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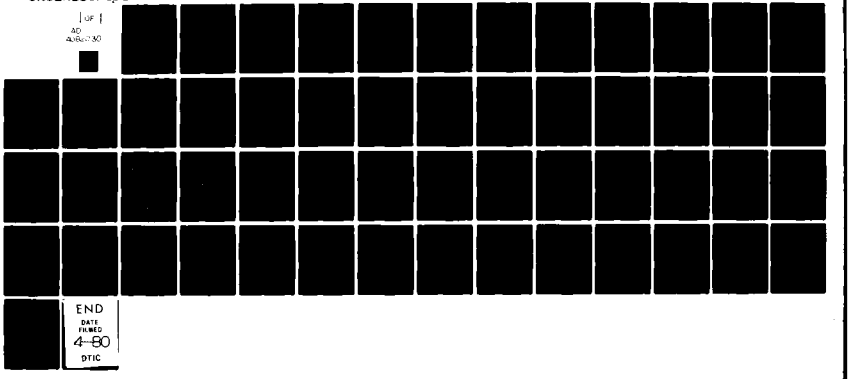

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PARTICLE-SIZE ANALYSIS OF ENGINE OILS
A Supplement to Spectrometric Analysis

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

Kent J. Eisentraut

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Particle Volume Distribution

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The Spectrometric Oil Analysis Program (SOAP) is a maintenance system used by the Air Force for continuous monitoring of engine oil samples. Total mass concentrations of various metals are measured to provide an indication of engine wear and to warn of impending malfunction; such data provide a basis for scheduling maintenance action in advance of failure. Supplementary methods of analysis are sought with the objective of characterizing oil samples more completely so as to sharpen SOAP decision criteria and achieve improvements
(Continued)

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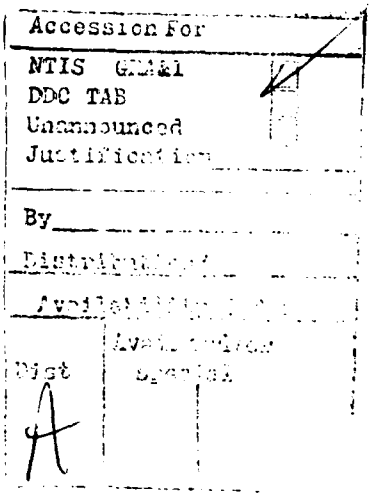
in reliability and cost effectiveness. One such technique is particle counting, which defines the size distribution of wear-metal particles and other debris if present. This report describes exploratory work which establishes a methodology for particle-size analysis of authentic engine oils and shows how the data can be applied for practical decision making. Indications are that the engine failure rate can be reduced to about 16% of its current level by supplementing each spectrometric analysis with a particle count. Instrumentation and technique are susceptible to automation which would permit the necessary particle size analysis to be made routinely in a SOAP laboratory within three minutes per sample. An approach to the problems of realizing and exploiting this potential is outlined.

PREFACE

This work was performed under Project 2303, Task Q2, Work Unit Directive #4. Dr. Kent J. Eisentraut of the Air Force Materials Laboratory monitored the effort; his encouragement and support, including the use of laboratory facilities and equipment, are gratefully acknowledged. Special thanks are due also to Mr. Julius G. Becsey of the Aeronautical Systems Division, who contributed invaluable help in developing the computer program described in this report.



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SECTION I

INTRODUCTION

In order to monitor the condition of each aircraft engine in its fleet, the Air Force periodically samples the lubricating oil and makes a spectrometric analysis of the metal content. These measurements serve as a guide to identify abnormal wear of parts and to schedule inspections or overhauls. As presently operated, the Spectrometric Oil Analysis Program (SOAP) prescribes alert levels for the concentration of critical metals for each engine type, and mandates particular actions in the field when such levels are detected. Pre-emptive time-scheduled maintenance is performed at long intervals on engines not flagged in the interim by SOAP.

The efficiency of the SOAP system is assessed by means of an after-the-fact classification of each sample analyzed. Four categories are defined:

a. Failure. An oil-wetted part failed although the immediately preceding spectrometric analysis was within prescribed limits.

b. Hit. The spectrometric analysis fell outside prescribed limits and the immediately subsequent inspection of the engine revealed damage to a part.

c. Routine. The spectrometric analysis fell within limits and no engine malfunction occurred prior to the next spectrometric analysis.

d. Miss. The spectrometric analysis fell outside limits but no damage was found upon inspection.

Some two million samples are analyzed each year at more than a hundred laboratories world-wide. Of these, the vast bulk are routines; all other categories are comparatively rare. Failures run about 100-200 annually,

hits 1200-1300, and misses 50-60. Yet the SOAP program pays for its considerable cost (estimated at around $10 per analysis) by the detection of the relatively small fraction of hits, each of which represents the averting of a possible failure that could result in the loss of an engine, an airplane, or the lives of aircrew. Prevention of failure is the central purpose of the program, and the goal of research and development in SOAP technology is to decrease the ratio of failures to hits. Even small improvements in this ratio exert a large favorable leverage on the cost-effectiveness of SOAP.

Various supplementary methods of analysis are under investigation with the aim of characterizing oil samples more completely to fine-tune the capability of SOAP with respect to identifying incipient failure. One such technique is particle counting, which defines the size distribution of wear metals and other particulate debris if present. This report develops a rationale whereby the measured total volume of particulates in a sample is compared with an expected value inferred from spectrometric analysis of the same sample. Experiments on authentic oil specimens, using this method of screening, indicate that the effectiveness of SOAP in preventing engine failure can be increased about sixfold by supplementing each spectrometric analysis with a particle count.

SECTION II

EXPERIMENTAL PROCEDURE

Equipment

The particle counter used in this work is a commercially available light scattering laser-beam instrument (Spectrex ILI-1000). A helium-neon laser beam (wavelength 0.6328 microns) scans the sample in a circular path for a measured period of time, and a photodetector collects pulses scattered forward by suspended particles. The intensity of each pulse is proportional to the square of the diameter of the scatterer, which is assumed spherical. The optics are designed to focus only pulses which originate within a zone of limited length (about 2 centimeters), the boundaries of which lie within the sample. This length, together with the diameter of the beam and the fixed circular rate of beam travel, determines the volumetric scan rate, which amounts to 0.6165 cm^3 per second for our particular instrument. The counter is coupled to a 15-channel pulse-height discriminator which sorts and stores counts according to their intensity---thus, according to the size of the scatterer generating the pulse. An additional summation channel counts all pulses received by the 15 sorting channels. Particles smaller than 1-2 microns do not scatter light at the laser wavelength and cannot be detected.

In order to avoid multiple scattering of pulses and also keep the rate of arrival of pulses within the resolving power of the detector, it is required that the total concentration of particles not exceed about 1500 per cm^3. Further, the pulse intensity received at the detector from a particle of a given size is dependent upon the attenuation (if any) of the laser beam due to absorption by the liquid under examination; a correction for this effect can be made if the opacity of the specimen is independently

measured, and this must be done as a part of the counting experiment. An opacity of 35% is about the limit for convenient operation; above this limit, the detector rapidly and progressively goes blind, except to strong pulses (from large particles). For these reasons it is necessary to dilute oil samples before counting, since both the particle concentration and the opacity of most used engine oils are well beyond the bounds mentioned.

Our particular assembly of equipment was calibrated before use against a standard polydisperse suspension of polystyrene spheres in water, the total concentration and size distribution of which were traceable to NBS determinations. Table 1 summarizes the results, showing the boundaries (in microns) of each of the fifteen channels as a function of opacity. This calibration is peculiar to the particular items of hardware and to the specific bias applied to the pulse-height discriminator; the design of the manufacturer's equipment does not permit any parameter of the system to be varied independently of all the rest, although a different biassing would result in a different calibration. The boundaries shown in Table 1 adequately cover the range of particle sizes found in engine oils.

Technique

A procedure was developed by means of which a useful particle count could be accomplished in a total time of 25 minutes with the general-purpose counter just described. Although this is too time-consuming for use as a field method, it was quite satisfactory for the intended purpose of assessing the usefulness of particle counting. Adaptation to field use appears to be a straightforward problem; this matter will be discussed later.

In the present work, the oil sample to be examined was diluted to reduce the opacity and particle concentration to tolerable values. As a

TABLE 1. CALIBRATION OF PARTICLE COUNTER

Spectrex ILI-1000 Serial No. 131, Coupled to Particle Profile Attachment Serial No. 0038

Bias Settings: Gain = 500, Threshold = 260

Entries show particle diameters, in microns, which bound each channel as a function of opacity

Channel	Opacity						
	7.5	10	15	20	25	30	35
01	2.07	2.16	2.34	2.53	2.74	2.96	3.21
02	5.22	5.42	5.86	6.32	6.83	7.37	7.96
03	10.67	11.07	11.94	12.86	13.87	14.94	16.11
04	16.17	16.77	18.06	19.44	20.93	22.53	24.26
05	24.36	25.26	27.16	29.20	31.41	33.78	36.32
06	32.07	33.24	35.71	38.37	41.25	44.32	47.62
07	36.26	37.57	40.36	43.35	46.58	50.04	53.75
08	39.82	41.26	44.31	47.58	51.11	54.89	58.94
09	43.01	44.56	47.84	51.36	55.17	59.23	63.59
10	45.88	47.52	51.02	54.76	58.81	63.14	67.77
11	48.72	50.46	54.16	58.13	62.42	66.99	71.90
12	51.37	53.20	57.10	61.27	65.78	70.59	75.75
13	54.15	56.08	60.17	64.56	69.30	74.37	79.79
14	56.68	58.69	62.97	67.56	72.51	77.80	83.46
15	59.45	61.56	66.04	70.84	76.02	81.55	87.48
	62.27	64.47	69.16	74.17	79.59	85.37	91.57

diluent, we used a fixed volume---usually 12.5 cm^3---of heavy white paraffin oil (opacity 7.5%, due entirely to reflection at the cell windows) contained in a conventional spectrophotometer cell of 5 cm path length. The engine oil was pipetted in to produce a suspension of known dilution, usually about 70 fold; in exceptional cases a lower dilution may be used to accomodate an oil having very low particle concentration. The mixture was well shaken and then degassed for a minute or two at low (house) vacuum in a desiccator. The opacity was then measured with an accessory photometer. A single run consisted of a preliminary blank count on the paraffin, followed by a second count after addition of the engine oil. The counting time was 450 seconds in each case---found by experience to be about the minimum required to give reproducible counting statistics in the highest populated channels. The viscosity of the paraffin (about 80 centipoise) was sufficient to obviate any appreciable sedimentation during the counting period. Counts stored in the pulse-height discriminator for both blank and sample were printed out in hard copy for each of the channels; these data, along with the measured dilution and opacity, were fed off-line to a computer and worked up by a program called NEWPART.

The NEWPART program

This computer program has been developed for the purpose of transforming the raw particle-count data into a table showing, for round values of the particle diameter at 5-micron intervals, two quantities N and P, defined as follows:

N = number of particles, per cm^3 of oil as received, which are larger than the listed diameter

P = volume of particles, microliters per liter of oil as received, which are larger than the listed diameter

```
SAMPLE F35****
              COMPUTATION TIME=    7.7 SECONDS
                    PREC(A,K)= .000100

A(BLANK )=7.552E+00    K(BLANK )=1.550E-01    N0= 2.669E+05      449 ITERATIONS


SAMPLE F35****
              COMPUTATION TIME=    6.4 SECONDS
                    PREC(A,K)= .000100

                  DILUTION= 6.350E+01

A(SAMPLE)=3.663E+00    K(SAMPLE)=2.188E-01    N0= 5.781E+03      352 ITERATIONS


          SUMMARY OF RESULTS

       D        N            P

       2    1.39E+03     6.83E+00   BELOW THIS DIA, N IS UNCERTAIN. INCREASE IN P IS NEGLIGIBLE.
       5    9.57E+02     6.82E+00
      10    5.05E+02     6.73E+00
      15    3.13E+02     6.54E+00
      20    2.14E+02     6.26E+00
      25    1.55E+02     5.92E+00
      30    1.17E+02     5.51E+00
      35    9.16E+01     5.05E+00
      40    7.33E+01     4.55E+00
      45    5.98E+01     4.01E+00
      50    4.96E+01     3.44E+00
      51    4.79E+01     3.33E+00   ABOVE THIS DIA, N AND P APPROACH ZERO RAPIDLY.

  N=NUMBER OF PARTICLES,PER CM3 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
```

Figure 1. Newpart Output for Authentic Oil Sample F35

```
SAMPLE R554****
              COMPUTATION TIME=    2.9 SECONDS
                    PREC(A,K)= .000100

A(BLANK )=1.183E+00    K(BLANK )=4.950E-01    N0= 1.282E+02      261 ITERATIONS


SAMPLE R554****
              COMPUTATION TIME=    4.8 SECONDS
                    PREC(A,K)= .000100

                  DILUTION= 3.230E+01

A(SAMPLE)=4.509E+00    K(SAMPLE)=2.753E-01    N0= 4.519E+04      431 ITERATIONS


           SUMMARY OF RESULTS

      D        N            P

      1     1.48E+04     5.23E-01   BELOW THIS DIA, N IS UNCERTAIN. INCREASE IN P IS NEGLIGIBLE.
      5     1.00E+03     4.35E-01
     10     1.95E+02     2.96E-01
     15     6.38E+01     1.75E-01
     18     3.74E+01     1.14E-01   ABOVE THIS DIA, N AND P APPROACH ZERO RAPIDLY.

   N=NUMBER OF PARTICLES,PER CM3 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
```

Figure 2. Newpart Output for Authentic Oil Sample R554

```
SAMPLE R437****
              COMPUTATION TIME=    4.5 SECONDS
                    PREC(A,K)= .000100

A(BLANK )=8.745E+00    K(BLANK )=1.911E-01    NO= 3.089E+06      400 ITERATIONS


SAMPLE R437****
              COMPUTATION TIME=    2.9 SECONDS
                    PREC(A,K)= .000100

                  DILUTION= 7.350E+01

A(SAMPLE)=1.085E+01    K(SAMPLE)=1.664E-01    NO= 3.224E+07      440 ITERATIONS



 NO SIGNIFICANT PARTICLE COUNT IN THIS SAMPLE.
 OLOW=  1    OHIGH=  4
 (SEE TABLE FOR Z VALUES PRINTED ON NEXT PAGE)
```

Figure 3. Newpart Output for Authentic Oil Sample R437

Certain mathematical constants generated during the data reduction are also recorded. Figures 1 through 3 are typical NEWPART printouts for authentic oils.

Table 2 gives a quick overview of the functions of this program, and Appendix A is a complete listing in FORTRAN language. A few comments may be helpful in illuminating essential details.

The input is supplied on punched cards. A parity check assures that the sum of all channel counts equals the total number of counts; this provides a safeguard against errors in keypunching.

The data for blank and sample are separately smoothed by a logarithmic fit of the function.

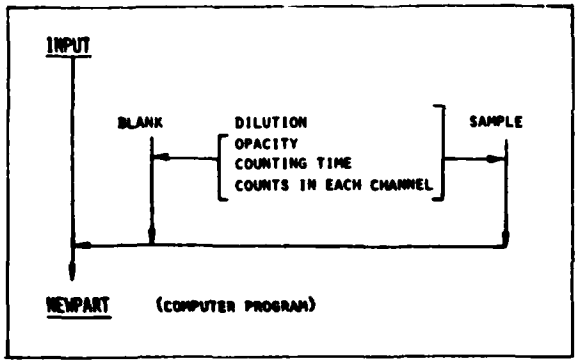
$$N = N_0 \exp(-aD^k) + N_0 \exp(-aD_{15}^k) \qquad (1)$$

which contains three adjustable constants (N_0, a, and k) and is formally similar to a Weibull distribution. However, we must regard it only as an empirical equation which fits available data well---a graphic example is shown in Figure 6 later on---and marshals them in a convenient form for analysis. The second term on the right arises from the fact that the top of channel 15 is closed, rather than open ended, so that particles larger than this top limit will not be counted even if present; but they will presumably lie on the curve.

With respect to the low cutoff diameter D_{LO}, we take this either as one micron (the smallest dimension visible to the particle counter) or as the smallest integer diameter for which the difference between the sample and blank curves is positive, whichever is greater. Extrapolation of the fitted curves to regions of smaller D generally yields specious values (predicts too

TABLE 2.

SYNOPSIS OF DATA PROCESSING



NEWPART

FOR BOTH BLANK AND SAMPLE:

A. GENERATES LIST OF TOTAL COUNTS Y LYING ABOVE LOWER DIAMETER BOUNDING EACH CHANNEL.

B. FITS THESE Y, D DATA WITH THE EQUATION

$$\ln N = \ln N_0 + \ln\left[e^{-aD^k} + e^{-aD_{15}^k}\right], \quad N = cY/t$$

WHERE N IS THE NUMBER OF PARTICLES LARGER THAN D PER CM^3, C IS A KNOWN INSTRUMENTAL CONSTANT, t IS THE COUNTING TIME, AND D_{15} IS THE UPPER BOUND OF CHANNEL FIFTEEN.

USING THE TWO FITTED CURVES:

C. FINDS SMALLEST NON-ZERO INTEGER DIAMETER D_{LO} WHICH SATISFIES THE CONDITION $N_S > N_B$ (USUALLY ONE MICRON).

D. COMPUTES A HIGH CUTOFF-DIAMETER D_{HI} AT WHICH THERE IS A FIFTY-FIFTY PROBABILITY (FROM POISSON STATISTICS) THAT NO SIGNIFICANT DIFFERENCE EXISTS BETWEEN N_S AND N_B.

E. IN THE RANGE $D_{LO} \leq D \leq D_{HI}$ CALCULATES OUTPUT DATA DESCRIBING PARTICLE POPULATION OF THE OIL SPECIMEN AS RECEIVED.

OUTPUT

OUTPUT

TABLE SHOWING, FOR ROUND VALUES OF D IN MICRONS, RUNNING VALUES OF TWO QUANTITIES N AND P ESTIMATED FOR THE ORIGINAL OIL SPECIMEN BEFORE DILUTION.

$N(D)$ = NUMBER OF PARTICLES LARGER THAN D, PER CM^3 OF OIL

$$= \text{DIL.}\left[N_S(D) - N_B(D)\right]$$

$P(D)$ = VOLUME OF PARTICLES LARGER THAN D, PER MILLION VOLUMES OF OIL

$$= \text{DIL.}\frac{\pi}{6}\cdot 10^{-6}\left[\int_{D_{LO}}^{D} D^3 \frac{dN_S}{dD}\,dD - \int_{D_{LO}}^{D} D^3 \frac{dN_S}{dD}\,dD + N_{LO} D_{LO}^3\right]$$

high a concentration); in particular, N_o is not a physically meaningful estimate of the total number of particles.

The high diameter cutoff D_{HI} expresses the fact that no real sample contains indefinitely large particles. Counts in the highest channels are rare events, governed by Poisson statistics in which the standard errors of N_B and N_S approach the square roots of the respective quantities. We may then apply the conventional criterion

$$Z = (N_S - N_B)/(N_S + N_B)^{1/2} \qquad (2)$$

to determine whether or not a significant difference exists between sample and blank. We choose (arbitrarily) to declare the difference in concentration as insignificant at the 50% level, for which Z = 0.675. A different criterion would raise or lower D_{HI} slightly, but the choice is not critical.

Once D_{LO} and D_{HI} have been determined, the quantity P(D) is computed for round values of D at 5- micron intervals in the range $D_{LO}<D<D_{HI}$ as indicated in the synopsis. The integration may be made by straightforward numerical quadrature or by noting that each of the two integrals (blank and sample) may be expressed in terms of incomplete gamma functions:

$$\int_{D_{LO}}^{D} D^3(dN/dD)dD = - N_o\, a^{-3/k}\left[\Gamma_{aD^k}(1+3/k) - \Gamma_{aD_{LO}^k}(1+3/k)\right] \qquad (3)$$

Efficient algorithms are available to evaluate the gamma functions and these are used by NEWPART rather than the more cumbersome numerical integration. The additional term in $N_{HI}\ D_{HI}^3$ is simply a rough estimate of the volume

(usually small) of those particles which may be distributed in some undefined way above the high cutoff diameter; there is a 50% probability that this increment is genuine for any given sample.

It is well to emphasize that NEWPART as listed contains the instrument calibration data shown in Table 1. If a different instrument were used, or if the bias were changed on the same instrument, the appropriate data would have to be introduced into NEWPART to replace the present tabulation.

Finally, note Figure 3, which states NO SIGNIFICANT PARTICLE COUNT IN THIS SAMPLE. The computer program returns this message in any case for which the fitted blank curve (N vs D) lies everywhere above the sample curve, or for which $D_{HI} < 5$ microns with a correspondingly small and uncertain maximum value of P corresponding to D_{LO}--- usually less than .05. This nil finding occurs rather frequently in the examination of authentic engine oils.

Synthetic suspensions

In order to test the validity of both the experimental techniques and the data reduction program, measurements were made on synthetic suspensions having known properties.

One such experiment was to make a normal 450-second count on the standard suspension of polystyrene spheres against which the instrument was originally calibrated. This was fundamentally a test of the computer program, although it also would reveal any outright blunders in performing the calibration. Figure 4 is a NEWPART printout, using an artificial blank input of negligible particle content. Superimposed on the printout is a table of the known values of N vs D for the standard, together with values of P

BLUE CAP STANDARD****
COMPUTATION TIME= 1.6 SECONDS
PREC(A,K)= .000100

A(BLANK)=1.767E+00 K(BLANK)=4.462E-01 NO= 1.453E+08 335 ITERATIONS

BLUE CAP STANDARD****
COMPUTATION TIME= 4.0 SECONDS
PREC(A,K)= .000100

DILUTION= 1.000E+00

A(SAMPLE)=4.820E-01 K(SAMPLE)=4.970E-01 NO= 1.801E+03 193 ITERATIONS

SUMMARY OF RESULTS

D	N	P	
1	1.11E+03	1.49E+01	BELOW THIS DIA,
5	6.16E+02	1.49E+01	
10	3.95E+02	1.49E+01	
15	2.93E+02	1.47E+01	
20	2.13E+02	1.45E+01	
25	1.66E+02	1.43E+01	
30	1.32E+02	1.39E+01	
35	1.07E+02	1.35E+01	
40	8.83E+01	1.29E+01	
45	7.36E+01	1.24E+01	
50	6.20E+01	1.17E+01	
55	5.27E+01	1.10E+01	
60	4.50E+01	1.02E+01	
65	3.88E+01	9.45E+00	
70	3.36E+01	8.61E+00	
75	2.92E+01	7.74E+00	
80	2.55E+01	6.85E+00	ABOVE THIS DIA

TRUE VALUES FOR STANDARD

D	N	P	
1	1.10E+03	1.48E+01	:N P IS NEGLIGIBLE.
5	6.16E+02	1.48E+01	
10	3.95E+02	1.48E+01	
15	2.82E+02	1.46E+01	
20	2.12E+02	1.44E+01	
25	1.65E+02	1.42E+01	
30	1.31E+02	1.38E+01	
35	1.07E+02	1.34E+01	
40	8.78E+01	1.28E+01	
45	7.31E+01	1.22E+01	
50	6.15E+01	1.16E+01	
55	5.22E+01	1.09E+01	
60	4.46E+01	1.01E+01	
65	3.83E+01	9.34E+00	
70	3.32E+01	8.50E+00	
75	2.88E+01	7.64E+00	
80	2.52E+01	6.75E+00	:DLY.

N=NUMBER OF PARTICLES,PER CM3 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

Figure 4. Analysis of Calibration Standard

derived by numerical integration. These data are seen to agree well with the corresponding values generated by NEWPART. The concordance could presumably be improved further by increasing the counting time, but this test indicates that the normal 450-second run is adequate for practical purposes.

A second kind of test consists of counting a suspension for which the total volume of particles is directly known---prepared by weighing out a quantity of pure metal powder and dispersing it into a known mass (or volume) of clean paraffin oil. A specimen of this suspension, diluted if necessary, is counted; the value of P (for D_{LO}) derived from the particle count is then compared with the value which is obtained by a trivial calculation involving the known densities of the paraffin and the metal in question. This experiment has been performed many times with uniformly satisfactory results; the NEWPART estimate consistently lies within $\pm$ 3% of the true value. Table 3 shows the results of one such experiment which is particularly interesting because it was a blind test; the suspension was prepared by a colleague, and neither the mass concentration nor the identity of the metal was revealed until after the particle count (Figure 5) had been made. Figure 6 is a plot of the raw values of N for sample and blank showing the best-fitted particle size distribution curves (Equation 1) and the cutoff diameters generated in the NEWPART analysis.

TABLE 3. TEST ON SYNTHETIC SAMPLE

IDENTITY OF SAMPLE: MAGNESIUM POWDER SUSPENDED IN PARAFFIN OIL
(PREPARED BY DIRECT WEIGHING OF METAL AND OIL)

NEWPART OUTPUT: P = 96.6 MICROLITERS METAL/LITER PARAFFIN

PREDICTED MASS CONCENTRATION:

$$M = P \times \frac{\text{DENSITY OF MAGNESIUM}}{\text{DENSITY OF PARAFFIN}} = \frac{96.6 \times 1.74}{.857} = 196. \text{ PPM}$$

ACTUAL MASS CONCENTRATION: M = 199. PPM

```
SYNTHETIC SAMPLE****
              COMPUTATION TIME=    9.0 SECONDS
                    PREC(A,K)= .000100

A(BLANK )=5.470E+01    K(BLANK )=3.098E-02    N0= 6.862E+25      440 ITERATIONS


SYNTHETIC SAMPLE****
              COMPUTATION TIME=    4.5 SECONDS
                    PREC(A,K)= .000100

                  DILUTION= 7.350E+01

A(SAMPLE)=1.087E-01    K(SAMPLE)=1.138E+00    N0= 1.904E+03      222 ITERATIONS


           SUMMARY OF RESULTS

       D        N           P

       1    1.17E+05    9.66E+01   BELOW THIS DIA, N IS UNCERTAIN. INCREASE IN P IS NEGLIGIBLE.
       5    7.05E+04    9.56E+01
      10    3.13E+04    8.70E+01
      15    1.30E+04    6.91E+01
      20    5.19E+03    4.80E+01
      25    1.99E+03    2.97E+01
      30    7.41E+02    1.65E+01
      35    2.65E+02    8.23E+00
      40    8.93E+01    3.51E+00
      43    4.41E+01    1.84E+00   ABOVE THIS DIA, N AND P APPROACH ZERO RAPIDLY.

  N=NUMBER OF PARTICLES,PER CM3 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
```

Figure 5. Analysis of Synthetic Suspension of magnesium powder in paraffin oil

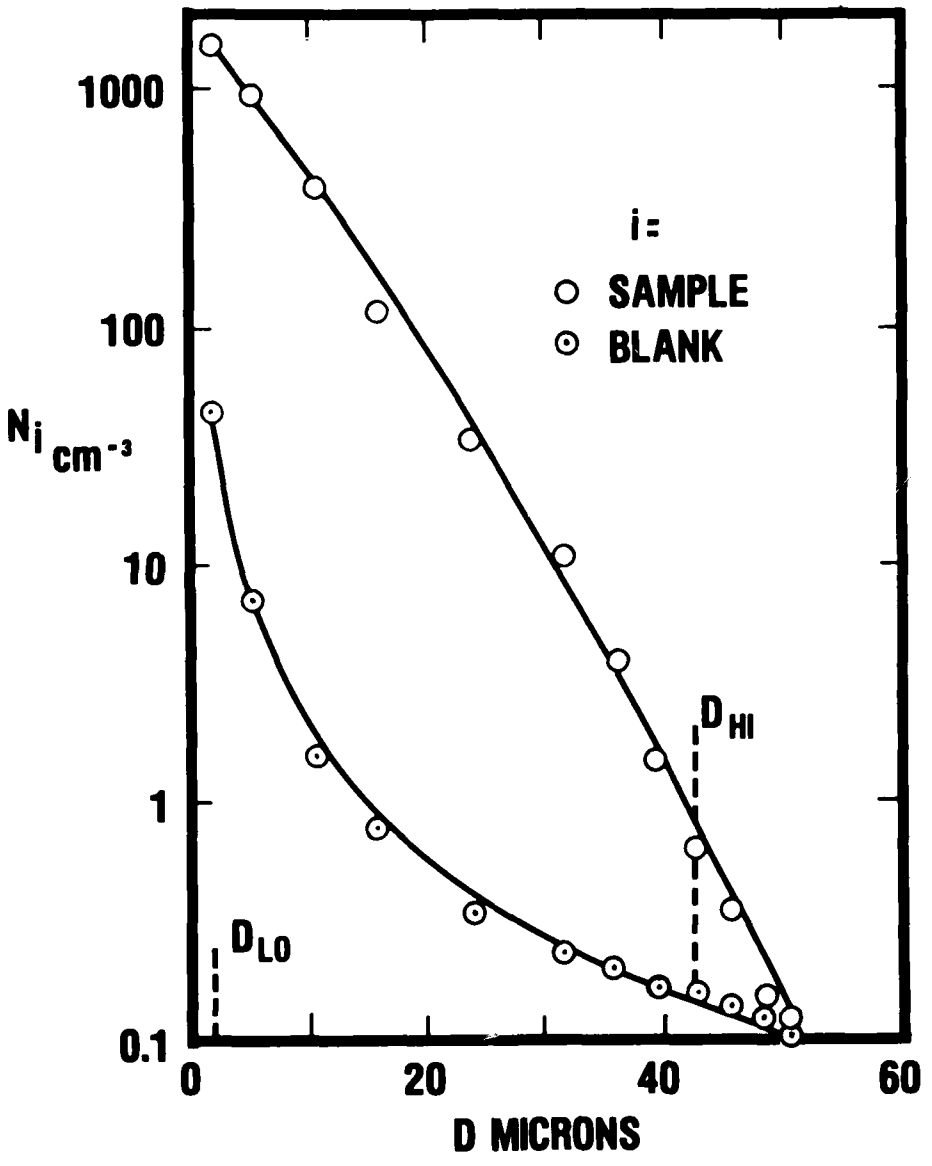


Figure 6. Raw Data for Synthetic Suspension of magnesium powder in paraffin oil, showing best-fitted curves generated by NEWPART program

SECTION III

EXAMINATION OF AUTHENTIC OILS

Data base

Over the past 18 months, AFML has received periodic inputs of authentic oil samples collected in the field, together with the spectrometric metal analysis made by a SOAP laboratory. These samples include all SOAP failures and hits experienced at the several participating Air Force stations, plus a random selection of routines, comprising in all a stock of about 1000 specimens of oil. Out of this grand lot, a sub-lot of 200 samples was subjected to particle counting by the procedure already described.

The essential data from these experiments are collected for reference in Appendix B. All available failures (31) were examined, the remainder being hits (24) and routines (145) randomly chosen; no misses were received from the field. The samples analyzed represent a variety of aircraft and engine types; the service age of the oils at the time of sampling covers a wide range.

For each sample, we list two parameters, X and Y, which form the basis of the screening system to be described presently. X is the total value of P, corresponding to D_{LO}, as reported by the NEWPART program. Y is an independent estimate of P inferred from the spectrometric analysis of the same sample, given by

$$Y = \rho \sum m_i V_i \qquad (4)$$

where m_i and V_i are respectively the spectrometric mass concentration (ppm) and the specific volume of the metal i, and ρ is the density of the lubricating oil (0.85 gm/cm^3 to a sufficiently good approximation). The following tabulation shows the specific volumes (cm^3/gm) of the twelve metals customarily determined

in SOAP analyses.

Al	0.37	Pb	0.09	Si	0.43
Cr	0.14	Mg	0.57	Ag	0.10
Cu	0.11	Mo	0.10	Sn	0.14
Fe	0.13	Ni	0.11	Ti	0.22

Metal particles in oil are of course usually present as alloys rather than in pure form. Equation 4 contains the implicit assumption that the specific volume of an alloy is a linear function of this property for its constituent metals.

To make this matter clear by a specific example, refer to the entry for sample F-035 in Appendix B and to Figure 1, which is the particle count for this sample. The entry for X in Appendix B is 6.83, which is simply the value of P read from Figure 1 at D_{LO}. To compute Y, we must know the spectrometric analysis for this sample. The result reported by the SOAP laboratory (ppm by mass) was Al = 5, Cr = 1, Mg = 1, and Si = 10, no other metals being detected. Applying Equation 4 gives Y = 5.83 as shown in Appendix B. Entries for all other samples are the result of the same process, requiring both a particle count and a spectrometric analysis.

Interpretation of Data

We now construct a rationale to show how particle-count data can be applied to supplement spectrometric analysis and improve SOAP decision-making. The scheme rests on the comparison of X and Y values for the samples in question. If the ratio X/Y exceeds unity, the sample is considered defective whether or not established SOAP protocols mandate an alarm. The argument is as follows.

A value X/Y>1 constitutes evidence for the existence of one or both of two conditions:

a. Large particles of metal are being generated, above 10-15 microns in diameter, which is the upper limit of effective spectrometric analyzability for most metals. Appearance of such large metal particles, undetected by spectrometry, is generally indicative of the onset of shaving, milling, or fatigue phenomena which are not normal wear modes.

b. The oil contains substantial quantities of non-metallic debris which in no event could be detected by spectrometric analyses. Such particles may originate from degradation of the oil itself through polymerization or sludge formation, or from external contamination by dirt, water, or damage to non-metallic seals and gaskets. Presence of such debris is an early warning of sub-standard oil condition presaging eventual increases in wear-metal production.

On the other hand, if X/Y<1 and if the spectrometric analysis lies within established limits, normal wear is indicated. The particle size distribution of wear metal (and of non-metallic debris, if present) is such that most particles do not exceed 1-2 microns in linear dimension---the smallest size of object visible to the particle counter. Therefore, oil and engine are operating in a healthy condition.

In brief, it is suggested that the existing single spectrometric test should be augmented by the introduction of a second screen (particle counting). The oil sample is then required to pass <u>both</u> tests. Figure 7 shows the scheme graphically.

Results and discussion

The feasibility of the dual-screening principle is readily demonstrated. Figure 8 is an X,Y plot of the extant data, showing that spectrometric routines (open circles) fall predominantly below the curve X = Y, whereas most failures

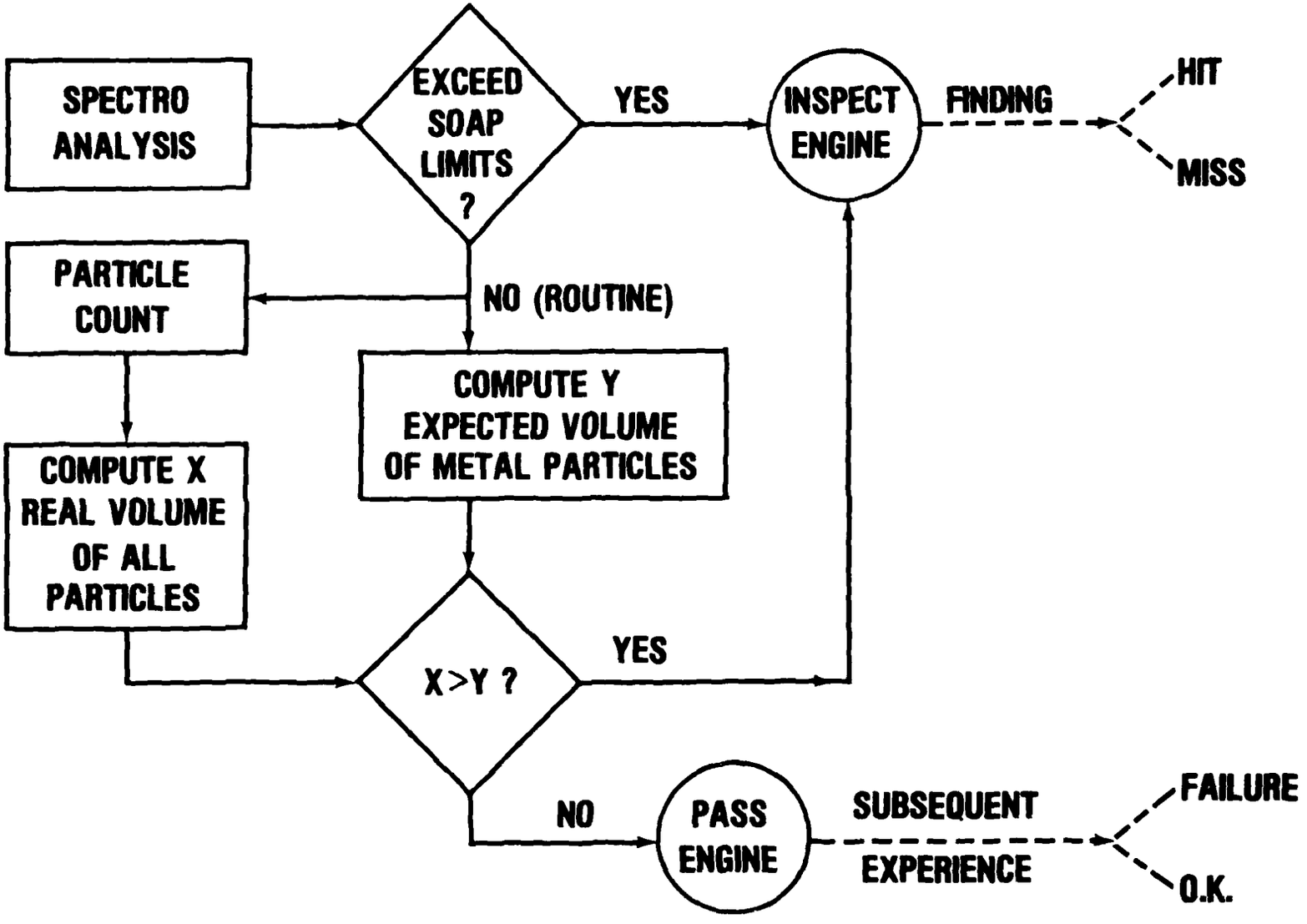


Figure 7, Dual Screening Scheme

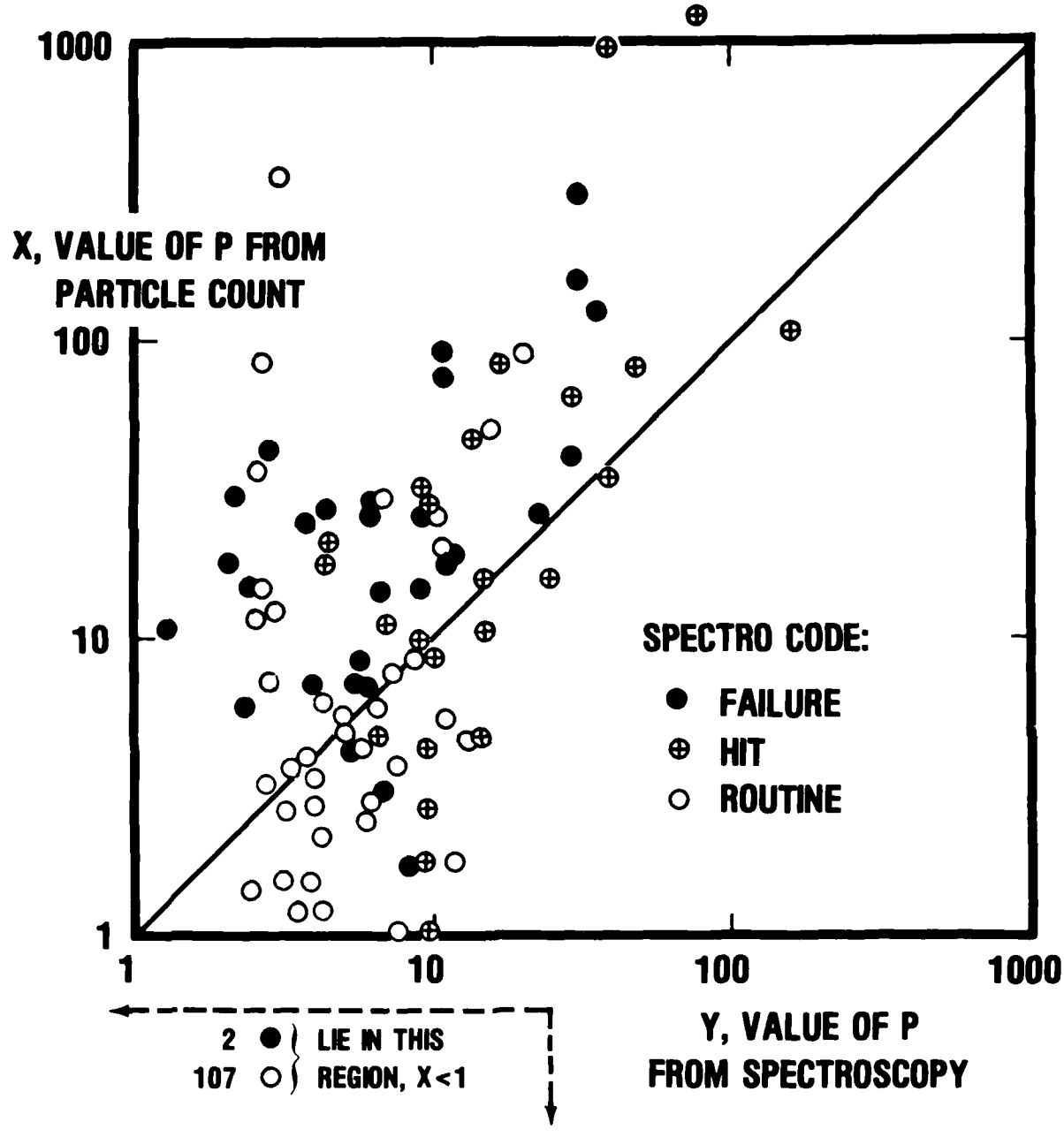


Figure 8. Failure Prediction
based on comparison of two estimates for P,
microliters of particulates per liter of oil

TABLE 4. EFFECTIVENESS OF PREDICTION

SPECTRO CLASS	TOTAL NUMBER	NUMBER DEFECTIVE	FRACTION DEFECTIVE	LIMITS OF 80% CONFIDENCE*	
FAILURE	31	26	0.84	0.72	0.90
HIT	24	11	0.64	0.33	0.58
ROUTINE	145	16	0.11	0.09	0.15
	200	53			

* Estimated from theory of sampling by attributes. Cf. Leslie E. Simon "Engineer's Manual of Statistical Methods", John Wiley and Sons, New York (1941), Chapter 2.

(filled circles) lie above it; hits (crossed circles) are almost evenly distributed. Table 4 summarizes the results in a compact form.

According to this evidence, supplementary particle counting, had it been a part of the SOAP screening process, would have identified 84% of the failure samples as defective and would have caused an inspection to be made before the failure occurred. In the case of hits, almost half of the samples had already surpassed the X/Y limit by the time the spectrometric analysis gave an alarm; the source engines would have been flagged for inspection at some previous juncture. And if the spectrometric routine samples are indeed representative of their class, then 11% of all engines now in service contain oil of a suspicious character; these are the engines most likely to yield future spectroscopic hits or failures. Again, supplementary particle counting would have precipitated an inspection of each of these engines at some earlier time, resulting in either a hit or miss finding. A point to be emphasized is that this would have occurred the first time the X/Y ratio exceeded unity. There could be no accumulation of dirty oil in the fleet; it would be purged upon discovery.

Ultimately, if we are to make reliable cost effectiveness studies, we need to know how supplementary particle counting would affect both the annual number of failures and the annual number of inspections (hits plus misses). The actual magnitude of these parameters can be determined only by a program of real-time dual analysis. Our present experiments allow us to judge with fair confidence that the number of failures will be reduced to about 16% of the present level; on-line experiments will serve principally to enlarge the statistical data base and refine the estimate a few percent either way. The situation is quite different with respect to forecasting the number of inspections

and their hit/miss ratio. Our present experiments on one-time grab samples can afford no quantitative answers to this question, which is of critical importance.

One might be tempted to suppose, from the results shown in Table 4 that supplemental particle counting would single out about 11% of all spectroscopic routine samples for inspection---an intolerable burden of cost and labor even if failures were entirely eliminated. However, this is an erroneous conclusion. All we can say is that 11% of all oil now in service is X/Y defective; we cannot connect this figure with an anticipated on-line inspection rate except to say that it would be an extravagant estimate. Let us examine the matter a little further to see why this is so.

Referring again to Appendix B, consider the data showing T, the operating time since oil change, for spectroscopic routine samples. Each of these samples was found, by particle counting, to be either defective ($X/Y>1$) or non-defective ($X/Y<1$). If we compute the mean and the variance of T for each of these subsets, we find by application of the standard t- and F- tests that there is no reasonable probability that they form two different populations. This result simply confirms that all the routine samples were indeed randomly selected---i.e., the particle counts were made at random times since the last oil change; on the average, the defectives had not been in service longer than the non-defectives, or vice versa. Note now that every engine that is yielding routine samples must eventually, upon continued sampling, issue a hit or miss sample, unless it first fails or is removed from service for time-scheduled maintenance. This is true whether or not the spectroscopic analysis is supplemented by particle counting. But in the experiments reported here, each defective sample---although the

source engine had not yet failed nor generated a SOAP alarm---came from oil that had been defective for some period of time. How long? Did damage already exist? What happened later on? We cannot say. On the other hand, each non-defective sample originated from an oil stock in an engine which would continue to pass subsequent X/Y screening, were it to be performed, for some additional period of sampling. How long? Again, one-time analysis affords no answer.

Our basic premise is that an X/Y-defective sample is in fact a genuine indicator of abnormal engine wear. To the extent that this concept is valid and uncomplicated by extraneous factors, real-time supplemental particle analysis would provide only hit findings, resulting in early detection and correction of the severe wear; the engine would then revert to normal slow-wear status. Thereafter it might pass dozens or hundreds of dual analyses. From this standpoint, it is clear that the size of the X/Y-defective oil pool now in the fleet is no index for estimating a new on-line inspection rate. That is quite another thing: namely, the number of inspections per analysis. If all X/Y-triggered inspections were indeed hits, then the increases in the annual number of inspections would approximate closely to the decrease in the number of failures (roughly a hundred, calculated as 84% of the 100-200 that now occur in a year); and every one of these additional inspections would represent pure benefit. We recognize, of course, that this ideal will not be realized in practice. Some fraction of X/Y-mandated inspections on spectroscopic routines will be misses; these false alarms will result at best in a prophylactic oil change, and we need to know the magnitude of this burden. Only continuous on-line supplemental analysis, with inspection feedback, can provide the required information; it cannot be extracted from our present data.

Finally, note that the X/Y criterion is potentially a flexible one insofar as the critical screening value is concerned. The value of unity used in the present exploratory experiments is not necessarily a universal constant, or even an optimum value. Although it works reasonably well when applied to the limited data available, we must remember that these data---in addition to their shortcomings as single grab-samples---represent an indiscriminately lumped pool of samples from different types of aircraft and engines; these in turn differ greatly among themselves with respect to severity of usage and rate of wear. For example, fighter engines frequently operate at maximum power, while transport engines are seldom run at maximum output. Further, depending upon the location of the engine airscoop relative to ground level, some aircraft are more prone than others to ingest dirt and debris which may find its way into the oil system. For these reasons, it is reasonable to expect that in future, given sufficient oil test data identified by aircraft type, specific X/Y values may be established which optimize screening for each particular case---less than unity for some types, greater for others.

Practical counting technique: a prospectus

We now consider briefly the problem of streamlining the particle counting procedure. As a prelude to any immediate program of real-time testing, it is necessary to reduce the time required for a particle count to the same order of magnitude (5 minutes) as that for a spectroscopic analysis. This objective can be achieved through straightforward adaptions of existing equipment. First, the particle counter must be modified to accept an undiluted thin film of sample, introduced into throwaway cuvettes or into a permanently installed flowthrough cell which can be flushed clean with a volatile solvent between runs. This obviates the necessity for a

separate blank count and eliminates the time and labor associated with this extra procedure. The film must be sufficiently thin to preclude multiple scattering and to produce a useable opacity of 35% or less. Simple calculations indicate that a film thickness of 0.75 mm will guarantee both these conditions; further, the total counting time is reduced to about 3 minutes. Refer to Appendix C for details. Preliminary tests on neat oils confirm these predictions but also show that the boundary diameters of each channel in the pulse-height discriminator are quite sensitive to the exact location of the thin sample within the 2-cm sensitive zone of the counter. The counter must therefore be calibrated for a particular position of the sample cell, which must in turn be rigidly controlled by a suitable mechanical mounting.

The second adaptation is to provide on-line real-time data readout by a dedicated microcomputer. The computer program would be a simplified version of NEWPART, purged of the unnecessary elements connected with the manipulation of data originating from the blank count; additionally, it might be augmented to accept the spectroscopic analysis as an auxiliary input and compute X/Y directly as a sole output, with the full NEWPART output also available at the operator's demand. One of the more elaborate hand-held programmable calculators with thermal printout, interfaced to the pulse-height discriminator, would be a satisfactory expedient.

For the purpose of immediate future tests, these fundamental modifications can be patched onto the available instruments in the laboratory. In the longer run, such features would best be integrated into the equipment by the manufacturer, along with additional automation to achieve maximum convenience and throughput. A few examples include

- o Built-in measurement of opacity, and adjustment to a standard value (e.g., 35%) by a servo-controlled variable density filter rotated into the laser beam.

- o Open-ended channels in the pulse-height discriminator, sorting pulse heights directly on an oversize basis; independent control of the threshold intensity (particle diameter) for each channel.

- o Automatic flush and feed, to allow a batch of samples to be run serially without intervention of the operator.

Improvements of this kind represent state-of-the-art technology. While custom design would be premature at the present stage of development, it offers capabilities susceptible to quick utilization when and if particle-counting is adopted as a supplement to SOAP.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

The exploratory phase of this work has been completed. Particle counting appears to be a promising candidate method of supplemental analysis from the standpoint of failure prevention. The question of cost effectiveness remains to be investigated, and this calls for a regime of testing different from what has been conducted thus far.

It is recommended that further work proceed along the following lines.

a. Modify equipment and procedure to accomplish rapid particle counting in the thin-film mode, incorporating data readout from a dedicated microcomputer.

b. Using this nimble capability, established in a central R&D laboratory, conduct a program of real time particle analysis on every spectrometric sample from a number of operational aircraft (perhaps 20). These aircraft should be selected to provide a cross section of engine types and severity of service; the test period should be of sufficient duration (at least a year) to guarantee a variety of maintenance experience.

c. During the test period, issue inspection advice and receive inspection feedback in order to assess the reliability and cost effectiveness of supplemental particle counting. Continuously refine decision criteria insofar as possible to improve performance.

d. Assuming favorable findings, move well-automated equipment and necessary instructions out to one or more SOAP laboratories to demonstrate the system as a field method.

APPENDIX A

NEWPART COMPUTER PROGRAM

The following pages comprise a FORTRAN listing of the program. It is reproduced here primarily for the reader who may wish more detailed information than that provided in the synopsis (Table 2). For the reader who may wish to adapt this program, or parts of it, for use in connection with his own particle-counting equipment, some cautions are in order. First, his computer must have access to the ISML (International Statistical and Mathematical Library) in order to call out algorithms for the incomplete gamma function; lacking this capability, he must modify the program so as to perform the relevant integrations by numerical quadrature. Second, in every case the BLOCK DATA section must be replaced with information pertinent to his own equipment; and the same remark applies at other places where specific instrumental constants appear---for example, in SUBROUTINE OILSUB, line 48, the constant 1.622 is the time required for our instrument to scan a volume of one cubic centimeter.

PROGRAM OIL

```
      1                 PROGRAM OIL(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
                        DIMENSION TITLE(12),IV(15)
                        COMMON/INPUT/OIL,N,T,OMEGA,V(10,16),IBLANK,PREC
                        COMMON/OUTPUT/DELN(21),DELP(21),A2,FK2,FN0,ITER,IM,ID(21),MI
      5                 COMMON/SOLVB/AB,FKB,FN0B,Z,IDLOW,IDHIGH,KRIT
                        COMMON/GRIDB/ITERA,NOENO
                        NAMELIST/DATA/OIL,N,T,OMEGA,IBLANK,PREC,IZTAB
                  1     FORMAT(12A6)
                  2     FORMAT(16F5.0)
     10           3     FORMAT(/3X,*CHECK THIS CARD*//10X,16I6)
                  4     FORMAT(//12X,*SUMMARY OF RESULTS*//9X,*D*,7X,*N*,11X,*P*/)
                  5     FORMAT(I10,1P2E12.2)
                  6     FORMAT(//4X,*N=NUMBER OF PARTICLES,PER CM3 OF SAMPLE,WHICH HAVE A
                       2DIAMETER LARGER THAN D *// 4X,*P=VOLUME OF PARTICLES,IN PPM OF SAMP
     15                2LE , WHICH HAVE A DIAMETER LARGER THAN D*/4X,*D=DIAMETER OF PARTIC
                       2LES IN MICRONS*)
                  7     FORMAT(/3X,*A OR K IS EQUAL OR LESS THEN ZERO.*)
                  9     FORMAT(/3X,*LESS THEN THREE DATA POINTS.*)
                  10    FORMAT(1X,*A(BLANK )=*,1PE9.3,3X,*K(BLANK )=*,E9.3,3X,*N0=*,E10.3,
     20           2I8,* ITERATIONS*//)
                  11    FORMAT(1X,*A(SAMPLE)=*,1PE9.3,3X,*K(SAMPLE)=*,E9.3,3X,*N0=*,E10.3,
                       2I8,* ITERATIONS*//)
                  12    FORMAT(2X,*INCOMPLETE,REQUEST MORE TIME*)
                  13    FORMAT(   15X,*COMPUTATION TIME=*,F6.1,* SECONDS*/21X,*PRED(A,K)=*
     25           2,F8.5/)
                  14    FORMAT(19X,*DILUTION=*,1PE10.3/)
                  16    FORMAT(1H+,36X,*BELOW THIS DIA, N IS UNCERTAIN. INCREASE IN P IS N
                       2EGLIGIBLE.*)
                  17    FORMAT(1H+,36X,*ABOVE THIS DIA, N AND P APPROACH ZERO RAPIDLY.*)
     30           19    FORMAT(//2X,*NO SIGNIFICANT PARTICLE COUNT IN THIS SAMPLE.*/2X,*DL
                       2OW=*,I3,3X,*DHIGH=*,I3/2X,*(SEE TABLE FOR Z VALUES PRINTED ON NEXT
                       3 PAGE)*)
                  21    FORMAT(* N AND P FELL RAPIDLY,*,I3,* ITEMS WERE DELETED IN TABLE*)
                  1000  READ(5,1)TITLE
     35                 IF(EOF(5).NE.0.)STOP"NORMAL EXECUTION"
                        OIL=1.
                        OMEGA=7.5
                        IBLANK=IZTAB=0
                        PREC=1.E-4
     40                 N=5
                        T=90.
                        READ(5,DATA)
                        DO 102 I=1,N
                        READ(5,2)(V(I,J),J=1,16)
     45                 S=0
                        DO 100 J=1,15
                  100   S=S+V(I,J)
                        IF(S.EQ.V(I,16))GO TO 102
                        DO 101 J=1,16
     50           101   IV(J)=V(I,J)
                        WRITE(6,1)TITLE
                        WRITE(6,3)(IV(J),J=1,16)
                        STOP"CHECK DATA"
                  102   CONTINUE
     55                 TIME=SECOND(S)
                        CALL OILSUB
                        WRITE(6,1)TITLE
```

```
      PROGRAM OIL
C
                  TIME=SECOND(S)-TIME
                  WRITE(6,13)TIME,PREC
   60             IF(OMEGA.GT.0.)GO TO 2001
                  IF(OMEGA.EQ.0.)WRITE(6,7)
                  IF(OMEGA.LT.0.)WRITE(6,9)
                  STOP"SEE MESSAGE"
             2001 IF(IBLANK.EQ.0)GO TO 3000
   65             WRITE(6,10)A2,FK2,FND,ITER
                  IF(NOEND.EQ.0)GO TO 1000
                  WRITE(6,12)
                  STOP"REQUEST MORE TIME"
             3000 WRITE(6,14)OIL
   70             WRITE(6,11)A2,FK2,FND,ITER
                  IF(NOEND.EQ.0)GO TO 4000
                  WRITE(6,12)
                  STOP"REQUEST MORE TIME"
             4000 IF(IM.GT.0)GO TO 5000
   75                   WRITE(6,19)IDLOW,IDHIGH
                  IF(MI.GT.0)WRITE(6,21)MI
                        CALL ZTABLE
                  GO TO 1000
             5000 WRITE(6,4)
   80             DO 103 I=1,IM
                  WRITE(6,5)ID(I),DELN(I),DELP(I)
                  IF(I.EQ.1)WRITE(6,16)
             103  IF(I.EQ.IM.AND.IM.LT.21)WRITE(6,17)
                  WRITE(6,6)
   85                   IF(IZTAB.EQ.1)CALL ZTABLE
                  GO TO 1000
                  END
```

SUBROUTINE OILSJB

```
      SUBROUTINE OILSUB
      DIMENSION W(15)
      COMMON/INPUT/DI[illegible],N,T,OMEGA,V(10,16),IBLANK,PREC
      COMMON/OUTPUT/DELN(21),DEL[illegible](21),A2,FK2,FN0,ITER,I[illegible],ID(21),MI
      COMMON/SOLVB/AB,FKB,FN0B,Z,IDLOW,IDHIGH,KRIT
      COMMON/GRIDB/ITERA,NOEND
      COMMON/DCAL/D(15,7)
      COMMON/AUX/M,X(16),Y(16),Y0,DD,SUMY,FX(16),YCAL(15)
      EXTERNAL SUMDEV,SOLVER
      IM=MI=0
      DO 100 J=1,15
      W(J)=0
      DO 100 I=1,N
  100 W(J)=W(J)+V(I,J)
      Y(16)=0
      DO 101 I=1,15
      M=16-I
      Y(M)=Y(M+1)+W(M)
  101 CONTINUE
      M=1
      DO 102 I=10,35,5
      M=M+1
  102 IF(OMEGA.EQ.FLOAT(I))NOM=M
      IF(OMEGA.EQ.7.5)NOM=1
      SUMY=M=IM=0
      DO 103 I=1,15
      IF(Y(I).EQ.0.)GO TO 103
      M=M+1
      X(M)=D(M,NOM)
      Y(M)=ALOG(Y(M))
      SUMY=SUMY+Y(M)
  103 CONTINUE
      IF(M.GT.2)GO TO 120
      OMEGA=-1.
      RETURN
  120 DD=D(16,NOM)
      ASTP=FKSTP=.03
           A=.25
           FK=1.
      PRECI=PREC
      CALL GRID2(SUMDEV,PRECI,ASTP,FKSTP,A,FK,S)
      IF(S.NE.1.E99)GO TO 150
      OMEGA=0
      RETURN
  150 ITER=ITERA
      A2=A
      FK2=FK
      FN0=1.622*EXP(Y0)/(FLOAT(N)*T)
      IF(IBLANK.EQ.0)GO TO 121
      FN0B=FN0
      AB=A
      FKB=FK
      IF(IBLANK.EQ.1)RETURN
  121 IF(NOEND.EQ.1)RETURN
      DELNXO=-1.E99
      DO 200 I=1,95
      IF(I.GT.1)DELNXO=DELNX
```

SUBROUTINE OILSJB

```
                      DELNX  = FNO *EXP(-A2*FLOAT(I)**FK2)
                     2         -FNOB*EXP(-AB*FLOAT(I)**FK9)
     50               IF(DELNX.LT.0.)GO TO 200
                      IF(DELNX.LT.DELNXJ)GO TO 201
                 200  CONTINUE
                 201  IDLOW=I-1
                          IF(IDLOW.GE.94)RETURN
     65               ID(1)=IDLOW
                      DLOW=IDLOW
                               DY=DLOW
                 9000          DY=DY+1.
                               IF(DY.GT.95.)GO TO 999
     70                        ZZ=SOLVER(DY,DUMY)
                               IF(ZZ.GT.0.)GO TO 9001
                               DY=DY-1.
                               GO TO 999
                 9001          IF(ZZ.GT..675.OR.KRIT.EQ.1)GO TO 9000
     75          999           IDHIGH=DY
                      IF(IDLOW.EQ.IDHIGH.OR.IDHIGH.LT.5)RETURN
                          IF(IDHIGH.GT.80)IDHIGH=80
                      DHIGH=IDHIGH
                      DO 300 I=1,2
     80               IF(I.EQ.1)FLOATI=DLOW
                      IF(I.EQ.2)FLOATI=DHIGH
                 300  DELN(I)=(FNO *EXP(-A2*FLOATI  **FK2)
                     2         -FNOB*EXP(-AB*FLOATI  **FKB))*OIL
                      DSAVE=DELN(2)
     85               XHIB=AB*DHIGH**FKB
                      XHIS=A2*DHIGH**FK2
                      ARB=3./FKB+1.
                      ARS=3./FK2+1.
                      PI6=ALOG(5.235989E-7)
     90               CALL MDGAM(XHIB,ARB,RHIB,IER)
                      CALL MDGAM(XHIS,ARS,RHIS,IER)
                 C    FOR FUNCTION NAMES SEE NEW IMSL LIBRARY
                          FLOGMB=ALGAMA(ARB)
                          FLOGMS=ALGAMA(ARS)
     95               XLOW=AB*DLOW**FKB
                      CALL MDGAM(XLOW,ARB,RLOW,IER)
                      P1=0
                          IF(RLOW.EQ.RHIB)GO TO 3000
                      P1=PI6+ALOG(FNOB)-3.*ALOG(AB)/FKB+FLOGMB+ALOG(ABS(RLOW-RHIB))
    100               IF(P1.LT.-84.)P1=-84
                      IF(P1.GT.86.)P1=86
                      PB=EXP(P1)
                 3000 IF(P1.EQ.0.)PB=0
                      XLOW=A2*DLOW**FK2
    105               CALL MDGAM(XLOW,ARS,RLOW,IER)
                      P2=0
                          IF(RLOW.EQ.RHIB)GO TO 4000
                      P2=PI6+ALOG(FNO )-3.*ALOG(A2)/FK2+FLOGMS+ALOG(ABS(RLOW-RHIS))
                      IF(P2.GT.86.)P2=86
    110               IF(P2.LT.-84.)P2=-84
                      PS=EXP(P2)
                 4000 IF(P2.EQ.0.)PS=0
                      DELP(1)=OIL*(PS-PB)
                              DELP(2)=0
```

SUBROUTINE OILSJB

```
                      DO 1111 I=1,2
                       IF(DELN(I).LT.0.)DELN(I)=0
                      IF(DELP(I).LT.0.)DELP(I)=0
                      IF(DELN(I).EQ.0..AND.DELP(I).EQ.0.)MI=MI+1
 1111  CONTINUE
 120   J=2
       DO 108 I=5,95,5
       IF(I.LE.IDLOW)GO TO 108
       IF(I.GE.IDHIGH)GO TO 500
       J=J+1
 125   DELN(J)=(FN0 *EXP(-A2*FLOAT(I)**FK2)
      2        -FN0B*EXP(-AB*FLOAT(I)**FKB))*DIL
            IF(DELN(J).LT.0.)DELN(J)=0
       XLOW=AB*FLOAT(I)**FKB
       CALL MDGAM(XLOW,ARB,RLOW,IER)
 130        P1=0
            IF(RLOW.EQ.RHIB)GO TO 1000
       P1=PI6+ALOG(FN0B)-3.*ALOG(AB)/FKB+FLOGMB+ALOG(ABS(RLOW-RHIB))
       IF(P1.LT.-84.)P1=-84
       IF(P1.GT.86.)P1=85
 135   PB=EXP(P1)
 1000  IF(P1.EQ.0.)PB=0
       XLOW=A2*FLOAT(I)**FK2
       CALL MDGAM(XLOW,ARS,RLOW,IER)
            P2=0
 140        IF(RLOW.EQ.RHIS)GO TO 2000
       P2=PI6+ALOG(FN0 )-3.*ALOG(A2)/FK2+FLOGMS+ALOG(ABS(RLOW-RHIS))
       IF(P2.GT.86.)P2=85
       IF(P2.LT.-84.)P2=-84
       PS=EXP(P2)
 145   2000  IF(P2.EQ.0.)PS=0
       DELP(J)=DIL*(PS-PB)
            IF(DELP(J).LT.0.)DELP(J)=0
            IF(DELN(J).EQ.0..AND.DELP(J).EQ.0.)MI=MI+1
            IF(DELN(J).EQ.0..AND.DELP(J).EQ.0.)GO TO 500
 150   ID(J)=I
 108   CONTINUE
 500   IM=J
            IF(IM.GE.3)GO TO 700
            IM=-IM
 155        RETURN
 700   JM=J-1
       DO 501 J=2,JM
       ID(J)=ID(J+1)
       DELN(J)=DELN(J+1)
 160   501  DELP(J)=DELP(J+1)
       ID(IM)=IDHIGH
            DELP(IM)=0
       DELN(IM)=DSAVE
            DO 600 I=1,IM
 165   600       DELP(I)=DELP(I)+5.235999E-7*DELN(IM)*(FLOAT(ID(I)M))**3
       RETURN
       END
```

SUBROUTINE ZTABLE

```
      1                 SUBROUTINE ZTABLE
                        COMMON/SOLVB/AB,FKB,FNOB,Z,IDLOW,IDHIGH,KRIT
                              WRITE(6,32)
                   32   FORMAT(1H1,10X,*TABLE FOR Z*)
      5                       WRITE(6,30)
                   30   FORMAT(/9X,*D*,7X,*Z*//)
                   31   FORMAT(I10,F9.3)
                   39   FORMAT(1H+,22X,*(NS+NB>10)*)
                   40   FORMAT(1H+,22X,*THIS IS THE COMPUTED DHIGH*)
     10                       DO 50 I=IDLOW,35
                              DY=I
                              S=SOLVER(DY,DUMY)
                              WRITE(6,31)I,Z
                              IF(IKRIT.EQ.1)WRITE(6,39)
     15            50         IF(I.EQ.IDHIGH)WRITE(6,40)
                              RETURN
                              END
```

FUNCTION SOLVER

```
      1                 FUNCTION SOLVER(DY,DUMY)
                        COMMON/OUTPUT/DELN(21),DELP(21),A2,FK2,FN0,ITER,IY,ID(21),MI
                        COMMON/SOLVB/AB,FKB,FNOB,Z,IDLOW,IDHIGH,KRIT
                        KRIT=0
      5                 IF(DY.LT.FLOAT(IDLOW).OR.DY.GT.95.)RETURN
                        FNS=FN0* EXP(-A2*DY**FK2)
                        FNB=FNOB*EXP(-AB*DY**FKB)
                             IF(FNS+FNB.GT.100.)KRIT=1
                             Z=(FNS-FNB)/SQRT(FNS+FNB)
     10                 Z=FLOAT(IFIX(Z*1.E3+.5))*1.E-3
                              SOLVER=Z
                        RETURN
                        END
```

FUNCTION SUMDEV

```
      FUNCTION SUMDEV(A,FK)
      COMMON/AUX/M,X(15),Y(16),Y0,DD,SUMY,FX(16),YCAL(16)
      SUMDEV=1.E99
      IF(A.LE.0..OR.FK.LE.0.)RETURN
      SUMX=0
      DO 100 I=1,M
      FX(I)=EXP(-A*X(I)**FK)-EXP(-A*DD**FK)
      IF(FX(I).LE.0.)RETURN
      FX(I)=ALOG(FX(I))
  100 SUMX=SUMX+FX(I)
      Y0=(SUMY-SUMX)/FLOAT(M)
      SUMDEV=0
      DO 101 I=1,M
      YCAL(I)=Y0+FX(I)
  101 SUMDEV=SUMDEV+(Y(I)-YCAL(I))**2
          SUMDEV=FLOAT(IFIX(SUMDEV*1.E9+.5))*1.E-9
      RETURN
      END
```

BLOCK DATA BLKDAT.

```
      BLOCK DATA
      COMMON/DCAL/D(16,7)
      DATA(D(1,J),J=1,7)/2.07,2.15,2.34,2.53,2.74,2.95,3.21/
      DATA(D(2,J),J=1,7)/5.22,5.42,5.86,6.32,6.83,7.37,7.35/
      DATA(D(3,J),J=1,7)/10.67,11.07,11.94,12.86,13.87,14.94,15.11/
      DATA(D(4,J),J=1,7)/15.17,16.77,18.06,19.44,21.93,22.53,24.26/
      DATA(D(5,J),J=1,7)/24.36,25.26,27.16,29.20,31.41,33.78,36.32/
      DATA(D(6,J),J=1,7)/32.07,33.24,35.71,38.37,41.25,44.32,47.62/
      DATA(D(7,J),J=1,7)/35.26,37.57,40.36,43.35,45.58,50.04,53.75/
      DATA(D(8,J),J=1,7)/39.82,41.26,44.31,47.58,51.11,54.89,58.94/
      DATA(D(9,J),J=1,7)/43.01,44.56,47.84,51.36,53.17,59.23,63.59/
      DATA(D(10,J),J=1,7)/45.88,47.52,51.02,54.76,58.81,63.14,67.77/
      DATA(D(11,J),J=1,7)/48.72,50.46,54.16,58.13,62.42,65.99,71.90/
      DATA(D(12,J),J=1,7)/51.37,53.20,57.10,61.27,65.78,70.59,75.75/
      DATA(D(13,J),J=1,7)/54.15,56.08,60.17,64.56,69.30,74.37,79.79/
      DATA(D(14,J),J=1,7)/55.68,58.69,62.97,67.56,72.51,77.80,83.46/
      DATA(D(15,J),J=1,7)/59.43,61.56,66.04,70.84,76.02,81.55,87.48/
      DATA(D(16,J),J=1,7)/62.27,64.47,69.16,74.17,79.53,85.37,91.57/
      END
```

SUBROUTINE GRID2

```
      1                 SUBROUTINE GRID2(FUNCMI,STEPLI,XSTEP,YSTEP,X,Y,F)
                        COMMON/GRIDB/ITERA,NOEND
                        NOEND=K=ITERA=0
                        PI=ATAN2(0.,-1.)
      5                 PI2=ATAN2(1.,0.)
                        F=F0=FUNCMI(X,Y)
                        TIME=THETA0=1.E99
                  1000      IF(TIMREM(1.).LT.SECOND(1.)-TIME+2.)NOEND=1
                            TIME=SECOND(1.)
     10                 IJ=I1=J1=1
                        ITERA=ITERA+1
                        IF(XSTEP.LT.STEPLI)I1=3
                        IF(YSTEP.LT.STEPLI)J1=3
                        IF(NOEND.EQ.1.OR.K.EQ.20)I1=J1=3
     15                 IF(I1+J1.LT.6)GO TO 100
                        F=FUNCMI(X,Y)
                        RETURN
                  100   XC=X
                        YC=Y
     20                 FC=F
                        DO 101 I=I1,3
                        FINC=FLOAT(I-2)*XSTEP
                        IF(I1.EQ.3)FINC=0
                        XG=XC+FINC
     25                 DO 101 J=J1,3
                        FJNC=FLOAT(J-2)*YSTEP
                        IF(J1.EQ.3)FJNC=0
                        IF(FINC.EQ.0..AND.FJNC.EQ.0.)GO TO 101
                        YG=YC+FJNC
     30                 FG=FUNCMI(XG,YG)
                        IF(FG.GT.F)GO TO 101
                        F=FG
                        X=XG
                        Y=YG
     35                 THETA=ATAN2(FJNC,FINC)
                        IJ=IJ+1
                  101   CONTINUE
                        IF(F.LT.FC)GO TO 102
                        IF(F.EQ.F0.AND.IJ+3*IABS(I1-J1).EQ.9)GO TO 103
     40                 F0=-1.E99
                        K=0
                        F=FC
                        X=XC
                        Y=YC
     45                 XSTEP=.5*XSTEP
                        YSTEP=.5*YSTEP
                        GO TO 1000
                  102   IF(THETA.EQ.THETA0)GO TO 103
                        K=0
     50                 THETA0=THETA
                        GO TO 1000
                  103   K=K+1
                        IF(ABS(THETA).NE.PI2)XSTEP=2.*XSTEP
                        IF(THETA.NE.PI.AND.THETA.NE.0.)YSTEP=2.*YSTEP
     55                 GO TO 1000
                        END
```

APPENDIX B

DATA BASE FOR AUTHENTIC OIL SAMPLES

Code for column headings:

T = operating hours elapsed since last oil change

X = microliters of particulates per liter of oil, measured by particle counting

Y = microliters of particulates per liter of oil, inferred from spectrometric analysis

SAMPLE NUMBER	ENGINE TYPE	AIRC TYPE	T	X	Y	X/Y
FAILURES(31)						
F-002	F-100	F-15	219	4.15	5.81	0.71
F-003	T-56-A7B	C-130E	113	5.75	2.35	2.4
F-004	T-56-A7B	C-130E	493	7.02	5.56	1.3
F-005	T-56-A7B	C-130E	755	0.055	11.0	<0.1
F-006	T-76-10A	OV-10	19	14.4	2.57	5.6
F-008	T-56-A7B	C-130E	689	90.7	10.8	8.4
F-009	J-69-25	T-37B	2	25.8	6.24	4.1
F-012	T-56-A7B	C-130B	76	14.5	9.27	1.6
F-013	TF-41-1	A-70	68	6.85	4.00	1.7
F-014	T-56-A7B	C-130E	535	1.66	8.67	0.19
F-015	T-56-A7B	C-130E	unk	158.	30.9	5.1
F-017	J-85-5	T-38	3	26.6	4.42	6.0
F-018	T-56-A7B	C-130E	527	125.	35.9	3.5
F-020	TF-33	C-141A	783	10.6	1.30	8.2
F-023	T-56-A7B	C-130E	400	307.	31.3	9.8
F-024	T-56-A7B	C-130E	439	0.387	11.3	<0.1
F-025	TF-33P7	C-141	814	23.7	3.78	6.3
F-026	J-79-15	RF-4C	unk	35.5	29.4	1.2
F-028	T-56-A7B	C-130	625	17.5	11.3	1.5
F-030	T-56-A7B	C-130E	790	8.25	5.76	1.4
F-031	T-56-A7B	C-130E	52	2.96	6.75	0.44
F-033	J-79-GE-15	RF-4C	51	28.1	6.57	4.3
F-034	T-56-A7B	C-130B	284	14.1	6.81	2.1
F-035	J-85-5	T-38	66	6.83	5.83	1.2
F-036	J-85-GE-5	T-38A	100	29.5	2.18	14.
F-037	TF-39-GE-5	C-5A	617	19.2	11.6	1.6
F-039	T-56-A7B	C-130E	130	26.1	23.3	1.1
F-040	T-56-A7B	C-130E	unk	26.2	10.1	2.6
F-041	T-56-A7B	C-130E	1081	74.6	11.1	6.7
F-042	T-56-A7B	C-130	1301	41.5	2.80	15.
F-046	F-100-PW-100	F-15A	149	17.7	2.21	8.0

SAMPLE NUMBER	ENGINE TYPE	AIRC TYPE	T	X	Y	X/Y
HITS(24)						
H-002	RT-6A	C-130T	18	16.0	15.4	1.0
H-009	J-75-17	F-106	107	25.2	9.69	2.6
H-015	J-79-15	F-4C	210	4.57	15.1	0.30
H-018	J-85-5	T-38	309	21.0	4.61	4.6
H-025	J-57-59W	KC-135	134	30.6	9.27	3.3
H-044	J-79-15	F-4C	84	46.5	14.0	3.3
H-048	J-85-5	T-38	unk	110.	163.	0.67
H-050	T-56-A7B	C-130	868	10.6	15.5	0.69
H-052	TF-39	C-5A	508	34.8	40.3	0.86
H-061	T-56-9	AC-130A	442	64.9	29.9	2.2
H-063	J-85-GE-5	T-38A	110	4.19	9.69	0.43
H-065	T-56-A7B	C-130E	568	15.8	25.3	0.62
H-070	J-79-GE-15	F-4C	150	1.01	10.0	0.10
H-074	J-85-GE-5	T-38	41	17.5	4.52	3.9
H-075	J-85-GE-5	T-38	138	4.55	6.72	0.68
H-077	J-79-GE-15	F-4C	550	1.75	9.52	0.18
H-078	TF-33-P-7	C-141	576	8.52	10.5	0.81
O-002	J-79-GE-15	RF-4C	221	83.2	17.0	4.9
P-002	GE-T-58-5	CH-3E	51	82.2	49.8	1.7
P-025	IO-360D	O-2A	44	1270.	77.7	16.
P-050	R-2800-103	C-131D	unk	968.	38.9	25.
P-069	T-400-CP-400	UH-1-NA	99	9.71	9.25	1.1
P-090	J-85-GE-15	T-38A	unk	2.66	9.95	0.27
P-091	J-85-GE-15	T-38A	unk	10.9	7.27	1.5
ROUTINES(145)						
R-001	TF-41	A-7D	56	nil	0.43	<0.1
R-002	TF-41	A-7D	24	nil	0.76	<0.1
R-003	T-56-A7B	C-130E	272	89.8	20.5	4.4
R-005	T-56-A7B	C-130E	310	nil	13.9	<0.1
R-007	TF-33	C-141	1	nil	1.74	<0.1
R-011	T-56-A7B	C-130	156	nil	2.70	<0.1
R-017	T-56-7	C-130	136	nil	3.48	<0.1
R-024	F-100DFCA	F-15	15	nil	0.50	<0.1
R-30	J-79-15	RF-4C	450	nil	2.24	<0.1
R-033	J-79-15	RF-4C	69	nil	1.79	<0.1
R-041	J-85-GE-5	T-38A	267	nil	3.49	<0.1
R-044	J-57-59	KC-135	77	nil	2.36	<0.1
R-053	J-79-15	RF-4C	556	nil	2.15	<0.1
R-056	J-57-59W	KC-135A	unk	nil	1.15	<0.1
R-058	T-56-A7B	C-130E	59	nil	0.63	<0.1
R-077	J-57-43W	B-52G	179	83.1	2.67	31.
R-082	J-57-59	KC-135A	0	nil	1.45	<0.1
R-084	J-57-59	KC-135	60	nil	2.75	<0.1
R-086	TF-41-A-1	A-70	49	nil	6.91	<0.1
R-089	J-79-15	RF-4C	304	nil	2.04	<0.1
R-103	J-57-43W	B-52G	0	nil	4.01	<0.1

SAMPLE NUMBER	ENGINE TYPE	AIRC TYPE	T	X	Y	X/Y
R-104	J-57-43w	KC-135	1132	nil	2.00	<0.1
R-106	TF-41	A-70	71	nil	3.66	<0.1
R-122	J-57-43wb	B-52	42	nil	4.44	<0.1
R-127	J-57-43	B-52G	220	nil	2.03	<0.1
R-129	J-79-GE-15	RF-4C	127	nil	2.24	<0.1
R-135	J-57-59w	KC-135	6	nil	3.33	<0.1
R-148	J-85-5	T-38A	22	nil	2.47	<0.1
R-149	J-85-5	T-38A	144	nil	2.88	<0.1
R-153	J-57-43wb	B-52G	1652	nil	2.30	<0.1
R-164	J-57-59w	KC-135	703	nil	2.64	<0.1
R-155	J-79-15	RF-4C	16	nil	0.43	<0.1
R-157	J-57-43w	B-52G	408	nil	1.39	<0.1
R-158	J-57-59	KC-135	900	nil	1.90	<0.1
R-161	J-79-15	RF-4C	571	nil	1.92	<0.1
R-164	J-57-59	KC-135	141	nil	1.27	<0.1
R-167	J-79-15	RF-4C	16	nil	0.91	<0.1
R-177	J-79-15	RF-4C	661	nil	2.00	<0.1
R-178	T-56-7	C-130	27	nil	2.35	<0.1
R-183	J-57-43wb	B-52G	812	nil	3.11	<0.1
R-186	J-57-59w	KC-135	300	nil	1.22	<0.1
R-190	J-69-T-25	T-37B	21	nil	0.87	<0.1
R-199	J-57-59w	KC-135	593	nil	2.01	<0.1
R-200	J-57-59w	KC-135A	107	nil	2.18	<0.1
R-201	J-57-59	KC-135A	505	nil	4.26	<0.1
R-203	J-57-59	KC-135A	328	nil	1.28	<0.1
R-204	J-57-59	KC-135A	291	nil	2.24	<0.1
R-206	J-79-15	RF-4C	412	nil	2.04	<0.1
R-215	TF-41-1	A-7D	92	nil	2.96	<0.1
R-219	J-57-43wb	B-52G	300	nil	0.45	<0.1
R-220	J-57-59w	KC-135	10	nil	1.33	<0.1
R-226	J-57-59w	KC-135A	462	1.77	12.1	0.15
R-227	T-56-7	C-130	380	nil	2.65	<0.1
R-229	J-57-43wb	B-52G	1169	nil	1.45	<0.1
R-238	J-57-59w	KC-135A	125	nil	1.82	<0.1
R239	J-57-43w	B-52G	277	nil	1.34	<0.1
R-240	J-79-15	RF-4C	6.3	nil	2.31	<0.1
R-241	J-57-59w	KC-135	9	nil	0.71	<0.1
R-245	J-57-59w	KC-135	526	nil	3.68	<0.1
R-246	J-57-43wb	B-52G	1434	nil	5.91	<0.1
R-247	J-57-43wb	B-52G	893	nil	3.73	<0.1
R-273	J-79-15	RF-4C	163	nil	1.25	<0.1
R-274	T-56-7	C-130	61	nil	4.45	<0.1
R-283	J-57-43wb	B-52G	300	nil	0.78	<0.1
R-298	J-85-5	T-38A	250	8.31	8.93	0.93
R-299	J-69-25	T-37	21	nil	1.30	<0.1
R-300	J-85-5	T-38	1	nil	1.26	<0.1
R-311	J-57-59W	KC-135	869	36.0	2.59	14.
R-315	J-57-43wb	B-52G	304	nil	1.96	<0.1
R-316	J-57-59w	KC-135	102	nil	3.03	<0.1

SAMPLE NUMBER	ENGINE TYPE	AIRC TYPE	T	X	Y	X/Y
R-317	J-57-43wb	B-53G	300	nil	1.03	<0.1
R-318	J-85-5	T-38A	102	7.70	7.56	1.0
R-319	J-79-15	RF-4C	318	nil	2.75	<0.1
R-324	T-56-7	C-130	1166	5.27	11.4	0.46
R-325	T-56-A7B	C-130E	11	3.33	4.07	0.82
R-340	J-57-P-43wb	B-53G	985	nil	1.72	<0.1
R-342	J-79-15	RF-4C	12	nil	1.14	<0.1
R-345	J-57-P-43w	B-52	222	nil	1.65	<0.1
R-353	J-85-GE-21	F-5E	3	nil	0.66	<0.1
R-366	J-85-GE-5	T-38A	91	nil	2.45	<0.1
R-372	J-79-GE-15	RF-4C	107	nil	1.45	<0.1
R-386	J-69-T-25	T-37B	80	nil	1.85	<0.1
R-387	J-85-GE-5	T-38A	42	nil	1.99	<0.1
R-390	J-85-GE-5	T-38A	109	nil	2.09	<0.1
R-391	J-69-T-5	T-37B	168	nil	1.56	<0.1
R-400	J-57-P-43wb	B-52G	972	nil	2.89	<0.1
R-404	J-57-P-43w	B-52G	149	nil	3.96	<0.1
R-423	J-57-P-59w	KC-135	615	nil	3.98	<0.1
R-424	T-56-A7B	C-130E	2034	49.6	16.0	3.1
R-429	J-85-GE-5	T-38A	150	5.36	5.11	1.0
R-433	J-79-GE-15	RF-4C	572	0.767	14.3	<0.1
R-435	J-57-P43w	B-52G	0	nil	1.67	<0.1
R-436	J-57-P-43w	B-52G	0	nil	2.12	<0.1
R-437	J-52-P-59W	KC-135A	817	nil	2.60	<0.1
R-438	J-57-P-43w	B-52G	1179	nil	1.78	<0.1
R-446	J-69-T-25	T-37B	1	nil	4.77	<0.1
R-452	J-85-GE-15	T-38A	unk	348.	3.14	110.
R-454	J-57-43wb	B-52G	90	1.20	3.62	0.33
R-455	J-57-43wb	B-52G	2731	2.39	6.11	0.39
R-456	J-57-43wb	B52G	32	11.5	2.64	4.4
R-457	J-57-59w	KC-135	unk	3.73	7.83	0.48
R-460	J-57-P-59w	KC-135	3405	12.0	3.03	4.0
R-461	J-57-P-59w	B-52G	1613	0.911	3.02	0.30
R-462	J-57-P-43	B-52G	1039	nil	1.6.	<0.1
R-465	J-57-43wb	B-52G	3099	nil	2.53	<0.1
R-466	J-57-43wb	B-42G	943	nil	2.74	<0.1
R-468	J-57-P-59	KC-135A	687	2.61	3.26	0.80
R-473	J-57-P-59w	KC-135	82	3.21	2.81	1.1
R-489	T-56-A7B	C-130E	39	nil	3.88	<0.1
R-497	J-57-P-59-w	KC-135	776	5.97	4.39	1.4
R-500	J-85-GE-5	T-38A	192	20.2	10.8	1.9
R-501	J-79-GE-15	RF-4C	183	2.67	4.12	0.65
R-502	J-79-GE-15	RF-4C	257	1.21	4.28	0.28
R-503	J-85-GE-5	T-38	6	25.4	10.6	2.4
R-504	J-85-GE-5	T-38A	136	0.260	8.14	<0.1
R-505	J-85-GE-5	T-38A	unk	7.04	2.85	2.5
R-506	J-57-43wb	B-52G	99	0.922	1.76	0.52
R-523	J-57-P-59w	KC-135	unk	nil	1.53	<0.1
R-524	J-57-P-59w	KC-135	313	nil	1.90	<0.1
R-525	J-85-GE-5	T-38A	210	29.0	6.92	4.2
R-527	J-85-GE-5	T-38A	274	1.03	7.84	0.13
R-531	J-79-GE-15	F-4C	437	nil	2.69	<0.1

SAMPLE NUMBER	ENGINE TYPE	AIRC TYPE	T	X	Y	X/Y
R-535	J-57-43wb	B-52G	268	nil	1.87	< 0.1
R-541	J-57-P-59	KC-135A	396	nil	3.26	< 0.1
R-542	J-69-T-25	T-37B	unk	nil	1.84	< 0.1
R-550	J-79-GE-15	RF-4C	281	1.48	4.00	0.37
R-551	J-85-GE-5	T-38	200	0.628	4.85	0.13
R-552	J-57-59w	KC-135	878	nil	2.36	< 0.1
R-553	J-57-P-59w	KC-135	1485	1.42	2.53	0.56
R-554	J-85-GE-21	F-5E	198	0.523	4.55	0.12
R-555	J-69-T-25	T-37B	unk	0.894	6.82	0.13
R-556	J-57-P-59w	KC-135	1252	4.74	5.16	0.92
R-561	J-79-GE-15	RF-4C	152	0.782	8.76	<0.1
R-562	J-69-T-25	T-37B	unk	0.652	4.14	0.16
R-563	T-56-A7B	C-130E	696	4.48	13.3	0.34
R-564	J-69-T-25	T-37	unk	4.20	5.85	0.72
R-565	T-56-A7B	C-130E	unk	14.4	2.67	5.4
R-566	T-69-T-25	T-37	unk	3.64	3.39	1.1
R-570	J-69-T-25	T-37B	135	3.88	3.79	1.0
R-572	J-85-GE-5	T-38A	141	nil	1.77	<0.1
F-032	T-56-A7B	C-130E	27	2.09	4.25	0.49
F-038	T-56-A7B	C-130E	765	2.77	6.28	0.44
H-031	J-85-21	F-5	150	5.80	6.74	0.86
H-062	J-79-GE-15	F-4C	179	0.109	11.1	<0.1
H-064	J-85-GE-5	T-38A	2	1.47	3.16	0.46

APPENDIX C

THIN FILM PARTICLE COUNTING

Here we analyze the feasibility of performing particle counts on a thin layer of undiluted oil. Based on experience in counting diluted oil samples, we show how the allowable film thickness is related to particle concentration, opacity, and counting time.

Particle concentration

According to our present measurements, the most heavily-charged oils may contain as many as 100,000 particles per cm^3 (larger than one micron in diameter). In the conventional mode of operation, such a specimen must be diluted to about 70 times its original volume in order to reduce the number density of particles below 1500 cm^{-3}; we recall that this is the tolerable limit for a five-centimeter path length if multiple scattering is to be avoided. The characteristic parameter governing this behavior is the number of particles per unit of cross-sectional area, and the critical value is seen to be 5 x 1500 = 7500 cm^{-2}. It follows directly that the maximum permissible thickness for an undiluted heavily-charged oil is L = 7500/100,000 = 0.075 cm = 0.75 mm. Since few oils approach a concentration of 100,000 cm^{-3}, this thickness is tolerable for any real specimen; for most samples, it is well within the limit.

Opacity

At a dilution of 70, the opacity of even the darkest oils never exceeds 35% in a five-centimeter cell; at least, no case of a higher opacity has yet been discovered, and the typical oil runs much lower. We wish to estimate the opacity of such a dark oil in the undiluted state. Applying the

Beer-Lambert law, we write

$$I/I_0 = 1-0.35 = 0.65 = 0.925 \exp(-kLc)$$

for the diluted sample. The factor 0.925 in this expression is the transmission of a glass or quartz cell containing pure paraffin oil, and represents the loss due to reflection at the cell walls; the paraffin itself absorbs practically no radiation at the laser wavelength. The constant k is the absorption coefficient of the undiluted engine oil. If we supply the values $L = 5$ cm and $c = 1/70$, we find $k = 4.94\ cm^{-1}$. Using this constant, we calculate the opacity of a layer of undiluted oil 0.075 cm thick to be almost exactly 35%. Thus we see that even an exceptionally dark specimen will not exceed the desirable opacity limit.

Counting time

Finally, we compare the counting rates for undiluted and diluted samples. The thickness of the undiluted sample is assumed to 0.075 cm. Recall that the sensitive zone of the counter is about 2 cm long, and this zone is fully utilized when a diluted sample is counted. If the dilution is d, then the ratio of counting rates (undiluted/diluted) is simply $0.075d/2 = 0.037d$. Hence for the typical oil, run at the normal dilution of about 70, the count rate in the undiluted mode will be about 2.6 times as fast as when diluted; in other words, a count time of 180 seconds produces as many scattering events as occur in 450 seconds in the diluted oil.

In the case of an oil sparsely populated with particles, which in the ordinary way might sometimes be run at a dilution of 35 or so (opacity permitting), the thin-film counting time would have to be doubled to realize equivalence in the total number of counts. An alternative choice would be to use a thicker layer (0.15)cm and retain the 3-minute counting time. However,

it is questionable whether either of these refinements would in fact be warranted; the principal motive in reducing dilution during a conventional run is to improve the blank correction, particularly at large particle diameters, and this problem does not arise in thin-film measurements.

*U.S.Government Printing Office: 1980 — 657-084/501