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RIG EVALUATION OF THE ON-LINE FERROGRAPH.(U)  
JAN 80 P W CENTERS  
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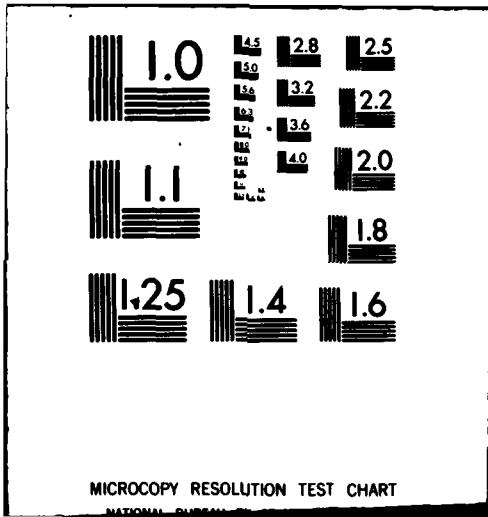
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P. W. Centers

Lubrication Branch  
Fuels and Lubrication Division

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This technical report has been reviewed and is approved for publication.



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FOREWORD

This report describes an in-house effort conducted by personnel of the Lubrication Branch (SFL), Fuels and Lubrication Division (SF), Air Force Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, under Work Unit 30480626, "Turbine Engine Lubricant Research".

The work reported herein was performed during the period 2 January 1979 to 31 May 1979, under the direction of P. W. Centers (AFAPL/SFL) with the assistance of Micheal Schumacher (AFAPL/TFF), Timothy Dues (AFAPL/TFF), and Susan Hartzell (AFAPL/SFL). Support was also kindly provided by AFML/MBT in supplying an iron standard and light scattering particle count analyses.

This report was released by the author in August 1979.

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SECTION I  
INTRODUCTION

The ferrograph (Ref 1) is a device to precipitate and roughly segregate magnetic wear debris from lubricant samples onto a specially prepared glass slide. The prepared ferrograms are examined using a bichromatic microscope. The amount of debris indicates the level of wear, while the difference between quantities of large and small wear debris indicates the severity of wear. Additionally, particle morphology suggests the wear mechanism.

In addition to the analytical ferrograph described above, a direct-reading ferrograph is manufactured which rapidly determines the relative amounts of large and small wear debris in a fluid. The purpose of the direct reader is to monitor trends of wear in equipment and to identify those samples exhibiting abnormal wear or those requiring additional analysis.

The on-line ferrograph developed by Foxboro Analytical, Burlington MA, as sponsored by the U.S. Navy, has recently become available for evaluation. The on-line device was designed to continuously monitor the wear state of equipment by cyclically measuring by capacitive techniques large and small wear debris in an operational lubricant or fluid system (Ref 2).

The on-line instrument is equipped with a pressure regulator and orifice so that if similar fluids (e.g., viscosity index) are analyzed, the temperature of the fluid can be used to establish the volume of the sample. The sample is forced across a magnet which tends to precipitate large debris at the entry and smaller debris near the exit. Capacitive sensors indicate the amount of debris present. From those values, the wear concentration as well as relative amounts of large and small debris, can be determined. This model is designed for stationary rather than on-board applications due to the weight and size of power supply and readout devices. Digital voltmeters are used to continuously monitor large and small debris concentrations as well as the cycle time. At the end of

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each cycle (30 sec - 30 min) the magnetic force is reduced at the sensor and the flow increased so that the unit is flushed prior to the start of the next cycle. Manufacturer's stated limits include 30 - 200 psig and up to 125°C (257°F). Sensor dimensions are 69 mm x 142 mm x 113 mm (2.75" x 5.63" x 4.5") with a weight of 1134g (2.5 lbs).

The objective of this effort was to assess the on-board ferrograph prior to test stand engine evaluation of the device. The effect of temperature, pressure, and change in wear debris concentration were to be determined. The wear debris data were also to be compared with data generated using other wear debris analytical techniques. The effort was cooperative in that AFAPL/TBC purchased the device for evaluation by AFAPL/SFL.

SECTION II  
EXPERIMENTAL

Due to the availability of certain required controls, a laboratory dynamic foam rig was selected for installation and assessment of on-line ferrograph prior to the test cell engine evaluation. The foam rig was the result of initial developmental efforts (Ref 3) followed by modification of synthetic turbine lubricants under various conditions. As shown in the schematic (Fig 1) the ferrographic sensor was piped into a bypass upstream of the orifice with the fluid returning to the main lubricant supply on exiting through the sensor. The installed sensor is shown in Fig 2. Because of rig controls, it was possible during these tests to vary fluid pressure from 207 to 759 kN/m<sup>2</sup> (30 - 110 psig) and temperatures up to 98.9°C (219°F).

The routine charge of fluids was 450 ml. That charge was determined by addition of known volumes of dissimilar lubricant to the test fluid, followed by gas chromatographic analyses of the resultant mixtures. Using that technique, it was possible to determine the "dead volume" and "true volume" of the system.

It should be noted that a gear pump is used in the rig. Although it was certainly possible, no evidence was found that the pump was contributing wear debris to the system during the tests reported.

The general test procedure, whether evaluating the effects of temperature, various pressures, or quantities of wear debris added to the system was identical. First, the system was drained, followed by adding the test fluid, running for at least five minutes, draining and repeating. After the fourth addition of the test fluid, the test cycle was initiated. Then the test temperature was attained under approximate flow and pressure conditions, after which excess lubricant was drained from the system. If wear debris additions were required, the pump was stopped and the fluids added, using a convenient port at the top of the rig. It was demonstrated that the operation added no extraneous debris to the system. When test

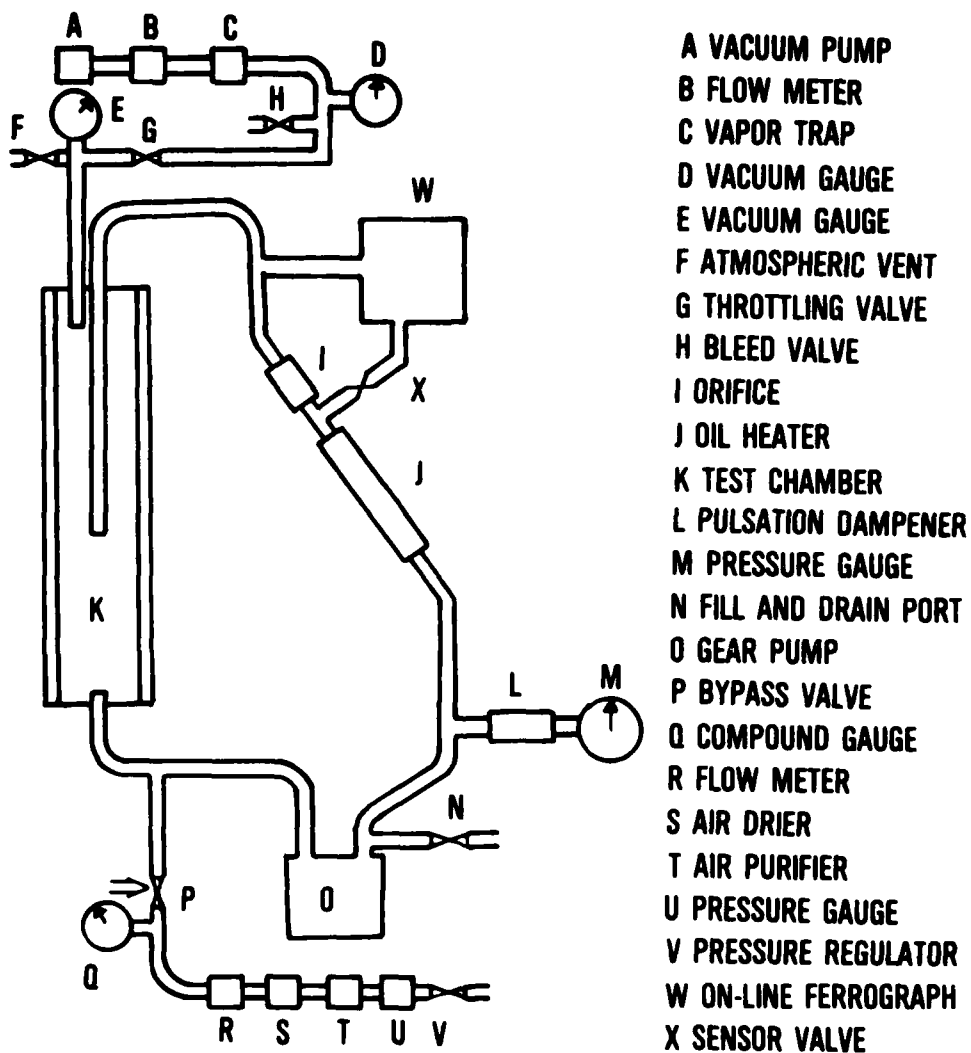


Figure 1. Flow Schematic of On-Line Ferrograph Installed in Dynamic Foam Rig

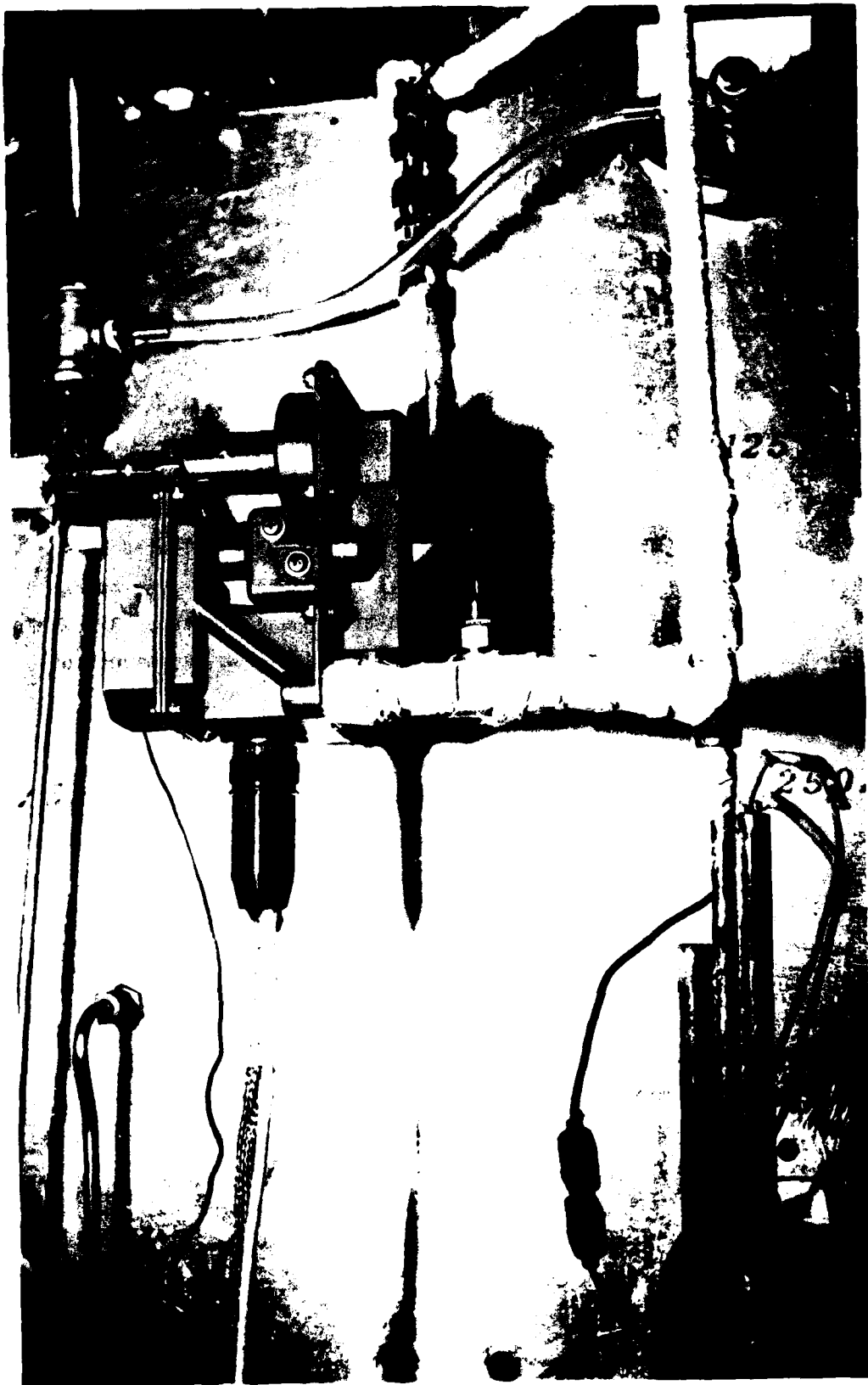


Figure 2. On-Line Ferrograph Sensor Installed in Dynamic Foam Rig

conditions were stabilized, five to ten cycles of test data were obtained. Mean values of output data were then calculated for comparative purposes. Cyclic data displayed on the digital volt meters were recorded by the operator. Data included large particle abundance ( $A_L$ ), small particle abundance ( $A_S$ ), and wear concentration (WC). A strip chart recorder was also employed to provide a permanent record of  $A_L$ ,  $A_S$ , and cycle time. The recorder and ferrographic output device are shown in Fig 3. After each test the system was flushed with filtered lubricant (0.8 $\mu$  Millipore) for return to the initial baseline.

The samples selected for evaluation were new and used MIL-L-7808 synthetic turbine engine lubricants. The fluids, which contained various amounts and types of wear debris, are described in Table I. Viscosities, which were not considered to be a significant factor in the on-line evaluation, are given in Appendix A. The lubricants were selected due to availability and with limited knowledge of the amount and type of debris present. Coverage of a wide range of possibilities was attempted. AFML/MBT provided a 100-ppm Fe standard which was used to add known increments of wear debris to the system.

Concurrently or subsequently to the rig tests, wear debris information using various techniques was gathered to achieve some of the initial objectives of the effort. AFML/MBT provided particle count data, using a Spectrex light-scattering instrument. Those data are summarized and/or extracted and used in several tables, while the data are reported totally in Appendix D. Richenbacker AFB, OH, provided spectrometric oil analysis (SOA) data. The data were generated with a Baird Atomic emission spectrometer, using standard methods (Ref 5). Selected data are incorporated in the following sections and raw data are provided in Appendix B. This laboratory prepared analytical ferrograms of each sample and performed a number of colorimetric iron determinations on each of the samples using the method of George (Ref 6). The ferrographic data are given in Appendix C.

During the initial experiments, the on-line unit was operated at various temperatures and pressures as described in Section III. In other experiments, the addition of ATL-7071 or 100-ppm Fe standard to a base fluid was made to

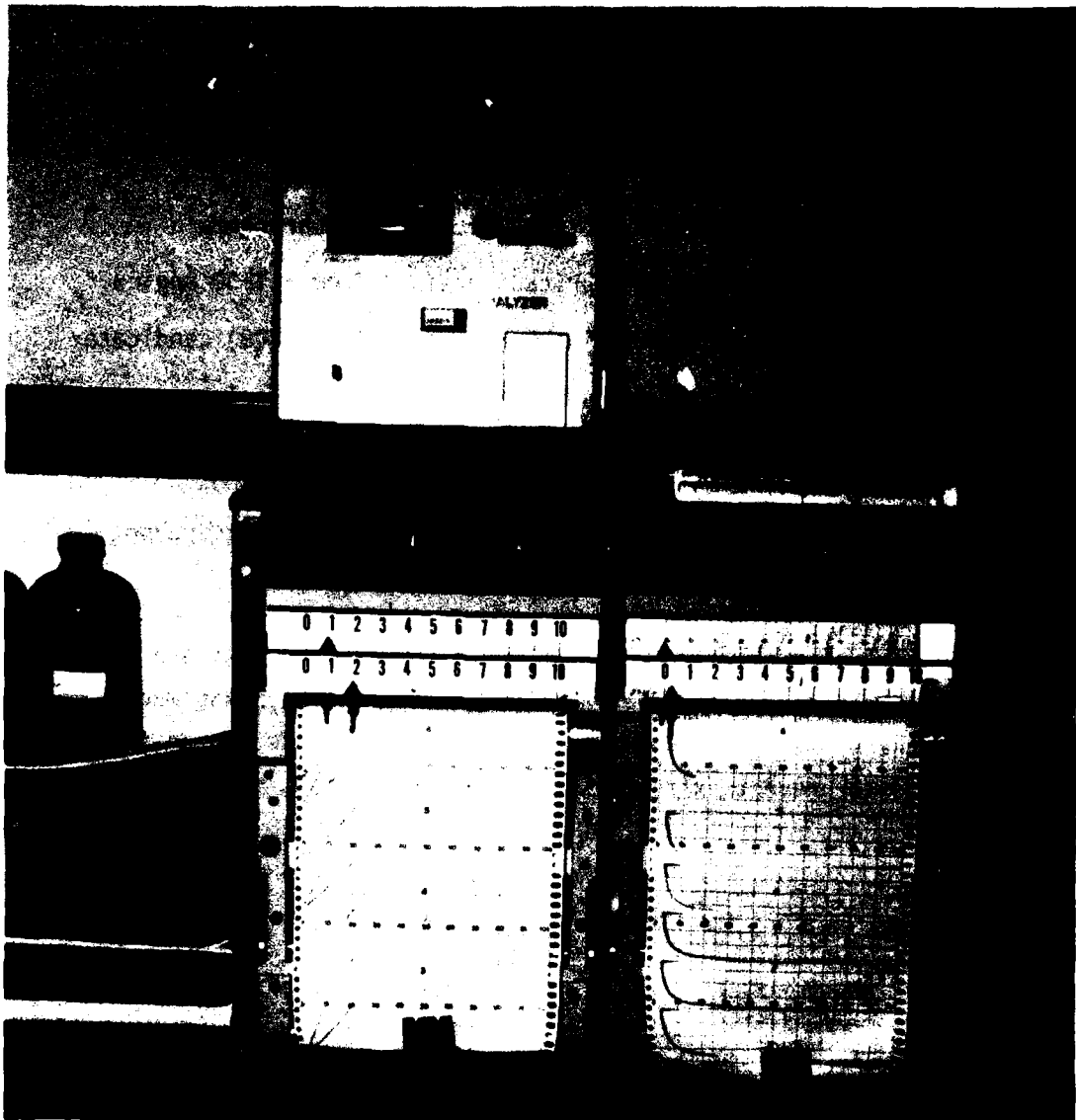


Figure 3. On-Line Ferrograph Output Device and Strip Chart Recorder

TABLE 1. SAMPLE DESCRIPTIONS

<u>Lubricant</u>	<u>Description</u>
0-76-4	A 0.8 $\mu$ M Millipore filtered MIL-L-7808 lubricant.
0-78-3A	A used MIL-L-7808 lubricant drained from a TF30 engine.
OP-130-9	A test-stand J57 engine lubricant (MIL-L-7808) candidate.
ATL-7071	Combination of used synthetic turbine engine lubricants taken from storage.
OP-151-9	A test-stand TF41 engine lubricant (MIL-L-7808).
100 ppm Fe	100-ppm Fe particulate standard prepared in MIL-L-7808 by AFML/MBT.

assess the unit's sensitivity to increases in wear debris. At the end of each test a sample was obtained for analysis. Every effort was made to insure that the system did not contain significant amounts of non-test lubricants and to prevent extraneous debris introduction.

SECTION III  
RESULTS AND DISCUSSION

A summary of test data is given in Table 2. The effects of temperatures and pressure on sensor operation were evaluated using OP-78-3A at fluid temperatures from 65.6 to 98.9°C (150 - 210°F) and pressures of 207 kN/m<sup>2</sup> to 552 kN/m<sup>2</sup> (30 - 80 psig). The rig was actually operated at more extreme temperatures and at higher pressures, but not while pumping the test fluids.

The data collected on temperature and pressure effects are summarized in Tables 3 and 4 and graphically in Figures 4 and 5. As the data indicate, no significant effects of temperature or pressure over the range examined were found. At very low start-up temperatures, e.g. 15°C, the sensor could be put into operation by manually initiating the flush cycle repeatedly until the sensor warmed up. Later, a laboratory heat gun was focused on the unit at start-up, and insulation was used to maintain the sensor temperature. In the laboratory, this inconvenience did not pose a problem, but for test cell operation it may be necessary to decrease sensor operational temperature limits, increasing through-put initially, or add heater capabilities.

To evaluate the sensitivity of the on-line device, mixtures of new and used lubricant (ATL-7071) and additions of known debris (100-ppm Fe standard) were analyzed. Plots of those data are given in Figures 6 and 7. The on-line ferrograph grouped data are given in Table 5 for comparative purposes.

On mixing ATL-7071 into new filtered lubricant, the "wear concentration" value increased from less than 10 to 80. ATL-7071 contains more debris, both metallic and non-metallic, than would normally be encountered in turbine engine operation. The relationship between volume ratios and wear concentration was not linear due to smaller than expected values at higher wear concentrations. However, the WC does appear to be useful in estimating wear concentration.

TABLE 2. ON-LINE FERROGRAPHIC DATA

TEST	TEMP (°F)	PRESSURE (psig)	SAMPLE	SCALE	AL	AS	AL-AS	WC
1								
2	180	80	Flush 0-76-4	1-100				7.2
3	180	80	Flush 0-76-4	1-100	0.41	0.22	0.19	9.4
4	180	80	OP-78-3A	1-100	0.44	0.19	0.25	9.2
5	180	80	OP-78-3A	1-100	0.42	0.21	0.21	8.8
6	180	50	OP-78-3A	1-100	0.41	0.21	0.20	9.0
7	180	30	OP-78-3A	1-100	0.42	0.21	0.21	7.17
11	180	50	OP-78-3A	1-100	0.42	0.21	0.21	8.0
12	210	70	OP-78-3A	1-100	0.44	0.19	0.25	9.36
14	180	80	0.5 OP-78-3A/0.5 0-76-4 (Fil)	1-100	0.42	0.21	0.21	9.74
15	180	80	0.25 OP-78-3A/0.76 0-76-4 (Fil)	1-100	0.42	0.20	0.22	8.32
16	180	80	OP-130-9	1-100	0.43	0.20	0.23	5.95
17	180	80	OP-151-9	1-100	0.41	0.22	0.19	7.88
18	180	80	ATL-7071	10-1000	1.91	1.13	0.78	79.4
19	180	80	0-76-4 (Fil) Baseline	1-100	0.43	0.19	0.24	6.36
20	180	80	0-76-4 (Fil) 3 Flushes	1-100	0.42	0.20	0.22	7.4
21	180	80	0-76-4 Baseline	1-100	0.45	0.17	0.28	8.44
22	180	80	0-76-4 + 20 ml 100 ppm Fe	10-1000	2.04	1.00	1.04	73
23	180	80	0-76-4 + 40 ml 100 ppm Fe	10-1000	2.01	1.04	0.97	109
23.5	---	80	0-76-4 + 60 ml 100 ppm Fe (Marmup)	10-1000	2.04	0.99	1.05	157
24	180	80	0-76-4 + 60 ml 100 ppm Fe	10-1000	1.96	1.07	0.89	125
25	180	80	0.5 ATL 7071/0.5 0-76-4 (Fil)	10-1000	1.938	1.10	0.838	46.8

TABLE 3. EFFECT OF TEMPERATURE ON WEAR DEBRIS VARIABLES

Sample	Test No.	Temp (°F)	Press (psig)	Scale	$\overline{AT}$	$\overline{As}$	$\overline{Wc}$
OP-78-3A	4	150	80	1-100	.44	.19	9.1
OP-78-3A	5	180	80	1-100	.42	.21	8.8
OP-78-3A	12	210	70	1-100	.44	.19	9.36

TABLE 4. EFFECT OF PRESSURE ON WEAR DEBRIS VARIABLES

Sample	Test No.	Temp (°F)	Press (psig)	Scale	$\overline{AT}$	$\overline{As}$	$\overline{Wc}$
OP-78-3A	7	180	30	1-100	.42	.21	7.2
OP-78-3A	6	180	50	1-100	.41	.21	9.0
OP-78-3A	5	180	80	1-100	.42	.21	8.8

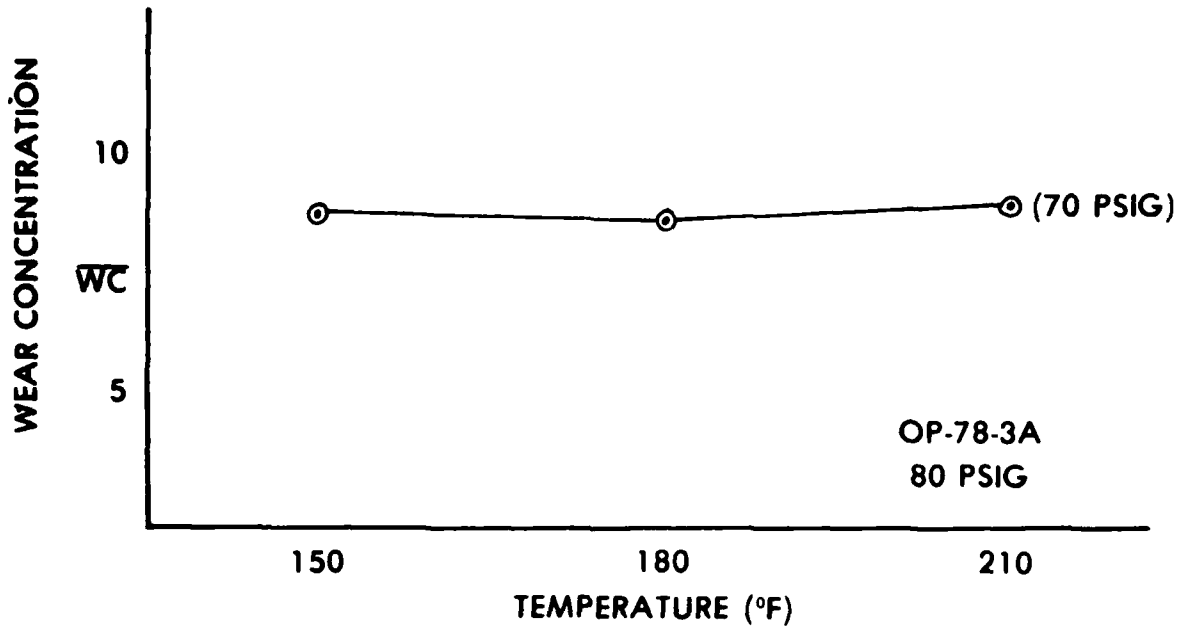


Figure 4. Effect of Temperature on Wear Concentration Output

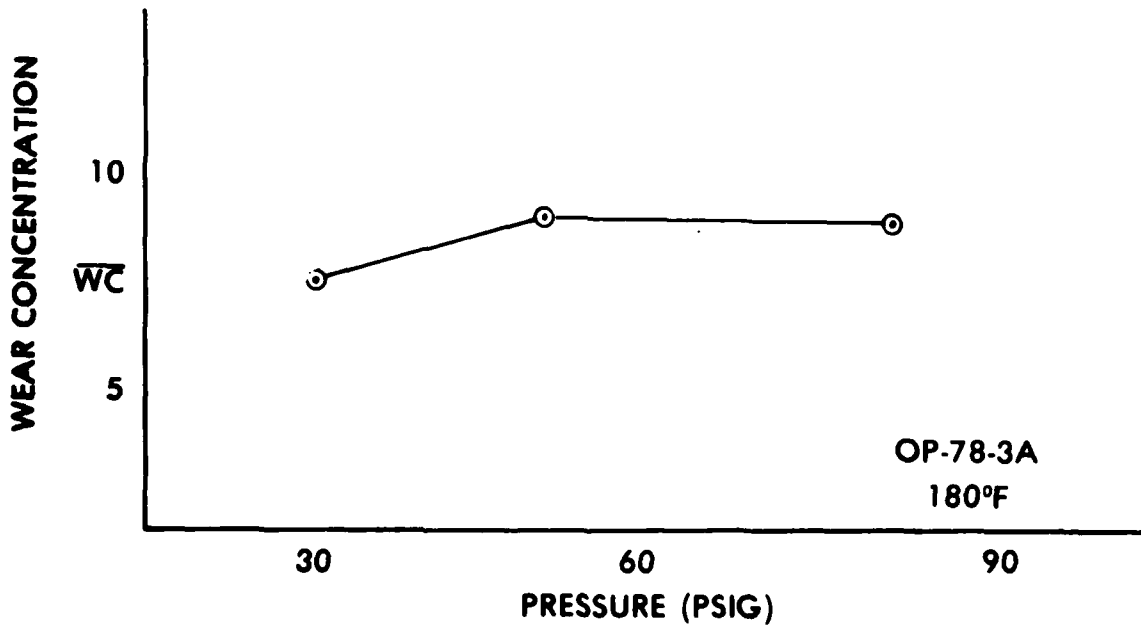


Figure 5. Effect of Pressure on Wear Concentration Output

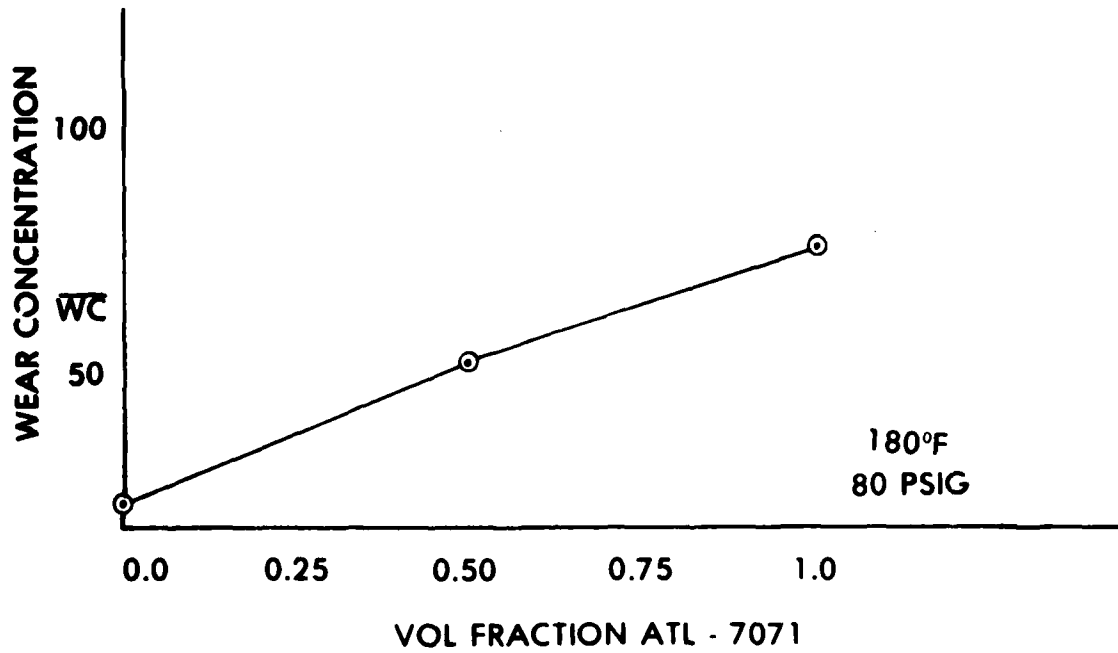


Figure 6. Effect of Sample Dilution on Wear Concentration (WC)

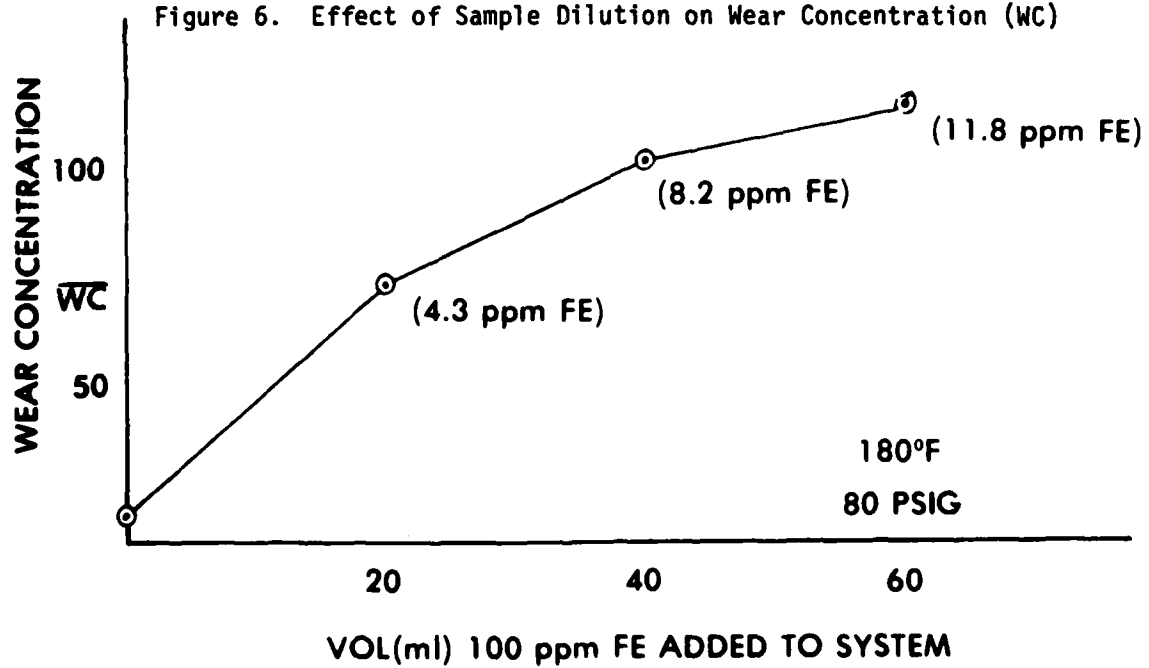


Figure 7. Effect of Ferrous Particulate Addition on Wear Concentration (WC)

TABLE 5. ON-LINE FERROGRAPH GROUPED DATA

SAMPLE	MIXTURE VOL PORTIONS	TEST NO.	TEMP (°F)	PRESS (psig)	SCALE	AT	AS	WC
OP-130-9	--	16	180	80	1-100	.43	.20	6.0
OP-151-9	--	17	180	80	1-100	.41	.22	7.9
0-76-4/OP-78-3A	1/0	19/20	180	80	1-100	.43	.19	7.4
	.75/.25	15	180	80	1-100	.42	.20	8.3
	.5/.5	14	180	80	1-100	.42	.21	9.7
	0/1	5	180	80	1-100	.42	.21	8.8
0-76-4/ATL-7071	1/0	19/20	180	80	1-100	.43	.19	7.4
	.5/5	25	180	80	10-1000	1.94	1.10	47.0
	0/1	18	180	80	10-1000	1.91	1.13	80.0
100 ppm Fe/0-76-4	20m1/453	22	180	80	10-1000	2.04	1.00	73.0
	40m1/543	23	180	80	10-1000	2.01	1.04	190.0
	60m1/453m1	24	180	80	10-1000	1.96	1.07	125.0

When small quantities of the 100 ppm standard were added to the system, significant increases in "wear concentration" were noted. Figure 7 suggests that 1 ppm of Fe addition would be detectable if the iron particulate added was of the type found in the standard. When the calculated system iron was about 11.8 ppm, the WC mean value was about 125. Thus, the on-line ferrograph appears to have adequate sensitivity to detect significant amounts of particulate iron wear debris. Analyzing the mixed 100-ppm Fe standard samples also provided an opportunity to evaluate the effects of wear debris mixing and settling. Figure 8 presents wear concentration as a function of the number of on-line analytical cycles. For the 4.3 and 8.2 ppm samples, there is a small downward trend in data, probably indicating some effects of settling. There are more significant changes in the 11.8-ppm Fe data. The initial downward slope may be rationalized by possible settling of the debris while the subsequent upward slope of data may possibly be the result of deagglomeration of debris and/or more effective mixing or particle break-up within the test loop. However, the wear concentration value did appear to be reasonably stable for each of the additions of particulate debris.

The experimental program did not provide an adequate examination of  $A_L$  and  $A_S$  values and their relationship to the wear situation in machinery. However, the quantities measured should provide a basis for comparative purposes when engine testing the device.

An extracted summary of analytical data appearing in the Appendixes is given in Table 6. Data include those from SOA, colorimetric, analytical ferrograph, particle counting and on-line ferrograph analyses. Each of the techniques is sometimes used to determine or estimate wear concentration by many laboratories. The data reported are either single values or the means of a small number of data, and caution should be employed in their use since sufficient data was not generated to determine statistical significance.

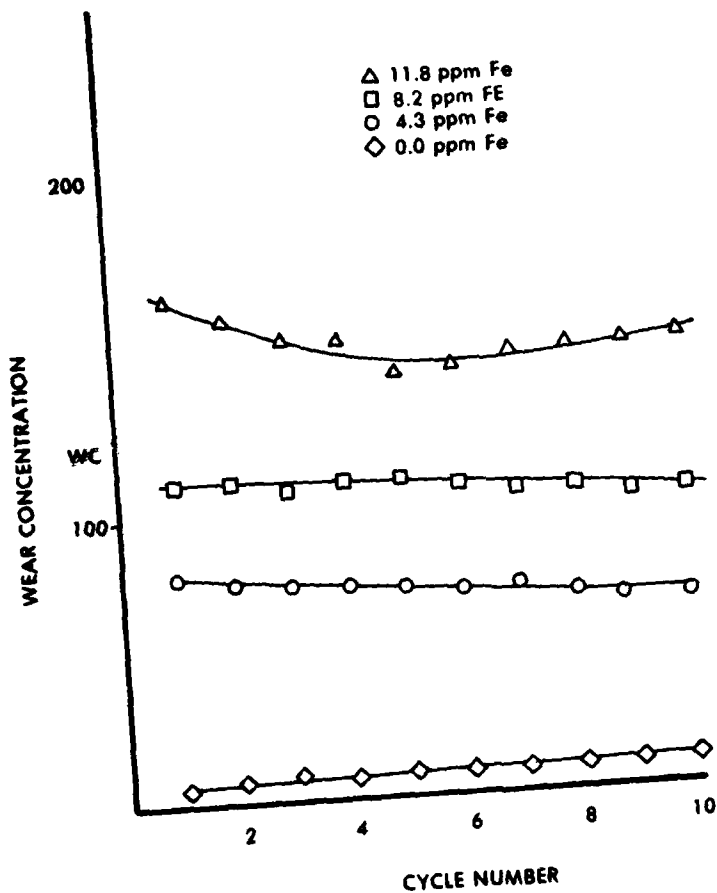


Figure 8. Wear Concentration as a Function of the Number of On-Line Ferrograph Test Cycles

TABLE 6. SUMMERIZED WEAR DEBRIS DATA

SAMPLE	SOAP Fe PPM	COLOR. Fe* PPM	ANALYTICAL FERROGRAPH % AREA COVERED (INCIDENT)	PARTICLES/m <sup>2</sup> 1-5 $\mu$ m 20-25 $\mu$ m	ON-LINE FERROGRAPH AT As WC
0-76-4	0	1	--	5340	158 0.42 0.20 7.5
OP-78-3A	15	5	1.5	--	284 0.43 0.20 9.0
OP-130-9	1	0	3.9	22580	44 0.43 0.20 6.0
ATL-7071	38	15, 30**	45	8800	9100 1.91 1.13 79.4
OP-151-9	2	0	3.9	8850	39 0.41 0.22 7.9
100 ppm Fe Standard	12	90	2050**	239600	293 16.75** 9.15 1068**

\* Method of George (Reference 3).

\*\* Max. Value Obtained by Using Reducing Acid to Aid in Oxide Dilution (Modification of George's Method).

\*\*\* Extrapolated Values

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For colorimetric analysis data, all values reported are the means of at least three analyses, however, the ATL-7071 value is reported as a range. It was possible by changing from oxidizing to reducing acid solution (Ref 6) used to dissolve and extract the ferrous debris to double the analyzed iron value. That is, the standard procedure gave Fe values of about 15 ppm, while by changing acid, it was possible to increase those values to 30 ppm. The analytical values obtained may be due to the abundance of oxides present in ATL-7071 as detected by analytical ferrography.

It is also apparent that the methods generated wear debris data which are sensitive to the nature of the debris. That point is well established when the data are normalized as given in Table 7. The data indicate, for the various types of samples employed in this program, often even the same trends in wear debris analyses are not followed.

The purpose of performing the multiple analyses was for comparison with on-line ferrograph data. On that basis, it appears that the general order found in on-line ferrographic data is also evident in analytical ferrograph results. There may also be limited correlation with particle count data. However, the other techniques did not produce values which could be correlated.

TABLE 7. NORMALIZED DEBRIS DATA

SAMPLE	SOAP Fe PPM	COLOR Fe PPM	ANALYTICAL FERROGRAM % AREA COVERED	TOTAL	PARTICLES/ml			ON-LINE FERROGRAPH		
					1-5 µm	20-25 µm	AT	AS	MC	
0-76-4	0	0.01	--	0.03	$2 \times 10^{-2}$	$1.7 \times 10^{-2}$	$3 \times 10^{-2}$	$2 \times 10^{-2}$	$7 \times 10^{-3}$	
0P-78-3A	0.39	0.06	$10^{-4}$	0.01	--	$3 \times 10^{-2}$	$3 \times 10^{-2}$	$2 \times 10^{-2}$	$8 \times 10^{-3}$	
0P-130-9	0.03	0	$2 \times 10^{-4}$	0.1	$9.4 \times 10^{-2}$	$5 \times 10^{-3}$	$3 \times 10^{-2}$	$2 \times 10^{-2}$	$6 \times 10^{-3}$	
ATL-7071	1	0.33	.02	0.4	$4 \times 10^{-2}$	1	0.11	0.12	$7 \times 10^{-2}$	
0P-151-9	0.05	0	$2 \times 10^{-4}$	.04	$4 \times 10^{-2}$	$4.3 \times 10^{-2}$	$3 \times 10^{-2}$	$2 \times 10^{-2}$	$7 \times 10^{-4}$	
100 ppm Fe STANDARD	0.32	1	1	1	1	$3.2 \times 10^{-2}$	1	1	1	

SECTION IV

CONCLUSIONS

Based upon evaluation of the on-line ferrograph on the dynamic foam rig, the following conclusions have been drawn:

- . Negligible temperature and pressure effects upon the operation of the on-line monitor were found.
- . Trends in magnetic wear debris can be detected at significant levels.
- . Direct correlation of wear debris measurements with the on-line device and other techniques, with the exception of the analytical ferrograph, was not found as might be expected.
- . The device permits wear debris quantitation in real time, requires no sampling, provides current and cycle information, and hard copy data are available in the system evaluated.
- . As noted in earlier discussions, start-up and low temperature operations along with the upper temperature limit of 125°C (257°F) may have to be considered in some applications but should not pose serious problems. Also, manual scaling is required which must be considered in a test cell environment.
- . The on-line ferrograph appears to be operational.

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SECTION V  
RECOMMENDATIONS

It is recommended that the on-line ferrograph be evaluated on a test cell engine at the earliest opportunity.

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APPENDIX A  
TEST FLUID VISCOSITIES

A. TEST FLUID VISCOSITIES

LUBRICANT	VISCOSITY	
	cS @ 37.8°C (100°F)	cS @ 98.9°C (210°F)
O-76-4	13.86	3.40
OP-78-3A	13.05	3.32
OP-130-9	14.20	3.32
OP-151-9	13.60	3.26
ATL-7071	12.65	3.26

## APPENDIX B

## EMISSION SPECTROMETRIC ANALYSIS

(PROVIDED BY RICKENBACKER AFB  
USING A BAIRD-ATOMIC-3)

## TRACE METALS (ppm)

SAMPLE	Al	Fe	Cr	Ag	Cu	Mg	Ni	Si	Ti
0-76-4	0	0	0	0	0	0	0	1	0
OP-78-3A	1	15	2	0	1	3	3	17	0
OP-130-9	0	1	0	0	0	0	0	8	0
ATL-7071	0	38	21	0	1	6	0	7	20
OP-151-9	0	2	0	0	0	0	0	4	0
100 ppm Fe	0	12	0	0	0	0	0	2	0

APPENDIX C

FERROGRAPHIC ANALYSIS OF ON-LINE SAMPLES

FERROGRAPHIC ANALYSES OF ON-LINE SAMPLES

SAMPLE (Ferrogram #)	MAXIMUM ENTRY Vol. ( $\mu\text{M}^3$ )	11X objective DENSITIES (incident)							
		E	F-5	54	50	40	30	20	10
*(Diluted 100-1) 100 ppm Fe (F374)	$8 \times 10^5$	20.5	3.2	26.9	3.7	0.4	0.6	0.7	0
OP-78-3A (F368)	$1.5 \times 10^3$	1.5	2.1	0.8	0.8	0.3	1.3	1.5	0.6
OP-130-9 (F369)	$3.2 \times 10^3$	3.9	1.0	3.0	1.9	0.7	2.7	1.3	1.3
ATL-7071 (F373)	$2.5 \times 10^6$	45.2	21.7	49.3	22.7	15.1	21.5	21.7	23.3
O-76-4FIL. (F372)	----	----	----	----	----	----	----	----	----
OP-151-9 (F370)	$1.75 \times 10^4$	3.9	3.3	4.0	4.4	3.1	3.9	4.0	3.5

\* Ferrogram of 100 ppm Fe standard sol'n. Calculated maximum entry volume for undiluted entry is  $8 \times 10^5 \mu\text{M}^3$

SAMPLE	FERROGRAM	RUBBING	CHUNKS	SPHERES	LAMINAR	SEVERE	CUTTING	CORROSIVE	OXIDES	METAL-OXIDES	NON-FERROUS	NON-METALLIC	AMORPHOUS
100 ppm Fe	F374	3	0	1	0	0	0	0	1	0	0	0	0
OP-78-3A	F368	1	1	1	0	0	0	0	1	0	X	0	1
OP-130-9	F369	1	2	1	0	0	1	0	1	0	0	0	1
ATL-7071	F373	2.5	1	0	1	0	1	3	3	1	1	1	2
O-76-4FIL.	F372	1	1	1	0	0	0	0	1	0	0	0	0
OP-151-9	F370	2	1	1	0	0	1	0	1	0	1	0	1.5

0 = NONE, 1 = FEW, 2 = MODERATE, 3 = HEAVY

APPENDIX D  
SUMMARY OF LIGHT-SCATTERING PARTICLE COUNT DATA

D	0-76-4(F11)		0P-78-3A		0P-130-9		ATL-7071		100 ppm Fe	
	N	P	N	P	N	P	N	P	N	P
1	$8.23 \times 10^3$	10.8	—	—	$2.41 \times 10^4$	3.83	$1.00 \times 10^4$	3.88	$2.52 \times 10^5$	37.7
5	$2.89 \times 10^3$	10.7	$2.15 \times 10^3$	15.4	$1.52 \times 10^3$	3.71	$1.15 \times 10^3$	3.82	$1.24 \times 10^4$	36.5
10	$1.27 \times 10^3$	10.4	$1.74 \times 10^3$	15.2	$4.53 \times 10^2$	3.52	$3.66 \times 10^2$	3.68	$3.21 \times 10^3$	34.9
15	$6.61 \times 10^2$	9.82	$1.22 \times 10^3$	14.7	$2.21 \times 10^2$	3.30	$1.83 \times 10^2$	3.49	$1.43 \times 10^3$	33.2
20	$3.80 \times 10^2$	9.55	$8.17 \times 10^2$	13.6	$1.33 \times 10^2$	3.06	$1.15 \times 10^2$	3.28	$8.00 \times 10^2$	31.5
25	$2.32 \times 10^2$	8.18	$5.33 \times 10^2$	11.9	$8.92 \times 10^1$	2.80	$7.31 \times 10^1$	3.05	$5.07 \times 10^2$	29.8
30	$1.48 \times 10^2$	7.28	$3.41 \times 10^2$	9.82	$5.44 \times 10^1$	2.54	$5.37 \times 10^1$	2.81	$3.48 \times 10^2$	28.1
35	$9.76 \times 10^1$	6.39	$2.13 \times 10^2$	7.54	$4.88 \times 10^1$	2.26	$3.97 \times 10^1$	2.56	$2.53 \times 10^2$	26.4
40	$6.61 \times 10^1$	5.53	$1.30 \times 10^2$	5.27	$3.84 \times 10^1$	1.97	$3.04 \times 10^1$	2.31	$1.91 \times 10^2$	24.7
45	$4.58 \times 10^1$	4.72	$9.54 \times 10^1$	3.97	$3.10 \times 10^1$	1.68	$2.40 \times 10^1$	2.05	$1.49 \times 10^2$	23.1
50	$3.23 \times 10^1$	3.97	—	—	$2.37 \times 10^1$	1.56	$1.93 \times 10^1$	1.79	$1.19 \times 10^2$	21.4
55	$2.32 \times 10^1$	3.28	—	—	—	—	$1.58 \times 10^1$	1.53	$9.75 \times 10^1$	19.7
60	$1.68 \times 10^1$	2.66	—	—	—	—	$1.47 \times 10^1$	1.42	$8.09 \times 10^1$	18.1
65	$1.24 \times 10^1$	2.09	—	—	—	—	—	—	$6.82 \times 10^1$	16.5
70	9.76	1.68	—	—	—	—	—	—	$5.81 \times 10^1$	14.9
75	—	—	—	—	—	—	—	—	$5.00 \times 10^1$	13.2
80	—	—	—	—	—	—	—	—	$4.83 \times 10^1$	11.7

N = Number of Particles, per  $\text{cm}^3$  of Sample, which have a diameter larger than D  
 P = Volume of Particles, in ppm of sample, which have a diameter larger than D  
 D = Diameter of Particles in microns