LaserNet Fines Reproducibility Test with Medium Test Dust

(Particle Counting & Shape Classification)

This application note presents data recently generated in reproducibility and repeatability tests performed on five LaserNet Fines (LNF) Wear Particle Classifier and Particle Counter instruments. The test was conducted with Medium Test Dust dispersed in mineral oil.

Introduction

The LaserNet Fines®-C (LNF-C), Figure 1, is a bench-top analytical tool that combines the oil analysis techniques of particle shape classification and particle counting in one instrument. The LNF-C analyzes hydraulic and lubricating oil samples from various types of equipment and machinery that are part of a machine condition-monitoring program. The monitoring is based primarily on the morphological analysis and the particle size distribution of the abnormal wear particles that are created from the internal components of the machine. The operator is presented with an assessment of particles found in the fluid sample and a history of previous results for the same equipment. LNF-C can be used as a stand-alone analytical instrument, or in conjunction with a full service oil analysis program.

Figure 1, LaserNet Fines®-C Particle Shape Classifier and particle Counter

Lockheed Martin Tactical Defense Systems developed the LaserNet Fines in cooperation with the Naval Research Laboratory for the Office of Naval Research as part of its Accelerated Capabilities Initiative for Condition-based Maintenance. The original LNF instrument was designed as a stand-alone instrument in a rugged, shock and vibration protected case meant for shipboard use. This version is known as the LaserNet Fines®-M (M for Military) and is no longer available. The LaserNet Fines®-C (C for Commercial) is a reconfigured and more affordable version that uses an external computer for control and data storage. Sample processing, software and results are the same for both the LNF-C and LNF-M. Therefore, in the following text we will refer to the instrument as the LNF, although it is the LNF-C model that is now commercially available.

As a particle shape classifier, the LNF provides the user with shape recognition of all particles greater than 20 µm by using a neural network. An algorithm sorts particles into the following categories: cutting, fatigue, severe sliding, nonmetallic and fibers. The shape recognition software also does a test for circularity so that bubbles and droplets greater than 20 µm are eliminated from the particle counting results. The instrument is also capable of giving approximate results of free water based on this feature.

As a particle counter, the LNF processes and stores thousands of images to obtain good counting statistics. Particles are sized directly and results can be displayed by ISO Code (>4 µm, >6 µm, and >14 µm), or other codes such as the NAS Code (5-15 µm, 15-25 µm, 25-50 µm, 50-100 µm and >100 µm). The direct imaging capability of this instrument eliminates the need for calibration with a test dust. Air bubbles greater than 20µm are ignored and the laser is powerful enough to process heavily sooted (black) oils.

The basic operating principle of the LNF is illustrated in Figure 2. A representative oil sample is taken from the lubricating system and brought to the instrument. The oil is drawn through a patented viewing cell that is back-illuminated with a pulsed laser diode to freeze the particle motion. The coherent light is transmitted through the fluid and imaged onto a digital CCD camera. Each resulting image is analyzed for particles, with several thousand images ultimately used to determine the characteristics of the suspended particles and to obtain good counting statistics. Concentrations are measured for particle sizes between 4 µm to over 100 µm.

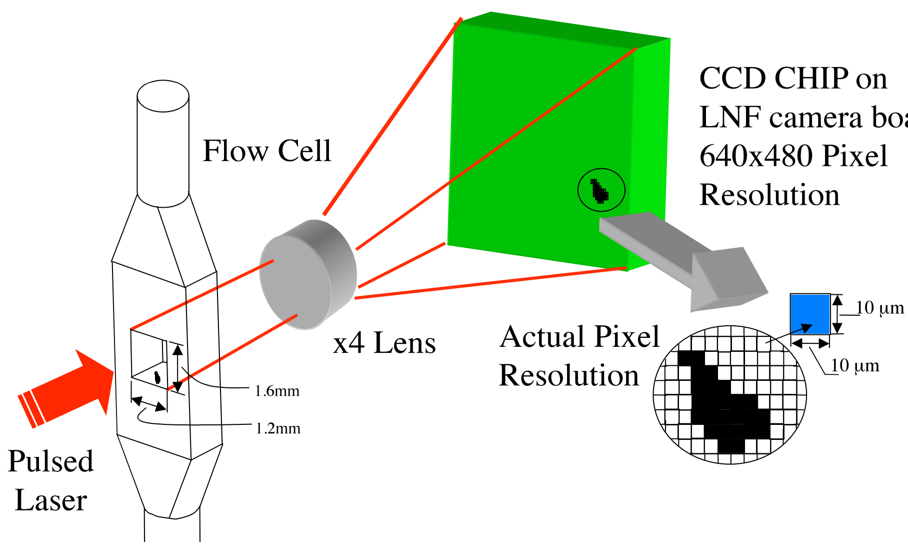

Figure 2, Basic Operation of LNF-C

LNF reports particle size in terms of maximum chord (maximum diameter) and also calculates equivalent circular diameter for compatibility with ISO cleanliness codes. Shape characteristics are calculated for particles greater than 20 µm, and the particles are classified into either a wear category or contaminant category. Classification is done with an artificial neural network that was developed specifically for the LNF system. Shape features were chosen to give optimal distinction between the assigned classes of fatigue, cutting, severe sliding, nonmetallic, fibers, water bubbles, and air bubbles. An extensive library of particles, which were identified by human experts, was used to train the artificial neural network. An example of the shape classification capability of LNF is shown in Figure 3.

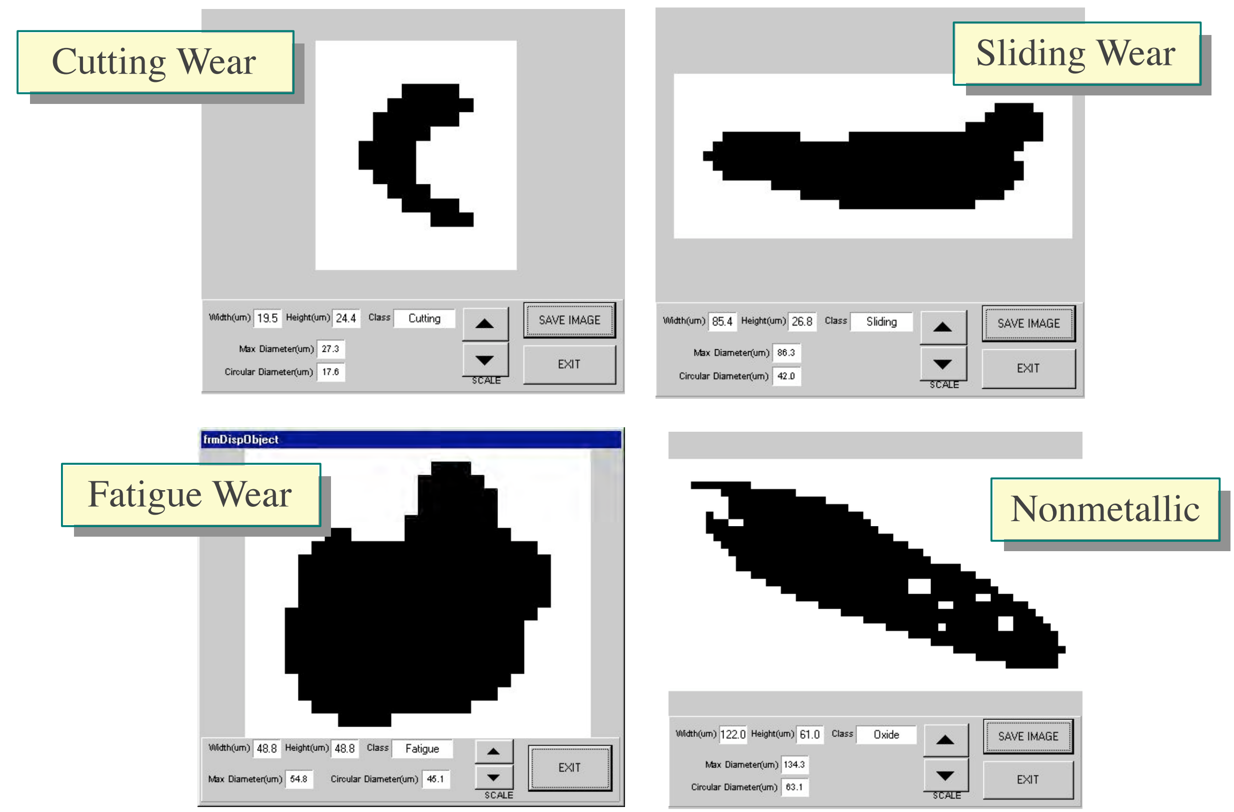

Figure 3, Shape Classification of LNF

The LNF was designed primarily as an automatic wear particle shape classifier and trending tool to assist in condition monitoring programs. However, because of its direct imaging capability it is also an accurate particle counter. It is ISO 4406:1999 compliant.

The LNF does not require calibration using NIST Standard Reference Material (SRM) 2806[2] because it directly images the particles. During manufacture, magnification is calibrated to objects of known linear dimensions. This is unlike conventional particle counters and eliminates the costly requirement to be sent back to the factory for an annual calibration.

It is noteworthy that the LNF correctly counts the NIST SRM 2806 (or its derivative, the commercially available PartiStan). The NIST determined counts for SRM 2806 by capturing the particles from SRM 2806 hydraulic fluid on a membrane filter and counting the particles by using a scanning electron microscope (SEM). Particles appear solid when viewed by an SEM, even though the particles might be transparent to visible and near visible light. Therefore, a SEM fills in the area of particles that might otherwise be partially transparent when passing by the sensor of a conventional automated laser light blockage particle counter. Automated light blockage particle counters correctly measure SRM 2806 because this is the very fluid they are calibrated with. On the other hand, the LNF correctly measures the SRM 2806 because it is an automated microscope calibrated to a known linear dimension, a much more fundamental calibration than using an arbitrary calibration fluid. The LNF directly images each particle whereas an automated light blockage particle counter measures only how much light is blocked. In essence, the LNF achieves the same counts that the NIST did for the SRM 2806 from first principles. An automated light blockage particle counter gives no information about particle shape.

A discrepancy may occur when comparing wear particle counts measured by an LNF with the counts from a conventional automated light blockage particle counter. The metal particles, being solid, will block more light proportional to their size than will transparent particles. Therefore, the light blockage particle counter will overestimate the size of metallic particles.

The LNF imaging may be thought of as an automated microscope system that captures digital images of the particles as they flow through the cell. The LNF fills in any translucent areas of fibers or nonmetallic particles that it may encounter in a sample, and calculates both the equivalent circular diameter and maximum diameter values for hydraulic cleanliness (ISO CODES) and wear particle trending, respectively. Because the LNF instrument records the total size resolution of all the particles that it records, it is able to report NAS and NAVAIR cleanliness codes. NAS 1638 was developed by the Aerospace Industries Association of America, and is similar to ISO 4406 in that it classifies cleanliness according to pre-defined particle counts of certain particle sizes. NAVAIR 01-1A-17 is the U.S. Navy standard for particulate cleanliness.

A suspension of test dust in oil such as NIST SRM 2806 may be measured by the LNF periodically to verify proper operation of the instrument, but the Standard Reference Material is never used to calibrate the LNF. A fluid check dialog is available, Figure 4, to show performance comparisons to certified NIST standards with cumulative graphical results.

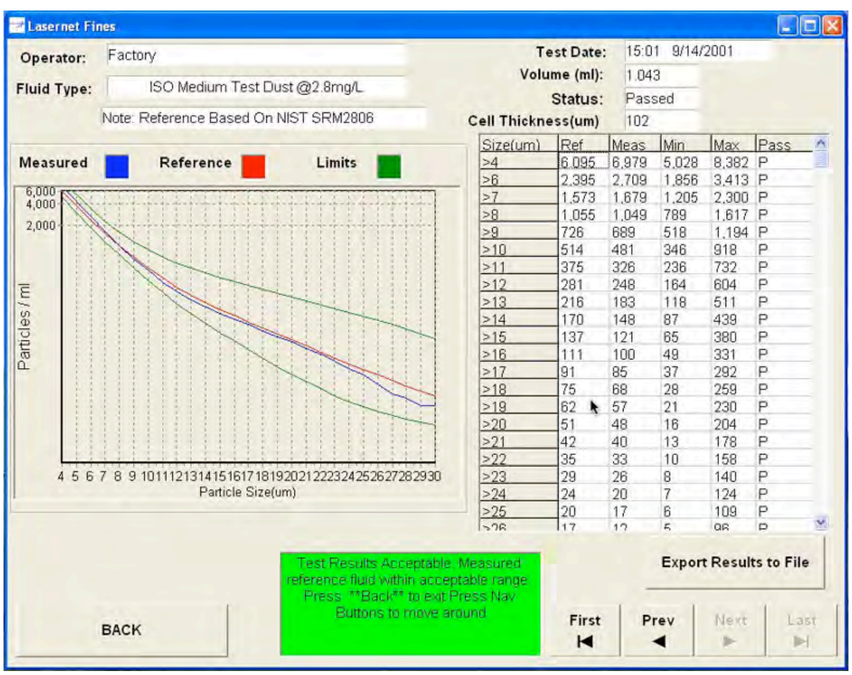

Figure 4, Calibration Verification Software Dialog

The LaserNet Fines became commercially available in 2000 and since then more than 200 instruments have been commissioned for various military and industrial applications in 38 countries around the world. Every LNF must successfully measure check fluid as described above, but a systematic test of LNF reproducibility has never been performed. This paper describes such a test.

Procedure –Sample Preparation

A master oil sample was prepared by mixing Medium Test Dust[1] with approximately 700 ml of purified mineral oil with a viscosity of 63 cSt at 40°C. The mineral oil was initially analyzed on the LaserNet Fines to check for particulate contamination and it was found to be very clean with a 13/11/6 ISO code. It contained only 48 particles per ml greater than 4 µm.

A one U.S. quart (950 ml) container was used to prepare the master sample. Approximately ¼ of the mineral oil was poured out of the container before the Medium Test Dust was added. The oil was removed to allow the contents to be easily shaken so that the dust would be well dispersed throughout the approximately 700 ml of mineral oil remaining in the container. The master sample with the Medium Test Dust was then used to prepare five identical samples.

Five 125 ml plastic wide mouth sample bottles were opened and lined up on a lab bench. Immediately after vigorously shaking the master sample, about 10 to 12 ml of master sample was poured into the first plastic sample bottle, then the second, then the third, etc. As soon as the first 10 or 12 ml was poured into each of the 5 sample bottles, the process was repeated 7 or 8 times until each bottle was approximately ¾ full. The purpose of this procedure was to make the particle population in each of the 5 bottles as similar as possible.

Procedure – Analysis of Samples

The five LNF's chosen for this test were a combination of old and new instruments. The oldest unit, S/N 0021, was manufactured approximately 6 years ago and S/N 0226 and S/N 0239 were brand new instruments removed from stock for the purpose of the test. The other two instruments, S/N 0079 and S/N 0186 have been in use for multiple years.

To verify proper operation, a check fluid was run through each of the five LNF's. The LNF check fluid used is a PartiStan, Medium Test Dust in Hydraulic Fluid; the commercial version of NIST Standard Reference Material 2806[2].

The reproducibility testing was conducted in such a way as to randomize the effects of the sample bottles as well as the order from which the samples were withdrawn from each bottle. Each of the 5 sample bottles was run once on each instrument. Each instrument sampled one of the bottles first from one of the five bottles, each instrument sampled one of the bottles second from one of the five bottles, each instrument sampled one of the bottles third from one of the five bottles, etc., until five samples were run from each of the five bottles.

Each time, before inserting the LNF sipper tube into the sample bottle to pull sample into the LNF for measurement, the sample bottle was vigorously hand-shaken to thoroughly disperse the particles it contained. Then air bubbles were removed by placing the bottle in an ultra-sonic bath with a power density > 4000 W/m^2 for two minutes. The sample bottle was then brought promptly to one of the five LNF's to begin the measurement procedure.

Analytical Results

The analytical results from the five samples as analyzed on the five LNF's are shown in Tables 1 through 7.

Table 1 – Reproducibility for this test is defined as test results obtained with the same test method on identical samples and on ***different*** instruments. Table 1 shows the order in which the samples were run, from which bottle each sample was withdrawn, on which instrument the sample was run and the corresponding analytical result. The reproducibility for the 25 runs is summarized as an average, standard deviation and relative standard deviation for each particle size range.

The percent RSD (Relative Standard Deviation) is 3.2% for particles greater than 4 µm. The counts are for particles with an equivalent circular diameter greater than the stated size. The LNF software converts the pixel image of each particle into an area by filling in any transparent interior pixels. An equivalent circular diameter is then calculated from the resulting area.

Table 2 - Repeatability is defined as test results obtained with the same test method on identical samples and the ***same*** instrument. Table 2 shows the repeatability for individual LNF instruments. As one would expect, repeatability on the same instrument is better than reproducibility on multiple instruments, and under these conditions, the percent RSD (Relative Standard Deviation) is an average of 2.7 % for particles greater than 4 µm.

Table 3a – This table compares averages of the 5 runs made on each instrument. It compares performance among the 5 instruments for particle counting.

Table 3b – This table compares the averages of the particle counts of the five samples taken from each bottle.

Table 3c - This table compares the average of the different "layers" taken from each sample bottle. Layer 1 being the first sample taken from the bottle, Layer 2 the second sample, etc. This attempts to determine if there are any differences among the sequence of when the samples were taken from each bottle.

Table 4 - This table presents data for the particle shape classifications made during the 25 runs.

Table 5 - This table presents data for particle shape classification for individual instruments.

Table 6a - This table compares averages for all five runs made on each instrument for shape classification categories. This table gives an indication of how closely shape classification agrees among different instruments.

Table 6b - This table compares the averages of the shape classification categories of the five samples taken from each bottle.

Table 6c - This table compares the averages of the shape classification categories for the different "layers" taken from each sample bottle. Layer 1 being the first sample taken from the bottle, Layer 2 the second sample, etc. This attempts to determine if there are any differences among the sequence of when the samples were taken from each bottle.

Table 7 - This table compares the NIST SRM 2806 particle distribution with the LNF results.

Discussion

Table 1 shows, as expected, that, in general, as the particles become larger, the RSD increases. The RSD becomes rather meaningless for the largest particles since there are so few present.

Table 2 data show that repeatability for individual instruments is better than reproducibility among several instruments, as would be expected.

Table 3a data show that the instruments are fairly consistent when sizing particles.

Table 3b data indicate that there appear to be little difference in particle size and concentration among the five bottles of test oil used in this study.

Table 3c indicates there is little difference whether the sample was taken first or last from each of the bottles.

Table 4 data show that RSD's are not nearly as low for shape classification as for particle counting for the smallest particles, but the LNF software does not attempt particle recognition until the particles are at least 20 μm in chord length (maximum diameter). The RSD for simply counting particles >20 μm is not so low either, at 11.0 %. Of note is that the combined total of particles in the cutting, sliding, fatigue and nonmetallic categories (C+S+F+N) shows reasonable reproducibility at 8.5 %.

The RSD for nonmetallic particles is 13.0 %, only slightly higher than the RSD for all particles >20 μm at 11.0 %. Please note that the number count for all particles >20 μm is about one-third the count for the sum of cutting, sliding, fatigue, and nonmetallic particles. The main reason for this is that the particle count of particles >20 μm is determined by equivalent circular diameter. The sizes of cutting, sliding, fatigue, and nonmetallic particles are determined by maximum diameter (maximum chord length). Therefore, any particle not exactly spherical will have an equivalent circular diameter less than its maximum chord length. For example, the area of a sliver 30 μm long may have enough area to only give an equivalent circular diameter of 10 μm.

Table 5 data indicate individual instrument repeatability for particle categorization is superior to the overall reproducibility for the 5 instruments.

Table 6 data indicate that differences in particle shape classification appear to be due to differences between instruments rather than differences between the particle population in each bottle or when the sample was withdrawn from each bottle.

Table 7 data indicate that the particle distribution measured by the LNF is consistent with the particle distribution of NIST SRM 2806. The median counts for SRM 2806 are 6095 particles per ml > 4 μm. The concentration of MTD in the fluid used in this test was approximately 12.3 times higher at 74,986 particles per ml > 4 μm. If a factor of 12.3 is applied to the median counts for the other size categories reported for SRM 2806, the resulting concentrations compare favorably with the data produced by the LNF's. Another way to compare this data is to divide the LNF result by the NIST median count number for each size category. Again, the resulting ratios indicate that the LNF reports substantially the same distribution as stated for SRM 2806.

Conclusion: Testing of 5 LNF instruments indicate excellent particle counting reproducibility and adequate particle shape classification reproducibility so that data from one LNF may be reasonably compared to data from any other LNF.

References

1. ISO 12103-1, A3 Medium Test Dust, Analysis 5259M, 2 May 2005, Powder Technology, Inc., Burnsville, MN, USA.
2. Certificate of Analysis. SRM 2806a, National Institute of Standards and Technology, Gaithersburg, MD, USA

Table 1 – LNF Reproducibility for Particle Counting

Bottle	LNF S/N	Run #	>4 µm	>5 µm	>6 µm	>10 µm	>14 µm	>15 µm	>20 µm	>21 µm	>25 µm	>38 µm	>50 µm	>70 µm
1	21	1	73646	44431	28957	8663	2584	2018	708	596	292	74	14	0
1	226	2	79117	46927	29928	9221	2787	2245	829	699	373	68	23	5
1	239	3	72897	40428	24693	8067	2740	2238	762	637	262	48	11	0
1	186	4	74304	45546	29992	9102	2422	1876	723	618	313	52	15	2
1	77	5	74295	45196	29476	8624	2223	1733	638	541	273	45	8	0
2	226	6	75743	43954	27628	8063	2228	1793	640	524	265	56	12	5
2	239	7	74438	40880	24607	8411	3197	2594	924	753	386	57	19	6
2	186	8	73822	45658	30156	9629	2562	1953	735	642	373	59	17	6
2	77	9	78763	45951	29133	8685	2286	1774	668	582	310	46	14	0
2	21	10	75907	45561	29508	9036	2806	2180	801	663	315	39	8	2
3	239	11	73703	41242	25308	8952	3329	2684	930	792	445	80	15	3
3	186	12	76434	45951	30023	9610	2617	2007	745	614	326	60	9	3
3	77	13	73934	45471	29841	8485	2107	1648	624	524	271	43	11	2
3	21	14	78449	47124	30390	9060	2696	2153	791	652	366	77	18	3
3	226	15	76725	45736	29344	8645	2380	1823	699	594	277	52	12	0
4	186	16	71917	43948	29020	9206	2480	1881	719	599	311	62	20	0
4	77	17	74869	45561	29957	8850	2256	1773	725	600	305	46	6	2
4	21	18	70252	43042	28397	8524	2410	1899	719	571	257	51	12	3
4	226	19	75322	45270	29114	8527	2404	1898	703	595	310	60	18	2
4	239	20	75205	42094	25890	8611	3047	2465	860	703	329	45	11	0
5	77	21	75997	46210	30314	8663	2281	1789	679	564	268	34	9	0
5	21	22	74094	44591	28859	8582	2476	1939	698	603	302	51	8	2
5	226	23	80084	46931	29779	8860	2631	2026	730	594	299	38	11	2
5	239	24	72243	40728	25026	8340	2955	2348	830	662	310	51	9	2
5	186	25	72480	44378	29236	9076	2372	1818	691	580	306	52	17	3
Average			74986	44512	28583	8780	2571	2022	743	620	314	54	13	2
Standard Deviatiomn			2372	2012	1889	402	315	276	82	65	45	12	4	2
% RSD			3.2	4.5	6.6	4.6	12.3	13.6	11.0	10.6	14.4	21.9	34.1	97.1

Table 2 – Repeatability of Individual LNF Instruments for Particle Counting

Bottle	LNF S/N	Run #		>4 µm	>5 µm	>6 µm	>10 µm	>14 µm	>15 µm	>20 µm	>21 µm	>25 µm	>38 µm	>50 µm	>70 µm
1	21	1		73646	44431	28957	8663	2584	2018	708	596	292	74	14	0
2	21	10		75907	45561	29508	9036	2806	2180	801	663	315	39	8	2
3	21	14		78449	47124	30390	9060	2696	2153	791	652	366	77	18	3
4	21	18		70252	43042	28397	8524	2410	1899	719	571	257	51	12	3
5	21	22		74094	44591	28859	8582	2476	1939	698	603	302	51	8	2
			Average	74470	44950	29222	8773	2594	2038	743	617	306	58	12	2
			Standard Deviation	3021	1511	763	256	161	125	48	39	40	17	5	1
			% RSD	4.1	3.4	2.6	2.9	6.2	6.1	6.5	6.4	13.0	28.4	37.7	69.7
1	77	5		74295	45196	29476	8624	2223	1733	638	541	273	45	8	0
2	77	9		78763	45951	29133	8685	2286	1774	668	582	310	46	14	0
3	77	13		73934	45471	29841	8485	2107	1648	624	524	271	43	11	2
4	77	17		74869	45561	29957	8850	2256	1773	725	600	305	46	6	2
5	77	21		75997	46210	30314	8663	2281	1789	679	564	268	34	9	0
			Average	75571	45678	29744	8661	2231	1743	667	562	285	43	10	1
			Standard Deviation	1948	402	454	131	73	57	39	31	20	5	3	1
			% RSD	2.6	0.9	1.5	1.5	3.3	3.3	5.9	5.5	7.0	12.0	31.0	136.9
1	186	4		74304	45546	29992	9102	2422	1876	723	618	313	52	15	2
2	186	8		73822	45658	30156	9629	2562	1953	735	642	373	59	17	6
3	186	12		76434	45951	30023	9610	2617	2007	745	614	326	60	9	3
4	186	16		71917	43948	29020	9206	2480	1881	719	599	311	62	20	0
5	186	25		72480	44378	29236	9076	2372	1818	691	580	306	52	17	3
			Average	73791	45096	29686	9325	2491	1907	723	611	326	57	16	3
			Standard Deviation	1766	878	518	273	100	74	20	23	27	4	4	2
			% RSD	2.4	1.9	1.7	2.9	4.0	3.9	2.8	3.8	8.4	7.6	25.4	82.4
1	226	2		79117	46927	29928	9221	2787	2245	829	699	373	68	23	5
2	226	6		75743	43954	27628	8063	2228	1793	640	524	265	56	12	5
3	226	15		76725	45736	29344	8645	2380	1823	699	594	277	52	12	0
4	226	19		75322	45270	29114	8527	2404	1898	703	595	310	60	18	2
5	226	23		80084	46931	29779	8860	2631	2026	730	594	299	38	11	2
			Average	77398	45764	29159	8663	2486	1957	720	601	305	55	15	2
			Standard Deviation	2102	1248	916	427	221	184	69	63	42	11	5	2
			% RSD	2.7	2.7	3.1	4.9	8.9	9.4	9.6	10.4	13.8	19.8	33.9	83.9
1	239	3		72897	40428	24693	8067	2740	2238	762	637	262	48	11	0
2	239	7		74438	40880	24607	8411	3197	2594	924	753	386	57	19	6
3	239	11		73703	41242	25308	8952	3329	2684	930	792	445	80	15	3
4	239	20		75205	42094	25890	8611	3047	2465	860	703	329	45	11	0
5	239	24		72243	40728	25026	8340	2955	2348	830	662	310	51	9	2
			Average	73697	41074	25105	8476	3054	2466	861	709	346	56	13	2
			Standard Deviation	1181	641	520	330	226	180	70	64	71	14	4	3
			% RSD	1.6	1.6	2.1	3.9	7.4	7.3	8.1	9.0	20.4	25.3	30.0	119.6

Tables 3 a, b, and c

Table 3a - Comparison of Averages for 5 Runs Made on Each Instrument for Particle Counting

	>4 µm	>5 µm	>6 µm	>10 µm	>14 µm	>15 µm	>20 µm	>21 µm	>25 µm	>38 µm	>50 µm	>70 µm
Unit 0021	74470	44950	29222	8773	2594	2038	743	617	306	58	12	2
Unit 0077	75571	45678	29744	8661	2231	1743	667	562	285	43	10	1
Unit 0186	73791	45096	29686	9325	2491	1907	723	611	326	57	16	3
Unit 0226	77398	45764	29159	8663	2486	1957	720	601	305	55	15	2
Unit 0239	73697	41074	25105	8476	3054	2466	861	709	346	56	13	2
Average	74986	44512	28583	8780	2571	2022	743	620	314	54	13	2
Std Dev	1542	1954	1962	323	301	270	72	54	23	6	3	1
% RSD	2.1	4.4	6.9	3.7	11.7	13.4	9.7	8.7	7.4	11.6	19.4	42.2

Table 3b - Comparison of Averages for 5 Runs from Each Sample for Particle Counting

Bottle 1	74852	44505	28609	8736	2551	2022	732	618	302	57	14	1
Bottle 2	75735	44401	28206	8765	2616	2059	754	633	330	51	14	4
Bottle 3	75849	45105	28981	8950	2626	2063	758	635	337	63	13	2
Bottle 4	73513	43983	28475	8744	2519	1983	745	614	302	53	14	1
Bottle 5	74980	44568	28643	8704	2543	1984	726	601	297	45	11	2
Average	74986	44512	28583	8780	2571	2022	743	620	314	54	13	2
Std Dev	934	402	281	98	47	39	14	14	18	6	1	1
% RSD	1.2	0.9	1.0	1.1	1.8	1.9	1.9	2.3	5.8	12.1	10.3	52.6

Table 3c - Comparison of Averages from 5 Runs Made from Each Layer Taken from Each Sample Bottle

Layer 1	74201	43957	28245	8710	2581	2033	735	615	316	61	14	2
Layer 2	75790	44782	28675	8935	2667	2111	784	654	338	56	13	3
Layer 3	74198	44306	28573	8713	2490	1953	714	594	292	48	12	2
Layer 4	75816	44924	28731	8743	2552	2010	743	622	322	57	15	2
Layer 5	74923	44593	28691	8798	2565	2004	738	616	300	47	11	1
Average	74986	44512	28583	8780	2571	2022	743	620	314	54	13	2
Std Dev	803	387	198	94	64	58	26	22	18	6	2	1
% RSD	1.1	0.9	0.7	1.1	2.5	2.9	3.5	3.5	5.8	11.8	11.9	48.9

Please Note - Each of the numbers presented in the above table are an average of 5 runs. For example, the value of 74470 counts for Unit 0021 for the >4 µm size range was obtained by averaging the five runs made, one from each of

Bottle #	LNF S/N	Run #		>4 µm
1	*21*	*1*		73646
2	*21*	*10*		75907
3	*21*	*14*		78449
4	*21*	*18*		70252
5	*21*	*22*		74094
			Avg	74470
			Std Dev	3021
			% RSD	4.06

Table 4 – LNF Reproducibility for Shape Classification

Bottle #	LNF S/N	Run	Cutting	Sliding	Fatigue	Nonmetallic	>20	C+S+F+N
1	21	1	378	87	170	1586	708	2221
1	226	2	333	100	110	1898	829	2441
1	239	3	297	46	107	1608	762	2058
1	186	4	418	84	179	1463	723	2144
1	77	5	459	61	124	1398	638	2041
2	226	6	289	58	114	1504	640	1964
2	239	7	362	69	108	2070	924	2610
2	186	8	438	102	231	1580	735	2352
2	77	9	414	83	147	1470	668	2114
2	21	10	382	88	174	1735	801	2378
3	239	11	325	54	144	2166	930	2689
3	186	12	446	85	176	1582	745	2290
3	77	13	449	82	117	1395	624	2043
3	21	14	353	92	150	1681	791	2277
3	226	15	319	65	97	1535	699	2016
4	186	16	362	91	176	1480	719	2108
4	77	17	475	67	120	1469	725	2132
4	21	18	406	76	141	1525	719	2148
4	226	19	310	83	106	1573	703	2072
4	239	20	330	52	113	1942	860	2437
5	77	21	466	81	135	1402	679	2083
5	21	22	354	69	132	1506	698	2061
5	226	23	369	62	89	1724	730	2244
5	239	24	329	54	125	1812	830	2319
5	186	25	420	71	203	1427	691	2120
		Average	379.3	74.4	139.6	1621.2	743	2214
		Standard Deviation	56.4	15.5	35.4	211.2	82	187
		% RSD	14.9	20.9	25.4	13.0	11.0	8.5

Table 5 – Repeatability of Individual LNF Instruments for Shape Classification

Bottle #	LNF S/N	Run #	Cutting	Sliding	Fatigue	Nonmetallic	C+S+F+N
1	21	1	378	87	170	1586	2221
2	21	10	382	88	174	1735	2378
3	21	14	353	92	150	1681	2277
4	21	18	406	76	141	1525	2148
5	21	22	354	69	132	1506	2061
Average			375	82	153	1607	2217
Standard Deviation			22	10	18	99	121
% RSD			5.9	11.6	11.8	6.2	5.5
1	77	5	459	61	124	1398	2041
2	77	9	414	83	147	1470	2114
3	77	13	449	82	117	1395	2043
4	77	17	475	67	120	1469	2132
5	77	21	466	81	135	1402	2083
Average			452	75	129	1427	2083
Standard Deviation			24	10	12	39	41
% RSD			5.3	13.2	9.5	2.8	2.0
1	186	4	418	84	179	1463	2144
2	186	8	438	102	231	1580	2352
3	186	12	446	85	176	1582	2290
4	186	16	362	91	176	1480	2108
5	186	25	420	71	203	1427	2120
Average			417	87	193	1506	2203
Standard Deviation			33	11	24	71	111
% RSD			7.9	13.1	12.6	4.7	5.0
1	226	2	333	100	110	1898	2441
2	226	6	289	58	114	1504	1964
3	226	15	319	65	97	1535	2016
4	226	19	310	83	106	1573	2072
5	226	23	369	62	89	1724	2244
Average			324	73	103	1647	2147
Standard Deviation			30	18	10	164	195
% RSD			9.3	24.2	9.6	10.0	9.1
1	239	3	297	46	107	1608	2058
2	239	7	362	69	108	2070	2610
3	239	11	325	54	144	2166	2689
4	239	20	330	52	113	1942	2437
5	239	24	329	54	125	1812	2319
Average			329	55	119	1920	2423
Standard Deviation			23	9	15	219	250
% RSD			7.1	15.9	12.9	11.4	10.3

Tables 6 a, b, and c

Table 6a - Comparison of Averages for 5 Runs Made on Each Instrument for Shape Classification

	Cutting	Sliding	Fatigue	Nonmetallic	>20	C+S+F+N
Unit 0021	375	82	153	1607	743	2217
Unit 0077	452	75	129	1427	667	2083
Unit 0186	417	87	193	1506	723	2203
Unit 0226	324	73	103	1647	720	2147
Unit 0239	329	55	119	1920	861	2423
Avg	379	74	140	1621	743	2214
Std Dev	55.7	12.2	35.0	188	72	128
% RSD	14.7	16.3	25.1	11.6	9.7	5.8

Table 6b - Comparison of Averages for 5 Runs from Each Sample for Shape Classification

	Cutting	Sliding	Fatigue	Nonmetallic	>20	
Bottle 1	377	76	138	1591	732	2181
Bottle 2	377	80	155	1672	754	2283
Bottle 3	378	76	137	1672	758	2263
Bottle 4	377	74	131	1598	745	2179
Bottle 5	388	67	137	1574	726	2166
Average	379	78	146	1631	743	2214
Std Dev	4.7	3.0	12.0	57	16	54
% RSD	1.2	3.9	8.2	3.5	2.1	2.5

Table 6c - Comparison of Averages from 5 Runs Made from Each Layer Taken from Each Sample Bottle

	Cutting	Sliding	Fatigue	Nonmetallic	>20	
Layer 1	364	74	148	1627	735	2213
Layer 2	394	78	129	1705	784	2307
Layer 3	392	74	137	1566	714	2169
Layer 4	365	79	141	1600	743	2185
Layer 5	382	67	142	1607	738	2199
Avg	379	74	140	1621	743	2214
Std Dev	14.4	4.7	6.8	52	26	54
% RSD	3.8	6.3	4.9	3.2	3.4	2.4

Please Note - Each of the numbers presented in the above table are averages of 5 runs. For example, the value of 375 counts for Unit 0021 for cutting wear particles was obtained by averaging the five runs made, one from each of the five bottles, as shown below.

Bottle #	LNF S/N	Run #		Cutting
1	21	1		378
2	21	10		382
3	21	14		353
4	21	18		406
5	21	22		354
			Avg	375
			Std Dev	22
			% RSD	5.9

Table 7 – Comparison of Particle Distribution in NIST 2806 with Distribution Measured by LNF

NIST SRM 2806 - Medium Test Dust in Hydraulic Fluid	>4 µm	>6 µm	>10 µm	>14 µm	>20 µm	>25 µm
Minimum Counts per ml for SRM 2806	5028	1856	346	87	16	6
Median Counts per ml for SRM 2806	6095	2395	514	170	51	20
Maximum Counts per ml for SRM 2806	8382	3413	918	439	204	109
LNF Results, Average of 25 Measuements	74986	28583	8780	2571	743	314
SRM Counts x 12.3		29465	6324	2091	627	246
LNF(>4 µm)/NIST (> 4 µm) = 74986/6095 = 12.3						
LNF Counts/NIST Counts	12.3	11.9	17.1	15.1	14.6	15.7