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THE PRECISION OF COAL MINE DUST SAMPLING

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16. Abstract (Limit: 200 words)

The precision of coal mine dust sampling was evaluated. Data was obtained from all relevant literature and unpublished studies conducted by the Mine Safety and Health Administration (MSHA), NIOSH, and the Bureau of Mines. Coefficients of variation were determined. Coefficients of variation as a function of error source were analyzed using data obtained by routine field sampling by the Dust Division of MSHA. The pooled average of the coefficients of variation of all field sampling data was approximately 20 percent, for a coal dust concentration of 2.0 milligrams per cubic meter. The coefficient of variation in the data obtained by the Dust Division of MSHA was 22.7 percent. The contributions from various sources of error were: weighing errors, 5.8 percent; pump flow errors, 2.3 to 2.6 percent; and random sampling errors, 21.8 percent. The contribution of weighing errors to the coefficient of variation increased as sample size decreased. The authors conclude that coal mine dust concentration measurements made in the field by trained personnel have a precision of approximately 20 percent. Most of the inaccuracy results from random errors in sampling.

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SUMMARY

The General Accounting Office has recommended that the federal agencies concerned with coal mine dust sampling "determine quantitatively the accuracy and reliability of dust measurements when taken with the current equipment by coal miners in underground mines." In response to this recommendation, the National Institute for Occupational Safety and Health (NIOSH), the Mine Safety and Health Administration (MSHA) and the Bureau of Mines (BOM) have undertaken this study of the sampling precision, i.e. the closeness of repeated measurements of the same dust concen- tration. The study's purpose is to estimate the precision in dust samples taken routinely by coal mine operators and Federal inspectors on the basis of public literature and data supplied by the three agencies.

Previously, the precision had been estimated by the National Bureau of Standards (NBS), the Mine Enforcement and Safety Administration (MESA), and Morton Corn, all in 1975-76. In response to the GAO's 1975 recommendation, BOM next funded a project by NBS to develop a plan for a field study to determine the precision of mine dust measurements. However, the actual field study was not carried out because BOM, MSHA, and NIOSH agreed that the probable result of the NBS proposal would not justify its cost. In any special field study, the actual precision of routine sampling may not be reliably determined because the miners or mine operators taking the samples could take more care in their dust control procedures due to the fact a study was being conducted.

However, much data from coal mine dust measurements are already available. For routine samples, precision data exist only for the weighing and calibration, although several independent assessments of the overall accuracy have been conducted in a limited manner. For the total precision of coal mine dust sampling, the most definitive data were obtained by research personnel on studies done for purposes other than the determination of measurement accuracy. Research studies have also been done during the past decade to determine the magnitude of errors in measurements with personal dust samplers due to various causes.

The present study looks at all the known available laboratory and in-mine data on precision of coal mine dust measurements. Special emphasis is placed on three studies done by the Dust Division at MSHA's Pittsburgh Technical Center. Following the sampling procedures presently required by Federal regulations, MSHA's three studies took measurements in coal mines with dust samplers placed side by side. The pooled coefficient of variation (standard deviation divided by the mean) for the Dust Division data is 22.7 percent. This is the precision expected for a single mine dust measurement made by the Dust Division or similarly trained personnel using the Federal procedures.

The precision found here is significantly different than the estimates made in 1975-76. On one hand, the 31.5 percent precision estimated by NBS is inflated by errors in the statistical procedures. On the other hand, the

10-15 percent estimates by MESA and Corn rely on laboratory precision studies, and neglect sampling errors which are present in field samples.

Most mine dust measurements by other research groups show precision similar to that found in the Dust Division studies. Personal, area and machine-mounted samples taken by most other research organizations in coal mines all have comparable precision. One research group did obtain somewhat better precision (10 to 14 percent) than MSHA's Dust Division, but their measurements were made using many special procedures which have not been shown to be practical for routine sampling by miners and mine operators.

The random errors from weighing and the pump flow rate were investigated in more detail, using MSHA data from routine sampling operations. Under the Federal procedures, the weighing errors are only 5.8% at the 2.0 mg/m^3 respirable dust standard, but get larger as the dust concentration decreases. Errors in the pump flow are shown to make a negligible contribution to the sampler's imprecision. By a process of elimination, the bulk of the random errors appear to result from a lack of uniformity in sampling procedures.

The results of all field studies indicate that coal mine dust measurements made by trained personnel will have an estimated precision of 20 ± 4 percent for a single sample at the compliance level. In the samples taken routinely in coal mines, the precision may be worse than the range from 16 - 24 percent. However, the lack of data on the routine samples prevents estimation of precision.

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I. INTRODUCTION

In 1975, the U.S. General Accounting Office recommended that a study be conducted "to determine quantitatively the accuracy and reliability of dust measurements when taken with the current equipment by coal miners in underground coal mines." To address this recommendation, the present report reviews the existing literature on the accuracy of the Federal government's method for sampling coal mine dust, and makes a quantitative determination of the sampling precision where the data are sufficient.

A. BACKGROUND

The present program for sampling respirable coal mine dust was established by the Federal Coal Mine Health and Safety Act of 1969, and has continued under the Federal Mine Safety and Health Act of 1977. These laws require:

> "Each operator of a coal mine shall take accurate samples of the amount of respirable dust in the mine atmosphere, to which each miner in the active workings of the mine is exposed."
> – Section 202 (a)

The Federal inspectors also take dust samples during their inspections. Under the law, the coal mine operator may be penalized if the results from either of these sampling programs show a violation of the dust standard. The current standard is 2.0 mg/m^3 for respirable coal mine dust with silica content below 5 percent, which was set in the 1969 Coal Act to prevent coal worker's pneumoconiosis.

The procedures under which the dust sampling takes place were first specified in 1971 for the mine operators in regulations (Code of Federal Regulations, Volume 30, Parts 70-74) promulgated by the Secretary of the Interior and the Secretary of Health, Education and Welfare. The dust sampling program has since been conducted by the Mining Enforcement and Safety Administration (MESA), now the Mine Safety and Health Administration (MSHA). The sampling regulations have since been revised (MSHA, 1980d and 1980e).

In the decade over which the Federal government has administered the monitoring of coal mine dust, the program and the accuracy of the dust measurements have been critically reviewed on several occasions. The General Accounting Office audited the sampling program in 1971 and 1972 with a follow-up review in 1973 (GAO; 1971, 1973).

The most complete review of the Federal program for coal mine dust sampling was conducted in 1975 by GAO (1975), together with the National Bureau of Standards (NBS, 1975). In this study, NBS undertook a quantitative review of only the sampling precision, not the overall accuracy. They concluded that the overall uncertainty in coal mine dust measurements came from weighing errors, the "intrinsic variability" in sampler performance seen in the laboratory, and the sampler performance in the mine environment (as measured by side-by-side samplers).

From their literature review, NBS estimated that the various sources of random error contribute the following coefficients of variation (CV) when a single dust measurement is made at a concentration equal to the dust standard of 2 mg/m^3:

Weighing Errors	7 percent
Intrinsic Sampler Variability	7
Performance in the Mine Environment	30

This estimate for the performance in the mine environment "can be expected from trained personnel who can afford to devote the same range of care and attention to the instrument which were exercised by the research scientists" (NBS, 1975). This figure does not allow for various abuses reported by NBS observers in routine mine operation of CMDPSUs.

To obtain the overall random error, NBS simply assumed that the three error sources above are independent and independently estimated, so the square of the component CVs may be summed to give a total coefficient of variation of 31.6 percent. To improve the sampling precision, NBS recommended the development of pumps with self-regulators and automatic timers, more rugged equipment and tamper-proof cassettes.

In a reply to the NBS study, MESA (MSHA's predecessor agency) made their own estimate of the sources of random errors (Frizell, 1976):

Weighing	7 percent
Instrument precision	5
Mine environment	5

which sum statistically to a total CV of 9.9 percent. MESA's weighing error is derived from the 0.1 mg sensitivity used in filter weighing; the instrument precision is taken from the ±5 percent error bounds required by the Federal regulations for the certification of CMDPSUs (30CFR74); and the mine environment error is MESA's estimate for the precision with which pumps can be adjusted in mines. These latter two error components are substantially smaller the those estimated by NBS (1975), and GAO (1975) commented: "MESA could not provide sufficient evidence to NBS to demonstrate that the dust-sampling equipment and program is as accurate and reliable as it [MESA] claims."

In the same period, Corn (1975) also discussed the random errors in coal dust sampling, and made the following estimates (as corrected by Leidel and Busch, 1975):

Weighing	3.5 percent
Pump flow rate	10.0
Instrument variability	10.0

which sums statistically to 14.6 percent. These three error analyses are difficult to reconcile, due to their differing approaches and sparse documentation. After a theory of dust sampling errors is developed in Section II, these earlier approaches will be discussed in more detail.

The GAO report (GAO, 1975) relied on the NBS (1975) findings, but they also audited the government's administration of the sampling program and the sampling procedures in several coal mines. GAO concluded:

"The Department of the Interior reported that 94 percent of the underground coal mine sections are within the statutory respirable dust concentration standard; however, we found that the dust-sampling program on which this conclusion was based contained discrepancies and uncertainties which made it difficult to determine accurately how many sections were complying.

"The uncertainty and discrepancies in measurements primarily resulted from:

— Operators and miners not following proper sampling practices.

— Dust-sampling equipment not providing accurate measurements of dust concentrations, weight loss of cassettes and inaccuracies in weighing dust cassettes."

GAO endorsed the recommendations in the NBS report (1975), and then said:

"We recommend that the Secretary of the Interior instruct MESA and BOM and the Secretary of HEW instruct NIOSH to conduct a joint study to determine quantitatively the accuracy and reliability of dust measurements when taken with the current equipment by coal miners in underground mines..."

Consequently, the Bureau of Mines contracted with the National Bureau of Standards and with the National Academy of Sciences for studies related to the accuracy of dust sampling. NBS designed a study "to determine quantitatively the accuracy and reliability of dust measurements" in an underground coal mine (Ku and Rosenblatt, 1979).

However, the Bureau of Mines, with the concurrence of NIOSH and MSHA, decided not to conduct the suggested accuracy study because the cost was high and the projected results were not considered to be directly relevant to the most common problems in routine dust sampling. In evaluating the NBS proposal, the agencies realized that any special study of the accuracy in dust measurements made by miners or by mine operators could be biased by deviations from the normal sampling routine by the subjects of the study who might wish to make a good impression.

In the National Academy of Sciences' study, a panel of scientists was assembled to review research needs on the "Measurement and Control of Respirable Dust in Mines," (NAS, 1980). Based primarily on the NBS (1975) review of CMDPSU precision, the National Academy of Sciences panel concluded: "Current sampling technology is adequate for measuring concentrations of respirable coal mine dust for compliance purposes." (NAS, p. 3, 1980).

B. PURPOSE AND PROTOCOL

GAO (1975) recommended that the "accuracy and reliability of dust measurements when taken with current equipment by coal miners in underground mines" be determined quantitatively. Technically, "accuracy" is defined as "the degree of agreement of . . . measurements with the true value of the magnitude of the quantity concerned" (Eisenhart, 1963). "Reliability" is defined as "the probability of no failure throughout a prescribed operating period" (Grant, 1972). Although these definitions can be applied to coal mine dust sampling (Ku and Rosenblatt, 1979; Bowman, Bartley, Breuer and Shulman, 1982), the evaluation of accuracy and reliability raises issues beyond the focus of the 1975 studies by GAO and NBS.

When the National Bureau of Standards made quantitative accuracy determinations, they always referred to the standard deviation (or coefficient of variation) of repeated measurements at the 2.0 mg/m^3 standard, e.g.

> "When operated in the laboratory, the sampler has yielded a precision on the order of 7 percent as evidenced by a standard deviation of 0.14 mg/m^3 at the compliance level."
>
> — NBS (1975)

Technically, GAO and NBS were concerned only with the "precision", which is defined as the "closeness together of successive independent measurements of a single magnitude" (Eisenhart, 1968). To be consistent, the present report will, therefore, evaluate the precision of a single dust sample taken in a coal mine with the procedures established by the Federal government.

To evaluate precision, the available literature and unpublished data were reviewed, and the precision determined quantitatively from those data using a consistent statistical method. Where possible, precision data on the samples taken routinely "with current equipment by coal miners in underground coal mines" will be examined, as GAO directed. Since the necessary precision data does not always exist for the routine samples taken by the coal miners, data will be examined from the most recent studies done in laboratories and coal mines by scientific professionals. Compared to the NBS (1975) review of the literature on dust sampling, the present stduy also developes a more detailed theoretical framework from which the precision is estimated for the different studies in a consistent manner.

This study of precision provides a quantitative framework for identifying and evaluating improvements in coal mine dust sampling procedures. Improvements are not addressed in this report, but are part of the research and development programs underway at MSHA, NIOSH and the Bureau of Mines.

II. METHOD

A. THEORY

According to the mathematical theory of errors (Eisenhart, 1963), the definition of accuracy starts with the specification of the measurement system. In this report, the Federal procedures for measuring respirable coal mine dust is the system under analysis.

In the Federal system, the respirable dust concentration is sampled with a Coal Mine Dust Personal Sampling Unit (CMDPSU), consisting of a 10 mm Dorr-Oliver cyclone, cyclone holder, pump and sealed cassette containing a pre-weighed filter capsule. The initial weight of the filter capsule, M_I, is determined by the manufacturer, after which the capsule is sealed into the cassette. The pump is calibrated to sample at a flow rate of $Q = 2.0$ L/min. For most samples, the CMDPSU is run for an entire 8-hour shift, so the sampling period T is 480 min. After the shift, the sample is mailed to the assigned Federal laboratory where the final weight of the filter M_F is measured. Then the sampled concentration of respirable dust C is calculated by the formula:

$$C = k\ (M_F - M_I)/(QT) \qquad (1)$$

where k is a calibration factor used to convert the cyclone measurement to its equivalent taken with the Mine Research Establishment (MRE) horizontal elutriator. The calibration factor k is set equal to 1.38 on the basis of a field study (Tomb, Treaftis, Mundell and Parobeck, 1973) comparing CMDPSUs with the MRE instrument.

Once the measurement system is defined, Eisenhart (1963) says that the next step in an accuracy analysis is to seek evidence of statistical control, i.e. "that either the measurements are the product of an identifiable statistical universe . . . or if not, that the physical causes preventing such identification may themselves be identified and, if desired, isolated and supressed."

In terms of experimental science, "statistical control" means that the results of a measurement are being successfully repeated within the limits of experimental error. To assess the state of statistical control, Eisenhart (1963) recommends the use of Shewhart control charts. However, experimentalists use many other methods for repeating their measurements, and showing that the errors are not influencing their conclusions.

This property of replicability is obviously a central requirement for the scientific method. As Eisenhart (1963) emphasizes, "an effort to follow a test method ought not to be known as a measurement process unless it is capable of statistical control . . . . Without this limitation on the notion of measurment process, one is unable to go on to give meaning to those statistical measures which are basic to any discussion of precision and accuracy."

In this report, the state of statistical control for coal mine dust sampling shall be examined on the basis of quality control records and control charts existing for the Federal sampling system. In addition, the samples taken by the mine operators have been compared with samples taken independently by both MSHA inspectors and NIOSH researchers.

Repeated measurements of the dust concentration under identical conditions will be scattered presumably in a normal distribution about the true concentration. If the measurement process is in a state of statistical control, this distribution of errors will be stable over time, and can be characterized theoretically by its mean value and its standard deviation. For a given experimental situation, the distribution mean $\underline{C}$ will be fixed, but repeated measurements of the dust concentration will still have some spread about $\underline{C}$. These random errors (or imprecision) can be quantitated by the standard deviation of replicate measurements. For comparison purposes, the measurement precision will be expressed using the coefficient of variation (expressed as a percentage):

$$CV_t = 100\% \times \text{Std. Dev.} / \bar{C} \qquad (2)$$

In CMDPSU sampling, random errors may be caused by the filter weighing process, pump flow which deviates from 2.0 L/min, small variations in the preparation of the cyclone sampler, and interactions between the CMDPSU and the environment. Estimates of the precision can be measured directly from taking replicate samples of the same dust concentration, or deduced indirectly from an analysis of the individual factors contributing to the errors.

In the direct measurement of precision, a group of CMDPSUs are exposed to coal dust, either in laboratory dust chambers or in coal mines. The CV_t for this group is then calculated from the mean concentration and the standard deviation for the run.

For the indirect precision analysis, data exist on the random errors found in the filter weighing and pump flow rates. However, random errors during sampling can not be reliably estimated. Therefore, the indirect precision analysis in this report does not estimate CV_t independently, but rather helps to quantify the various causes of error in the precision estimated directly.

The conventional propagation of errors can be applied to the measurement of a quantity, $y = f(x_1, x_2, \ldots)$, which is a function of other measurable variables x_i. The random errors in the x_i cause random errors in y, which can be quantified by doing statistics over a collection of replicate measurements. In the theory for propagation of errors (Ku, 1966), the mean $\underline{y}$ over the replicate measurements is:

$$\bar{y} = f(\bar{x}_1, \bar{x}_2, \ldots) \qquad (3)$$

If the errors in the variables x_i are independent of one another, then the variance in y over the replicate measurements is given by:

$$var(y) = \sum_i [\partial y/\partial x_i]^2 \; var(x_i) \qquad (4)$$

where the partial derivative in brackets is evaluated with the variable means $\bar{x}_i$. Equation (4) can also be used to derive CV_t because:

$$(CV_t)^2 = var(y) \; / \; (\bar{y})^2 \qquad (5)$$

To apply the theory to coal dust sampling, we identify three independent sources of random errors:

1) <u>Pump flow rate errors.</u> Bartley and Breuer (1982) have studied the effect which variations in the pump flow have on the dust mass sampled by the 10mm nylon cyclone. In their results, an instantaneous deviation δQ from the target flow rate Q_o = 2.0 L/min changes the rate of dust collection dM/dt by an amount $\delta(dM/dt)$ which can be expressed:

$$\frac{\delta(dM/dt)}{dM/dt} = \gamma \frac{\delta Q}{Q_o} \qquad (6)$$

where γ is a coefficient dependent only on the cyclone's properties and the dust size distribution.

To get the mass M_s collected on the filter over a time T, eq. (6) can be integrated (assuming δQ is independent of changes in dM/dt) to give:

$$M_s = M_o \; (1 + \gamma \; \Delta Q) \qquad (7)$$

where M_o is the dust mass sampled at Q_o over sampling time T, and ΔQ is the time-weighted average of the relative pump flow fluctuations:

$$\Delta Q = T^{-1} \int_o^T dt \; \delta Q \; / \; Q_o \qquad (8)$$
$$= (\bar{Q} - Q_o) \; / \; Q_o$$

ΔQ is assumed to be distributed normally with zero mean and variance $var(\Delta Q)$. This flow rate error is also described by Corn (1975).

2) <u>Weighing errors.</u> Parobeck, Tomb, Ku and Cameron (1981) have measured the standard deviation s_M in repeated weighings at MSHA's Dust Laboratory. Presumably, the dust mass M, obtained as the difference between the initial mass M_I and final mass M_F in eq. (1), will differ from the mass M_s on the filter by a weighing error ϵ_M:

$$M = M_s + \epsilon_M$$
$$= M_o \; (1 + \gamma \; \Delta Q) + \epsilon_M \qquad (9)$$

ϵ_M is distributed normally with zero mean and variance estimated by $(s_M)^2$. The same weighing errors appear in all earlier error analyses (NBS, 1975; Frizell, 1975; Corn, 1975).

3) Sampling errors. All other random errors are presumed to result from the design, manufacture, maintenance, preparation and operation of the sampler. The mechanisms, such as the fit of the vortex finder on the cyclone, inlet effects, re-entrainment of over-sized particles within the cyclone body, leakage in the cyclone, etc, have not generally been studied independent of the other sources of error.

In NIOSH's validation protocol for sampling and analytical methods (Busch and Taylor, 1981), such sampling errors are treated as random errors with a coefficient of variation CV_s independent of the pump and analysis errors which also contribute to CV_t. To obtain this result for dust sampling, the sampling error ϵ_s in a single measurement plausibly appears in the measured concentration C as:

$$C = \frac{k}{Q_o T} [M_o (1 + \gamma \, \Delta Q) + \epsilon_M] + \epsilon_s \qquad (10)$$

where ϵ_s is normally distributed with zero mean and a standard deviation proportional to $\underline{C}$, i.e.:

$$\mathrm{var}(\epsilon_s) = \bar{C}^2 \, (CV_s)^2 \qquad (11)$$

Although CV_s is found to be independent of concentration in many industrial hygiene methods (Busch and Taylor, 1981), the hypothesis of a constant CV_s has not been tested for dust sampling in coal mines.

The assumed independence between flow rate errors and the sampling equipment also should be verified. In theory, changes in the cyclone's configuration between samples could change the value of γ, as well as ϵ_s. In the absence of quantitative evidence, this possible interaction between flow rate errors and sampling errors will be neglected.

The other variables affecting the calculation of the dust concentration C (eq. 1) have negligible random errors. The errors associated with the sampling time T would be a few minutes out of 8 hours. The calibration constant k is the same for all samples taken under Federal procedures, and therefore cannot affect the precision. Likewise, the pump flow rate is assumed to be a constant $Q_o = 2.0$ L/min in the concentration calculation.

The random errors in the measured concentration C (eq. 10) can now be substituted into the propagation of error theorems above to give the mean concentration $\underline{C}$ (eq. 3):

$$\bar{C} = k \, M_o \, / \, Q_o \, T \qquad (12)$$

$$= k \, \bar{M} \, / \, Q_o \, T$$

The partial derivatives $\partial C/\partial \varepsilon_M$, $\partial C/\partial \Delta Q$, and $\partial C/\partial \varepsilon_s$ can be calculated from eq.(10), and substituted into the variance (eq. 4) to give:

$$\mathrm{var}(C) = (k/Q_oT)^2 \, \mathrm{var}(\varepsilon_M) + (\gamma \, k\bar{M}/Q_oT)^2 \, \mathrm{var}(\Delta Q) + \mathrm{var}(\varepsilon_s) \tag{13}$$

Alternatively, the propagation of errors will give the coefficient of variation (eq. 5) by substituting $\underline{C}$ and the values assumed for the variances into equation (13) to give:

$$(CV_t)^2 = (s_M/\bar{M})^2 + \gamma^2 \, \mathrm{var}(\Delta Q) + (CV_s)^2 \tag{14}$$

In this expression, all terms but CV_s have been determined from independent studies. Therefore, CV_s can be estimated by using eq. (14) with values of CV_t, s_M, and var(ΔQ) measured directly. The resulting sampling errors, as expressed by CV_s, cannot be attributed to specific causes from the theory alone.

Compared to the earlier error analyses in the literature (Section I), eq. (14) is very similar to the error expression derived by Corn (1975), and elaborated by Busch and Leidel (1975). The most significant difference in eq. (14) is that the sampling error (called "instrument variability" by Corn, 1975) is identified as the residual random errors after weighing and pump errors are subtracted. In contrast, Corn (1975) estimated the instrument variability term from CV_t values reported from laboratory studies without any correction. Thus, his final CV_t estimate counts weighing and pump errors twice.

The same mistake is repeated in the accuracy estimate by NBS (1975). Their estimate for "intrinsic sampler variability" is obtained directly from CV_t measured in the laboratory. The errors due to sampler performance in the mine environment is also estimated from CV_t values without any apparent corrections. Then, NBS (1975) sums the variances derived from these CV_t estimates, along with the variance from weighing, implicitly assuming that these three sources of error are independent. The NBS result is thus triple counting weighing error and double counting other error sources found in both the laboratory and the mine.

The error analysis conducted by MESA (Frizell, 1976) correctly includes only independent sources of error. However, the sources of error identified by MESA ("instrument precision" and "mine environment") do not correspond exactly with either the pump flow or sampling errors defined in the present analysis.

B. DATA SOURCES

To estimate CV_t, we have collected all the relevant literature and unpublished data supplied by MSHA, NIOSH and BOM. For the direct determination of CV_t, replicate samples must be taken in the same dust concentration. Such replicate measurements are also the best proof that the measurement system is in a state of statistical control. Replicate measurements with the 10mm nylon cyclone have been taken for various purposes in the laboratory (Table 1) and in workplaces (Table 2).

TABLE 1

Studies with replicate cyclone measurements -- Laboratory samples

Study	Purpose	Type of Sampler	Samples per Group	Number of Groups	Comments
Bowman, Bartley, Breuer, Doemeny, & Murdock (1982)	Accuracy test development	MSA units	4	6	Weighing with microbalance
MSHA data (1981)	Leak tests	Bendix units, Model 3900 pumps	6-8	5	
Gray & Tillery (1979)	Vibration effects	Custom-made heads, cricial orifices	2-4	88	Only control samples considered
Harris, DeSieghardt and Rivera (1976)	Machine-mounted sampling	MSA and Bendix units	2	38	Raw data reported only for MSA units
Almich and Carson (1974)	Charge effects	Custom heads, critical orifices	4	22	Only mean CV and 95% conf. limits reported
Bureau of Mines data (1972)	Certification Criteria	MSA units	3-7	14	Some Bendix pumps used
Jacobson (1971)	Sampling variability	MSA and Bendix units	2	15	Only units with pulse dampeners considered

TABLE 2

Studies with replicate cyclone measurements -- Field samples

Study	Location	Type of Sampler	Samples per Group	Number of Groups	Comments
		AREA SAMPLES			
MSHA data (1981)	Underground coal mines	2 CMDPSUs	2	14	Dust Division study
Alvarez, *et al*.(1980)	Surface coal mine facilities	1 MSA and 1 Bendix unit	2	57	Dust Division study
Kost and Saltsman (1977)	Underground mining machines	BCR's custom-made heads, MSA pumps	4	35	Only relative concentrations reported
Harris, De Sieghardt and Riva (1976)	Underground mining machines	Bendix units and MSA units	2	176	Only the pooled CV_t reported
Breslin (1975)	Underground coal mines				
BCR study		Custom units	2	43	Microbalance
BuMines study		MSA units	4	20	
Tomb, *et al*. (1973)	Underground coal mines	MSA units	2	78	Dust Division study
		Bendix units	2	50	
		PERSONAL SAMPLES			
Budenaers, *et al*. (1977)	Chippers in metal casting shop.	Custom-made heads, MSA pumps	3	66	Analysis for respirable dust and silica
Breslin, Page and Jankowski (1982)	Technicians in longwall coal mines	MSA heads, DuPont flow-regulating pumps	2-4	68	17-122 min. sample time; microbalance

As these tables show, many different combinations of equipment and sampling procedures were used in these different studies. The studies which most closely duplicate the Federal procedures used in routine coal mine dust sampling were conducted by the Dust Division at the Pittsburgh Technical Center of MSHA (previously administered by MESA and BOM). The data from the Dust Division studies will therefore be used to derive the best estimate of the precision potentially obtainable "with the current equipment", as GAO specified.

All the replicate sampling studies, including those of the Dust Division, were performed by scientific professionals, rather than the coal mine personnel who routinely take dust samples under the Federal system. Therefore, these studies indicate the precision potentially obtainable in dust sampling, and not necessarily the precision routinely maintained in the coal mines under the Federal program.

The absence of replicate sampling data taken "by coal miners in underground mines" also means that the state of statistical control in the Federal sampling program cannot be assured by this approach. However, indirect evidence that the routine dust samples taken by mine operators are reliable measurements comes from comparisons with samples taken independently on the same coal mine sections, either by Federal inspectors (Tomb, 1976; MSHA, 1972-80) or by NIOSH researchers (Burkhart _et al_., 1984). The results of these comparative studies are discussed in Section III.E.

The indirect estimation of the precision, using the propagation of error formula (eq. 14), is based on studies of the random errors in the weighing process (Table 3) and the pump flow rate (Table 4). Unlike the replicate sampling data, some of the measurements of weighing and pump flow errors are conducted routinely by MSHA in the process of coal mine dust sampling. MSHA's Dust Laboratory maintains a Quality Control system for the accuracy of the initial weights taken by the CMDPSU manufacturers, and the precision of the final weights taken by MSHA. MSHA inspectors check the flow rate calibration of the pumps used by the coal mine operators. The precision estimated from these data is therefore an indirect indication of the precision maintained routinely "in dust measurements when taken by current equipment in underground mines", as requested by GAO.

The indirect analysis of sampling precision also leads to an estimate of CV_s, the coefficient of variation for random sampling errors. Although the exact causes of these sampling errors are difficult to determine, possible sources which have been studied are different details in the sampling technique (Table 5) and interferences from the sampling environment (Table 6). These studies have been reviewed in order to explain the magnitude of CV_s estimated from the indirect error analysis.

TABLE 3

Data on the Accuracy of Weighing CMDPSU Filters

Source	Description	Weighing Sensitivity
MSHA data sheets (1978-80)	MSHA re-weighs filters from CMDPSU manufacturers	0.1 mg
Parobeck, Tomb, Ku and Cameron (1981)	Development of QC system for weighing precision at MSHA's Dust Laboratory	0.01 mg
MSHA control chart (1980)	Maintained under the Parobeck _et al_. QC system from 6/78 to 9/80	0.01 mg
Bowman, Bartley, Breuer, Doemeny, and Murdock (1982)	Development of QC system for weighing precision in NIOSH's CMDPSU certification	0.001 mg

TABLE 4

Accuracy Studies on Personal Dust Sampling Pumps

Study	Data Presented	Conditions Sampled	Pump Types
Gray & Tillery, 1979	Eight hour average flow rates for MSHA-calibrated CMDPSU's (replicated three times)	Clean air	MSA Model G, Bendix Micronair, Bendix BDX-30, Bendix C-115 (5 each)
Gray & Tillery, 1979	Bubble meter calibration checks by two operators of NIOSH-calibrated pumps.	Clean air	MSA Model G, Bendix Micronair, Bendix BDX-31 (4 to 9 each)
NIOSH lab data (Table 12)	Instantaneous flow rates at 1/2-hour intervals for 4-hour period	4 mg/m^3 coal dust in laboratory chamber.	MSA Model G (24 runs)
MSHA field data (Table 13)	Bubble meter check of flow rate of pumps used by mine operators.	Check in clean air of units used in mines.	Unknown
MSHA field data (Table 14)	Initial flows (recalibrations) for 31 CMDPSU units recalibrated 5 to 9 times.	Recalibration in clean air of units used in MSHA inspections.	MSA Model G
Parker, Lee and Sharpe, 1977	Flow versus time for eight hours at various temperatures; flow rate versus pressure drop; motor current demand.	Clean air	MSA Models G and S (5 each) and other personal sampling pumps.
Wood, 1977	Flow rate versus pressure drop	Clean air	MSA Model G and other personal sampling pumps.

TABLE 5

Studies of the Effects of Sampling Techniques on Cyclone Accuracy

FACTOR	STUDY	CONCLUSIONS
Filter treatment	Lowry and Tillery (1979)	Long storage, desiccation, high and low temperatures can change filter weight as much as 0.1 mg.
Pump pulsation	Lamonica and Treaftis (1972)	No significant effect with pulsation dampeners
	Huggins (1977)	In one CMDPSU, higher pulsation increased imprecision
Anti-Stat solution	Almich and Carson (1974)	No improvement in precision with charged particles
Over-sized particles	Harris, De Sieghardt and Riva (1976)	Microscope checks eliminate out-of-control samples.
Cyclone assembly	Caplan, Doemeny and Sorenson (1977)	Irregular alignment of vortex finder on MSA units caused out-of-control samples.

TABLE 6

Studies of Environmental Interferences with Cyclone Sampling

FACTOR	STUDY	CONCLUSION
Ambient air speed	Caplan, Doemeny and Sorenson, 1977 (CDS)	No effect at 50-100 fpm; 6% increase in random errors at 300 fpm.
Ambient air direction	CDS (1977)	No significant effect.
Humidity	Sansone, Bell and Buchino (1973)	No significant effect with coal dust.
	Held and Cooper (1979)	Theoretical bias <u>if</u> coal dust is hygroscopic.
Particle charge	Almich and Carson (1974)	Doubles mean CV from 4.7 to 9.6%.
	Blachman and Lippmann (1974)	Increases cyclone collection efficiency.
	CDS (1977)	Increases imprecision.
High concentration; heavy loading	Blachman and Lippman (1974)	Collection efficiency "variable and erratic" at 100 mg/m^3; particle reentrainment "suggested" by results at 7.5 mg/m^3.
	CDS (1977)	No significant effect up to 6 mg/m^3.
	Fairchild, Tillery and Ettinger (1977)	10% decrease in penetration with loading (up to 7 hours at 1.8 mg/m^3).
	Bowman, Baron and Murdock (1980)	No significant difference with talc at at 77 mg/cu.m.
Cyclone orientation	Treaftis and Tomb (1974)	No significant effects up to 135 degrees from vertical.
	Blachman and Lippmann (1974)	No significant effect down to 1.25 L/min.
	CDS (1977)	No significant effects up to 90 degrees from vertical.
Vibration	Gray and Tillery (1979)	No significant effects except at 3 resonance frequencies.

III. RESULTS AND DISCUSSION

A. PRECISION ESTIMATES FROM REPLICATE SAMPLES

When several sampling units are used to measure the same dust concentration simultaneously, the coefficient of variation:

$$CV_t = 100\% \times \text{Std. Dev.} / \bar{C} \qquad (15)$$

is a measure of the measurement precision. CV_t estimates the true coefficient of variation with confidence limits dependent on the degrees of freedom, f, which is the number of replicate samplers minus one.

Such studies of the precision in respirable dust sampling with the 10mm cyclone have been performed several times, both in the laboratory (Table 1) and in field situations (Table 2). Most of the field studies done in coal mines took area samples, either placing a package of samplers on a mining machine or carrying it to a fixed location in the mine. Only two studies are available on the precision of personal sampling for respirable dust, one conducted in a casting shop (Budenaers et al., 1977) and the other conducted in longwall coal mines (Breslin, Page and Jankowski, 1982).

The first observation from all these studies is the wide range of experimental and methodological conditions under which they were conducted. Since many of these factors could theoretically influence the precision, one goal of this analysis is to identify the variables which contribute significantly to CV_t. However, no study in the literature was designed to measure quantitatively the effects of all variables of interest upon CV_t.

In order to draw some qualitative conclusions, we will examine the effects of the following variables:

1. Sampling environment. The different studies, as shown in Tables 1 and 2, took either laboratory, area or personal samples. "Area" samples include machine-mounted as well as fixed-location samples.

2. Sampling methods. This important variable will be examined by assuming the laboratory performing the precision study used a consistent sampling method. Particular attention will be focused on the field studies, of MSHA (1981), Alvarez, et al. (1980), and Tomb, et al. (1973), which were all done by the Dust Division of MSHA and its predecessor agencies. Special attention will also be given to Bituminous Coal Research (BCR) studies (Kost and Saltsman, 1977; and the data from "Contractor A" in Breslin, 1975) because BCR uses sampling equipment and methods different from the Federal procedures.

3. Sampling Equipment. In this realm, the only consistent comparison is from the data comparing MSA and Bendix (Unico) CMDPSUs. However, this comparison must be made cautiously because evolutionary improvements have been made in the sampling equipment over the past decade.

4. Inter-sample Variation. Bowman, et al.(1982) designed a precision experiment to measure the contribution to CV_t from differences between individual CMDPSU equipment. They report an "inter-sampler" coefficient of variation equal to 1.62 percent with MSA sampling units. Such a low variability indicates excellent uniformity in the mechanical components of the pump rotameter and the collection surfaces of the cyclone. This inference is supported by the measurements made on the Dorr-Oliver cyclones by Lippmann and Chan (1974), who say: "The 10-mm nylon cyclone retains one significant advantage over the larger stainless steel cyclones, i.e. uniformity of dimensions. The nylon cyclones are injection molded and show negligible variability from unit-to-unit."

   The small inter-sampler variation is also negligible compared to the other sources of random errors, especially in the field. Therefore, we will not consider this component further, but include it as part of the general treatment of random errors.

5. Dust Concentration. Although CV_t has been shown to be constant with concentration for many sampling methods (Leidel, Busch and Lynch, 1977), this relationship is not necessarily so for dust sampling. At low dust concentrations, CV_t may be dominated by random weighing errors, whose contribution to CV_t varies inversely with dust mass on the filter (see eq. 14). At high dust concentrations, the loading of dust in the cyclone is reported to alter the penetration efficiency either randomly or systematically (Blachman and Lippmann, 1974; Fairchild, Tillery and Ettinger, 1977).

Another observation from the studies in Tables 1 and 2 is that a quality control program is needed to insure that respirable dust measurements measurementsare in a state of statistical control. In all the studies, even some of the laboratory studies, samples had to be discarded for various reasons, such as pump failures or other equipment failures. In Budenaers et al.(1977), 6.5 percent of samples were discarded for such reasons.

In many studies, the investigator reported evidence of improper sampler operation seen on the final sample, such as leakage in the cassette or "over-sized particles." Such samples were also discarded from the data set before calculating the precision. In addition, a comparison of the CV's between groups of replicate samplers often showed that a few groups were "outliers" from the distribution established by the others. In the study of personal sampling (Budenaers et al., 1977), 7.4 percent of the groups were outliers.

If all such suspect samples and outlier groups are discarded, then the remainder of the samples appear to be in a state of statistical control. In using data from such special research studies to evaluate precision in the Federal dust sampling program, it must therefore be assumed that the routine QC measures in coal mines are equally effective in identifying and eliminating faulty samples. For samples taken routinely under the Federal system, there is no assurance of statistical control comparable to the research studies..

The quantitative precision analysis starts with the identification of the outlier groups. To do this, each group of replicate samples within a study was grouped into classes according to their mean concentrations. The divisions between concentration classes was chosen somewhat arbitrarily to create classes with at least 10 groups. Then, the distribution of CV_t was displayed with Tukey's (1977) box-and-whisker plots (Figures 1-7). Values which Tukey labels "far out" (1/200 chance in a normal distribution) are assumed to be out-of-control, and are trimmed from the data set.

The next step in the precision analysis is to test each concentration class for homogeneity of variance, i.e. the CV_t for all the groups are estimates of the same true coefficient of variation (with random differences). To test for homogeneity, we use both Bartlett's test (Dixon and Brown, p. 778, 1979) and Box's test (Scheffe, p. 83, 1959). Although these are tests for the homogeneity of the variance, applying them to coefficients of variation is reliable if the mean concentration in the denominator of CV_t does not fluctuate significantly between groups. When the mean concentration does vary, these tests would be conservative tests for the homogeneity of CV_t (i.e. biased towards inhomogeneity).

Within concentration classes, these tests generally showed no significant inhomogeneity. The only exceptions were the class for the mean dust concentration $\underline{C}$ of 1-2 mg/m^3 in the Bureau of Mines study (Breslin, 1975) and the class for $\underline{C}$ greater than 2 mg/m^3 in Gray and Tillery (1979) and Budenaers, et al. (1979). The homogeneity of variance in the other studies is an indication that the sampling system is in statistical control and that CV_t is constant within a limited concentration range.

Where CV_t is homogeneous, the coefficients of variation for each sampler group i can be pooled, according to the formula:

$$(CV_{pool})^2 = \sum_i f_i \cdot (CV_{ti})^2 \;/\; \sum_i f_i \qquad (16)$$

where f_i = degrees of freedom for the group.

When f_i is equal for all groups, the pooled CV is equal to the root-mean-square or rms CV:

$$(CV_{rms})^2 = N^{-1} \sum_i (CV_{ti})^2 \qquad (17)$$

where N is the number of replicate sampling groups. The rms CV is reported in studies such as Harris, De Sieghardt and Riva (1976).

The pooled CV's for the different classes are graphed against the mean dust concentration in Figure 8. From these results as well as some of the Tukey box plots (e.g. Figures 5 and 6), a definite increase in the pooled CV_t

Figure 1--Tukey box plots of the CV from replicate samples versus the mean respirable dust concentration. CV distributions are for classes of n sample groups lying within the same concentration range.
SOURCE: Laboratory study by Gray and Tillery (1979).

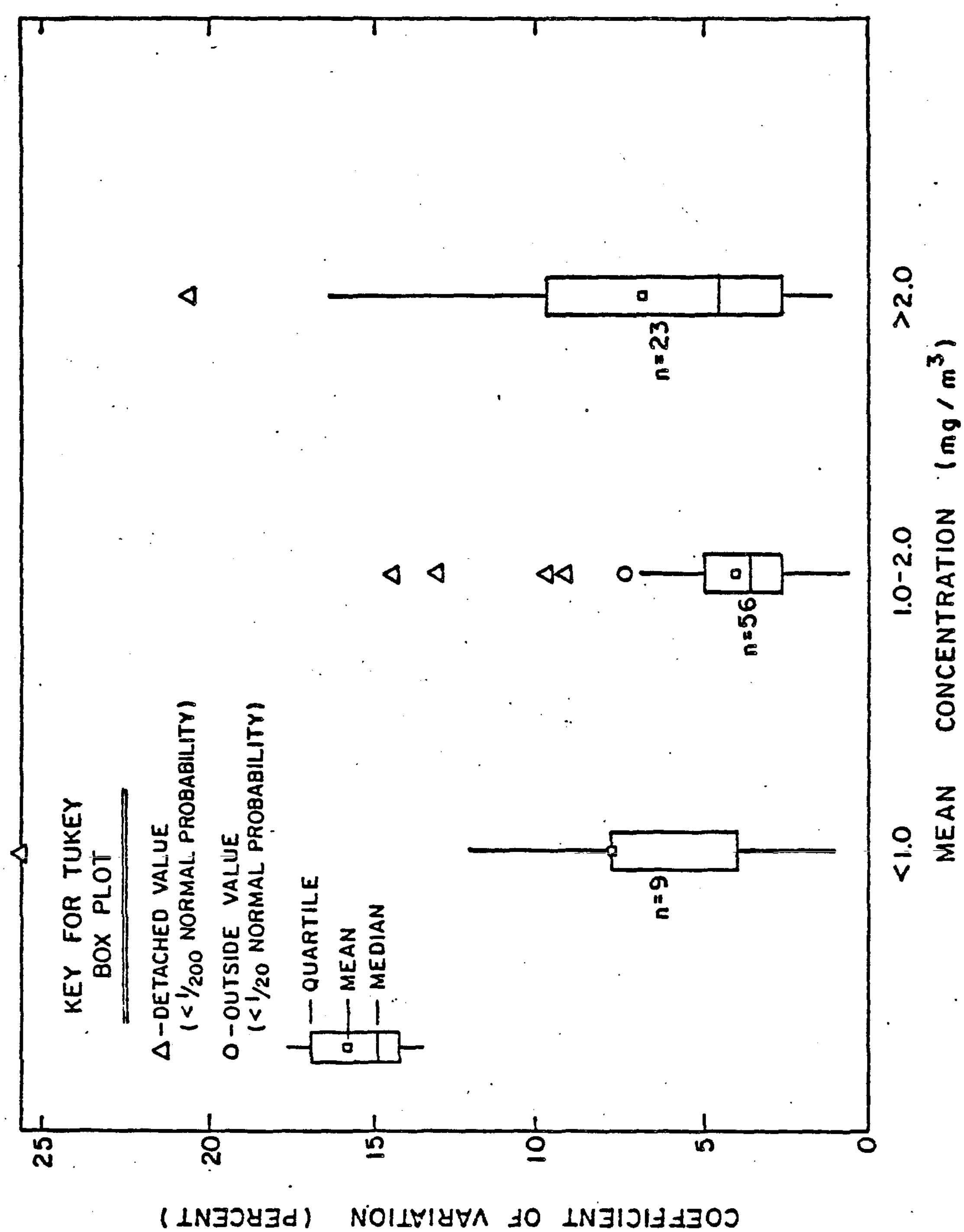


Figure 2--Precision from replicate samples.
SOURCE: Laboratory study by Harris, De Sieghardt and Riva (1976) using MSA sampling units.

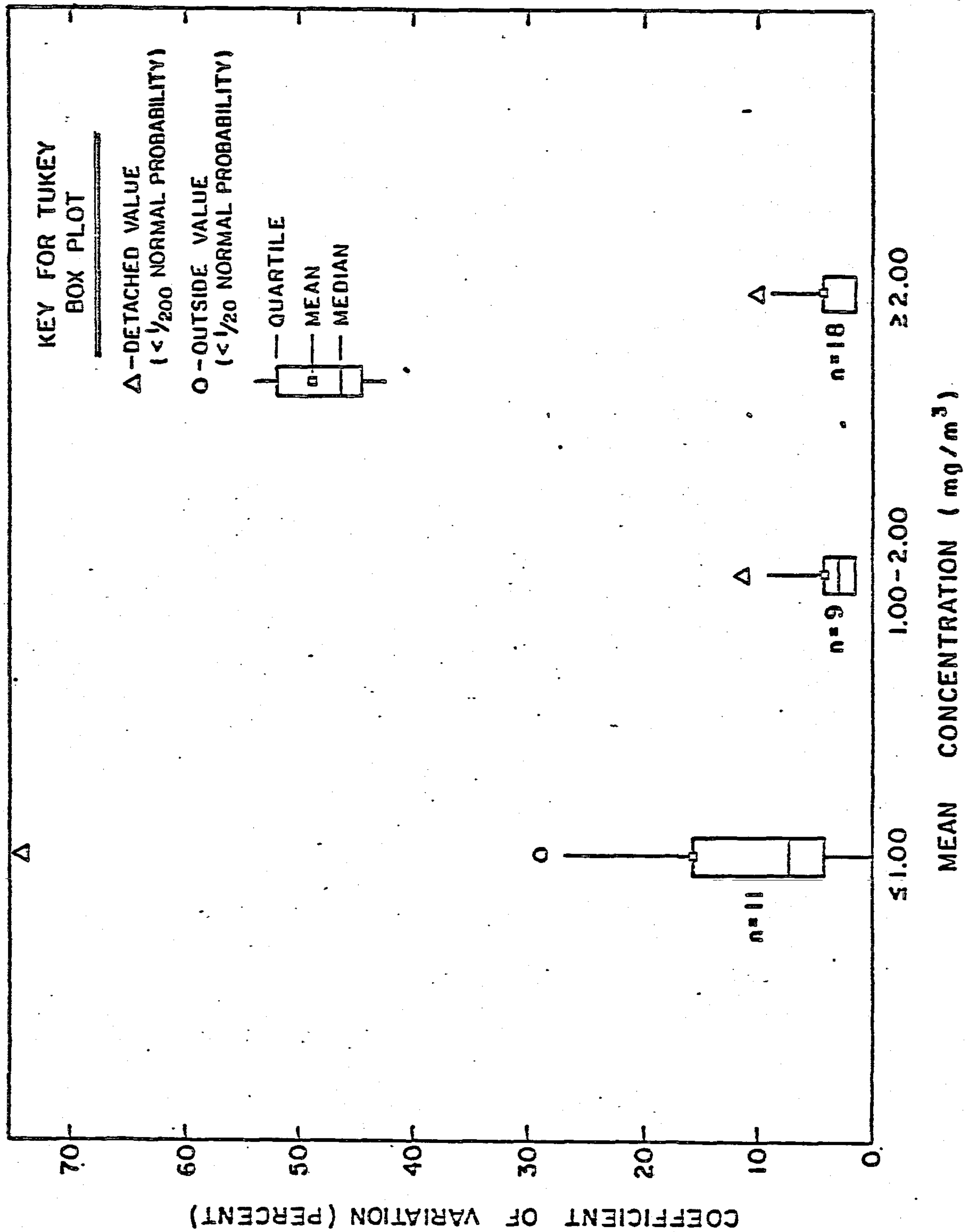


Figure 3--Precision from replicate samples.
SOURCE: Area samples taken by the Bureau of Mines (Breslin, 1975).

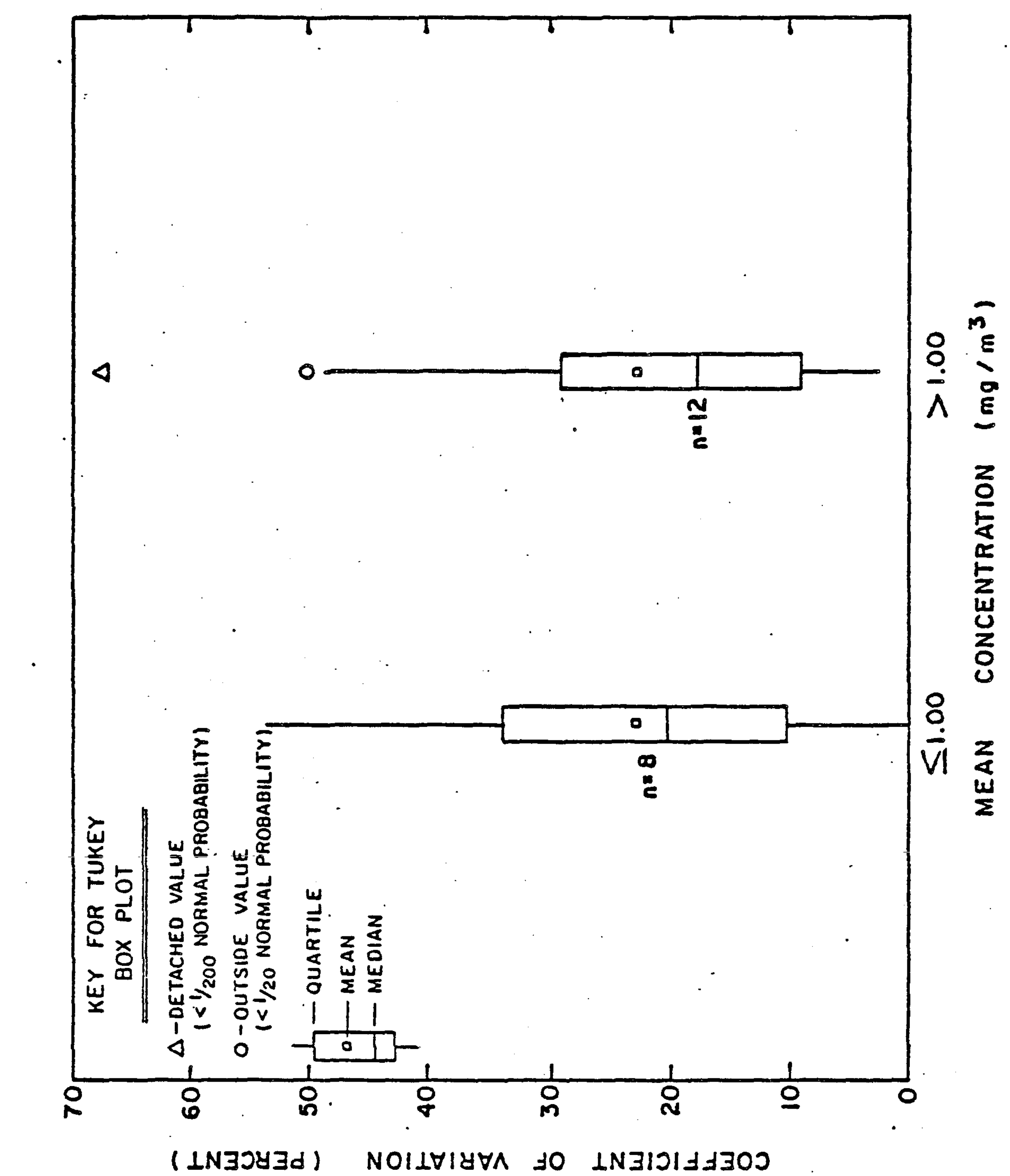


Figure 4--Precision from replicate samples.
SOURCE: Area samples taken by Bituminous Coal Research (Breslin, 1975).

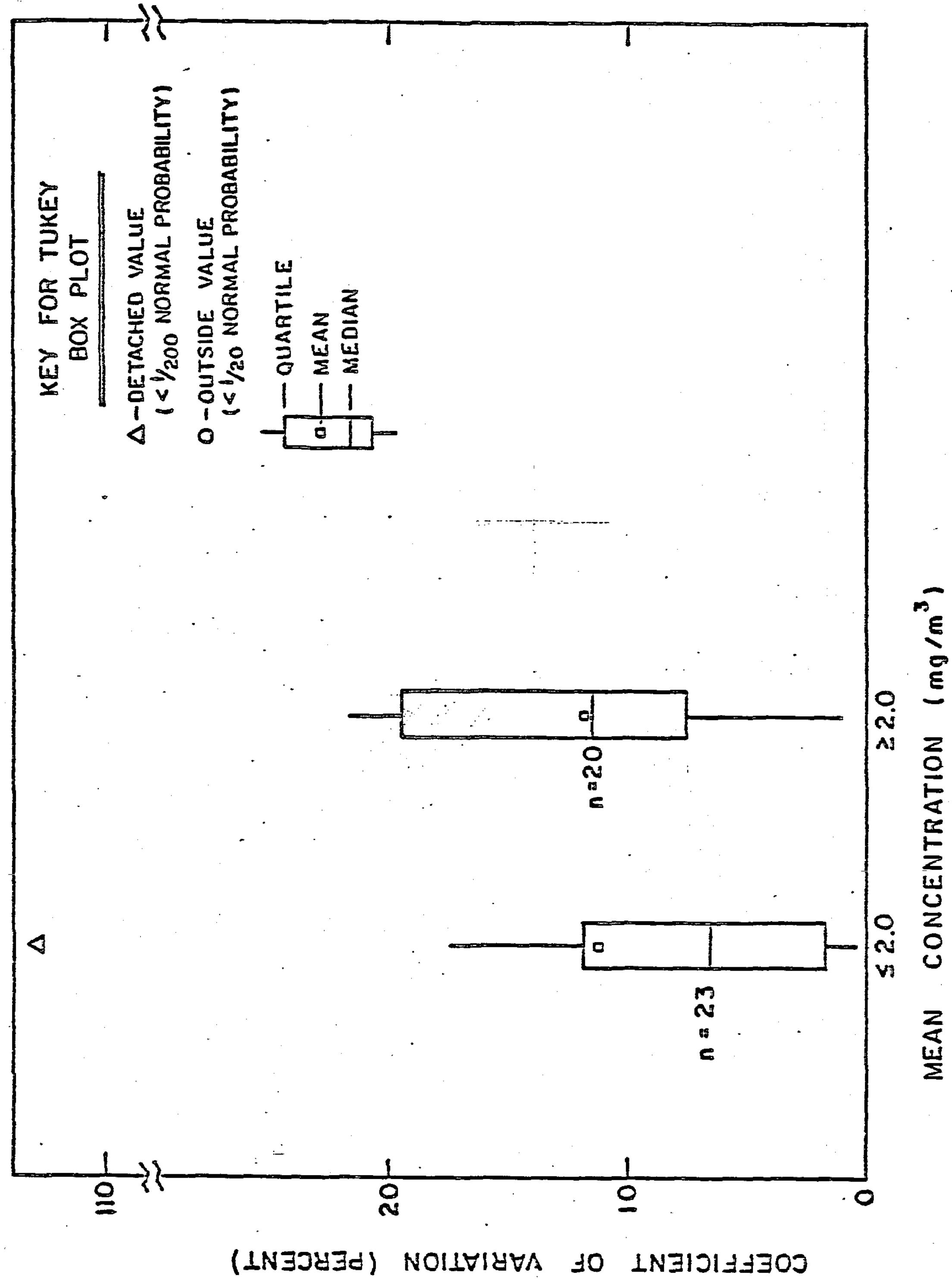


Figure 5--Precision from replicate samples.
SOURCE: Area samples taken by Tomb *et al* (1973) with MSA sampling units.

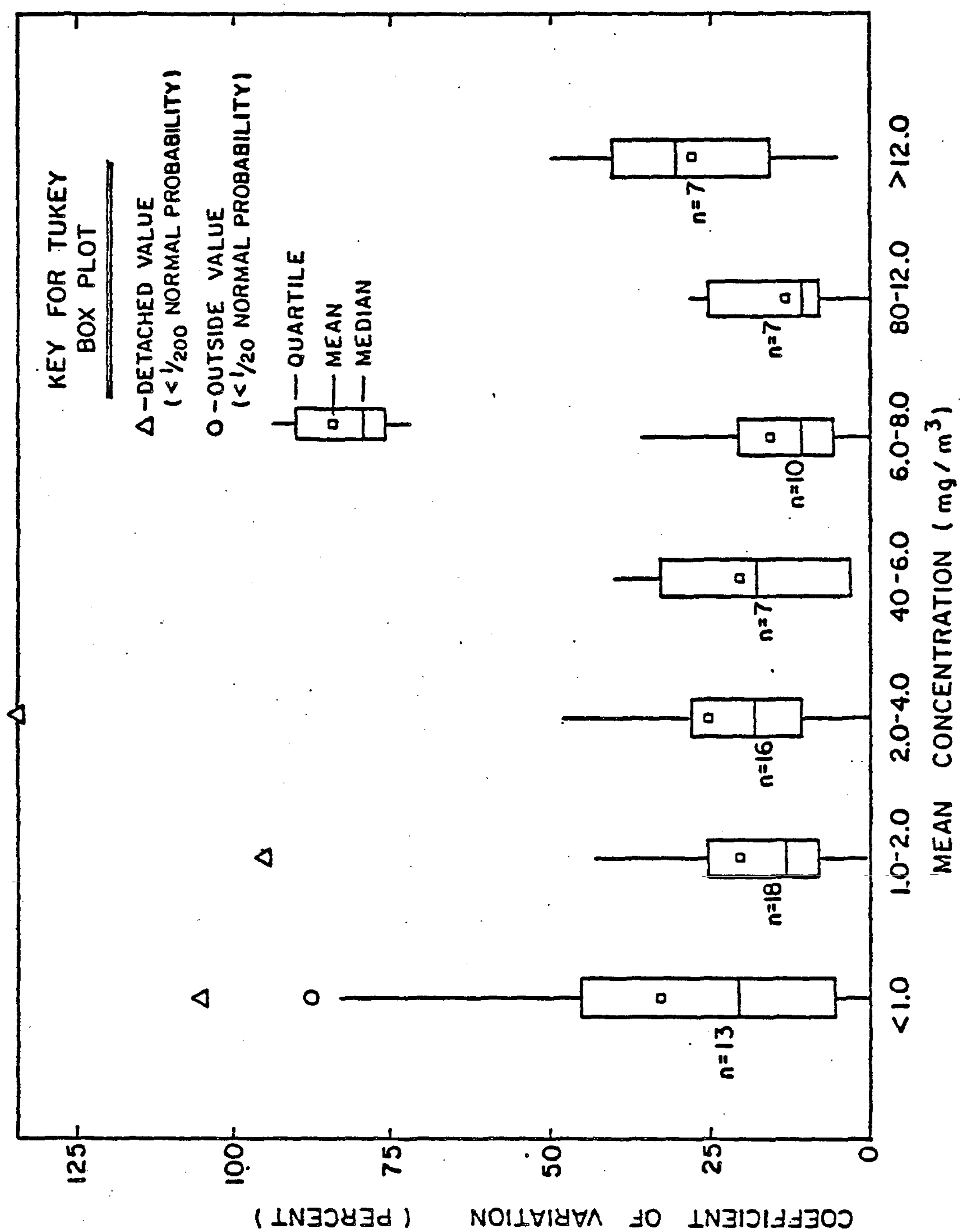


Figure 6--Precision from replicate samples.
SOURCE: Area samples taken by Tomb _et al_ (1973) with Bendix sampling units.

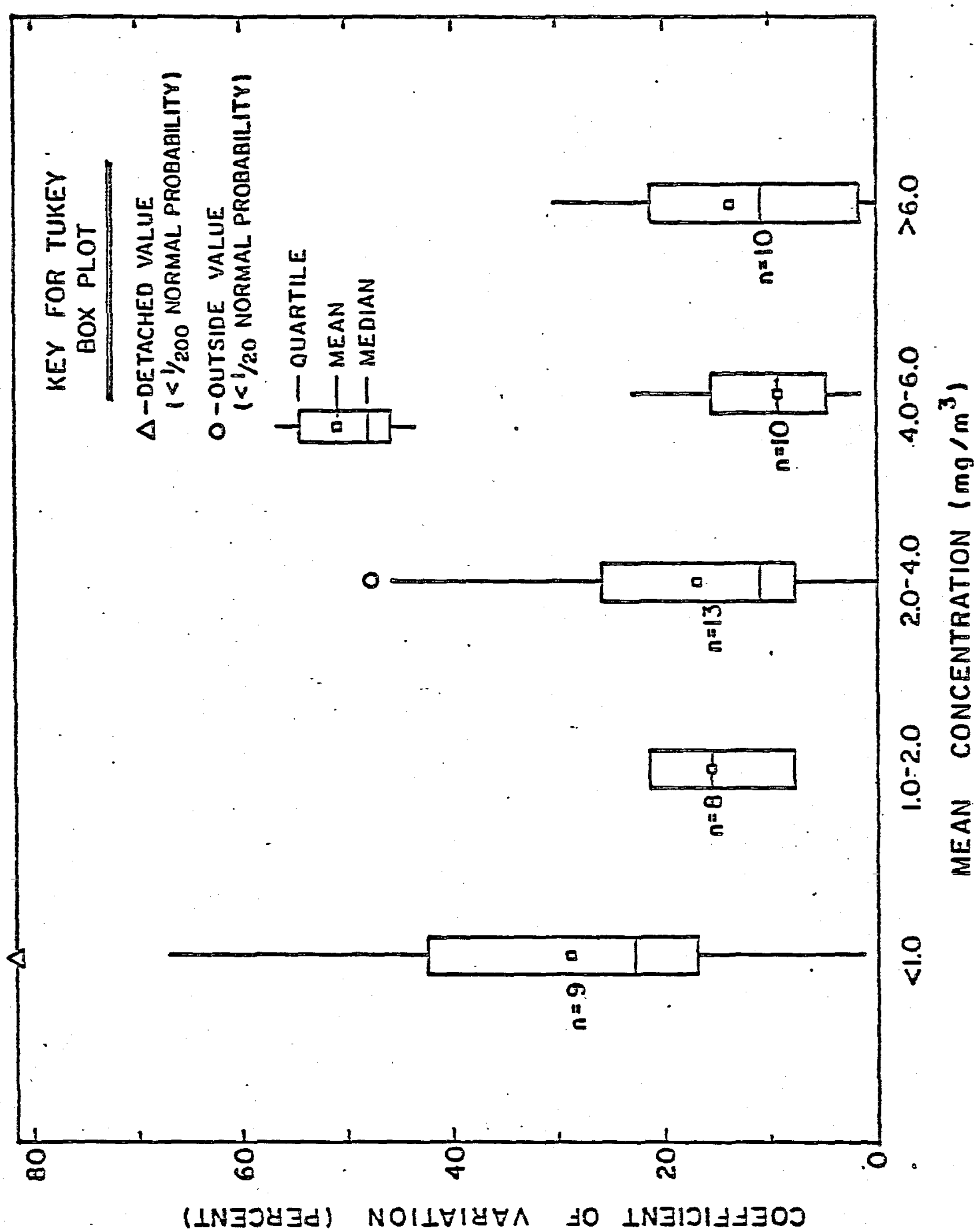
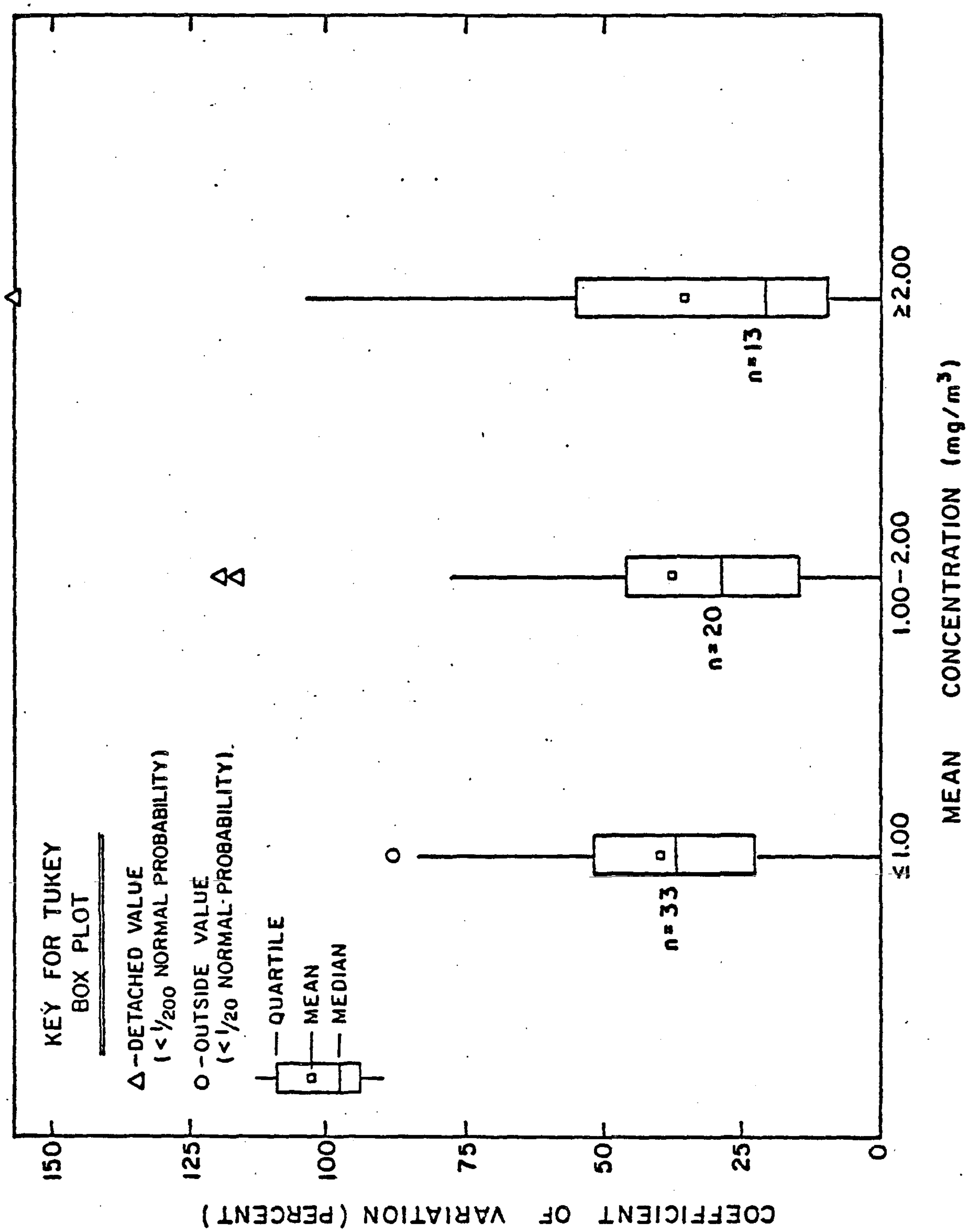


Figure 7--Precision from replicate samples.
SOURCE: Personal samples (gravimetric analysis) by Budenaers et al (1977)



can be observed for dust concentrations less than 1 mg/m^3. In addition, the coefficients of variation can be clearly ranked according to the sampling environment, with the laboratory samples (circles) having CV_t less than the area samples (squares) and personal samples (triangles) taken in the field. (In some of the field sampling studies, the CV_t is as good as that reported by the older laboratory studies.)

The increased CV_t in the field studies may have several causes. Either the more rugged sampling environment increases the random errors in cyclone sampling, or differences in the dust concentrations between the samplers in the replicate package (usually less than a foot across) inflates the measured CV_t above the true sampler precision.

The next step in the analysis is to try pooling CV_t over all concentration classes in a single study, providing that the variance is homogeneous. The results of the homogeneity test over all classes (Tables 7 and 8) show that CV_t can be pooled in the majority of studies. Of the studies with non-homogeneous or marginal variances, two studies (Gray and Tillery, 1979; and the Bureau of Mines data in Breslin, 1975) had already shown non-homogeneous variance in one of the concentration classes. However, two other studies (Harris, et al., 1976; and the Bendix samplers in Tomb, et al., 1973) had been homogeneous within concentration classes, but showed signs of non-homogeneity over the entire range of concentrations. This latter outcome suggests that the high CV_t values for concentrations less than 1 mg/m^3 are significantly different from CV_t at higher concentrations.

In Budenaers, et al. (1977), the data were homogeneous over all concentrations, but non-homogeneous in the class with concentrations greater than 2 mg/m^3. This contrary result appears to be caused by the low number of degrees of freedom ($f = 19$) in the non-homogeneous class compared to the total degrees of freedom ($f = 105$) for the entire group.

The homogeneity in CV_t across all concentrations would seem to conflict with the concentration dependence in the pooled CV_t seen in Figure 8. The explanation lies in the large spread in the individual coefficients of variation, as shown in Tukey box plots (Figures 1-7). When the spread in the individual CV_t is greater than the difference between CV_{pool} for different concentration classes, then the Bartlett's test and/or Box's test will show the variance to be homogenous overall.

Where the tests of homogeneity were positive, the pooled CV_t is reported in Tables 7 and 8. Where the tests were negative or marginal, the range of CV_t pooled within the different concentration classes with homogeneous variance is reported.

Figure 8--Pooled values of CV_t as a function of the mean dust concentration for that class of replicate sampling groups. The numbers within each symbol refer to the various studies in Tables 7 and 8.

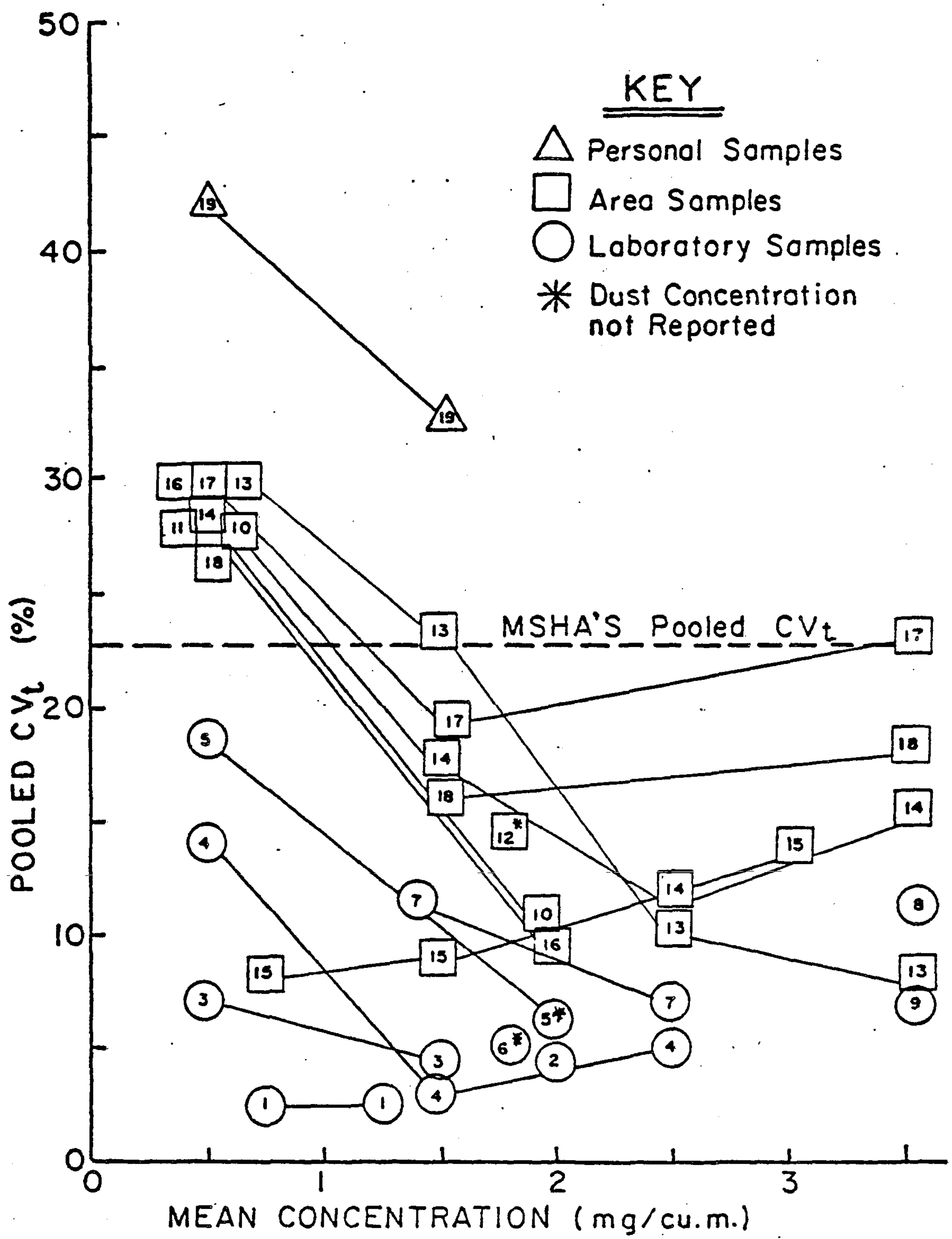


TABLE 7

Laboratory Measurements of the 10 mm Cyclone's Precision. CV_t is pooled over all concentrations when the variance is homogeneous; otherwise, we report the range of CV_t pooled for the concentration classes shown in Figure 8.

	Study	Degrees of Freedom	Pooled CV	Homogeneity of Variance
1.	Bowman, <u>et al</u>. (1982)	18	2.3%	Yes
2.	MSHA data	29	4.3	Yes
3.	Gray and Tillery (1979)	154	7.1–4.6%	No (Pr .05)
	Harris, De Sieghardt and Riva (1976)			
	4. <u>MSA units</u>	37	8.0 (4.9–13.1%)	Marginal – Box, no Bartlett test, yes
		38	14.5	*
	5. <u>Bendix units</u>	39	11.8	*
6.	Almich and Carson (1974)	66	4.8	*
7.	Bureau of Mines data (1972)	58	8.0	Yes
	Jacobson (1971)			
	8. <u>Bendix samplers</u>	8	6.4	Yes
	9. <u>MSA samplers</u>	7	11.1	Yes

* CV estimate from original paper. Without raw data, homogeneity could not be tested.

TABLE 8

Field Measurements of the Precision in 10 mm Nylon Cyclone Samples. CV_t is pooled over all concentrations when the variance is homogeneous; otherwise, we report the range of CV_t pooled for the concentration classes shown in Figure 8.

Study	Degrees of Freedom	Pooled CV	Homogeneity of Variance
		AREA SAMPLES	
10. MSHA data (1981)	14	22.5%	Yes
11. Alavarez, et. al. (1980)	23	25.5	Yes
12. Kost and Saltsman (1977)	40	14.4	Yes, at only 2 mines out of 4
Harris, De Sieghardt and Riva (1976)			
13. Bendix samplers	176	22.5	*
14. MSA samplers	241	23.7	*
Breslin (1975)			
15. BCR Contract	42	11.3	Yes
16. Bureau of Mines	57	30.0 - 9.0%	No (Pr .01)
Tomb, et al. (1973)			
17. MSA samplers	74	24.2	Yes
18. Bendix samplers	49	19.2 (26.5 - 16.1%)	Marginal, (Pr .05)
All Dust Division field studies	160	22.7	Yes
		PERSONAL SAMPLES	
Budenaers, et al. (1977)			
19. Gravimetric analysis	105	43.3	Yes
Silica analysis	86	15	*
20. Breslin, Page, and Jankowski (1982)	118	18.9	Yes

* CV estimate from original paper. Without raw data, homogeneity could not be tested.

Studies such as Almich and Carson (1974) and Budenaers et al (1977) presented special analysis problems because they used different statistics to summarize their precision. Instead of pooling the coefficients of variation, they reported the mean:

$$\overline{CV_t} = N^{-1} \sum_i CV_{ti} \qquad (18)$$

and the variance (or a related statistic):

$$var(CV_t) = (N-1)^{-1} [\sum_i (CV_{ti})^2 - N (\overline{CV_t})^2] \qquad (19)$$

Since these studies both happen to have equal degrees of freedom, f_i, in all replicate groups, the pooled CV reduces to the CV_{rms} (eq. 17). Substituting the above definitions into the formula for the root-mean-square CV gives:

$$(CV_{rms})^2 = (\overline{CV_t})^2 + var(CV_t) \ (N - 1) \ / \ N \qquad (20)$$

Therefore, the pooled CV can be derived from the mean and variance measures given in these studies. These results are shown in Tables 7 and 8.

Another special case is the study by Kost and Saltsman (1977), which only reported relative concentrations RC_{ij} for a group of machine-mounted samples C_{ij} (j=1 to 4) compared to the concentration C_{io} of a personal sample taken at the same time:

$$RC_{ij} = (C_{ij} - C_{io})/C_{io} \qquad (21)$$

Although the absolute concentrations C_{ij} are not reported, we can still derive the relative means, $\underline{RC_i}$, and variances, $var(RC_i)$, for each group i of machine-mounted samples. By noting that:

$$\overline{RC_i} = (\overline{C_i} \ / \ C_{io}) - 1 \qquad (22)$$

and:

$$var(RC_i) = var(C_i) \ / \ (C_{io})^2, \qquad (23)$$

then the coefficient of variation for each replicate group i can be derived:

$$\begin{aligned}(CV_{ti})^2 &= (100\%)^2 \times var(C_i) \ / \ (\overline{C_i})^2 \\ &= (100\%)^2 \times var(RC_i)/(\overline{RC_i} + 1)^2 \qquad (24)\end{aligned}$$

With this formula, exact values for CV_t could be calculated from the Kost and Saltsman (1977) results, although an analysis of concentration effects was impossible. Since Kost and Saltsman report their results from different mines, we were able to select the data from 2 mines where the variance was homogeneous, and this result is reported in Table 8. The data from the other two mines were not homogeneous, either separately or together.

The results in Tables 7 and 8 show strong differences between the CV_t taken in the three environments -- personal, area and laboratory sampling. In the laboratory tests (Table 7), the pooled CV range between 4.3 - 14.5 percent, with the exception of Bowman, et al. (1982), who got a lower CV_t using a microbalance. The range of precision shown by the lab studies is great, as shown by a non-homogeneous result on Bartlett's test. These differences are probably due to the differences in equipment and sampling methods used in the different laboratories.

In the area samples (Table 8), the pooled CV's fall into two groups -- studies done by Bituminous Coal Research and all other results. This outcome can be explained by the unique sampling methods used by BCR. While all the other studies used conventional CMDPSUs and the official sampling methods, BCR has adopted the following quality control measures:

* custom-made sampling heads in which the cyclone and cassettes are mounted in a straight line (as in the MSA unit), but are each clamped independently to the frame (as in the Bendix unit).

* a tube clamp holds the hose onto the sampling head.

* calibrate pumps to within 0.05 L/min of the target flow rate.

* check assembled sampler for leaks with a manometer

* prepare blank filter cassettes (2 blanks per shift; 6-10 blanks per week of sampling)

* technicians routinely take replicate samples in a dust chamber as a QC measure

* the current drawn by the pump motors is recorded on control charts to identify pumps needing maintenance.

These informal QC measures in the BCR studies resulted in pooled CV's of 14.4 percent (Kost and Saltsman, 1977) and 11.3 percent (data in Breslin, 1975). The latter result is lower because the filters were weighed on a microbalance. This CV_t is significantly lower than the range of 19.2 - 25.5 percent reported by the other area sample studies.

The Dust Division's field studies were also tested for homogeneity and pooled. The pooled CV = 22.7/percent (f = 160) is the best estimate of the precision in coal mine dust samples taken with Federal procedures under conditions where outlier samples may be identified and eliminated. This pooled CV_t is calculated, of course, from samples taken at all concentrations. Where the concentration is known to be limited, the concentration-specific values of CV_t in Figure 8 would be more accurate.

To further examine the concentration dependence of the precision, a regression analysis was performed on the Dust Division studies alone. According to the theoretical analysis of precision in eq. (14), $(CV_t)^2$ is a linear function of the inverse square of the mass $\underline{M}$ of dust on the filter. Since $\underline{M}$ is proportional to the concentration $\underline{C}$ as long as the flow rate and sampling time are the same, the theory therefore suggests a regression model of the form:

$$(CV_t)^2 = a + b\ /\ (\bar{C})^2 \qquad (25)$$

Using this model with the Dust Division data, the best regression was obtained from the MSA samples taken by Tomb, et al. (1973). In this case, a = 386.0 (Standard Error of Estimate = 85.0) and b = 103.5 (SEE = 39.0). The other Dust Division data sets gave estimates for a and b which were not significantly different over comparable concentration ranges.

The R^2 for this regression is only 0.1000, indicating that the model in eq. (25) fits the data poorly. However, both parameters a and b are significantly different from zero ($Pr < 0.01$), showing that the postulated concentration dependence truely exists. Therefore, the small R^2 is due to a variability in the CV_t for each group of replicates which is large compared to the change in CV_t due to the mean concentration. This same phenominom was noted above in the results from the homogeneity of variance tests.

For samples taken at the standard ($C = 2.0\ mg/m^3$), the regression model (eq. 25) predicts CV_t = 20.3 percent with a 95 percent confidence interval from 15.8 to 24.0 percent. The pooled estimate of 22.4 percent therefore lies within the confidence interval of the regression analysis at the 2.0 mg/m^3 standard, thus confirming that the two statistical methods give consistent results. Considering both analyses, the precision of the CMDPSU measurements by the MSHA Dust Division is therefore estimated to be 20 ± 4 percent.

Another conclusion from Tables 7 and 8 is that the 2 different brands of CMDPSUs may have different levels of precision. In the earlier studies, the Bendix units were more precise than the MSA. In the latest field study (Harris et al., 1977), the two brands showed no significant difference.

Finally, the personal sampling results from Budenaers et al. (1977) are contradictory. In this study, a package of 3 cyclones was mounted on workers who were chipping sand and metal off castings. The filters were both weighed to obtain the respirable dust concentration and analyzed with X-ray diffraction for the silica concentration.

The gravimetric analysis results gave CV_{pool} = 43.3 percent, but the silica analysis gave CV_{pool} = 15 percent. Since X-ray diffraction is significantly less precise than gravimetric analysis, this discrepancy can be most probably attributed to the inhomogeneous dust in the casting shop which is composed of silica and metal chips. If the high-density metal chips was sampled with less precision than the lower-density silica, then the CV_t of the gravimetric samples could be high while that of the silica samples is low. However, a density dependence for the precision has not been otherwise suggested by theory or experiment.

This explanation of the Budanears et al. results is reinforced by the precision estimated for personal samples in coal mines by Breslin, Page and Jankowski (1982). In this study, scientific professionals wore groups of 2-4 dust samplers for periods of 17-122 minutes while they followed the shearer on longwall faces. Their results gave CV_{pool} = 18.9 percent at an average dust mass of 0.30 mg on the filters. This mass corresponds to an average concentration of 0.43 mg/m^3 if the same mass had been collected over eight hours. These personal samples thus have precisions more in agreement with the 15 percent found by Budenaers et al. (1977) for the silica analysis, than the 43.3 percent found for the gravimetric analysis.

Breslin, Page and Jankowski (1982) also calculated the coefficient of variation for replicate area samples taken by Bituminous Coal Research (BCR, 1976), allowing the comparison of area and personal samples taken by similar methods. Their estimated CV_{pool} for the BCR area samples is 14.6 percent, not far different from the precision of the personal samples. On this basis, it is concluded that personal samples may have precision nearly as good as area samples taken with the same procedures.

B. FILTER WEIGHING

The precision of the filter weighings can be easily measured by replicate weighings of the same filters. The effects to be measured and controlled by such replicate weighings are variations due to different operators, changes in the balance room environment, the sensitivity of the balance and the repeatability of the weighing process.

In the Federal system for monitoring coal mine dust, the initial filter weighings are done by the CMDPSU manufacturer, and the weighing quality is checked by MSHA on 10 blank filters randomly selected from each production shift of filters manufactured. Both the CMDPSU manufacturers and MSHA do their weighing on balances which read to 0.01 mg, but weights are truncated to 0.1 mg. Filters whose weighings by MSHA and the manufacturer disagree by more than ± 0.1 mg are noted and acted upon. MSHA provided the data sheets for these QC weighings from 1979-81. The results are shown in Table 9. A review of this data shows that the accuracy of the filter's pre-weight is excellent.

After a dust sample is taken, the final weight is taken by MSHA's Dust Laboratory (Jacobson and Parobeck, 1971). Weight determinations made in this laboratory are monitored using a quality control program developed by MSHA and the National Bureau of Standards. Statistical control is demonstrated weekly on repeated weighings of 10 filters by different operators on different days (Parobeck et al., 1981).

The results of this quality control study, and the control charts still maintained by MSHA show that the government's weighing system is maintained in a state of statistical control. Both within-day variability and between-day variability are monitored by this QC system.

The results of this QC effort also allow the estimation of the standard deviation s_M in the mass of sampled dust M_S. To estimate s_M from MSHA's quality control data, assume:

1. The standard deviation in the initial weighing is the same as in the final weighing.

TABLE 9

Filter weight differences between MSHA and the CMDPSU manufacturer

Weight Difference (mg)	Number of filters MSA	Bendix
0.0	3496	2251
+ 0.1	375	184
- 0.1	293	184
more than 0.1	6 (1.6 - 0.2 mg)	3 (0.7 - 0.3 mg)

SOURCE: MSHA data sheets (1978-80)

2. The moisture content of the coal dust is constant between the two days when the weighings are done.

On these provisions, the standard deviations s_M in the filter weighings are summarized in Table 10. Also added are the results from a similar QC effort with a microbalance (Bowman <u>et al</u>., 1982), and the relative standard deviation s_M/M_S in an 8-hour sample at the concentration of 2.0 mg/m^3.

Comparison of the respective standard deviations for weighing in Table 10 shows that the current procedure of truncation to 0.1 mg adds only 0.013 mg to the s_M for a balance with 0.01 mg sensitivity. For a sample weighed on a microbalance (sensitivity of 0.001 mg), the current Federal weighing procedures add 0.068 mg to s_M.

Based on the propagation of error analysis in Section IIA, these random weighing errors contribute a term $s_M/\underline{M}$ to the total coefficient of variation in eq. (14). Since the dust mass $\underline{M}$ is related to the respirable dust concentration $\underline{C}$ by eq. (12), an "analytical" coefficient of variation can be defined for gravimetric dust sampling:

$$CV_a = 100\% \; s_M \; k \; / \; \bar{C} \; Q_o \; T \qquad (26)$$

In Figure 9, the analytical CV from the weighing is plotted against dust concentration (assuming an 8 hour sample). It can be seen that the analytical imprecision will become significantly large at concentrations below 1.0 mg/m^3 unless the weighing is done with a sensitivity of .001 mg. This concentration dependence of the weighing errors is especially important where the coal mine dust standard is reduced below 2 mg/m^3 due to silica content above 5 percent.

C. PUMP FLOW RATE

The sampling pump is the driving force for the coal mine dust personal sampling unit (CMDPSU). The pumps used are battery powered and generally of simple construction. However, much depends on their ability to maintain a known flow rate accurately over an 8-hour period.

The pumps in CMDPSUs must be certified by NIOSH in accordance with design and performance regulations in Part 74, Title 30, <u>Code of Federal Regulations</u>. Part 74 currently requires that the pump be capable of maintaining a flow of 2.0 L/min within $\pm$0.1 L/min over an 8-hour period. If the flow rate deviates at all from 2.0 L/min during a sample, the following errors may occur:

i) In calculating the respirable dust concentration according to eq. (1), the flow rate Q will not be accurately known.

ii) The amount of dust drawn into the cyclone increases with larger flow rates.

iii) The proportion of dust passing through the cyclone decreases with larger flow rates.

TABLE 10

Standard deviation in the measured mass of dust on filter, due to random errors in weighing.

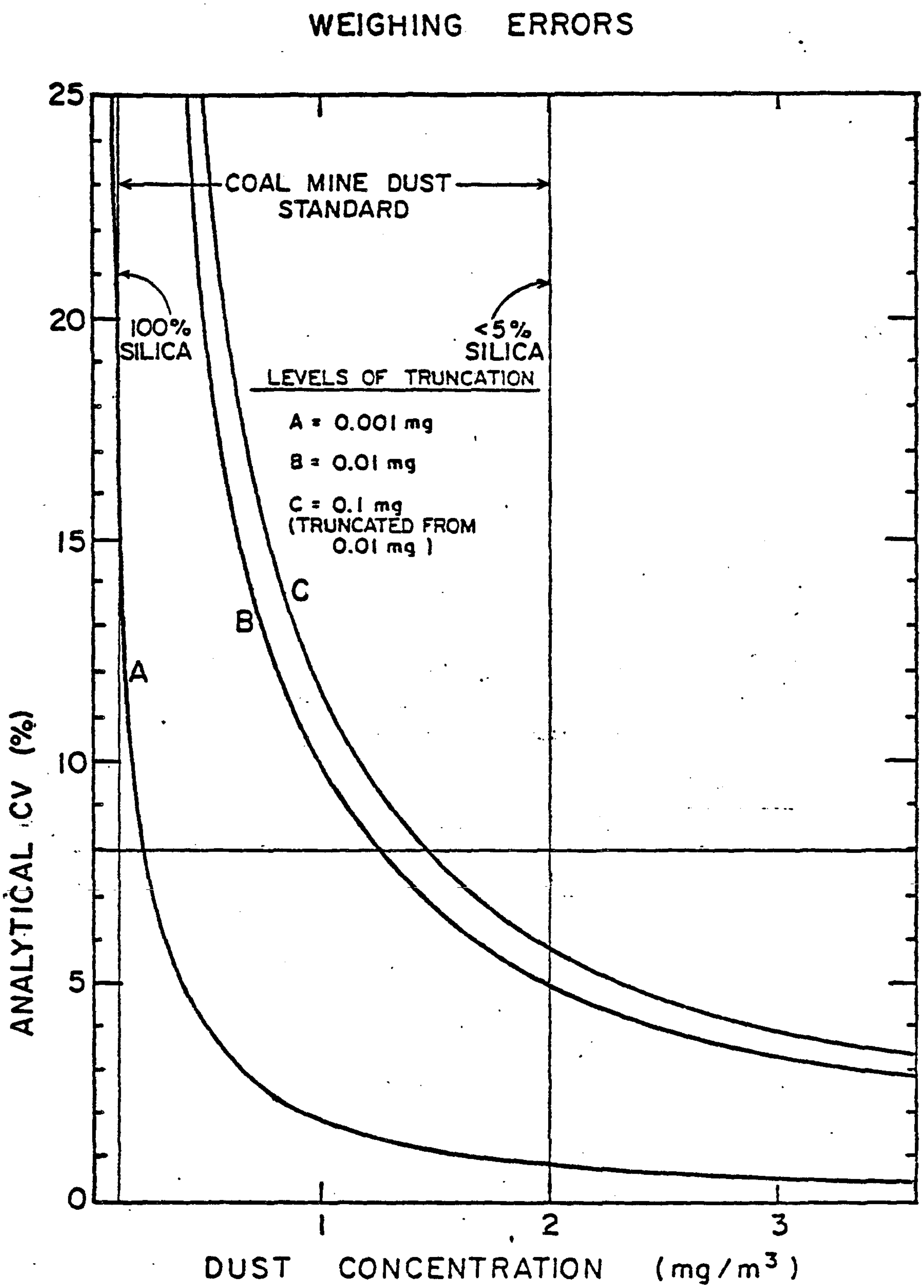
Balance Sensitivity	Standard Deviation (mg)	Relative Std. Dev., on a 2.0 mg/m^3 sample
0.001 mg	0.013	0.9%
0.01 mg	0.068	4.9
0.1 mg (truncated from 0.01 mg)	0.081	5.8

SOURCES:

Parobeck, Tomb, Ku and Cameron (1981)

Bowman, Bartley, Breuer, Doemeny, and Murdock (1982)

Figure 9--Coefficient of variation due to the gravimetric analysis of the dust samples versus the respirable dust concentration.



In the Federal procedures for CMDPSU sampling, error i) is simplified by assuming that the flow rate is equal to the "target" value Q_o of 2.0 L/min. Setting the flow rate is usually accomplished by calibration of the pump before sampling and by subsequent adjustment to the 2.0 L/min mark during the shift. To a good approximation, pump flow errors thus affect the dust concentration primarily through mechanisms ii) and iii) only.

Considering only these two mechanisms, Bartley and Breuer (1981) have derived the changes in the sampled mass as a function of deviations from the target flow rate Q_o. As given in equation (7), the sampling fluctuations are directly proportional to the variance in the relative pump flow fluctuation ΔQ:

$$\Delta Q = (Q - Q_o) / Q_o \tag{27}$$

where Q is the time-weighted average flow rate. The constant of proportionality γ defined in eq. (6), is a function of the cyclone's penetration efficiency and the dust size distribution, as shown in Figure 10.

The relevant measurements of dust size distributions in coal mines have been reviewed by Bowman, Bartley, Breuer, Doemeny and Murdock (1984). As shown in Table 11, the size data from coal mines have been taken by different methods under different conditions, so the results must be compared cautiously. Nonetheless, the distributions listed in Table 11 define a region within which lie all the best measurements of coal mine dust size distributions currently availible. By superimposing the distributions from Table 11 over the contours in Figure 10, γ can be seen to range between ± 1 for samples taken in coal mines. For the many distributions where γ is close to zero, random pump flow variations would have negligible effect on sample accuracy. With better size data, the estimate for γ may change.

Since γ is less than ± 1, the pump flow's contribution to the overall precision can be no less than ΔQ. In the remainder of this section, the magnitude of ΔQ and other measures of the pump flow rate accuracy in the government-regulated sampling will be assessed from a review of the government's procedures and the available literature.

(One more mechanism which may affect CMDPSU accuracy is the pulsation in the flow rate. As a result of an early study by Lamonica and Treaftis (1972), the certification regulations in Part 74 now require pulsation dampeners in the CMDPSU pumps, which must bring the units within ±5 percent of the concentration sampled with a non-pulsating air flow. Still, Huggins (1980) found some differences in the accuracy of CMDPSUs with pulsation dampeners. However, none of this evidence demonstrates that the regulations on pump pulsation in Part 74 do not adequately assure CMDPSU accuracy. In general, pulsation effects have been difficult to estimate from either theory or experiment, and will not be considered further.)

Figure 10--Coefficient γ for the bias due to deviations in the pump flow rate from 2 L/min. Contours for constant γ are given as a function of the dust size distribution. Superimposed are the range of size distributions measured in coal mines (Table 11).

SOURCE: Bartley and Breuer (1982)

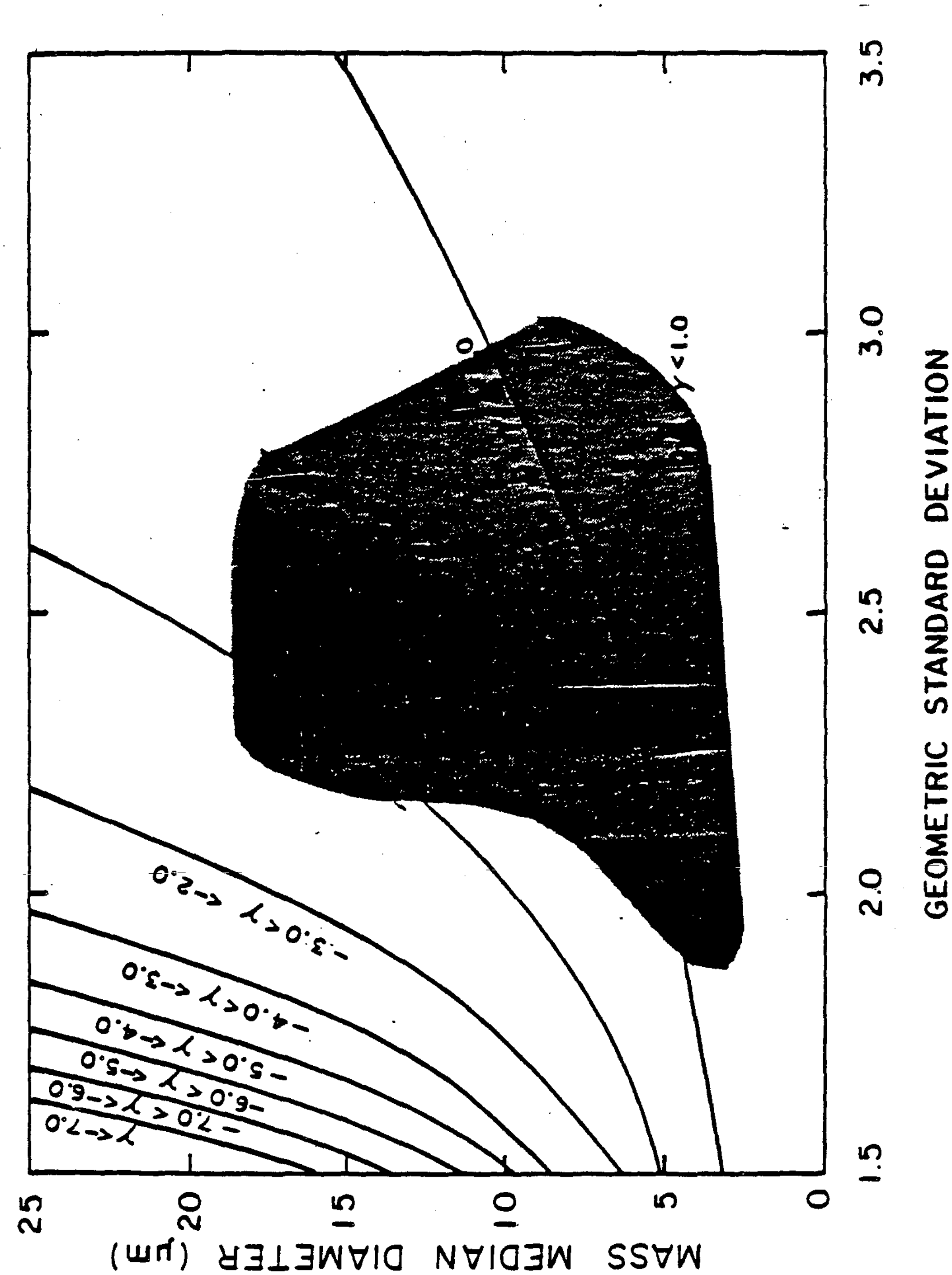


TABLE 11

Extreme Dust Size Distributions Measured in Coal Mines

SOURCE: Bowman, Bartley, Breuer, Doemeny, and Murdock (1984).

Reference	Nation	Sampling and Sizing Instruments	Sampling Location	MMD (um)	GSD
Tomb, Treaftis and Gero (1983)	USA	Total dust filter, Coulter counter	Dump point	3.0	1.9
			Contin. mining	2.9	2.2
			Dump point	3.1	2.8
			Contin. mining	10.1	2.9
			Dump point	7.7	3.0
Breuer (1967)	Germany	GOTHE filter, Andreasen sedimentation	Pneumatic pick	17.2	2.8
Fay and Ashford (1960)	Great Britain	Std. Thermal Precipitator, microsope	Away from face	18.6	2.3
			Longwall face	8.0	2.15

In a study of the flow rates in several coal mine dust personal sampling units with clean air, Gray and Tillery (1979) recorded the average flow rates in each of three eight-hour runs (see Table 12). The pumps had been calibrated by MSHA; the calibrations were corrected by MSHA for the difference in altitude between the MSHA laboratory and the Los Alamos Scientific Laboratory (LASL); and the units were then run as received at LASL. The flows were checked and reset at one-half hour and four hours and were checked at the end of the eight-hour run. A wet test meter measured the total volume drawn by the pump over the 8-hour sample, from which the average flow rate Q can be calculated.

The accuracy of the average flow rate Q is difficult to interpret because of the adjustment for the altitude difference (some 2 km). Thus any deviation of Q from 2 L/min reflects both the accuracy of the altitude adjustment and the accuracy of the pump calibration. As can be seen from the data in Table 12, however, the pooled CV about the average flow in each of three runs (for those pumps able to complete three runs) was 2.25, 6.71, 2.55, and 1.9 percent for the MSA model G, Bendix Micronair, Bendix BDX-30, and Bendix C-115 pumps respectively.

If the altitude corrections in Gray and Tillery (1979) are assumed not to affect the variability in ΔQ, then $[CV(\text{inter-sample})]^2$ is a good estimate of var(ΔQ). According to their data, all the pumps except the Bendix Micronaire had an inter-sample CV well within 5 percent. Such accuracy can be expected of a pump properly calibrated and checked according to Federal procedures. Since the effect of pump flow on the sampled mass is less than var(ΔQ) for coal mine dust size distributions, the magnitudes of the pump variations from Gray and Tillery (1979) would have negligible effects, compared to the total sampler variations of 20-25 percent estimated in Section IIIA.

Relatively little additional data seem to be available on the variability of the eight-hour average flow of pumps under conditions similar to those of actual use. In some work at NIOSH (Murdock and Bowman, 1981), the flow of several CMDPSU's were monitored from their rotameters at 1/2 hour intervals for 4 hour periods while sampling a chamber containing 4 mg/m^3 coal dust; the flows were reset, if necessary, at 0.5 hour and at 3.5 hours. Table 13 lists the 4-hour average flow rate and its standard deviation for each of the 24 sets of data (4 MSA Model G pumps per run, 6 runs total). The average of the 4-hour average flows was 1.983 L/min with a inter-sample CV of 1.2 percent. This is less than the CV of 2.3 percent for the variation of the 8-hour average flows obtained by Gray and Tillery for the same model pump about their mean of 1.952 L/min; the difference may be due to the shorter time period. In both of these studies the flow is reset twice during a run, just as is required in the Federal regulations.

Murdock and Bowman (1981) also measured the MSA model G pump flow rate every one-half hour during a four hour run, resetting the flow to the original 2.0 L/min at 0.5 and 3.5 hours. The intra-run coefficient of variation is given in Table 13 for each run; the pooled coefficient of variation for all 24 runs was 1.6 percent.

TABLE 12

Statistics for Time-Weighted Average Flow Rates of Personal Sampling Pumps in Three 8-hr Trials

SOURCE: Gray and Tillery, 1979

Pump	Pump No.	Mean Flow, L/min	CV (inter-sample)
MSA Model G	1	1.911	0.55%
	2	1.974	1.13
	3	1.983	1.28
	4	1.941	0.62
	5	1.949	4.65
	Pooled	1.952	2.25
Bendix Micronair	1	Failed to finish three runs	
	2	2.290	3.41%
	3	2.125	11.51
	4	2.321	2.60
	5	2.337	5.43
	Pooled	2.268	6.71%
Bendix BDX-30	1	2.135	2.26%
	2	Did not operate properly	
	3	Did not operate properly	
	4	2.230	2.83
	5	2.158	2.53
	Pooled	2.174	2.55%
Bendix C-115	1	Three runs were not done	
	2	1.723	1.28%
	3	Failed to finish three runs	
	4	1.919	0.86
	5	Failed to finish three runs	
	Pooled	1.821	1.09%

TABLE 13

Time-Weighted Average Flow Rate for MSA Model G Pumps in One 4-hour Run (9 Rotameter Readings).

SOURCE: Murdock and Bowman (1981)

Run No.	TWA Flow (L/min)	CV (Intra-run), %
1	1.996	0.62
2	2.013	2.41
3	2.021	3.63
4	1.954	1.56
5	1.958	1.97
6	2.004	1.08
7	1.952	1.26
8	1.979	0.86
9	1.950	1.29
10	1.974	1.23
11	1.976	1.15
12	2.026	0.81
13	1.950	1.29
14	1.962	1.98
15	1.972	1.62
16	1.987	1.62
17	1.991	1.25
18	2.026	0.79
19	1.992	1.18
20	1.983	1.27
21	1.991	1.25
22	1.996	0.61
23	1.971	2.47
24	1.975	0.78
Pooled	1.983	1.57

(Inter-sample CV = 1.18%)

Parker, Lee and Sharpe (1977) also monitored the flows of several personal sampling pumps (including the MSA models G and S CMDPSU pumps) for eight hour operation at various temperatures following initial setting at 2.1 L/min at room temperature, but they were interested in the effect of temperature from 25 to -50 degrees Centigrade and did not evaluate the variance of the flow for the pumps. In general, the pumps were significantly influenced by low temperatures, providing sampling capability at -10 to -20 degrees C, but marginal performance was achieved at lower temperatures (none were useful at -50 degrees C).

In the case of the MSA models G and S CMDPSU pumps, some of the temperature effect was due to the batteries, but the pump also required more current (up to about twice the room temperature current demand), indicating an effect on the pump also. Two of these studies provide data on the variation of flow rate <u>during</u> a run. Parker, Lee and Sharpe (1977) show graphs of the flow over an eight hour run for five samples of several personal sampling pumps, including the MSA models G and S CMDPSU pumps. The MSA models decreased in flow from the originally set 2.1 L/min to about 2.0 L/min (approximately 5 percent) over the first one to two hours and were then relatively stable at 24 degrees C ambient temperature.

The auditing program established by MSHA provides data on the calibration of pumps actually used by mine operators. Six replicate measurements are made on each of a selected sample of pumps using a 1 liter bubble meter. These data are summarized on a "Dust Sampling Program Survey Sheet" attached to the "Coal Mine Inspection Report" filled out for each mine inspected. Reports on ten mines, with 69 sets of replicate measurements, were obtained from MSHA. Because the same data for pumps from a central store (which may furnish pumps for several mines) are reported for each mine, these actually represent spot checks on a total of 23 different pumps from four supply centers. The data are summarized in Table 14. Except for one pump, the six readings on each pump were the same. From the data it can be seen that no pump was more than 1.5 percent off the target flow rate of 2.0 L/min. The average flow rate for the 23 pumps was 1.997 L/min with a standard deviation of 0.013 L/min (CV = 0.63 percent).

MSHA recalibrates the CMDPSU pumps used in its inspections every 80 operating hours and maintains a record of these recalibrations. The records for 31 pumps were reviewed and the data are summarized in Table 15. The data recorded for each pump are the date and time in minutes (to the nearest hundredth) required to pump nine liters. For the 31 pumps--a total of 213 recalibrations--the average time required was 4.496 minutes (flow rate Of 2.002 L/min) with a pooled CV of 0.41 percent; no calibration was more than 0.7 percent from the target flow rate of 2 L/min. The calibration procedure is assumed to be without significant error with quality control as currently specified (MSHA, 1980 a,b,c).

Gray and Tillery (1979) did bubble meter calibrations by each of two operators for pumps previously calibrated by NIOSH. Again, the altitude correction makes exact comparisons tenuous; they concluded that the altitude correction was necessary and sufficient for some types of CMDPSU, and necessary but not sufficient for other types; there is, however, some

TABLE 14

MSHA Calibration Checks on 23 Pumps Used by Mine Operators

Pump No.	Supply Center	Flow Rate, L/min (ave. of 6 checks)
1	1	2.00
2	2	2.00
3	2	2.00
4	3	2.00
5	3	2.00
6	3	2.01
7	3	2.01
8	3	2.00
9	3	2.00
10	3	2.02
11	3	2.00
12	3	2.00
13	3	2.00
14	3	2.00
15	3	2.00
16	4	1.97
17	4	1.97
18	4	2.00
19	4	2.00
20	4	2.00
21	4	1.97
22	4	1.98
23	4	2.00
		av. 1.997 $\pm$ 0.013 (0.63%)

SOURCE: MSHA data sheets

TABLE 15

Representative MSHA Pump Flow Calibration Data

Pump No.	No. of Recal.'s	Ave. Days Between	Time (min.) to draw 9L air: Average	Std. Dev.	Coeff. of Variation, %
630	8	133	4.491	0.020	0.44
635	6	131	4.485	0.014	0.31
637	5	145	4.492	0.016	0.37
646	6	151	4.500	0.023	0.51
653	5	150	4.484	0.011	0.25
654	7	174	4.500	0.018	0.41
685	6	201	4.503	0.018	0.39
740	5	262	4.490	0.019	0.42
752	6	199	4.498	0.016	0.36
783	5	122	4.516	0.013	0.30
790	8	132	4.493	0.023	0.52
798	7	150	4.504	0.022	0.49
799	9	156	4.481	0.015	0.34
825	6	196	4.500	0.022	0.49
827	6	175	4.482	0.012	0.26
828	7	267	4.504	0.024	0.53
832	7	125	4.499	0.016	0.35
836	7	143	4.506	0.021	0.48
846	8	115	4.501	0.022	0.48
847	8	187	4.494	0.018	0.39
849	7	141	4.493	0.021	0.46
854	7	143	4.487	0.015	0.33
856	8	125	4.501	0.022	0.50
857	7	162	4.490	0.018	0.41
858	6	151	4.495	0.015	0.34
860	6	207	4.488	0.017	0.38
870	8	120	4.499	0.019	0.42
871	8	154	4.498	0.023	0.51
872	7	138	4.487	0.011	0.25
873	8	149	4.508	0.020	0.45
	Total = 213	Ave. = 160	Ave. = 4.496		Pooled CV = 0.41%

SOURCE: MSHA data sheets

question whether the flow measurements were properly made to test the altitude correction (Treaftis, 1980). Differences between the two operators were "within the expected rotameter error"; the greatest differences were observed for those pumps with relatively unstable rotameter floats (Bendix Micronair and Bendix BDX-30 pumps).

The accumulation of dust on the filter changes the pressure drop and consequently the pump flow rate. This effect has been studied by Parker, Lee and Sharpe (1977) and Wood (1977) for a number of pump models, including the MSA Model G. This effect is significant for most of the pumps. In these studies the change in flow is about 0.07 L/min per inch of water (Wood, 1977), and ranges from 0.03 to 0.07 L/min per inch over 5 pumps (Parker, Lee and Sharpe, 1977). This characteristic varies quite a bit among individual pumps and is a very large variation among types of pump.

This effect may present a problem in predicting or controlling the variation of flow rate as the filter is loaded. To estimate the effect of dust loading, a simple pressure drop measurement was made on moderately loaded MSA filter cassettes, and was found to be 1 to 1.5 inches of water more than with clean filter cassttes. This measurement agrees with the estimate in Wood (1977) that a 10 mg dust loading would add on a 0.4 to 1.6 inch pressure drop. Therefore, the effect of loading on the flow through a MSA Model G pump should be less than 5 percent.

Finally, the Swedish National Testing Institute recently completed tests on the MSA Model G and other personal sampling pumps (Akesson, Wikstroem, Stridh and Lundgren, 1980). For respirable dust sampling, the MSA Model G was found to be acceptable, but compared to the other pumps, it gave "poor" results in the tests for sound level, operation at low temperatures and flow rate as a function of pressure drop.

From this limited data base, some conclusions can be drawn, although these must necessarily be of a tentative nature pending more adequate data on CMDPSU's in the mining environment. Among the conclusions drawn are:

* The calibrated flow rate of CMDPSU's now used in mines is adequately controlled at 2 L/min with a coefficient of variation of less than 1 percent using present government-specified calibration and maintenance procedures.

* Based on laboratory measurements, the flow rate for the duration of a 4 to 8 hour sampling period using an MSA model G pump is adequately controlled at 2.0 L/min with a coefficient of variation of approximately 3 percent. The Bendix BDX-30 and C-115 samplers are comparable; the Bendix Micronair has a coefficient of variation near 7 percent. These latter pumps were unreliable in several studies.

* For purposes of estimating measurement accuracy, the contribution to the total coefficient of variation from pump flow errors is approximately equal to the variance in ΔQ. Values of this CV measured over the 4 to 8-hour samples have more theoretical validity, but have only been studied in the laboratory.

Because the current Federal procedures only provide data for estimating the CV in the initial (calibrated) flow rates for samples taken routinely in coal mines, values of ΔQ for full-shift samples would be underestimated. Because full-shift field data on pump flow rate variability are unavailible, those laboratory measurements of the inter-sample CV by Gray and Tillery (1979) seem to be the best current estimate. Therefore, the contribution to the total CV from the pump flow rate fluctuations is generally less than 3 percent. This is negligible compared to other sources of sampling error.

* Controlling the intra-run variability to achieve this level of precision in the pump flow rate requires resetting the pump flow rate during the second hour of operation as presently required by Federal regulations.

* The end-of-run flow rate check presently required by the regulations shows that the pump was able to sample at 2.0 L/min for the full shift.

In summary, pump flow errors appear to make a neglible contribution to the random variations in coal mine dust measurements, although the data supporting this conclusion are not always from samples taken "by coal miners in underground mines".

D. SAMPLING ERRORS

The sampling errors can be estimated from equation (14), which may be rearranged to give:

$$(CV_s)^2 = (CV_t)^2 - (s_M / \overline{M})^2 - \gamma^2 \, \mathrm{var}(\Delta Q) \qquad (28)$$

Using the results of the three previous sections, samples taken under MSHA procedures are characterized by the following:

$CV_t = 22.7\%$	for Dust Division studies (Table 8)
$s_M = 0.081$ mg	for the MSHA Dust Laboratory (Table 10)
$\overline{M} = \overline{C}Q_oT / k$	
$= 1.39$ mg	for an 8-hour sample at 2.0 mg/m^3
$\gamma^2 = 0 - 1$	for coal mine dust size distributions (Figure 10)
$\mathrm{var}(\Delta Q) = 2.3\%$	for MSA sampling pumps (Table 12)

At the coal mine dust standard, CV_s is therefore 21.8 - 22.0 percent, depending on the value of γ for the particular dust size distribution.

This relatively large quantity requires some explanation. Many investigators have suggested that the imprecision measured by replicate field samples is inflated by unequal dust concentrations hitting the various sampler inlets (even though they are only a few inches apart). However, the CV_t = 11.3 - 14.4 percent obtained by Bituminous Coal Research with similar experimental arrangements suggests that a large part of these random errors results from the sampling procedures and/or the effects of the mine environment.

Studies bearing on these sources of random errors are summarized in Tables 5 and 6. None of the studies clearly explains the magnitude of CV_s. The charge effect studied by Almich and Carson (1974) is the largest increase in the CV (from 4.7 to 9.6 percent) which has been conclusively demonstrated. Significant changes in the penetration efficiencies were attributed to heavy cyclone loading by Fairchild, Tillery and Ettinger (1977), but other authors found no such effects. The presence of over-sized particles is a potential source of errors which could appear as a random effect in an uncontrolled study. However, no evidence exists on this point.

Some of the factors contributing to CV_s, such as leaks in the cyclone assembly, can be eliminated by more careful experimental procedures. For example, Caplan, Doemeny and Sorenson (1977) found that leakage around the cyclone inlet due to faulty placement of the vortex finder showed up as a wide variation in replicate sampling results. Cyclones with leaks measured concentrations which varied randomly from the samples taken without cyclone leakage. This problem has been markedly reduced in the MSA sampler heads by the use of thicker steel in the cyclone holder and the introduction of a clip to hold the vortex finder in place. Such sources of variability should not be considered random errors although they would appear as components of CV_s.

In examining the CV_t = 22.7 percent estimated for the government's procedures, it appears that the bulk of this variability is not uncontrollable random errors, but is due to a lack of uniformity in the sampling procedures. No studies have shown the existence of an environmental factor which produces random errors in cyclone sampling any larger than the CV_t = 9.6 percent found by Almich and Carson (1974) in the laboratory study with charged particles. In fact, the precision obtained by BCR in their field studies equals Almich and Carson's lab results within confidence limits on the CV_t estimates. Thus, the level of precision obtained by BCR should also be possible in any other program of area sampling (or machine-mounted sampling) if equivalent quality control measures are used.

Moreover, this large sampling error is deduced only after "outliers" have been trimmed from the data. These outliers can be detected only by comparison with the other groups of samples. In the study of personal sampling (Budenaers et al., 1977), 7.4 percent of the respirable dust samples were questionable when compared to the other samples in their group.

E. INDEPENDENT ACCURACY ASSESSMENTS

The precision assessments made so far are based largely on studies done by scientific professionals. Whether these precision estimates also apply to "dust measurements ... taken with current equipment by coal miners in underground mines" (GAO, 1975) is therefore an important question for the Federal dust sampling program.

To answer this question definitively, replicate samples would have to be taken as part of the routine dust sampling done in coal mines. Since this kind of replicate sampling has not been done outside of the research studies, we instead examine three studies which compare routine mine operator sampling with independent samples taken by Federal inspectors (Tomb, 1974; MSHA, 1972-80) and by NIOSH (Burkhart et al., 1984).

In the first study, Tomb (1974) compares compliance decisions made on underground coal mine sections on the basis of Federal inspector and mine operator sampling (Table 16). From this data, Tomb concluded that the compliance decisions from the operator sampling "are in agreement with decisions based on coal mine health inspection measurements (approximately 10 percent difference)."

The percent agreement of all sections in Table 16 does range from 85-92 percent, as Tomb notes. The hypothesis that the two sets of compliance decisions are equal can be tested statistically by the Kappa test (Fleiss, 1973). Only for the 29 mine survey from 7/72 - 9/72 can that hypothesis be accepted with probability of error less than 5 percent (Table 16). In the other two cases, the agreement hypothesis has a probability of error larger than 5 percent, due to the sections where the inspector and operator sampling lead to different decisions.

In addition, we can calculate the agreement percentage for the sections in the same compliance status (in or out of Compliance, according to the inspector samples). Taking the example of sections found in compliance, the agreement percentage by status is given by:

$$\text{Agreement}_{In} = 100\% \times \frac{\text{Sections found in by operator and inspector}}{\text{All sections in compliance by the inspector}} \qquad (29)$$

The percentages by status (Table 16) show that the greatest disagreement comes over the sections which the Federal inspectors decide are out of compliance. Such a result is a bias, and would not probably be caused by the random experimental errors in weighing or sampling.

The comparison of compliance decisions has severe disadvantages in assessing the state of statistical control because the results are strongly affected by the different sampling strategies and compliance criteria applied to the operator and inspector sampling. An alternative method for comparing these two sets of data are the aggregate averages which MSHA and its predecessor agencies compiled from the dust sampling results (MSHA, 1972-80). Historically, these statistics have been watched by MSHA for any indication of extreme discrepancies in sampling results.

TABLE 16

Comparison of Compliance Decisions
in Underground Coal Mine Sections
(Operator vs. Inspector Dust Sampling)

SOURCE: Tomb (1974)

Sample Type and Compliance Decision	7/72 - 9/72, (Std. = 3.0 mg/cu.m.)				12/73 - 2/74 (Std. = 2.0 mg/cu.m.)	
	All Mines		29 Mine Survey		29 Mine Survey	
Inspector Sampling:	In	Out	In	Out	In	Out
Operator Sampling:						
Sections in Compliance	699	83	41	3	33	4
Sections Out of Compliance	15	12	1	4	2	1
Agreement (%):						
By Status	98%	13%	98%	57%	94%	20%
Total	88%		92%		85%	
Probability of error in agreement hypothesis	Pr<20%		Pr<1%		Pr<33%	

TABLE 17

Average Dust Concentration--mg/m^3
(and Number of Samples)
from Inspectors and Mine Operators

Year	Continuous Miner Operator		All Occupations	
	Operator	Inspector	Operator	Inspector
CY 1972	2.1 (39,185)	1.8 (2566)	1.6 (187,618)	1.5 (25,556)
CY 1973	1.6 (94,097)	2.1 (1503)	1.2 (346,538)	1.9 (9,347)
CY 1974	1.6 (85,476)	2.0 (1748)	1.2 (317,872)	1.8 (10,457)
CY 1975	1.6 (103,916)	1.6 (1630)	1.2 (384,905)	1.5 (9,939)
CY 1976	1.6 (108,853)	1.4 (1823)	1.3 (395,432)	1.2 (14,245)
CY 1977	1.4 (80,933)	1.3 (1348)	1.0 (301,483)	1.1 (11,357)
FY 1978	1.4 (74,319)	1.3 (1213)	1.1 (274,740)	1.2 (12,557)
FY 1979	1.3 (104,171)	1.3 (2347)	1.1 (387,809)	1.2 (20,223)
FY 1980	1.3 (89,730)	1.3 (2513)	1.0 (320,427)	1.2 (21,436)

SOURCE: Mine Safety and Health Administration (1972-80)

Table 17 shows the average dust concentrations from operator and inspector sampling for both the continuous miner operator (by far, the most-sampled occupation) and all occupations. Between the two types of sampling, the averages for the years before 1975 differ by as much as 0.7 mg/m^3 (58%), but after that year, the averages converge to within 0.1 mg/m^3. The major difference between the two time periods is found in the inspector's sampling strategy. Before 1975, the Federal inspectors took many half-shift samples for screening, and only took full-shift samples (the ones compiled in Table 17) when the half-shift sample showed non-compliance. After 1975, the screening samples were eliminated. The agreement in the average concentrations is strong evidence that the sampling procedures for the operator and the inspectors are in agreement and have no large biases. The only weakness in this data is that an average over a very large number of samples might hide inaccurate samples taken in a small fraction of mines.

Burkhart, Wheeler, Hearl, Attfield, McCawley, Morring and Cocalis (1984) did conduct section-by-section comparisons of samples taken by NIOSH industrial hygienists with the operator samples taken during the months before and after the NIOSH measurements. At each mine, the NIOSH hygienists sampled two sections themselves, and gave the samplers from two other sections to the foremen "with no special sampling instructions. As far as (the foremen) knew, the samples could be for compliance .... This was done intentionally to investigate if the hygienists' presence biased dust concentrations by causing altered work practices."

The results in Table 18 show no difference between the NIOSH and operator samples which is significant at the 95 percent confidence level in a t-test (Burkhart, et al, 1984). The largest difference (Section L) is 1.75mg/m^3 (49 percent), but this is not significant because the standard deviation in the 19 samples from Section L is 1.71 mg/m^3. The results in Table 18 also show that neither NIOSH nor operator samples are consistently higher than the other. Finally, Burkhart, et al comment: "From these results it can be assumed that an observer on a mining section may not have an effect on work practices or dust levels."

Burkhart et al. can only make limited conclusions about the accuracy of the operator samples because their study design confounds environmental variability with measurement errors. In order to detect a measurement error at the 95 percent confidence level on Section L, for example, the difference between NIOSH and operator samples would have to reach 2.3 mg/m^3, far beyond the measurement errors seen in the research studies. This poor power to detect differences results from the limited number of samples in the NIOSH study and pooled standard deviations which range from 41-92% of the mean. This relative standard deviation, due mainly to environmental variability, makes it very difficult to detect measurement errors.

Taken together with the MSHA statistics, the NIOSH study does provide strong circumstantial evidence that the operator sampling results are generally repeatable and can be considered "a measurement process", as defined by Eisenhart (1963). However, quantitative evidence on the measurement precision in routine operator sampling and its exact state of statistical control is still lacking.

TABLE 18

Comparison Between NIOSH and
Mine Operator Samples

SOURCE: Burkhart, Wheeler, Hearl, Attfield,
McCawley, Morring and Cocalis (1984)

Mine Section	Average Concnetration - mg/cu.m. (and number of samples) NIOSH	Operator*	t - value**
A	0.55 (4)	0.71 (19)	1.03
B	0.91 (5)	1.09 (20)	0.82
C	0.51 (5)	0.53 (19)	0.16
D	0.75 (5)	1.15 (10)	0.93
E	1.41 (5)	1.08 (19)	0.62
F	0.58 (5)	1.15 (15)	1.74
G	2.64 (5)	1.52 (15)	1.90
H	0.85 (3)	1.49 (15)	1.61
I	1.07 (5)	1.04 (19)	0.08
J	2.59 (4)	1.73 (18)	1.29
K	1.36 (4)	1.96 (10)	0.79
L	3.60 (3)	1.85 (16)	1.63
M	0.40 (5)	0.59 (19)	0.47
N	1.19 (4)	1.44 (18)	0.30
O	1.80 (5)	2.35 (15)	0.76
P	1.26 (4)	0.82 (18)	0.91
Q	2.63 (4)	2.05 (20)	1.68
R	0.54 (3)	1.03 (20)	0.75

* Average value of two sampling periods before and
two periods after NIOSH survey.

** For Pr = 0.05, t = 2.07 - 2.11, depending on number
of samples.

IV. CONCLUSIONS

The precision of sampling for respirable coal mine dust has been assessed as far as the available data allow. In this review of the data, the evidence on the state of statistical control for coal mine dust sampling taken routinely under Federal procedures is incomplete. The filter weighing and pump calibration have been routinely checked for accuracy and are in control. For the complete dust measurement, however, there is only circumstantial evidence that the routine operator samples agree with the results of samples taken independently. Even under conditions more controlled than those found in the routine sampling, a portion of dust samples (about 10 percent) are out-of-control. In routine samples of coal mine dust, such out-of-control samples cannot be easily detected.

If we assume, however, that the routine samples are in the same state of control as the research studies, then the precision of dust sampling in coal mines can be estimated for determining compliance with the 2.0 mg/m^3 standard (Table 19). The pooled coefficient of variation is 22.7 percent for replicate samples taken by the Dust Division under Federal sampling procedures. Considering all the other available precision data, the expected CV lies in the range of 20 ± 4 percent for single samples taken under Federal procedures by trained personnel.

The estimated CV_t in Table 19 is substantially different than the previous precision estimates. The NBS (1975) estimate of 31.6 percent is inflated by repeatedly counting the weighing and pump flow errors, as outlined in Section IIA. In addition, NBS estimates the random errors from "performance in the mine environment" as 30 percent, much larger than what we find from the same replicate sampling data. The NBS report does not give details of their estimation procedures, so we can only speculate that the different estimates are due to different statistical methods such as the elimination of faulty samples and outliers in the present study. On the other hand, the estimates in both Corn (1975) and Frizell (1976) are 10-15 percent because they rely primarily on laboratory studies of sampling precision, and thus miss the sampling errors which are present in field studies.

One source of random errors is the filter weighing. Although these fluctuations are controlled by MSHA's Dust Laboratory at a level acceptable for deciding compliance with the 2.0 mg/m^3 dust standard, the weighing errors are a significant concern in measurements of dust concentrations lower than 1 mg/m^3. The presence of free silica at a level of 5 percent or greater causes the respirable dust stnadard to be lowered below 2 mg/m^3. In this case of a lowered dust standard, the applicable weighing error should be calculated from eq. (26).

Another source of random errors is the pump. Analysis of the pump flow fluctuations show that they cancel out for many dust size distributions typical of coal mines. Even where this cancellation does not occur, laboratory studies of the sampling pumps suggest that they contribute less than 3 percent to overall random errors.

TABLE 19

Summary of random errors estimated for an 8-hour sample of coal mine dust at 2.0 mg/m^3 taken according to Federal procedures.

ERROR SOURCE	COEFFICIENTS OF VARIATION
Weighing Errors (Section III B)	5.8%
Pump Flow Errors (Section III C)	2.3% (MSA Model G) 2.6% (BDX - 30)
Sampling Errors (Section III D)	21.8%
Total Observed Variability (Section III A)	22.7%

In Table 19, the record on random errors due to filter weighing (5.8%) and pump flow rate errors (less than 3%) does not explain the magnitude of CV_t. Furthermore, the environmental conditions such as particle charge and sampler vibration do not appear to contribute enough random errors to explain the coefficient of variation. Since studies conducted by Bituminous Coal Research Corp. under more controlled conditions do not have such large imprecision, the bulk of the "sampling errors" is assumed to be due to a lack of uniformity in the sampling procedures.

In summary, the data existing on the precision of coal mine dust sampling under Federal procedures do provide a partial answer to GAO's 1975 recommendation "to determine quantitatively the accuracy and reliability of dust measurements when taken with the current equipment by coal miners in underground mines." On one hand, evidence does exist on the state of statistical control for the dust samples taken routinely in coal mines by MSHA inspectors and mine personnel. However, the lack of replicate measurements during the routine sampling in coal mines makes the precision impossible to estimate from existing data.

On the other hand, the precision can be estimated from dust samples taken by scientific professionals using procedures similar to those used by MSHA inspectors and mine personnel. From these studies, the Federal dust sampling procedures potentially have a precision in the range of 20 ± 4 percent for a single sample taken at the compliance level.

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