PARTICLE COUNTING: AN ANALYSIS OF THE PROBLEM OF CALIBRATION AND UNCERTAINTY

By

GARY ALLEN ROBERTS

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

1973

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
MASTER OF SCIENCE
July, 1975

PARTICLE COUNTING: AN ANALYSIS OF THE PROBLEM OF CALIBRATION AND UNCERTAINTY

Thesis Approved:

Carl B. Estes
Thesis Adviser

E C Fitch

M. Palmer Terrell

N N Durham
Dean of the Graduate College

ACKNOWLEDGEMENTS

This thesis and in fact the graduate study which preceded it would have been impossible without the advice, assistance, and encouragement of many people.

A special note of appreciation is due my thesis adviser Dr. Carl B. Estes who performed above and beyond the call of duty.

Dr. M. Palmer Terrell served as graduate adviser as well as a member of my committee.

Dr. E. C. Fitch, whose contribution both to this study and my entire professional career is beyond estimation also served on my committee.

My colleagues at the Fluid Power Research Center, especially R. K. Tessmann, L. E. Bensch, R. L. Brown, L. Moore, and Nallaigounderduraiswamy were a continuing source of help.

Dr. M. O. Locks contributed greatly to the statistical development through personal contact, an excellent text, and a most valuable index to the SAS computer system.

Finally a very special thank you to my wife Nancy and daughter Renee who accepted this activity as a rational endeavor despite overwhelming evidence to the contrary.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The capability to accurately estimate the parameters of the distribution of sizes of small particles (i.e., 1 to 100 micrometres) is very important in a number of diverse fields. In medicine, blood cell counts are based on the size difference of red and white cells. The ultimate characteristics of sintered products in powder metallurgy is critically dependent on particle size. Of special concern to the author, the technology of contamination control in fluid power systems is totally dependent on accurate, easily obtained, counts of various size particles entrained in fluid samples.

There are a number of techniques employed in particle counting. Manual counts using microscopes have been used for many years. By the late 1960's, it had been recognized that microscopic counting techniques were neither accurate enough nor sufficiently economical to support the research and development effort required to evaluate the filters and components used in fluid power systems. The opto-electronic automatic particle counter was the most promising technique for a general methodology if a suitable standard method could be developed for calibration and use of the instrument.

The Fluid Power Research Center (FPRC) of Oklahoma State University undertook the task of developing and promulgating such a standard, and, in 1973, the American National Standard B93.28-1973 was adopted. This standard is presently being circulated for ballot as an international (ISO) standard. As is the case with all such standards, the method proposed is a compromise of the technology in order to meet political constraints. The standard incorporates the use of Shewhart $\overline{X}$ and R charting which was virtually unknown to the participating committee members both in the U.S.A. and abroad. At the time the standard was promulgated, the requirements were considered far too severe. The standard is now under attack as unacceptably lenient.

This is a healthy sign, reflecting the growing sophistication of the industry. The scope and nature of the problems of particle counting are much more generally understood, and the environment is conducive to the acceptance of statistical control techniques.

There are two considerations in applying statistical control aspects to automatic particle counting: (1) the physical nature of counting process including optical and electronic effects, and (2) the nature of the size vs. frequency of occurrence of various contaminants encountered. This thesis presents the results of an extensive investigation of the counting phenomena, an analysis of a large body of data from actual particle counts, and proposes a set of statistical quality control techniques to be incorporated into a revised proposed standard method.

CHAPTER II

SURVEY OF RELATED TOPICS

Over one hundred papers, books, and monographs relating to particle counting were reviewed in preparation of this thesis. Only fifteen made any mention of calibration or uncertainty. Nine of the papers were concerned with particle distributions, another nine addressed particle behavior, and the balance either advanced new particle counting methods or reviewed existing techniques. The lack of concern with the metrological aspects is surprising in view of the widespread interest in particle counting. Prior to the introduction of the first automatic particle counter in 1956 by W. H. Coulter, all particle counting was performed manually by microscope examination which may explain the absence of calibration studies.

As early as 1929 it was recognized that the most useful information about particulate contamination would be in the form of a mathematical relationship between particle size and frequency of occurrance [1]. Subsequently a number of investigations have postulated appropriate models including the Hyperbolic [2] and the log-normal [3]. These probabilistic models are intellectually appealing since most naturally occurring contaminants are of essentially infinite supply. However, the automatic particle counter yields only the number of particles greater than a selected size. There is no way to determine the total number of particles in a sample for estimating relative frequency. A model proposed by Cole [4] provides a useful transformation of the log-normal. This equation is very tractable and particularly well suited for graphical analysis. The model is of the form

$$n = A \int_{-\infty}^{\ell n X} \exp(-B \ell n^2 X) \qquad (2\text{-}1)$$

where A and B are emperical constants for the contaminant in question. This model has been generally accepted in the Fluid Power Industry and is an integral part of several American National Standards dealing with contamination control. Particle counting is concerned principally with the estimation of the parameters of this model and any method of calibration must be relevant to this application.

The major impetus for standardization came with the space program when strict cleanliness standards were imposed on various components being manufactured at different locations. A research group at Oklahoma State University was working on contamination sensitivity and filtration for N.A.S.A. and an evaluation of automatic particle counters was a part of the study. The study by Zaloudek [5] is one of the earliest attempts to quantify the uncertainty of an automatic particle counter. Zaloudek presented data which strongly supported the proposal by Michaelson [6] that the appearance of particles in the counter was a Poisson process.

In the late 1960's both the National Fluid Power Association and the Society of Automotive Engineers began the development of calibration standards for automatic particle counters. The SAE standard which was published in 1970 as Aerospace Recommended Practice (ARP) 1192 was an outgrowth of earlier work with microscopic counting and in fact relied on correlation with microscopic results. The limitations of the latter technique were widely known and as a result ARP 1192 received little acceptance.

The N.F.P.A. Standard was directly the result of a broadly based study by the Fluid Power Research Center at Oklahoma State University which included a series of International Round Robin Tests using known and unknown (i.e., undisclosed) samples. The procedure uses an arbitrary calibration standard, A.C. Fine Test Dust, the distribution of which is accepted knowledge and conforms to the log-log^2 model. This standard was adopted as an American National Standard in 1973.

At the time the ANSI standard procedure was developed it was not uncommon to observe a 200% variation in counts of the same fluid by different laboratories. The round robin test of 1971-72 showed a coefficient of variation of 74% for laboratories not using the proposed procedure. Within two years of publication a large number of users had become sufficiently expert in the science of particle counting to detect serious deficiencies in the procedure. Primarily these problems are the result of the use of statistical procedures which do not discriminate against a process which does not have an origin in a stable region. If the particle counting process has an extremely large variance, or is operating in an invalid concentration region when the calibration procedure is started, the results are unrealistic.

The objective of this thesis is to develop analytical descriptions of the counting process and to apply these models to the structuring of a fundamental and general calibration and control procedure for automatic particle counters.

CHAPTER III

THE COUNTING PROCESS AND SOURCES OF ERROR

All of the automatic particle counting devices in use today exhibit a degree of non-repeatibility and error. Although the actual counting technique varies widely between the different types of instruments, the concepts employed are similar and the basic sources of error are common to all. The total light reduction principle is by far the most widely used technique and will be used to illustrate the problems associated with reducing the uncertainty of particle counts.

The basic particle counting device is illustrated in Figure 1. A stream of fluid is passed through a transparent chamber (usually quartz) across which a collimated beam of light is focused. A photoelectric device (typically a photo diode) measures the intensity of the light passing through the fluid. If a particle whose index of refraction is sufficiently different from the fluid [7] passes between the light source and the detector, the light is scattered and/or blocked resulting in a reduction of intensity which is directly proportional to the projected area of the particle. The output of the photo detector is amplified and conditioned electronically to provide a train of pulses such as that shown in Figure 2. A level detector(s) determines whether or not the pulse exceeds a preset value. If it does, a counter is incremented. The levels correspond to the intensity reduction caused by a circular cross section particle of the specified

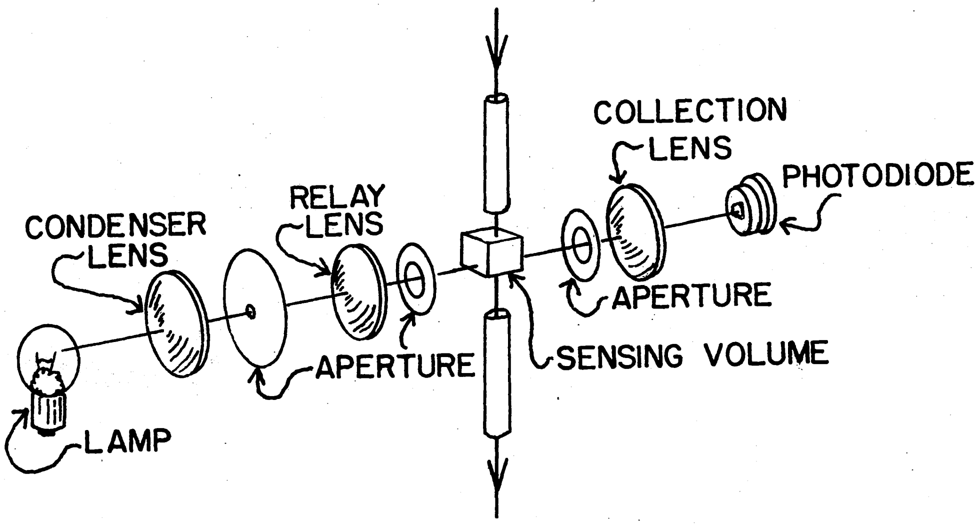

Figure 1. Particle Counting Device

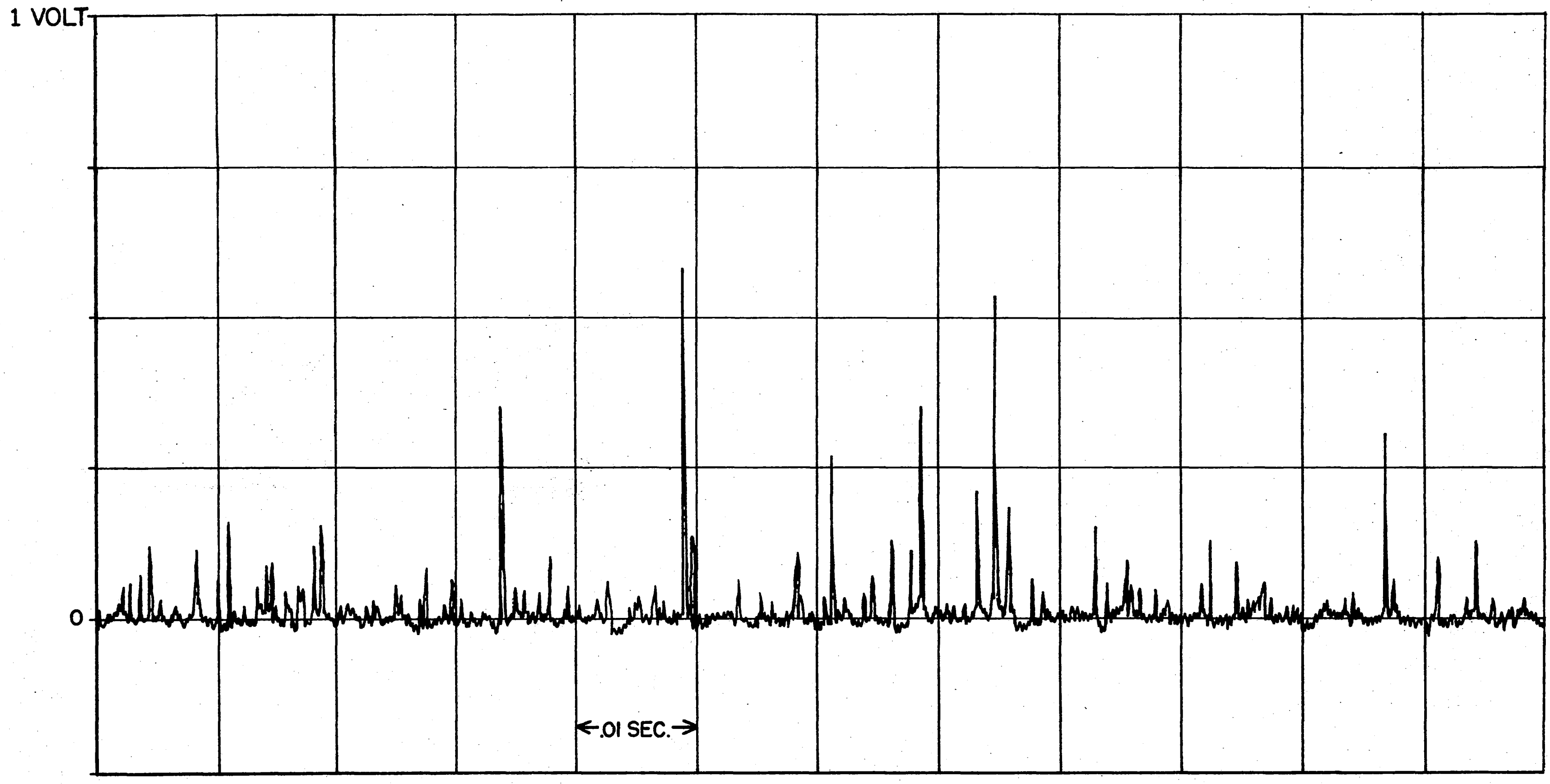

Figure 2. Electrical Output From Sensor

diameter. The result is the number of particles greater than a specified diameter which passed the sensing zone.

To the user, the variation in counts obtained from repeated samples is in the form of scatter of the counts about a mean value, the deviation of the mean from a known or expected correct count, and the failure of the observed count to increase proportionately with increasing particle concentration. This latter condition is generally called saturation and is depicted in Figure 3.

From an analytical viewpoint the sources of error can be grouped into three categories: (1) procedural, often erroneously called operator induced, which are effects not related to the actual counting phenomenon; (2) functional, which are limitations of the counting device; and (3) inherent variation in the counting process.

Generally the particle counting procedure consists of obtaining a sample of contaminated fluid from the system in a suitable container, passing a known portion of the sample through the sensing zone and reporting the result in terms of a standard volume, usually one millilitre. If the count exceeds the saturation level discussed above, the fluid is diluted with clean fluid and the process repeated. If the sample container is not extremely clean, the background contamination in the container will add to the actual count. Any variation in measurement of the fluid volume passing the sensor results in a directly proportional error in the perceived count. If dilution is required the inaccuracies of the volume measurements will reflect directly on the magnitude of the count and if the sample is not properly mixed, very erratic results are obtained. In addition, the particles tend to either settle or float in the fluid and care must be

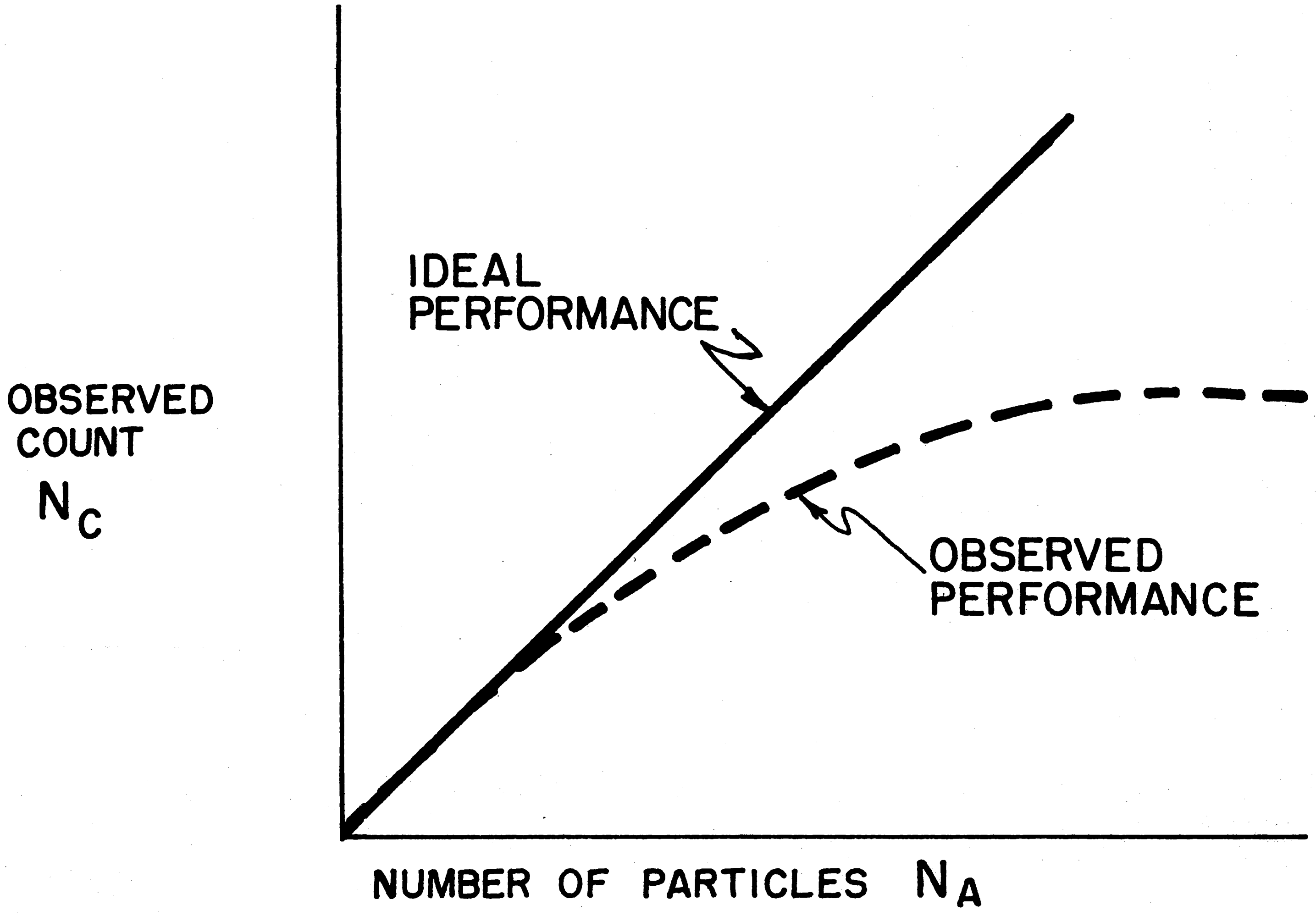

Figure 3. The Saturation Phenomenon

taken to assure proper dispersion of the particles. Until very recently these procedural effects were the major source of uncertainty in particle counts and in fact may still be significant. However, in 1970 a sample container cleanliness verification procedure was developed at the Fluid Power Research Center which has since been adopted as an international standard. Improved particle counters which incorporate photo-electric volume measuring have sharply reduced the variance from this source.

The requirement for dilution imposes a severe burden on the particle counting technician. Dilutions of 40 to 1 and higher are not uncommon and this requires very precise measurement of small volumes of fluid.

The functional errors of the particle counter are related both to design variables and the condition of the counter. The counter may simply fail to count correctly due to erratic behavior of the counting or display electronics. Variations in the reference level voltages will result in counts which represent a particle diameter other than that intended. Due to the extreme nonlinearity of the particle distribution a reduction in level would result in a positive increase in count much larger than the decrease associated with an equivalent upward shift in level. It should be noted that the signal from the photo detector is a function of the area and not the diameter and therefore if linear amplification is used the change in perceived particle size is proportional to the square root of the change in threshold setting.

The signal from the photo detector is a function of the rate at which the light source in the sensor is blocked. This is in turn a function of the size of the particle and the flow rate. If the amplifiers and associated circuitry do not exhibit acceptable frequency response, the output for a given particle size is lower for increasing flow rate. This effect is the same as increasing the threshold level so that increasing flow causes reduced counts. If the apparatus is calibrated in too high a flow region it will be operating within only a portion of the normal electronic regions.

The lowest particle size which can be counted accurately is for any particular instrument configuration ultimately determined by the signal to noise ratio. Any counter exhibits a random signal which results from vibration of sensor elements, electromagnetic interference and thermal emission. Instrument design and environment influence this phenomenon to a considerable degree but it cannot be eliminated; there is a threshold below which the counter will register the passage of a particle even when the sensor is empty. Electromagnetic fields may induce electrical impulses of a magnitude well above the normal noise level. While these might properly be called procedural problems related to the environment, the sensitivity to such phenomena are so strongly related to circuit design that they must be considered functional.

All of the light blocking counters currently in use employ assyncronous counting. Therefore it is essential that the signal from the photo detector fall below the threshold level for a sufficient length of time for the comparator and counter circuits to reset. This implies that no particle or group of particles with a total area greater than the size of interest may be in the sensor during the reset interval.

If all the sources of error described thus far were eliminated one would still expect some variation in repeated counts (unless by some means all the fluid in the population were counted) due to the natural difference in samples. In addition there exists a possibility that two or more particles will be passing through the sensor simultaneously. This phenomenon is called coincidence and is widely discussed in the literature and among users of particle counters. Coincidence is offered as an explanation for nearly every major defect including saturation.

It is apparent that not all of the potential sources of error can be of equal significance. In order to determine the appropriate statistical control techniques for evaluating particle count uncertainty, it is necessary to determine the degree to which each potential error can occur and the influence of the error on the resulting count. This is developed in the next chapter.

CHAPTER IV

ANALYSIS OF THE ERROR PROBABILITIES

In order to evaluate the error probabilities it is necessary to postulate a model for the appearance of the particles in the sensing zone. Most investigators have proposed the Poisson model. This is attractive both for the tractability of the mathematics and from experience with similar mechanisms encountered in industrial and natural processes. Analysis of a large amount of particle count data from various sources shows excellent agreement with this hypothesis.

The Poisson is a distribution on the number of occurrances in some interval or area [7]. The probability mass function is

$$P(X = x;\lambda) = \frac{e^{-\lambda}\,\lambda^{x}}{X!}\ ;\ X = 1,2,\ \ldots,\ n. \tag{4-1}$$

Lamda has units of occurrances per unit opportunity. In the case of estimating the coincidence probability this is particles per sensor volume which can be estimated as particles per millilitre of fluid multiplied by the volume of the sensing zone in millilitres. Thus for a particular particle size lambda can be estimated if the distribution is known. For example using Cole's model for A.C. Fine Test Dust the number of particles greater than 10 micrometers is

$$N > 10 = Ke^{-\beta \ln^2 D} = 144 \text{ particles per microgram} , \qquad (4\text{-}2)$$

where

$K = 1751.9$, and

$\beta = 0.4714$.

In a 28 mg/ℓ solution of test fluid this would yield a Lambda of .11 with a sensor volume of 2.58×10^{-5} ml. The probability of 2 or more particles residing in the sensor simultaneously is given by

$$P(2 \text{ or more}) = 1 - P(1 \text{ or less}) = 1 - \sum_{K=0}^{1} \frac{e^{-\lambda} \lambda^K}{K!} . \qquad (4\text{-}3)$$

Unfortunately, repeated tests by a number of investigators including the particle counter manufacturer have shown that the ratio of observed count to expected count under these conditions is about .90 which implies a .10 coincidence probability. A careful analysis of the requirement for coincidence error reveals that this is almost certainly not occurring in any realistic particle counting situation.

If any two or more particles of a size greater than the threshold size (D) appear in the window at the same time, a count will be missed. If a particle of size $\geq$ D and any quantity of particles $<$ D appear simultaneously, no error occurs. However, if two or more particles of size $<$ D, whose combined area is greater than the area associated with D, appear during an interval when no particle greater than D is in the sensor, a false count will be recorded (see Figure 4).

Analyzing multiple occurrances of particles in various size intervals requires that Lambda be a function of particle size and that the probabilities be evaluated for an infinite number of intervals. This

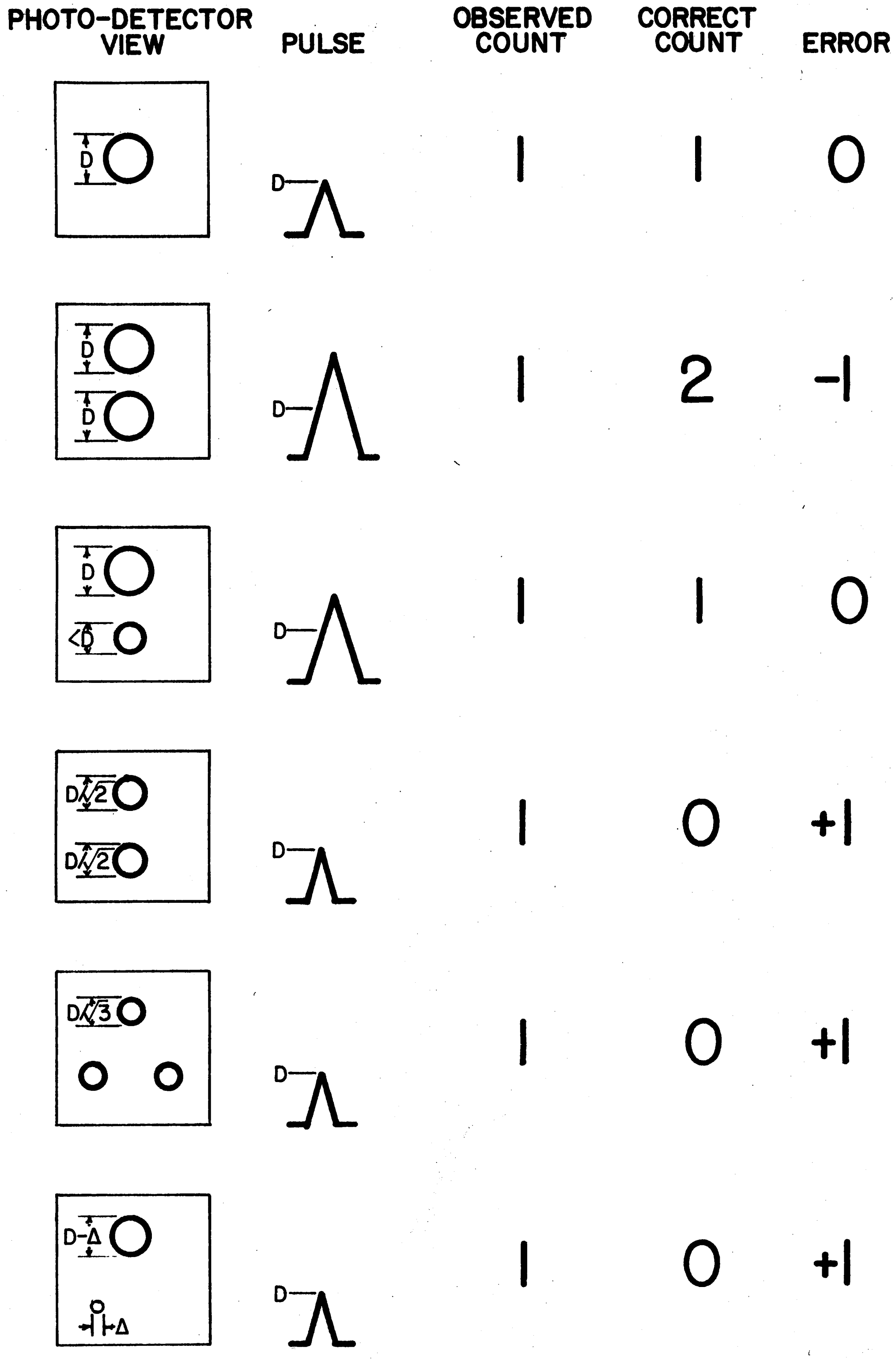

Figure 4. Coincidence Error

of zero occurrances in an interval of time t is

$$P(\circ) = e^{-\lambda t} \qquad (4\text{-}5)$$

where λ has the same meaning as described earlier. To translate Lambda from the volume domain to the time domain requires the consideration of flow through the sensor which is 30 ml per minute in current practice. Thus

$$\lambda = \frac{.11 \text{ particles}}{2.58 \times 10^{-5} \text{ ml}} \times \frac{30 \text{ ml}}{\text{min}} \times \frac{60 \text{ min}}{\text{sec}} = 2131.78 \qquad (4\text{-}6)$$

considering the particle to be a point (a reasonable assumption for particles which are substantially smaller than the sensing volume) the time for a particle to transit the sensor is

$$\frac{2.58 \times 10^{-5} \text{ ml}}{.5 \text{ ml/sec}} = 5.16 \times 10^{-5} \text{ sec} \quad . \qquad (4\text{-}7)$$

The particle counter requires a reset time of 12 μs so that the total time between particles must be 63.6×10^{-6} sec. Therefore the probability that reset will occur is

$$e^{-2131.78(63.6 \times 10^{-6})} = .87 \qquad (4\text{-}8)$$

which shows excellent correlation with published data [8, 9]. The equation can be generalized as follows

$$P(\text{count}) = e^{-N_D(V_S + QT_R)} \qquad (4\text{-}9)$$

where

N_D = actual number of particle ≥ size D,

V_S = sensor volume,

Q = flow rate, and

T_R = minimum time to reset.

The error rate is sensitive to flow rate, especially for large reset times, which has also been documented by Moore [10].

The reduction in particle count due to increases in flow rate may also be caused by roll-off of the amplifier circuits as a function of the frequency response. However, the rate of change of the area shaded by a particle is a function only of the sensor configuration, particle size and particle velocity, thus the count loss due to frequency response characteristics is independent of particle concentration in the fluid. The effects of roll-off and reset error can therefore be separated.

If the coincidence and reset constraints are met, a lower bound can be placed on the counting uncertainty by virtue of the Poisson assumption. As has been implied in the earlier discussion, the parameter Lambda can be estimated from the particle counts. The unbiased point estimate of Lambda [11] can be determined as the ratio of total occurrances to the total opportunity. In the volume domain this is

$$\lambda = \frac{\text{particle count x volume of sensor}}{\text{volume counted}} . \qquad (4\text{-}10)$$

Probabilities of various particle counts can be computed readily using Equation (4-1). As a practical matter we are seldom concerned with a single count; the use of averages of five counts is the common practice. For this case we utilize the central limit theorem and the characteristics of the Poisson which dictate that the mean and the variance are both equal to Lambda [11], so that the confidence limits on the mean are

$$n + \tfrac{1}{2} c^2_{\alpha/2} \pm \sqrt{(n\, c^2_{\alpha/2} + \tfrac{1}{4} c^4_{\alpha/2})} \qquad (4\text{-}11)$$

where c_α is the upper α point of the unit normal distribution and n is the estimate of λ. For large values of n this can be approximated by

$$n + c_{\alpha/2} \pm \sqrt{n} \quad . \qquad (4\text{-}12)$$

The effects of volume measurement and dilution error are linear with particle count while sampling, mixing and cleanliness problems will most likely be more pronounced in the smaller particle sizes. There is no way to predict such errors individually from an unknown sample but various experimental designs incorporated into the calibration procedure can assign expected upper limits to these effects.

For example if solutions of A. C. Fine Test Dust of 2, 5, 10, 20, and 50 are diluted by 2 to 1, 5 to 1, etc., the resulting counts should be within the same limits as repeated samples from 1 mg/ℓ solution. The variation in excess of this amount must be attributed to procedure. The uncertainty associated with procedural defects must be incorporated in any estimate of the accuracy of the particle counting process.

Industrial specifications that require contamination assessment for measuring performance criteria must be based on the assumption that reproducible and accurate particle counting is performed. Each of the potential sources of error must be evaluated and controlled by a methodology which is essentially free from subjective judgement.

The next chapter presents a general procedure which meets this objective.

CHAPTER V

PROPOSED CONTROL PROCEDURE FOR PARTICLE COUNTING

The extent of the uncertainty which can be tolerated in any measurement is related to the intended use of resulting information. The tape measure which is wholly satisfactory to the carpenter, finds little use in a precision machine shop. In the same manner, a laboratory attempting to identify small differences in filters would require much greater precision and repeatibility in particle counting than would be needed for field contamination assessment of operating systems.

The flow rate and concentration effects inherent in the particle counter impose a direct trade off between minimal uncertainty and operating flexibility. The design of many particle counters is such that narrow confidence intervals would dictate such low concentration that virtually every sample would require dilution. The limitation of the procedural capabilities would effectively eliminate such instruments. In the recommendations which follow, this problem is avoided by addressing only the question of establishing .90 confidence limits. These limits may be too restrictive, but the techniques presented are not limited to the particular value chosen.

The calibration of the instrument must be accomplished independently of procedural errors if this is at all possible. The ANSI B93.28-1973 Standard avoids this question by pre-supposing that the laboratory is fully competent in such areas. This approach is necessary to some extent as the standard contaminate (A.C. Fine Test Dust) is a particulate solid and must be suspended in a fluid for use. There are now a number of organizations marketing certified suspensions. Regardless of the source, the procedure must begin from an established base which is a solution containing a known concentration of A.C. Fine Test Dust.

The concentration to be used for calibration of the threshold levels of the counter must be such that the error due to the minimum reset time requirement is small. This is recognized in the ANSI Standard by placing the saturation procedure first. If the reset error is to be maintained at less than 1% then the value of N_D $(V_S + QT_R)$ must be less than .01. If V_S or T_R is not known, an empirical approach such as a least squares fit to EG (4-9). If the equation is formulated as

$$\frac{N_C}{N_D} = ae^{-bN_D} \qquad (5\text{-}1)$$

and repeated observations are made at various fluid concentrations, then

$$b = \frac{\Sigma X_i \ell n Y_i - \frac{1}{n}(\Sigma X_i)(\Sigma \ell n Y_i)}{\Sigma X_i^2 - \frac{1}{n}(\Sigma X_i)^2} \qquad (5\text{-}2)$$

where X_i is the actual count and Y_i the ratio of observed count to actual count for the i^{th} concentration. b is a good approximation to $(V_S + QT_R)$. The coefficient a is given by

$$a = \exp\left[\frac{\Sigma \ell n Y_i}{n} - \frac{b\Sigma X_i}{n}\right] \qquad (5\text{-}3)$$

and is a measure of the calibration error and should be equal to one for a correctly calibrated particle counter. The use of this method is shown in Figure 5, based on data from a HIAC particle counter.

The flow rate used for calibration must be such that frequency response is not a significant factor. Many of the counters in use do not exhibit such a region. It may be necessary for the purpose of developing a practical standard to require only that the flow rate be held within the range .99 to 1.01. Counters with poor frequency response characteristics would then be limited to a very narrow flow rate tolerance.

It is advantageous to determine the ultimate limitations of the counting process, at least approximately, before proceding to the final calibration. This can be accomplished by testing the null hypothesis that a series of counts of a constant concentration are distributed as the Poisson with λ equal to the mean. Such a test is given by [12]

$$\chi^2 = \sum_{i=1}^{m} \frac{(f_i - e_i)^2}{e_i} \qquad (5\text{-}4)$$

where

f_i = observed frequency, and

e_i = the expected frequency.

The null hypothesis is rejected if

$$\chi^2 \geq \chi^2_{\alpha, m-2}$$

where

m = number of terms added, and α = confidence level.

This test is not very practical for use with very small samples

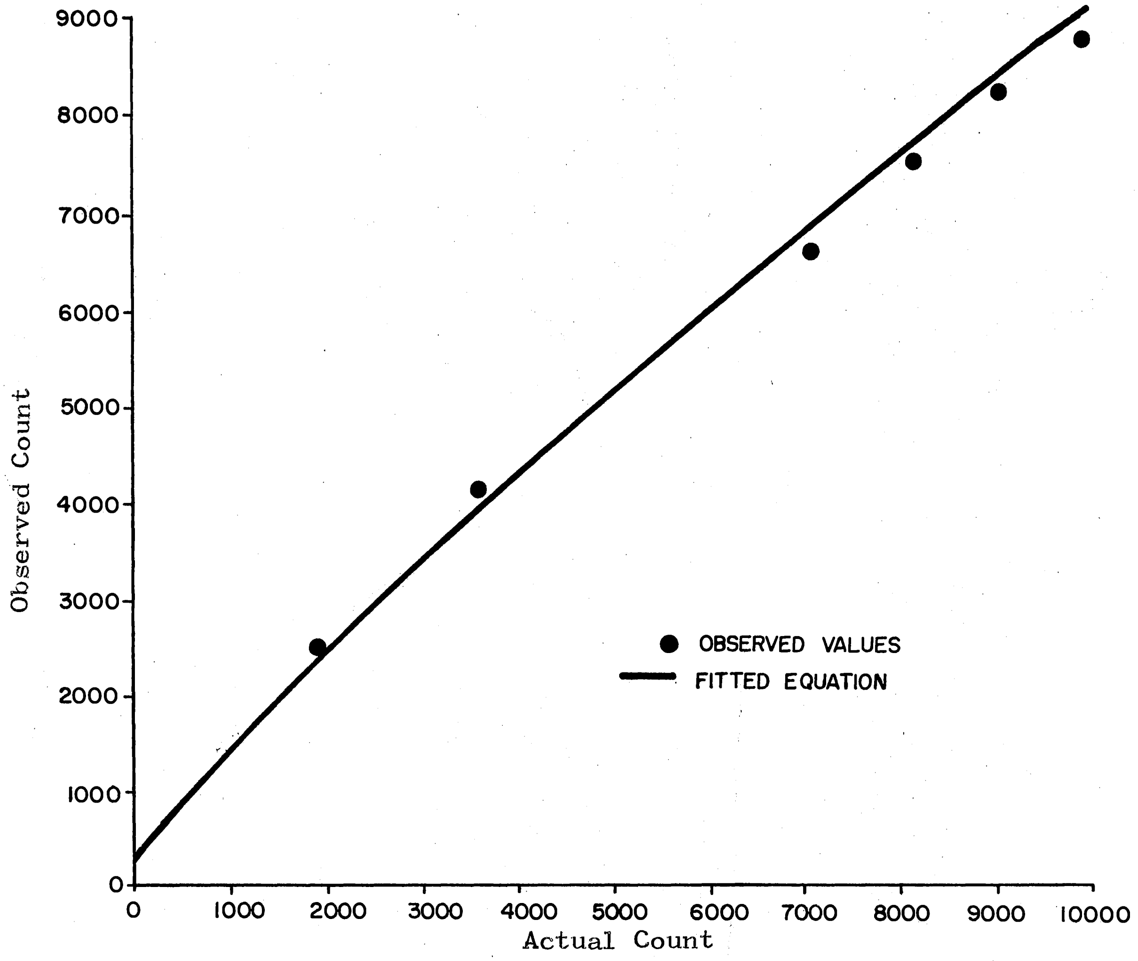

Figure 5. Analysis of Saturation Data

since the observed frequency for a particular value is almost certain to be 1. An alternative is proposed by Cox and Lewis [11] of the form

$$d = \sum_{i=1}^{k} \frac{(n_i - \bar{n})^2}{n} \tag{5-5}$$

where

n = the observed value and

$\bar{n}$ = the mean value of k observations.

This is essentially a test of the hypothesis that $\lambda = \bar{n}$ which is precisely the question posed. d is approximately distributed as Chi Square with k - 1 degrees of freedom.

A large sample of particle count data collected by the Fluid Power Research Center was evaluated with this test. The results are summarized in Table I, and the original data are contained in the appendix. The tests are ranked in increasing order of the mean count, and it can be seen that the number of samples which do not fit the Poisson model increases rapidly at the higher levels, where saturation is probably a factor. In the cases where rejection occurs at the lower levels, such as ID No. 328C5, it is obvious that spurious counts were included at the 20 and 30 micrometer level.

If the null hypothesis is rejected the test may be altered as follows. If the principle deviation from Poisson behavior is caused by variation in volume counted, the variance of the volume, which is in fact a variation in λ, may be independent of the volume measured. Thus $\bar{n} = f(N_D, V, X)$ where X is a R.V. with a mean of zero and V is the volume counted. If volume measurement is the dominant error, it should

TABLE I

TEST FOR POISSON FIT OF PARTICLE COUNT DATA

TEST FOR POISSON FIT...* INDICATES REJECTION AT .10 SIGNIFICANCE

CBS	ID	MMIC5	TEST5	R5	TEST10	R10	TEST20	R20	TEST30	R30	TEST40	R40
1	329B7	2587.4	1.757		3.8195		2.3514		5.7273		9.0000	*
2	329B8	2751.4	9.721	*	4.0153		2.7761		5.2857		2.6667	
3	328C8	3351.6	5.343		1.2203		0.5872		1.0000		9.7647	*
4	328C7	3536.8	1.555		0.9795		3.6667		1.2308		0.6667	
5	328C6	3761.0	12.516	*	3.0349		5.8033		4.2222		5.3333	
6	328C5	3806.2	6.328		4.0000		8.5000	*	10.3636	*	3.7143	
7	329B6	3841.4	0.292		2.8218		2.2963		5.8182		4.0000	
8	328J4	4061.4	7.804	*	6.6184		3.5000		4.6250		3.0000	
9	328J3	4087.0	123.555	*	7.0153		6.8571		3.2500		1.0000	
10	328J2	4518.4	13.138	*	1.0433		1.9420		6.3333		5.6667	
11	329B5	4523.8	13.950	*	7.4171		12.9620	*	6.5185		13.8571	*
12	328I1	4611.6	4.910		5.4422		2.0000		5.0000		3.5000	
13	328J1	4884.2	9.443	*	3.5967		3.5303		3.0526		2.0000	
14	328G1	4928.6	12.002	*	6.4031		5.8136		5.1875		11.2727	*
15	328G3	5113.8	17.465	*	3.6471		5.1264		3.3750		12.2857	*
16	328G2	5116.0	28.239	*	0.3870		5.2187		2.7500		3.5000	
17	328I3	5588.4	3.865		4.4248		5.8681		3.1111		1.2727	
18	328I2	5626.8	2.926		0.1620		3.4468		1.2000		0.4615	
19	328G4	6366.0	48.503	*	2.2613		17.3902	*	8.5882	*	16.0000	*
20	328I4	7157.2	18.676	*	2.2528		15.1613	*	9.3333	*	5.3333	
21	334C5	25268.4	72.001	*	3.7023		2.8950		8.0000	*	8.2500	*
22	329B3	26731.8	50.685	*	16.3964	*	6.4927		9.8394	*	14.4444	*
23	329B4	29094.2	271.623	*	38.2751	*	4.9944		9.7828	*	13.3176	*
24	329B2	29149.0	206.696	*	85.3937	*	53.6018	*	36.0676	*	36.1250	*
25	329B1	30415.0	208.802	*	50.8339	*	21.8071	*	28.9496	*	38.3701	*
26	328C4	30952.8	193.357	*	46.5396	*	42.9070	*	46.9036	*	50.0036	*
27	328G5	31485.0	3.150		10.5952	*	10.0219	*	18.8423	*	19.6364	*
28	328I5	31521.8	8.336	*	15.6651	*	21.4829	*	24.3861	*	17.6792	*
29	328I6	31724.2	253.155	*	25.1213	*	22.3812	*	52.3867	*	46.7124	*
30	328G7	31993.0	2.315		4.0323		10.9198	*	7.3881		12.6836	*
31	328G6	32097.0	7.941	*	5.2009		6.3798		4.2670		6.2110	
32	334C8	32332.2	106.773	*	6.1275		5.4041		3.5556		2.3333	
33	328I7	32545.6	113.942	*	25.6854	*	11.4016	*	18.0359	*	26.0885	*
34	328C3	32799.8	10.900	*	8.8920	*	26.2195	*	38.4678	*	50.6753	*
35	328J7	33320.8	4.373		7.8756	*	14.5221	*	36.9158	*	30.1148	*
36	328I8	33483.2	192.770	*	40.2330	*	19.8845	*	18.6050	*	19.8304	*
37	328J5	34671.4	239.525	*	55.6834	*	28.9261	*	17.7631	*	10.6499	*
38	328J6	34821.6	82.803	*	6.3777		4.7030		6.5303		2.1862	
39	328G8	34908.4	67.713	*	18.3826	*	8.1226	*	5.5868		8.1719	*
40	328C2	35322.2	15.650	*	22.7216	*	16.5303	*	34.5419	*	23.3919	*
41	328J8	35556.8	29.693	*	14.0220	*	9.6149	*	6.7526		10.3500	*
42	328C1	36229.2	74.126	*	7.7686		25.6976	*	33.0524	*	53.5914	*
43	334C6	41969.4	97.213	*	3.2513		1.7706		5.4211		5.6667	
44	334C7	50803.6	9.983	*	3.6414		4.9988		2.7879		6.0000	
45	334C1	59995.4	48.805	*	13.3831	*	4.6624		16.4757	*	16.8702	*
46	334C4	68745.0	41.838	*	9.4989	*	5.2160		7.9460	*	12.2215	*
47	334C2	72436.8	44.470	*	9.4267	*	1.0205		2.2633		12.6742	*
48	334C3	84453.8	48.823	*	4.7178		3.6542		9.0407	*	15.4639	*

be possible to find a counting volume for which d is not sufficient to reject H_o.

It should be noted that the methods used in most volume measuring mechanisms is such that the error is increasing for increasing flow rate. For this reason it is desirable to repeat the flow and reset error analysis after the optimum volume is selected.

The final calibration procedure specified in the A.N.S.I. Specification requires very little alteration. The grand average of a series of particle counts of a correctly calibrated counter converges stochastically on the correct value. The problem for the user is to determine when to stop adjusting the machine. The Shewhart control chart provides this information. However it may be desirable to modify the chart by using the Poisson model, for which the control limits for .90 confidence are given in Chapter IV, specifically

$$N + 0.98 \pm \sqrt{3.84N + 3.69} \quad .$$

These limits replace those calculated as the setting tolerance. The range chart is replaced by the test for a Poisson distribution. The value of d must not exceed 7.779.

If the counter is properly calibrated and conforms to a Poisson process, the same procedure can be used to provide a confidence interval on counts from an unknown sample. The use of the d statistic provides a continuing measure of procedural control.

When unknown samples are evaluated, another source of error is raised particularly if the sample represents a system which incorporates a filter. The particle count distribution may not follow the log-log[2] model or even if it does, the slope parameter may be so large that the particles in the size range below the counting level are so many as to create a significant coincidence factor. An analysis of this phenomenon requires the evaluation of a Gamma function with a parameter λ which is in turn a function of particle size. There is no analytical method available for solving this equation but a simulation technique could be applied. Even this approach requires that the particle distribution be known. As a practical alternative it may be advisable to use the lowest size for which the counter is calibrated as a check on the next higher level so that the former is not reported nor used as a reliable count. The optimum size interval for such a practice is probably D to $D/\sqrt{2}$ although this does not preclude errors induced by a drastic change in slope below the lower count level. Although not specifically a part of the calibration and control procedure, such consideration must be given in the practical application of particle counting.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

An analytical description of the particle counting process has been developed. The models postulated are fundamental and are applicable to any counter using the light reduction technique. Each of the basic sources of error in the particle counting process is evaluated and a mathematical technique is formulated to measure the degree to which that error is contributing to the total uncertainty.

There are four key elements in the calibration and control process:

(1) The determination or estimation of the concentration saturation curve to locate a suitable operating region.

(2) The evaluation of the extent of procedural errors affecting the count, especially the effect of volume measurement error.

(3) The determination of sufficient convergence of the mean count with the true value to justify termination of the calibration procedure.

(4) The continued surveillance of observed counts to detect the onset of procedural defects, saturation or coincidence error.

Recommendations for Further Development

The present American National Standard has two major weaknesses, both related to the use of the normal distribution model to develop control limits for a Shewhart Chart. The saturation level is determined by counting at increasing concentrations until the average count falls outside the control limits. If the procedure is begun at too high a concentration, the control limits change as rapidly as the mean, and no out-of-control level is reached.

This procedure should be replaced using the same data to fit Equation (5-1). Saturation could then be defined as the point at which the ratio N_C/N_D falls below an arbitrary value.

A Shewhart Chart is also used to terminate calibration and provide continued control of the counting process. The control limits (called a setting tolerance in the ANSI standard) should be determined with Equation (4-11) with Equation (5-5) used to establish that the counting procedure is properly conducted.

The exact levels of confidence and numerical values are not purely technical questions. There are economic implications which must be considered. The selection of such values is properly a task of standards-formulating committees. A modified standard should be prepared and circulated to users for evaluation and comment. If the technique is generally acceptable and suitable parameters for the tests can be found, the document should be promulgated as a revised standard.

BIBLIOGRAPHY

1. Hatch, Theodore, and Sarah P. Choate. "Statistical Description of the Size Properties of Non-Uniform Particulate Substances." Journal of the Franklin Inst. (March, 1929), p. 269.

2. Bader, Henri. "The Hyperbolic Distribution of Particle Sizes." Journal of Geophysical Research, Vol. 75, No. 15 (May, 1970), p. 2822.

3. Grandillo, A. D. "A Statistical Evaluation of Powder Characteristics with Three Systems." International Journal of Powder Metallurgy (1970), p. 3.

4. Cole, Fred W. "Particle Count Rationalization." American Assoc. of Contamination Control, Paper No. ER-478 (Feb., 1966), p. 8.

5. Zaloudek, Michael W. "An Evaluation of the Coulter Automatice Particle Counter." (Unpublished Masters Thesis, Oklahoma State University, 1963.)

6. Carver, Leon D. "Particle Counters for Fluid Cleanliness Measurement." Paper presented at Fluid Power Update, University of Wisconsin, Milwaukee, Jan. 31-Feb. 1, 1974.

7. Grant, E. L. Statistical Quality Control, 3rd Edition. New York: McGraw-Hill, 1964.

8. Locks, Mitchell O. Reliability, Maintainability and Availability Assessment. Rochelle Park, N.J.: Hayden Book Co., Inc., 1973.

9. Bensch, L. E. "Counting Particles Less Than 10 Micrometers." Eighth Annual Fluid Power Research Conference, Stillwater, Oklahoma, Oct. 8-9, 1974.

10. Moore, L. C. "Factors Involved in Obtaining Reliable Particle Counts." Eighth Annual Fluid Power Research Conference, Stillwater, Oklahoma, Oct. 8-9, 1974.

11. Cox, D. R., and P. A. W. Lewis. The Statistical Analysis of Series of Events. New York: John Wiley and Sons, Inc., 1966.

12. Freund, John E. Mathematical Statistics, 2nd Edition. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1971.

APPENDIX

```
                F.P.R.C. PARTICLE COUNT DATA

------------------ ID=328C1 -------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1     35597      6609      2312       982       462
  2     36943      6661      2279       881       432
  3     36231      6420      2119       874       393
  4     37129      6466      2074       750       281
  5     35246      6660      2061       829       346

------------------ ID=328C2 -------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1     35051      6696      2270       987       486
  2     35921      6729      2263       933       475
  3     35432      6604      2189       918       446
  4     35023      6349      2096       845       367
  5     35184      6321      2062       761       400

------------------ ID=328C3 -------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1     32295      6114      2062       869       389
  2     33059      6086      1995       797       380
  3     32942      5888      1920       733       299
  4     32781      5977      1890       752       323
  5     32922      5855      1765       637       232

------------------ ID=328C4 -------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1     28910      5368      1809       737       333
  2     31775      5900      1979       762       362
  3     31740      5812      1977       812       390
  4     31629      5856      1849       740       345
  5     30710      5415      1638       568       222

------------------ ID=328C5 ------------------

OBS     MIC5     MIC10     MIC20     MIC30     MIC40

  1     3808      106         9         1         1
  2     3779       94         5         1         1
  3     3854      118        16         6         3
  4     3897      108         8         3         2
  5     3693       94         6         0         0
```

```
                 F.P.R.C. PARTICLE COUNT DATA

------------------ ID=328C6 ------------------

OBS     MIC5      MIC10     MIC20     MIC30     MIC40

  1     3610       147        10         3         1
  2     3790       143         8         1         0
  3     3850       168        11         3         0
  4     3864       145        19         5         0
  5     3691       143        13         6         2

------------------ ID=328C7 ------------------

OBS     MIC5      MIC10     MIC20     MIC30     MIC40

  1     3483       154         8         2         1
  2     3564       155        13         3         1
  3     3524       162        17         4         2
  4     3535       163        11         2         1
  5     3578       148        11         2         1

------------------ ID=328C8 ------------------

OBS     MIC5      MIC10     MIC20     MIC30     MIC40

  1     3322       160        23        12         5
  2     3323       171        20        10         7
  3     3452       166        24         8         0
  4     3380       158        20        11         4
  5     3280       153        22         9         1

------------------ ID=328G1 ------------------

OBS     MIC5      MIC10     MIC20     MIC30     MIC40

  1     4778       162        16         4         2
  2     5011       191        30         7         0
  3     4822       207        26        10         3
  4     4977       178        27         8         6
  5     5055       175        19         3         0

------------------ ID=328G2 ------------------

OBS     MIC5      MIC10     MIC20     MIC30     MIC40

  1     4859       182        17         3         1
  2     4988       178        13         5         1
  3     5336       178        14         3         2
  4     5202       171        14         4         0
  5     5195       180         6         1         0
```

```
                   F.P.R.C. PARTICLE COUNT DATA

------------------ ID=328G3 ------------------

OBS      MIC5      MIC10      MIC20      MIC30      MIC40

  1      4849       227         21          6          5
  2      5170       212         19          2          0
  3      5187       219         11          3          1
  4      5209       231         22          3          1
  5      5154       250         14          2          0

------------------ ID=328G4 ------------------

OBS      MIC5      MIC10      MIC20      MIC30      MIC40

  1      5976       274         30          8          4
  2      6228       257          9          3          0
  3      6386       250         15          3          0
  4      6556       263         18          1          0
  5      6684       280         10          2          0

------------------ ID=328G5 -------------------

OBS       MIC5     MIC10      MIC20      MIC30      MIC40

  1      31630      5467       1808        756        343
  2      31626      5447       1791        746        355
  3      31364      5292       1711        708        343
  4      31525      5204       1726        664        289
  5      31280      5248       1644        619        265

------------------ ID=328G6 -------------------

OBS       MIC5     MIC10      MIC20      MIC30      MIC40

  1      31988      5503       1859        755        362
  2      32234      5524       1842        782        364
  3      32474      5638       1909        822        420
  4      31901      5529       1878        786        371
  5      31888      5400       1764        750        369

------------------ ID=328G7 -------------------

OBS       MIC5     MIC10      MIC20      MIC30      MIC40

  1      31924      5563       1896        762        371
  2      31878      5638       1903        786        393
  3      31909      5515       1850        753        360
  4      32208      5448       1812        752        342
  5      32046      5479       1730        686        304
```

```
                F.P.R.C. PARTICLE COUNT DATA

----------------- ID=328G8 ------------------

OBS      MIC5      MIC10      MIC20      MIC30      MIC40

  1     33605      5752       1897        761        339
  2     34888      6045       1928        803        409
  3     35372      6119       2063        824        394
  4     35538      6187       1970        839        402
  5     35139      6059       1945        771        376

----------------- ID=328I1 -----------------

OBS     MIC5     MIC10      MIC20      MIC30      MIC40

  1     4508      108          7          1          1
  2     4584      145         11          4          0
  3     4713      125         10          2          1
  4     4612      127          6          3          2
  5     4641      126          9          0          0

----------------- ID=328I2 -----------------

OBS     MIC5     MIC10      MIC20      MIC30      MIC40

  1     5715      225         21          5          3
  2     5614      228         21          4          3
  3     5555      231         15          7          2
  4     5666      232         23          4          2
  5     5584      232         14          5          3

----------------- ID=328I3 -----------------

OBS     MIC5     MIC10      MIC20      MIC30      MIC40

  1     5553      226         23          4          3
  2     5488      223         10          2          2
  3     5582      217         19          2          1
  4     5667      240         22          4          3
  5     5652      257         17          6          2

----------------- ID=328I4 -----------------

OBS     MIC5     MIC10      MIC20      MIC30      MIC40

  1     6888      370         43         10          6
  2     7146      354         29          6          2
  3     7224      333         16          3          1
  4     7134      364         27          6          2
  5     7394      359         40         14          4
```

```
                F.P.R.C. PARTICLE COUNT DATA

------------------ ID=328I5 -------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1     31207      5384      1788       718       322
  2     31566      5464      1833       776       353
  3     31747      5521      1873       810       370
  4     31779      5395      1793       750       337
  5     31310      5141      1617       634       270

------------------ ID=328I6 -------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1     29226      5207      1749       700       313
  2     32020      5616      1940       863       401
  3     32652      5653      1882       816       391
  4     32483      5531      1823       700       303
  5     32240      5370      1688       619       254

------------------ ID=328I7 -------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1     30847      5248      1711       652       279
  2     33121      5681      1858       756       370
  3     33108      5671      1884       793       389
  4     32922      5681      1802       736       338
  5     32730      5498      1753       680       297

------------------ ID=328I8 -------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1     31222      5185      1701       724       342
  2     34128      5769      1886       758       336
  3     34209      5755      1930       823       403
  4     33894      5620      1788       690       342
  5     33963      5616      1751       678       287

------------------ ID=328J1 ------------------

OBS     MIC5     MIC10     MIC20     MIC30     MIC40

  1     4722       259        27         7         3
  2     4841       224        18         5         2
  3     5003       251        28        11         5
  4     4921       250        30         9         2
  5     4934       231        29         6         3
```

```
                 F.P.R.C. PARTICLE COUNT DATA

------------------ ID=328J2 ------------------

OBS      MIC5      MIC10      MIC20      MIC30      MIC40

  1      4487       191         16          5          3
  2      4507       173         11          1          0
  3      4726       188         11          0          0
  4      4464       187         16          3          2
  5      4408       185         15          3          1

------------------ ID=328J3 ------------------

OBS      MIC5      MIC10      MIC20      MIC30      MIC40

  1      3779       170         19          3          1
  2      4691       218         17          0          0
  3      3893       210         11          2          1
  4      4071       193          7          1          1
  5      4001       192         16          2          1

------------------ ID=328J4 ------------------

OBS      MIC5      MIC10      MIC20      MIC30      MIC40

  1      3924       236         16          3          2
  2      4059       245         18          1          1
  3      4104       282         27          6          4
  4      4054       233         20          4          2
  5      4166       262         19          2          1

------------------ ID=328J5 -------------------

OBS        MIC5     MIC10      MIC20      MIC30      MIC40

  1       32349      6056       2045        874        424
  2       34189      6383       2180        944        504
  3       35798      6658       2265        973        479
  4       35488      6759       2365       1051        514
  5       35533      6750       2323        928        464

------------------ ID=328J6 -------------------

OBS        MIC5     MIC10      MIC20      MIC30      MIC40

  1       33345      6483       2279        997        470
  2       34882      6736       2317       1003        493
  3       35410      6627       2197        931        484
  4       35163      6510       2213        928        471
  5       35308      6633       2289       1006        509
```

```
                 F.P.R.C. PARTICLE COUNT DATA

------------------ ID=328J7 --------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1     33090      6251      2157       983       514
  2     33443      6339      2189      1000       506
  3     33401      6444      2185       961       491
  4     33147      6195      1977       818       371
  5     33523      6175      2110       813       504

------------------ ID=328J8 --------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1     34654      6701      2263       958       470
  2     35681      6943      2398      1038       538
  3     35909      7138      2455      1068       550
  4     35842      6892      2310      1025       486
  5     35698      6937      2378      1000       482

------------------ ID=329B1 --------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1     28238      4895      1704       666       300
  2     30783      5428      1782       707       318
  3     31516      5549      1773       679       331
  4     30850      5152      1637       631       285
  5     30688      5147      1554       531       198

------------------ ID=329B2 --------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1     27723      4749      1443       576       248
  2     29980      5316      1699       670       302
  3     30804      5350      1710       612       239
  4     28611      4793      1401       476       171
  5     28627      4685      1632       626       240

------------------ ID=329B3 --------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1     25839      4720      1485       552       225
  2     26743      4825      1533       554       247
  3     26595      4878      1506       552       238
  4     27342      5089      1543       576       239
  5     27140      4782      1419       480       176
```

```
                    F.P.R.C. PARTICLE COUNT DATA

------------------ ID=329B4 -------------------

OBS       MIC5     MIC10     MIC20     MIC30     MIC40

  1      26832      5023      1609       617       278
  2      29204      5389      1693       670       305
  3      29742      5500      1709       595       255
  4      29065      5270      1613       564       229
  5      30628      5611      1650       611       246

------------------ ID=329B5 ------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1      4329       171        17        10         8
  2      4471       171        18         4         3
  3      4603       168        10         5         2
  4      4577       159         8         2         0
  5      4639       206        26         6         1

------------------ ID=329B6 ------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1      3815       149        10         2         1
  2      3843       135        13         4         2
  3      3858       124         7         0         0
  4      3853       143        11         1         0
  5      3838       145        13         4         2

------------------ ID=329B7 ------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1      2635       122        18         5         2
  2      2605       132        18         8         5
  3      2547       150        13         4         3
  4      2579       137        13         4         0
  5      2571       124        12         1         0

------------------ ID=329B8 ------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1      2612       123        11         2         2
  2      2748       118        11         0         0
  3      2793       139        15         4         2
  4      2817       146        12         3         2
  5      2787       129        18         5         3
```

```
                 F.P.R.C. PARTICLE COUNT DATA

------------------ ID=334C1 -------------------

OBS       MIC5     MIC10     MIC20     MIC30     MIC40

  1      58497      6844      2041       892       446
  2      60397      7160      2124       877       398
  3      60366      7222      2064       804       369
  4      60604      6976      2029       782       365
  5      60113      6975      1992       761       341

------------------ ID=334C2 -------------------

OBS       MIC5     MIC10     MIC20     MIC30     MIC40

  1      70918      7776      2184       870       437
  2      73155      8091      2197       825       406
  3      73035      8114      2134       817       352
  4      72639      7922      2174       819       358

------------------ ID=334C3 -------------------

OBS       MIC5     MIC10     MIC20     MIC30     MIC40

  1      83421      9206      2334       873       422
  2      83629      9137      2317       908       442
  3      84324      9361      2380       928       422
  4      85886      9387      2265       842       374
  5      85009      9268      2278       821       347

------------------ ID=334C4 -------------------

OBS       MIC5     MIC10     MIC20     MIC30     MIC40

  1      67290      8725      2277       895       462
  2      69417      9113      2394       884       418
  3      68745      8912      2334       856       382
  4      69159      9030      2300       832       407
  5      69114      8940      2253       793       372

------------------ ID=334C5 -------------------

OBS       MIC5     MIC10     MIC20     MIC30     MIC40

  1      24996       826        45         9         4
  2      24462       776        48         7         3
  3      25030       783        37         1         0
  4      25635       840        50         5         1
  5      26219       806        39         3         0
```

```
                 F.P.R.C. PARTICLE COUNT DATA

------------------ ID=334C6 --------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1     40632      1624       100         2         0
  2     41210      1644        95         9         3
  3     42389      1707       108        10         0
  4     42551      1705       109         9         1
  5     43065      1663       111         8         2

------------------ ID=334C7 --------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1     50221      2474       191        14         1
  2     51080      2507       156        16         1
  3     50770      2413       166         8         0
  4     50846      2428       161        14         3
  5     51101      2521       157        14         0

------------------ ID=334C8 --------------------

OBS      MIC5     MIC10     MIC20     MIC30     MIC40

  1     31706      2111       153        12         1
  2     31020      2055       186        12         1
  3     32740      2180       159         6         2
  4     33114      2154       182         8         0
  5     33081      2197       159         7         2
```

VITA

Gary Allen Roberts

Candidate for the Degree of

Master of Science

Thesis: PARTICLE COUNTING: AN ANALYSIS OF THE PROBLEM OF CALIBRATION AND UNCERTAINTY

Major Field: Industrial Engineering and Management

Biographical:

Personal Data: Born in Hutchinson, Kansas, October 18, 1938, the son of Thomas and Rubie Roberts.

Education: Graduated from Western Military Academy, Alton, Ill., in May, 1956; received Associate of Arts degree from Hutchinson Community Junior College in May, 1961; received the Bachelor of Science degree, with a major in Industrial Engineering and Management from Oklahoma State University in May, 1973; completed the requirements for the Degree of Master of Science in July, 1975.

Professional Experience: Manager, Quality Engineering, Cessna Fluid Power Division, 1964-1970; Program Manager, Fluid Power Research Center, Oklahoma State University, 1970 to date.

Professional Organizations: Senior Member of American Society for Quality Control, Member of American Society of Agricultural Engineers, Member of American Institute of Industrial Engineers, Alpha Pi Mu.