detected inside the fixture after the test, or only 1.25×10^{-4} percent of the particles passed through. Figure 15 shows some of the stainless steel particles which migrated through the bearing.

The specially designed bearing shields performed the best. Figure 16 shows the aluminum oxide particles which migrated through on one of the tests. These particles were characterized on the EPMA,

and the size range was between 3 and $13 \mu\text{m}$ with a total number of 78 particles composed mainly of aluminum oxide with a few silicon and iron particles included. The other EPMA results were similar for another test using aluminum oxide with 200 particles detected. Figure 17 shows one result of the stainless steel particles, and Figure 18 shows the results of the tungsten particles. Even with the dense tungsten particles, the seals allow very few particles to pass.

Overall, the KCD-designed bearing proved to be the best barrier for particle migration. The commercial sealed bearing was very effective in preventing particle migration except for the dense tungsten. With the millions or billions--depending on which media--of particles available, even particle

Figure 15. Stainless Steel Particles Migrated Through Commercial Sealed Bearing Using Smaller Sample Size (75X)

Figure 16. Aluminum Oxide Particles Migrated Through KCD-Designed Sealed Bearing (6.5X)

Figure 17. Stainless Steel Particles Migrated Through KCD-Designed Sealed Bearing (6.5X)

Figure 18. Tungsten Particles Migrated Through KCD-Designed Sealed Bearing (6.5X)

counts in the lower thousands migrating through the bearing represent only a millionth of a percent of the particles available.

There is currently an extensive evaluation of the manufacturability of the KCD-designed bearing because the manufacturing of the seals and the assembly of the bearing were very difficult. Manufacturing of the seals are being pursued at KCD and Sandia National Laboratory in Albuquerque.

Torque data was gathered comparing all three types of bearings with an unshielded commercial bearing. The KCD-designed bearing torque was approximately nine times the torque of the commercial sealed bearing and 69 times the torque of the

regular bearing. The test method and results are included in Appendix B.

Accomplishments

A process for testing the barrier capability of shielded and sealed bearings to small particles was developed. A test fixture was designed and fabricated and is flexible enough to analyze other designs. Three types of particulate media were procured and screened to yield particles of less than 38 μm in size. Three types of bearings were tested, two commercially available and the third a KCD-designed sealed bearing. The test results showed the KCD design to be the best barrier to particles. The commercially available sealed bearing was very comparable with only a fraction of a percent of available particles able to migrate through the bearings. The

shielded bearing was not a good barrier for particulates in that it allowed most particles to get through the bearing. Torque was measured of the three different sealed/shielded bearings and compared with that of an unshielded bearing.

Future Work

Additional testing may be prudent when a design of the actual shaft/bearing selection has been made. A different bearing size would only require a new middle plate, which is easily manufactured, to hold the bearing. The stronglink design will also dictate what type of particles should be tested. Once a dry film lubrication is identified, particles of it could be tested to determine the sealing effect of the bearing.

The testing has shown that particles could migrate through a sealed bearing. The effect on the laser performance of these particles is not currently known. Additional work will be performed looking at the effects of particles on optical elements in the laser.

Appendix A

Particle Characterization Summary

The Particle Recognition and Characterization (PRC) program is a FLEXTRAN program which is used to locate, size, and chemically analyze well dispersed, low-aspect ratio particles. When the video signal is between the threshold values, then a particle is said to be detected. The particle center is located, and a set of eight rotated diameters is measured. Values for the average diameter, maximum diameter, minimum diameter, crude area, and perimeter for each particle are calculated and stored. When the sizing is complete, the electron beam is repositioned at the particle center and an energy dispersive spectrum is acquired. Figures A-1 and A-2 show examples of how the information can be displayed. Figure A-1 shows the results of three stainless steel particles, listing the element (aluminum, silicon, chromium, iron, and nickel) count and relative abundance (percent). It also shows the

average, maximum, and minimum diameter, the area, and perimeter. Figure A-2 shows the same data in a different format. This data is for aluminum particles and lists the area, perimeter, maximum, minimum, and average diameter, and the chemical composition of each particle.

Figure A-3 shows the summary of the aluminum standard. Figures A-4 and A-5 show the summary of the stainless steel and tungsten standards, respectively.

After the particles are sized and classed chemically, multiple frame average sizes and diameter histograms are accumulated for each type as well as unknown particles. This can be adjusted for certain particle classes, such as chemistry only and size value range. Figure A-6 shows the histogram of the tungsten standard.

```

PART NO.  23 TYPE:  31 UNKNOWN      CLASS:      30
ELEMENTS:      AL      SI      CR      FE      NI
COUNTS  :      0      42      391      1291      128
REL ABUN:      0       2       21       69       6
PK RATIO:  0.000  0.032  0.302  1.000  0.099
AVE DIA=    12.74 MX DIA=    26.44 MN DIA=    6.12
AREA=    172.38 PERIMETER=    66.11 SHAPE FAC=    2.01

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PART NO.  24 TYPE:   3 FE/CR/NI CLASS:      28
ELEMENTS:      AL      SI      CR      FE      NI
COUNTS  :      0      17      365      1066      83
REL ABUN:      0       1       23       69       5
PK RATIO:  0.000  0.015  0.342  1.000  0.077
AVE DIA=    14.61 MX DIA=    35.35 MN DIA=    6.40
AREA=    186.88 PERIMETER=    82.26 SHAPE FAC=    2.88

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PART NO.  25 TYPE:  31 UNKNOWN      CLASS:      30
ELEMENTS:      AL      SI      CR      FE      NI
COUNTS  :      0      58      358      1271      122
REL ABUN:      0       3       19       70       6
PK RATIO:  0.000  0.045  0.281  1.000  0.095
AVE DIA=    11.83 MX DIA=    21.43 MN DIA=    6.40
AREA=    124.46 PERIMETER=    48.57 SHAPE FAC=    1.50

```

Figure A-1. Measured Data for Three Stainless Steel Particles

PART.	CHEM. TYPE	AREA (UM^2)	PERIM	MAX	MIN	AVE	SHAPE FACTOR	ELEMENTS		
				MICRONS				AL	SI	FE
157	UNKNOWN	2.69	6.26	2.22	1.46	1.80	1.15	99	0	0
158	UNKNOWN	12.00	15.17	6.33	2.15	3.68	1.52	100	0	0
159	UNKNOWN	2.34	6.40	2.50	1.04	1.60	1.39	98	0	0
160	UNKNOWN	37.19	23.45	8.07	6.19	6.95	1.17	100	0	0
161	UNKNOWN	87.89	57.06	22.68	2.78	9.04	2.94	99	0	0
162	UNKNOWN	2.61	6.12	2.29	1.32	1.73	1.14	99	0	0
163	UNKNOWN	1.15	3.96	1.39	1.04	1.18	1.08	100	0	0
164	UNKNOWN	145.99	59.29	25.05	4.31	11.90	1.51	99	0	0
165	UNKNOWN	8.51	15.31	5.42	1.39	2.92	2.17	100	0	0
166	UNKNOWN	18.68	16.00	5.42	4.59	4.87	1.09	99	0	0

Figure A-2. Measured Data for Ten Aluminum Particles

SUMMARY OF RESULTS

LABEL: LASER PARTICLES

NUMBER OF FRAMES 47

NUMBER OF PARTICLES 1005

MAG= 400

FIELD WIDTH= 267.60 UM

UM/PT OFF= 0.97 UM/PT ON= 0.06

FIELD AREA= 5.719500E+04 UM²

AVERAGE RESULTS FOR CHEMICAL TYPES

TYPE	NAME	AVE.DIA.	MAX	MAX/MIN	AREA	PERIM
0	ALL TYPES	2.57 +- 1.99	3.46	1.87	8.76E+00	9.50E+00
31	UNKNOWN	2.60 +- 2.03	3.47	1.65	9.00E+00	9.54E+00

PARTICLE COUNT SUMMARY

TYPE	NAME	NUMBER	#(%)	T.AREA(%)
0	ALL TYPES	1005	100.00	0.32
30	NON-INT	52	5.17	0.00
31	UNKNOWN	953	94.82	0.31

Figure A-3. Summary of Results for Aluminum Particle Standard

SUMMARY OF RESULTS
 LABEL: S.S. STANDARD LTR 280461
 NUMBER OF FRAMES 100
 NUMBER OF PARTICLES 707
 MAG= 200
 FIELD WIDTH= 535.20 UM
 UM/PT OFF= 0.97 UM/PT ON= 0.13
 FIELD AREA= 2.287799E+05 UM^2

AVERAGE RESULTS FOR CHEMICAL TYPES

TYPE	NAME	AVE.DIA.	MAX	MAX/MIN	AREA	PERIM
0	ALL TYPES	15.56 +- 7.54	26.15	4.17	2.52E+02	7.13E+01
3	FE/CR/NI	15.64 +- 7.59	27.68	4.96	2.58E+02	7.78E+01
31	UNKNOWN	15.51 +- 7.48	25.92	4.08	2.50E+02	7.02E+01

PARTICLE COUNT SUMMARY

TYPE	NAME	NUMBER	%(%)	T.AREA(%)
0	ALL TYPES	707	100.00	0.77
3	FE/CR/NI	106	14.99	0.11
30	NON-INT	13	1.83	0.01
31	UNKNOWN	588	83.16	0.64

Figure A-4. Summary of Results for Stainless Steel Particle Standard

SUMMARY OF RESULTS
 LABEL: TUNGSTEN PARTICLES
 NUMBER OF FRAMES 200
 NUMBER OF PARTICLES 1024
 MAG= 200
 FIELD WIDTH= 530.50 UM
 UM/PT OFF= 0.96 UM/PT ON= 0.13
 FIELD AREA= 2.247839E+05 UM^2

AVERAGE RESULTS FOR CHEMICAL TYPES

TYPE	NAME	AVE.DIA.	MAX	MAX/MIN	AREA	PERIM
0	ALL TYPES	6.81 +- 9.57	8.85	1.72	1.10E+02	2.47E+01

PARTICLE COUNT SUMMARY

TYPE	NAME	NUMBER	%(%)	T.AREA(%)
0	ALL TYPES	1024	100.00	0.25

Figure A-5. Summary of Results for Tungsten Particle Standard

AVERAGE DIAMETER HISTOGRAM FOR TYPE: 0 ALL TYPES

BIN MAX	NO.	%	00---10---20---30---40---50---60---70---80---90---100
3.33	637	62.2	[*****]
6.67	120	11.7	[*****]
10.00	70	6.8	[*****]
13.33	44	4.2	[***]
16.67	29	2.8	[**]
20.00	18	1.7	[*]
23.33	21	2.0	[**]
26.67	12	1.1	[*]
30.00	19	1.8	[*]
33.33	9	0.8	[*]
36.67	16	1.5	[*]
40.00	11	1.0	[*]
43.33	11	1.0	[*]
46.67	4	0.3	[*]
50.00	0	0.0	[
53.33	3	0.2	[*]
56.67	0	0.0	[

XEQ:

Figure A-6. Representative Histogram Based on Particle Size for the Tungsten Sample

Appendix B

Sealed/Shielded Bearing Torque Data

Bearing Torque Testing

All three bearing types (commercial shielded, commercial sealed, and KCD-designed) were torque tested on a Bearing Torque Tester. This tester provides an axial load, and the torque is measured over one revolution in both clockwise and counterclockwise directions. The tester provides a strip chart recording of the bearing torque along with calculations of the average run torque, peak running torque, maximum hash width, and average hash width.

Average run torque is the average between the torque measured in the counterclockwise rotation and the torque measured in the clockwise direction. The

peak running torque is the difference between the highest value or maximum peak and the average run torque. Maximum hash width is found by subtracting the highest peak from the lowest valley on a particular rotation. Average hash width is determined by the average between the high peaks and the average of the low peaks.

The tests consisted of testing three of each type of bearing and testing each bearing three times. An axial load of 75 grams (2.64 oz) was applied to the bearings during the torque measurements.

Tables B-1 through B-4 show the results of the bearing tests.

Table B-1. Bearing Average Run Torque Results

Bearing Type	mgmm		In-Oz (x 10 ⁻⁶)	
	Average	σ	Average	σ
Standard	236	79	327	110
Commercial Shielded	176	57	244	79
Commercial Sealed	1490	589	2067	817
KCD P-T*	16,341	92	22,673	128
KCD P-P**	33,710	234	46,772	325

*Bearing had Teflon inner shield and PEEK outer shield (two bearings tested).

**Bearing with PEEK for both shields (one bearing tested).

Table B-2. Bearing Peak Run Torque Results

Bearing Type	mgmm		In-Oz (x 10 ⁻⁶)	
	Average	σ	Average	σ
Standard	2367	1388	3284	1926
Commercial Shielded	1074	271	1490	376
Commercial Sealed	2572	1136	3569	1576
KCD P-T*	18,057	229	25,054	318
KCD P-P**	37,472	635	51,992	881

*Bearing had Teflon inner shield and PEEK outer shield (two bearings tested).

**Bearing with PEEK for both shields (one bearing tested).

Table B-3. Bearing Average Hash Width Results

Bearing Type	mgmm		In-Oz (x 10 ⁻⁶)	
	Average	σ	Average	σ
Standard	495	43	687	60
Commercial Shielded	413	73	573	101
Commercial Sealed	332	39	461	54
KCD P-T*	1656	150	2298	208
KCD P-P**	1640	126	2276	175

*Bearing had Teflon inner shield and PEEK outer shield (two bearings tested).

**Bearing with PEEK for both shields (one bearing tested).

Table B-4. Bearing Maximum Hash Width Results

Bearing Type	mgmm		In-Oz (x 10 ⁻⁶)	
	Average	σ	Average	σ
Standard	4019	2603	5576	3612
Commercial Shielded	1734	488	2406	677
Commercial Sealed	1860	1185	2581	1644
KCD P-T*	4057	640	5629	888
KCD P-P**	7608	1883	10,556	2613

*Bearing had Teflon inner shield and PEEK outer shield (two bearings tested).

**Bearing with PEEK for both shields (one bearing tested).

END

**DATE
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11/30/93