THE MISAPPLICATION OF "COMPOSITE CORRELATION OF CLEANLINESS LEVELS"

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Abstract: Contamination control for hydraulics and lubricants is a proactive approach to achieve extended machine life. Particle counting is a proven contamination monitoring method and is an essential part of contamination control. Many particle counting standards have been developed and are in widespread use. Some include ISO 4406 code, particles per ml >10 micron, gravimetric method (mg/L), MIL STD 1246a, NAS 1638 code, and SAE code (Disavowed). The table, "Composite Correlation of Cleanliness Levels," has been used in many referenced publications to show equivalent relationships between all of these standards. In its correct application, this table shows the equivalence between these standards when using air cleaner fine test dust (ACFTD) standard contaminant. A frequent misapplication of this chart is to assume (incorrectly) that it describes equivalence when testing used hydraulic and lubricant oil samples instead of ACFTD standard contaminant. This paper shows the extent to which particle count data collected from actual samples does not comply with this table. It shows how one can be led to incorrect condition monitoring analysis and wrong recommended actions by using this table to translate "particles per ml > 10 microns" into ISO and NAS code levels. It shows the importance of actually counting particles at multiple sizes rather than assuming the size distribution of ACFTD standard contaminant.

Key Words: Particle count, flow decay, size distribution, filter blockage, cleanliness, Air Cleaner Fine Test Dust, ACFTD, ISO 4406, NAS 1638

Introduction: Table 1 , "Composite Correlation of Cleanliness Levels," or one very similar, has been printed in several publications.[1] This table shows a general comparison between several industry standard particle counting methodologies. This paper describes the error introduced using a single measurement to predict particle counts at various sizes. A study has been conducted of 3670 samples to determine how well one can estimate the ISO 4406 and NAS 1638 cleanliness codes based on particle counts measured in only one size range. For example this study shows that if one uses accurate > 10 micron data to

[1] Pg. 2 of SAE J1165 dated MAR 86, "Reporting Cleanliness Levels of Hydraulic Fluids"; pg. 203 of The Lubrication Engineers Manual, Second Edition, AISE dated 1996; pg. 78 of Fluid Contamination Control by E. C. Fitch, FES Inc. dated 1988; and page 283 of Handbook of Wear Debris Analysis and Particle Detection in Liquids by Trevor M. Hunt, dated 1993.

estimate particle counts and ISO codes at > 5 micron and >15 micron ranges, then only about half the results will report the correct code values and more than 10% of the results will be wrong by at least two ISO code values.[2]

Table 1. Composite Correlation of Cleanliness Levels

ISO Code	Particles/mL > 10 micron	ACFTD (mg/L)	MIL-STD-1246A	NAS 1638	Disavowed "SAE" Level
26/23	140000	1000			
25/23	85000		1000		
23/20	14000	100	700		
21/18	4500			12	
20/18	2400		500		
20/17	2300			11	
20/16	1400	10			
19/16	1200			10	
18/15	580			9	6
17/14	280		300	8	5
16/13	140	1		7	4
15/12	70			6	3
14/12	40		200		
14/11	35			5	2
13/10	14	0.1		4	1
12/9	9			3	"0"
11/8	5		100	2	
10/8	3				
10/7	2.3			1	
10/6	1.4	0.01			
9/6	1.2			"0"	
8/5	0.6				
7/5	0.3		50	"00"	

Particle counting is an accepted practice for monitoring fluid cleanliness affecting the life of hydraulics and lubricated machinery. Industry standards for particle counting (ISO 4406, NAS 1638, MIL-STD 1246C, SAE AS 4059B, DEF STAN 05-42/2, NAVAIR 01-1A-17, and others) all require particle counting to be accomplished at two or more relevant size ranges. All of these standards require measurements in the >5 micron and >15 micron ranges. All except ISO 4406 also require independent counts at >25 and >50 micron size ranges as well. When particle counts are measured at two different size ranges, one is able to measure both total contamination, and size distribution. Both are very important when monitoring fluid cleanliness.

[2] The ISO 4406 or NAS 1638 code values increase by one unit when particle count ranges double, and they increase by two units when particle count ranges quadruple. Since each code value in this study represents a large statistical population of data with approximately half the data in the top half of the range and approximately half the data in the bottom half of the range for that code value, it is reasonable to use the midpoint of the particle count range when comparing code values in this study.

Figures 1 through 6 illustrate the importance of particle size distribution for these industry standards.[3] Figure 1 shows how count distributions vary for ACFTD in concentrations ranging from 0.002 mg/L (lowest line) to 64 mg/L (highest line). . The dotted lines in Figures 1 through 6 represent 1 mg/L of ACFTD (same as one part per million using weight/volume units). Figures 2 and 3 show that for ISO 4406 a 3-code gap is parallel to ACFTD, while a 5-code gap traverses the distribution of ACFTD. Figure 4 shows how the NAS 1638 code also traverses the distribution of ACFTD. Figures 5 and 6 show how MIL STD 1246C distribution parallels ACFTD and how DEF STAN 05-42 Table B distribution traverses it. Size distribution must be measured for all of these standards.

Particle Counting by Light Extinction: "Light extinction" is an accepted method for all of the above standards when counting particles and measuring size distribution for hydraulic and lubricant samples. Light is extinguished (blocked) when they flow with the sample through an optical window. This sensor sizes every particle as it is counted, one-at-a-time. "Light extinction" sensors have three significant limitations: 1) false counts are logged when water droplets pass through the sensor, 2) false counts are logged when air bubbles pass through the sensor, and 3) the sensor becomes ineffective with extremely dark /opaque fluids or with sufficiently high particulate contamination levels to cause coincidence errors[4]. Procedures have been developed to compensate for each of these limitations including 1) masking water[5], 2) degassing samples, and 3) diluting samples.

Particle Counting by Flow Decay: "Flow decay" is an alternative method for estimating particle counts in single size category such as counts for particles > 10 micron size. Since it does not involve optical measurement, flow decay is not affected by water droplets, air bubbles, or dark fluids. This sensor detects the rate of blockage for a precision screen as particles larger than the screen pore size accumulate on the screen.

There are two common levels of flow decay contamination meter.[6] One level uses multiple screens (generally two or three with different pore sizes) so that size distribution can be effectively measured. The second level is simpler and requires less sample fluid because it uses only a single screen to trap contamination. It is this second level, the single screen type flow decay meter, that yields questionable ISO 4402 and NAS 1638 results since these standards demand measurement of size distribution.

The single screen flow decay meters measure the rate of change in flow when a screen, typically with 10 micron pore size, is being blocked with solid particles. A computer is used to translate this decay rate into actual particle count data which is reported in the >2

[3] Figures 1 through 6 provided by Trevor M. Hunt, Consulting Engineer.

[4] Coincidence errors occur when contamination levels are sufficiently high that two particles are likely to be in the light path at the same instant in time.

[5] A procedure has recently been developed accurately counting particles by light extinction with high water contamination. See "Masking Water in Mineral Oils When Using a Laser Particle Counter" by M. Lin, J. Mountain, and A. Carey, JOAP 98.

[6] The technique of flow decay used here is intended to reflect "filter blockage" as defined in British Standard 3406 Part 9 which describes two types: 1) a constant flow and measured pressure drop and 2) a constant upstream pressure and measured flow decay. Both types can have single or multiple screens.

micron, >5 micron, >15 micron, >25 microns, >50 micron, >100, as well as other micron size ranges. Implicit in this report is the assumption that all contaminants match a known size distribution such as that of the calibration standard, Air Cleaner Fine Test Dust (ACFTD). The only practical[7] way to make a single measurement with one mesh size and then report data at different sizes is to assume a consistent proportional relationship between these size ranges. This way if one knows the number of particles >10 micron size then all others are automatically known. Furthermore, this assumption must be made if one chooses to report ISO 4406 or NAS 1638 code values from a single flow decay measurement since these standards automatically include multiple size ranges.

This assumption is NOT valid. Real world contaminants found in lubricants and hydraulics do not match the size distribution of ACFTD. Sometimes the distribution is flatter. Most of the time it is steeper. Steeper distributions are often found in systems with fine filtration. Flatter distributions are often found when contamination ingression or abnormal wear are occurring. The shape, or at least the slope, of the particle size distribution is just as important as the overall level of contamination.

Note also that the introduction to ISO 4406:1987 includes: "Most methods of defining solid contaminant quantities are based on the supposition that all contaminants have similar particle size distribution. This supposition may be valid for natural contaminants, such as airborne dust, but it is not valid for particles which have been circulated in an installation and subjected to crushing in pumps and separation in filters." Note also that ISO 3939:1986 includes: "The assumption is made that particle count distribution curves approximate straight line segments when plotted on log/log-squared graph paper. The assumption of straight line distribution (when plotting particle count data on log/log-squared co-ordinates) may not always be valid."

A single measurement for >10 micron size can only predict the counts at other sizes if the contaminant is a standard such as the particle counting calibration standard, ACFTD. When one measures the contamination level at one size with ACFTD, all other sizes are automatically known[8] and increase or decrease in proportion to the mg/L of ACFTD. This was a critical factor in selection of ACFTD as the calibration standard for nearly all particle counters manufactured for the purpose of measuring particulate contamination in either lubricants or hydraulics.[9]

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[7] The logarithmic decay of particle counts with size creates a practical limitation for quantifying size distribution with flow decay through a single mesh. In effect, the numerically dominant contributor to mesh plugging (flow decay) is the group of particles which are a little larger than the mesh opening size. The very large particles are too few in number and the very small particles pass through the mesh. However, R. Lewis gave some evidence that the rate of change in pressure decay might be "related to the different particle size distributions" shown in Figures 4 through 7 of his paper, "An integrated Oil Analyzer," pg. 412-422, Condition Monitoring 94. In this paper Lewis concluded that small particles cause increasing flow decay as they fill interstitial spaces between larger particles.

[8] The "known" size distribution for ACFTD is under revision by standards committees responding to new data from the National Institute for Standards and Test (NIST). Revisions, when published will affect all particle counting methods and standards in a similar way. Data reported in this study assumes the historical ACFTD counts at > 5 and > 15 microns. It is now understood that these counts actually apply to > 6 and > 14 microns.

[9] Note that latex spheres and other materials may be used when calibrating particle counters for other purposes.

A Study Comparing ACFTD Size Distribution to More Than 3000 Actual Oil Samples. A study of particle count data from 3670 different samples[10] was performed to investigate the similarity of ACFTD size distribution to that found in "real world" used lubricant and hydraulic oil samples. The study was done to investigate the likelihood of error resulting from estimating ISO 4406 codes for both 5 ("ISO5") and 15 ("ISO15) micron sizes and estimating the NAS 1638 code using only the true particle count at 10 micron size and the assumption that the size distribution matched that of ACFTD. The results were surprising.

ISO 5 micron code: The study showed that the ISO5 code was correct approximately 45% of the time when using accurately measured counts at >10 micron size to estimate counts in the >5 micron size range, and assuming the log/log squared distribution to be the same as ACFTD. See Figure 7. In fact, 10.5% of the measurements (10.5 = 3.3 + 5.7 + 1.3 + 0.2) are in error by 2 or more ISO5 code levels. This implies that the average estimated particle counts > 5 microns can be either understated by more than 75% or overstated by more than 400%.

ISO 15 micron code: This study also indicated that the ISO15 code was correct approximately 39% of the time when using accurately measured counts at >10 micron size to estimate counts in the >15 micron size range, and assuming the log/log squared distribution to be the same as ACFTD. See Figure 8. In this case, 14.6% of the measurements (14.6 = 0.1 + 0.1 + 10.8 + 3.6) are in error by 2 or more ISO 4406 code levels. This implies that the average estimated particle counts > 15 microns can be either understated by more than 75% or overstated by more than 400%.

Variations in Sample-to-Sample Size Distributions: The reason why the >10 micron particle count cannot be reliably used to estimate the counts at neighboring sizes, >5 and >15 micron is simply a matter of variation in actual size distributions. To explore this, 24 typical oil samples were selected including hydraulics, gearboxes, compressors, and other industrial machinery. Table 2 shows that for ACFTD the >5 micron count is always 359% (3.59 times) of the >10 micron count, and the >15 micron count is always 38% of the >10 micron count. However, in a sampling of 24 actual oil samples, the >5 micron count averaged 1449% of the 10 micron count (instead of 359% for ACFTD) and the >15 micron count averaged 25% of the 10 micron count (instead of 38% for ACFTD). The range of proportional differences between >5 and >10 micron counts in actual data varied from 295% to 13,242%, a factor of 44 times or 6 ISO 4406 code levels. The range of proportional differences between >15 and >10 micron counts in actual data varied from 3% to 44%, a factor of 14 times or 4 ISO 4406 code levels. Although ACFTD is in the ranges for both sizes, neither ACFTD nor any other standard contaminant, could be selected to represent the variations observed in real world samples.

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[10] These samples represent a consecutive block of data collected by the CSI Trivector oil analysis lab.

Table 2. Size distribution variations between ACFTD and "real world" samples.

	ACFTD	24 Typical Oil Samples		
		max.	min.	ave.
100% * (count @ 5) / (count @ 10)	359%	13,242%	295%	1449%
100% * (count @ 15) / (count @ 10)	38%	44%	3%	25%

If the >10 micron particle count cannot be reliably used to estimate the counts at neighboring sizes, it follows that it is meaningless to use it to estimate counts at other sizes such as >2, >25, >50, and >100 micron. This is exactly what must be done if one is to apply this approach to industry standard codes such as NAS 1638 which require independent counts for each range: 5 to 15 micron, 15 to 25 micron, 25 to 50 micron, 50 to 100 micron, and >100 micron.

NAS 1638 code: This study of 3670 samples showed that the NAS 1638 code was correct approximately 51% of the time when using accurately measured counts at >10 micron size to estimate counts in specified size ranges, and assuming the log/log squared distribution to be the same as ACFTD. See Figure 9. In this case, 12.2% of the measurements (12.2 = 3.9+ 7.2 + 0.4 + 0.7) are in error by 2 or more NAS 1638 code levels.

ISO and NAS codes: Figure 10 shows the error plots for ISO 4406 at both >5 and >15 microns, as well as NAS 1638 cleanliness codes if one were to extrapolate from a single >10 micron flow decay type measurement. It is important to note that one finds valuable information in the "tails" of these distributions. For instance, a few particles per ml > 50 micron will trigger the NAS 1638 Code without affecting the ISO 4406 alarms. This approach can give early indication of wear problems, filtration problems, and contamination problems that may otherwise have gone unnoticed..

Actual Distributions Do Not Follow ACFTD: Figures 11 and 12 show actual data from typical oil samples (4 hydraulic, 4 compressor, 4 gearboxes, 3 spindles, and 5 crank ends) plotted on a background of ACFTD data (dotted lines). This graph clearly shows that some of the time the actual distribution is flatter than the ACFTD although most of the time it is steeper. The spacing between dotted ACFTD lines in this plot is two (2) ISO 4406 or NAS 1638 codes or 400% count difference per space. The lowest dotted line is ISO 6/3 due to 0.001 mg/L[11] of ACFTD, and the highest dotted line is 26/23 due to 1,024 mg/L of ACFTD. It is interesting to note that the target cleanliness level for vane pumps, piston pumps, or motors of 16/13[12] per ISO 4406 or 11 per NAS 1638. This corresponds to only 1.0 mg/L, or about 1 ppm ACFTD!

[11] Note that "mg/L" units are commonly used for particulate contamination and represent parts per million (ppm) with mixed units of weight per unit volume.

[12] Page 14 from "The Handbook of Hydraulic Filtration" by Parker Filtration.

Conclusion: The primary conclusion of this report is that at least two measurements at differing size ranges must be made in order to make reasonable conclusions about particle size distribution. While ACFTD, which is an excellent calibration standard, may be sufficient to represent wind blown dust; it does NOT represent the size distribution for contamination found in typical industrial machines. It appears that contamination in industrial machinery lubricants and hydraulics can have size distributions with slopes differing by hundreds, even thousands, of percent. The often cited table, "Composite Correlation of Cleanliness Levels," is useful as a qualitative comparison between various industry standards assuming the contaminant measured is ACFTD. However, since this table gives no allowance for variations in size distributions, it may not be appropriate to use it for cross referencing actual sample data.

Figure 1. ACFTD Standard Contaminant

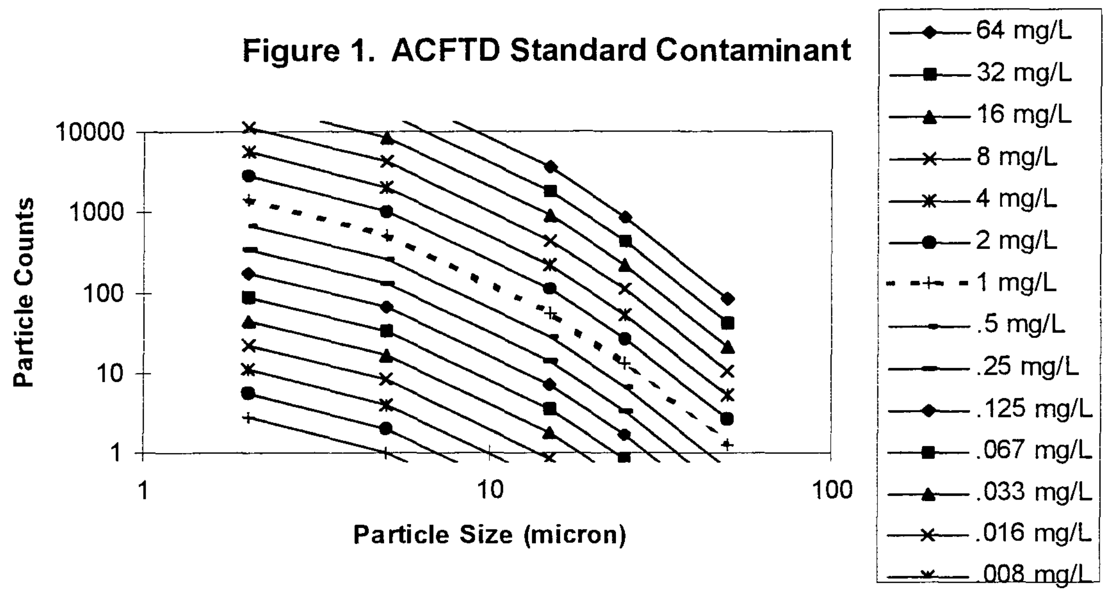
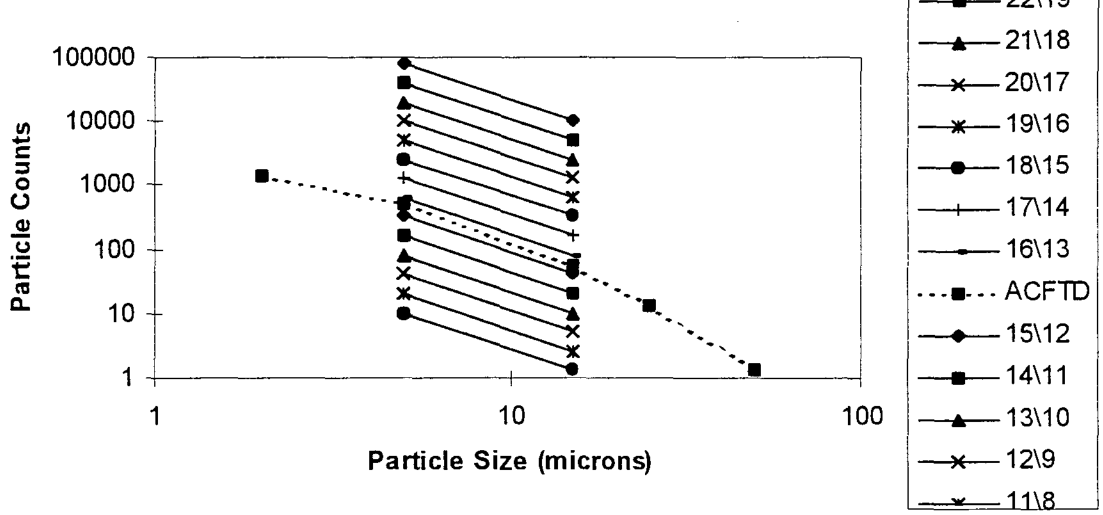


Figure 2. ISO 4406 w/ 3 Code Gap



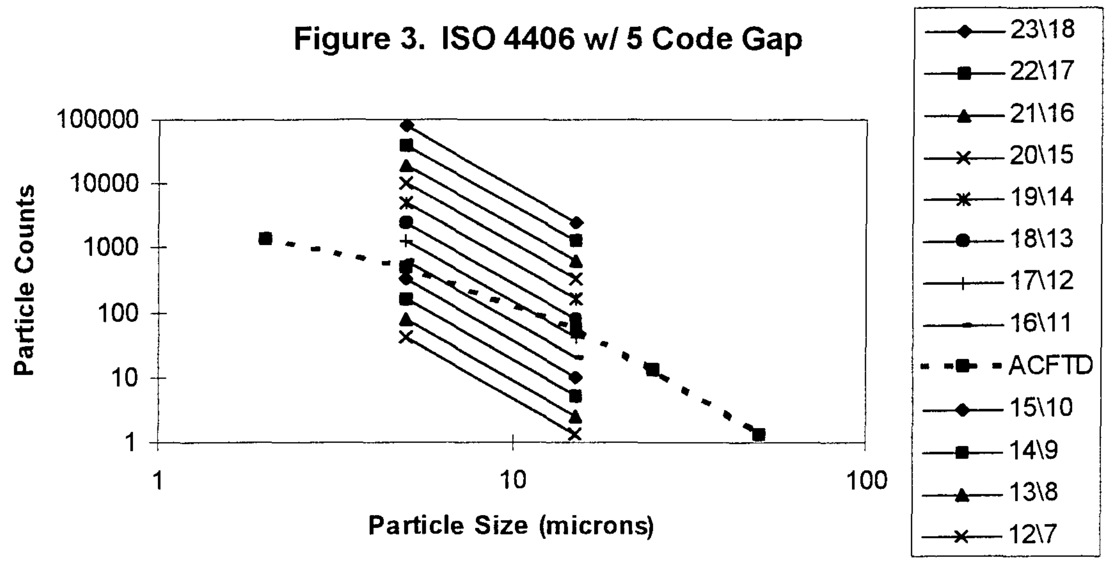


Figure 3. ISO 4406 w/ 5 Code Gap
100000
10000
1000
100
10
1
Particle Counts
1
10
100
Particle Size (microns)
23\18
22\17
21\16
20\15
19\14
18\13
17\12
16\11
ACFTD
15\10
14\9
13\8
12\7

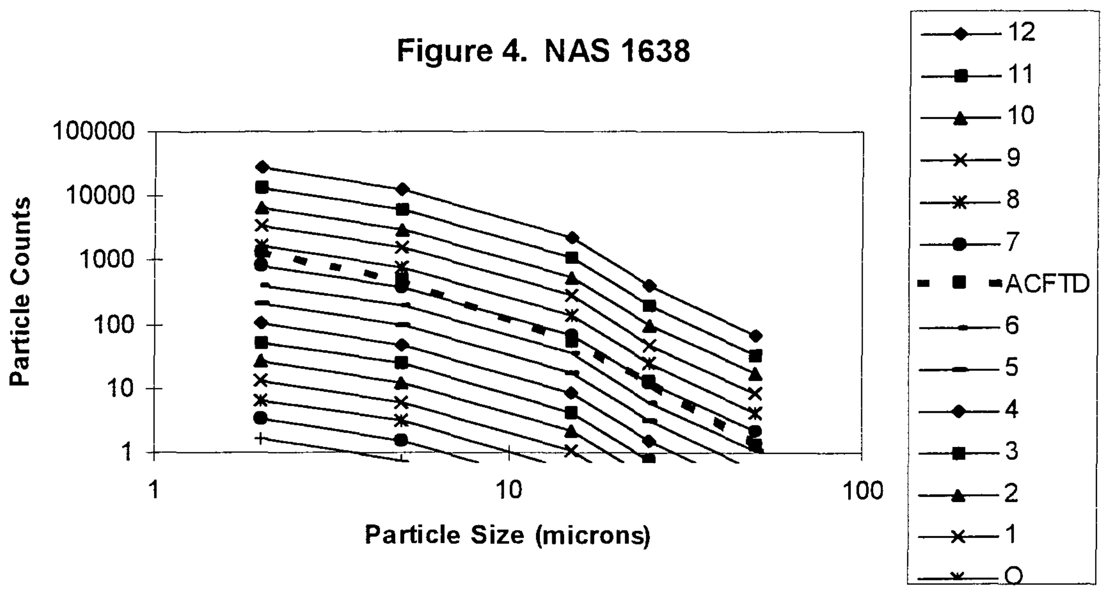


Figure 4. NAS 1638
100000
10000
1000
100
10
1
Particle Counts
1
10
100
Particle Size (microns)
12
11
10
9
8
7
ACFTD
6
5
4
3
2
1
O

Figure 5. MIL STD 1246C

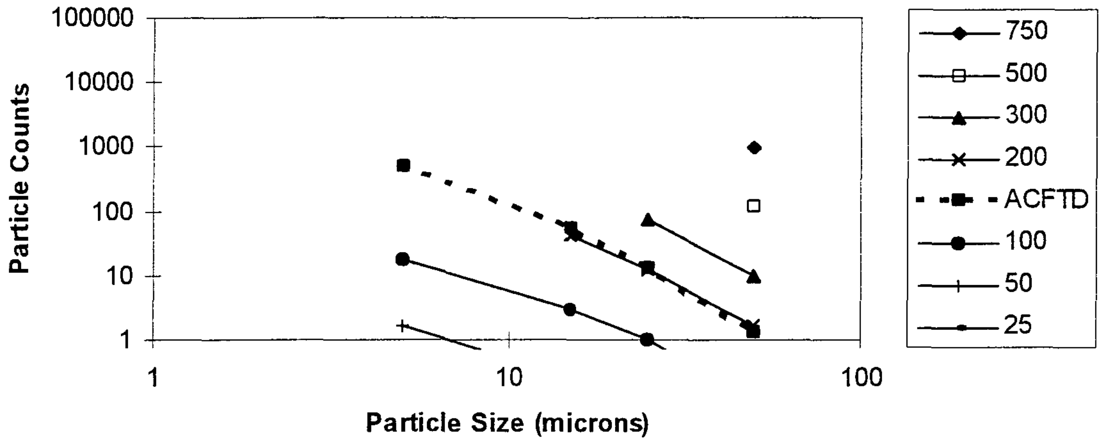
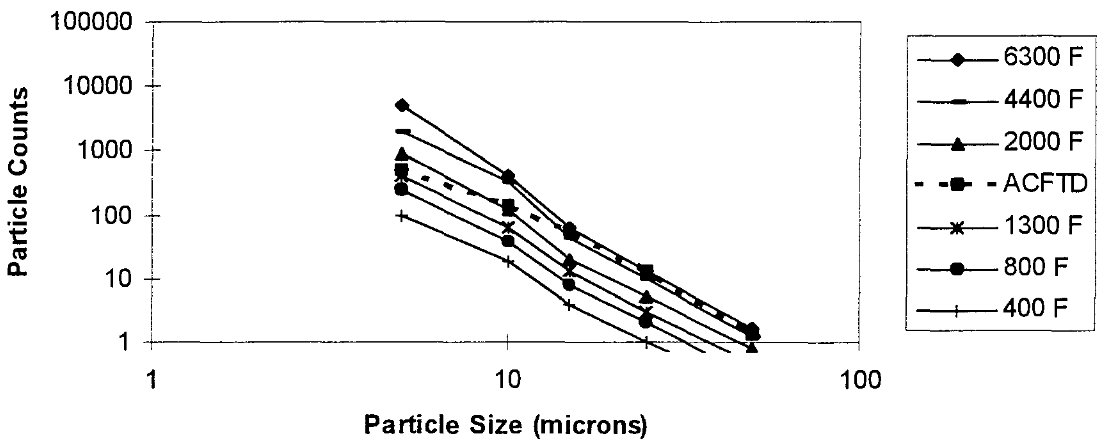


Figure 6. DEF STAN 05-42 Table B



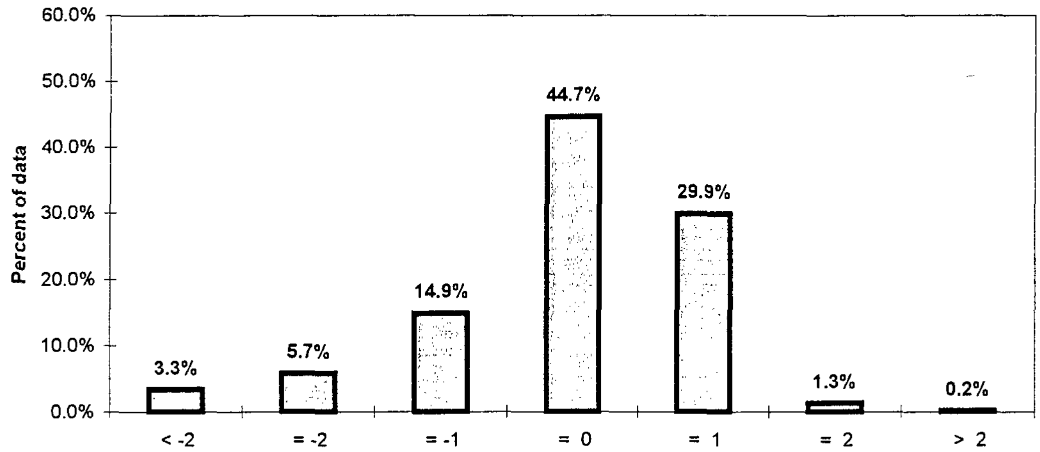


Figure 7. Estimated ISO 5 - Measured ISO 5 Code for 3670 Samples
Estimated ISO 5 Code is extrapolated from measured 10 micron count using slope of ACFTD

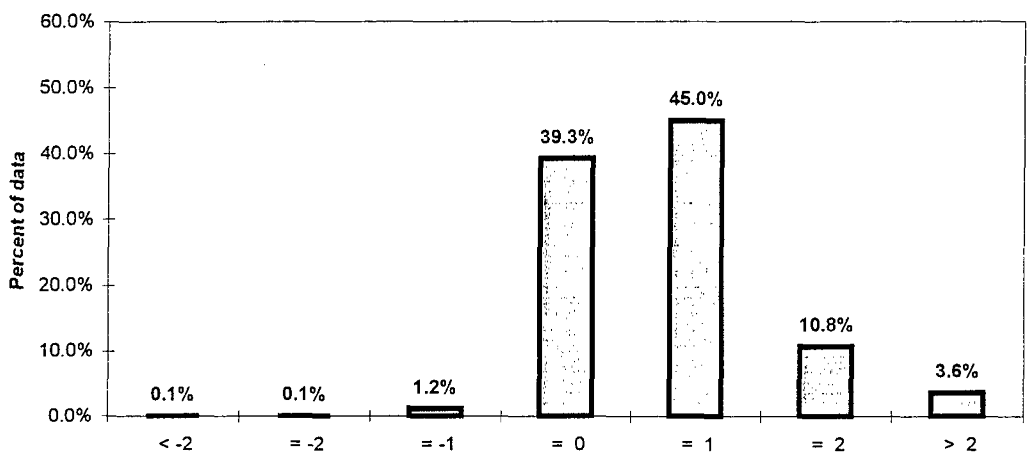


Figure 8. Estimated ISO 15 - Measured ISO 15 Code for 3670 Samples
Estimated ISO 15 Code is extrapolated from measured 10 micron count using slope of ACFTD

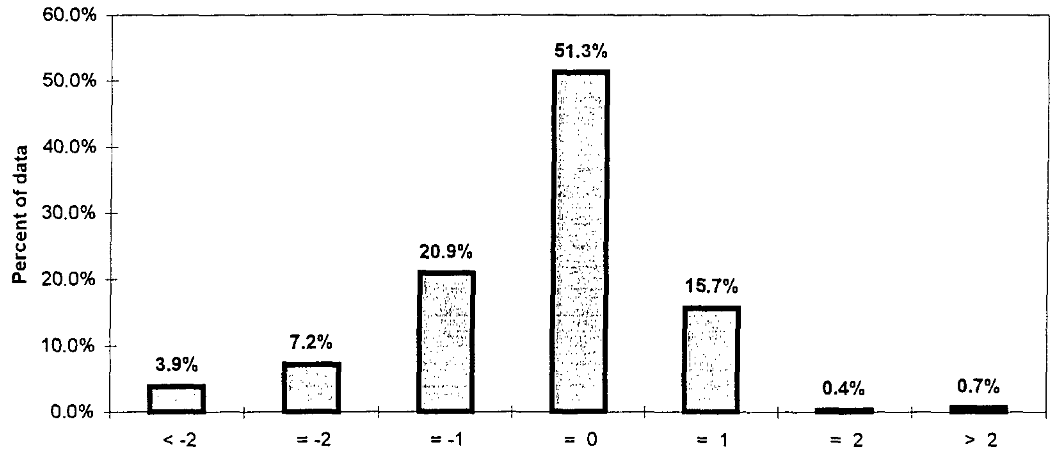


Figure 9. Estimated NAS - Measured NAS Code for 3670 Samples
Estimated NAS Code is extrapolated from measured 10 micron count using slope of ACFTD

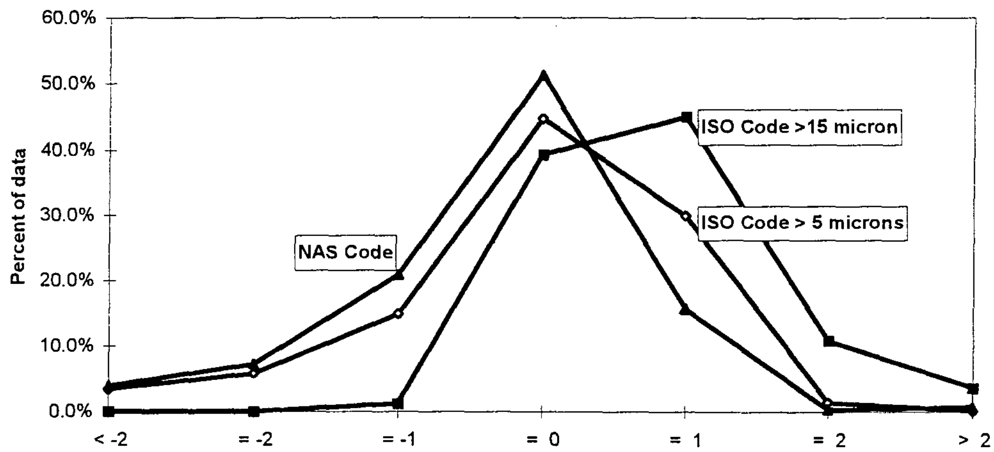


Figure 10. Estimated Code - Measured Code for 3670 Samples
Estimated Code is extrapolated from measured 10 micron count using slope of ACFTD

Figure 11. Comparison typical sample size distributions (solid lines) with ACFTD size distributions (dotted lines)

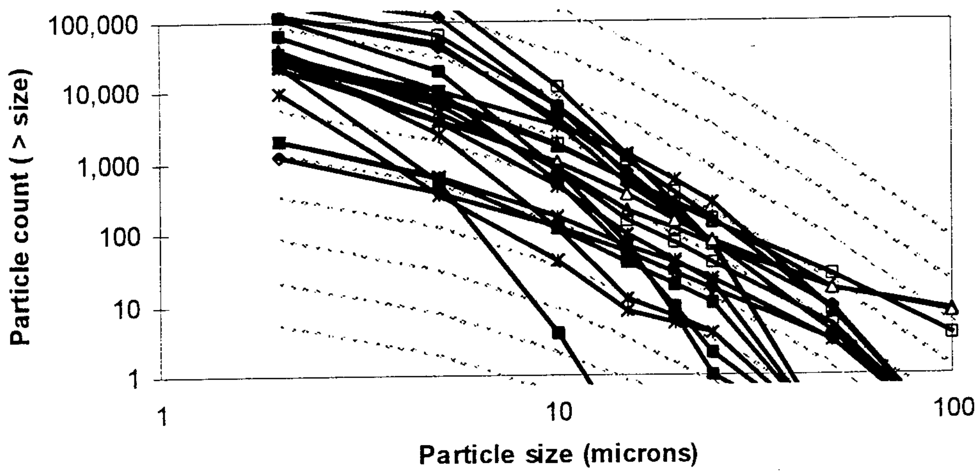


Figure 12. Comparison typical sample size distributions (solid lines) with ACFTD size distributions (dotted lines)