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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cfm	cubic foot per minute	m	meter
ft	foot	m^2	square meter
fpm	foot per minute	min	minute
ft^2	square foot	pct	percent
in	inch	yd	yard

MEASUREMENT OF AIR VELOCITY IN MINES

By Edward D. Thimons [1] and Jeffrey L. Kohler [2]

ABSTRACT

This Bureau of Mines investigation addressed two primary issues of air velocity measurement in mines: the determination and use of correction factors, and the development of guidelines for the selection of a suitable site at which the measurements should be taken. Other facets of the investigation included a comparison of measurement methods and devices, and aircourse cross-sectional area measurement.

The study consisted of theoretical, laboratory, and in-mine investigations. The measurement devices included in the experimental phase were vane anemometer, vortex shedding anemometer, a prototype thermoanemometer, smoke tube, and oil of wintergreen sprayer. The measurement methods included single-point centerline, timed-point traverse, continuous traverse for the anemometers, and various distances and cloud positions for the smoke tube and oil of wintergreen devices.

The study resulted in guidelines for measurement site selection that are applicable to most in-mine situations. It also showed that the use of correction factors is problematic. There are many potential pitfalls and there are cogent arguments against using certain correction factors. However, generalized correction factors were developed that can be successfully applied in routine ventilation work, provided that their use is properly understood.

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INTRODUCTION

The proper control and distribution of ventilation air is a key aspect in the productivity of an underground mining operation, and is crucial to the health and safety of mine workers. Accurate methods of determining the air volume flow rates are necessary to properly control and distribute the air. Today, these determinations are commonly achieved by using a vane anemometer or smoke tube, in conjunction with an area measurement. The air speed measurements require careful site selection and application of correction factors to account for such variables as flow profile. Area measurements require a careful selection of a method to insure that the area of an irregularly shaped airway is accurately determined, although a single horizontal and vertical tape measurement is typically used to determine the area.

A variety of anemometer and smoke measurement techniques are in common practice. These include single-point centerline and traverse measurements, among others, for vane anemometers; leading edge and center-of-cloud methods are used with smoke tubes. The duration of the measurement interval is variable.

Despite substantial work by numerous investigators to address issues such as site selection, measurement methodology, and correction factors, there are no universally accepted practices, or even agreement about procedures and correction factors among practicing engineers. Agricola, in his 1556 text *De Re Metallica*, describes the "design" of mine ventilation systems by the earliest "mining engineers." Since that time, mine ventilation has developed as both an art and a science. A review of measurement practices quickly reveals that flow determination is more of an art than a science.

BACKGROUND

Air velocity measurements are taken in mines to satisfy statutory requirements and to support mine planning activities. In a coal mine, for instance, these measurements are taken throughout the mine at intervals that range from minutes to weeks between measurements based on 30 CFR (Code of Federal Regulations) requirements. Sometimes the measurements are taken to determine only the air velocity, but in most cases it is the average volume-flowrate that is of interest. This parameter is defined as the product of the air velocity and the cross-sectional area of the airway where the velocity measurement was made.

Calculation of this parameter may involve the use of as many as three correction factors. The first is an instrument correction factor. The instrument reading is multiplied by this factor, which is related to a calibration curve supplied by the manufacturer of the instrument. This type of correction factor was not of concern in this study, but it should be noted that it is essential to recalibrate measurement devices periodically and to properly apply this instrument correction factor. The second correction factor is a location factor which is used to multiply the corrected instrument reading, to account for erroneously low or high readings that are obtained when the measurement is taken at certain undesirable locations, such as near obstructions and intersections. As will be discussed later, this factor should not be used. Rather, appropriate sites should be chosen according to the guidelines presented in this report.

The third correction factor, and the one of interest here, is commonly known only as "correction factor." The measured velocity represents the velocity at one point, or sometimes several points. It is not the *average* velocity required to compute *average* volume-flowrate. The purpose of this correction factor is to convert a point value to an average value. Determination of this correction factor was the major thrust of this study.

As a first step in this study, a detailed literature review was conducted to locate any information concerned with velocity measurement in mines. A detailed summary of this search is contained in the appendix.

EXPERIMENTAL METHODOLOGY

This section summarizes the in-mine experiment design and methodology used in this study to determine appropriate velocity measurement correction factors and to develop guidelines for selecting suitable velocity measurement sites in mines.

Three mines, two metal-nonmetal and one coal, were selected for detailed in-mine experimentation. Additionally a fourth mine was selected for collection of certain data elements needed to define appropriate sample sizes for the work at the other three mines. Data collected by Thimons (31)[3] at a fifth mine were also used to aid in the determination of sample sizes. Some characteristics of these mines are shown in table 1.

The two most important considerations in the experiment design were (1) the establishment of adequate controls so that true volume flow rate could be computed, thereby allowing comparisons based on accuracy rather than just precision; (2) the selection of sufficient sample sizes to facilitate statistical validation and analysis of the results.

TABLE 1. - Characteristics of mines included in this investigation

Mine	Type	Airway cross section area, ft^2	Volume flow rates, cfm
1...	Coal, room and pillar.	66	4,000 12,000 14,000
2...	Limestone, block caving.	180	6,000
3...	Salt, open stope with pillars.	205	10,000 20,000 28,000 135,000
4...	Coal, room and pillar.	110	22,000
5...	Limestone, open stope with pillars.	NA	NA

NA Not available.

NOTE.--Mines 4 and 5 were only used to collect data required for experiment design aspects of the investigation. Data from mines 1, 2, and 3 comprise the data base for this study's analysis and recommendations.

AIR VELOCITY SAMPLE SIZE

If an air velocity reading (sample) is taken with any one of the device method combinations included in this study and shown in table 2, the reading cannot be confidently taken as the true value, due to uncertainties that surround the experiment. For example, the flow variations that can occur in a mine ventilation system over a few hours can introduce significant errors into the experience.[4] However, as the number of readings or samples is increased, the average value of the readings will tend towards the true value.[5] Unfortunately, the practical consideration of time severely limits the number of samples that can be taken. Thus, increasing the size of a sample, and consequently decreasing the sampling error, must be weighed against the probable increase in error due to

[3]Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

[4]Any changes in the flow would be recorded at the control station; these changes would, in themselves, not be a source of error. However, secondary effects of flow changes, e.g., isovel, (flow pattern) shifts, etc., could bias the experiment.

[5]The data collected in mines 4 and 5 were found to be normally distributed. The normality of the data was also verified for the data subsequently collected at mines 1, 2, and 3.

actual flow changes during the course of the experiment.

This problem was approached by defining an acceptable level of statistical sampling error, and then determining the required level of accuracy, as characterized by a confidence interval. A number of analytical methods for computing sample sizes were examined. A simple and well-known axiom of normal distributions was found to best approximate the required sample size. The bound on the error of estimation, B, is given by $B = 2s/\sqrt{n}$,

TABLE 2. - Measurement methods included in this study

	Identification[1]
VANE ANEMOMETER	
Centerline:	
Handheld	1
Stickheld	2
Remote operator	3
Continuous traverse:	
Handheld	4
Stickheld	5
Split traverse:	
Handheld	6
Stickheld	7
Timed-point traverse:	
Handheld	10
Stickheld	11
VORTEX SHEDDING ANEMOMETER	
Centerline: Handheld	21
Split traverse: Handheld	22
Continuous traverse: 2 min	27
Timed-point traverse: Handheld	28
THERMOANEMOMETER	
Centerline:	
Handheld	31
Remote operator	32
SMOKE TUBE	
Centerline:	
Leading edge, 10 ft	41
Leading edge, 20 ft	42
Leading edge, 30 ft	43
Cloud center, 20 ft	44
OIL OF WINTERGREEN	
50 ft	50
100 ft	51
200 ft	52

[1]Method identification numbers used in the summary tables of this report.

where s is equal to the sample standard deviation and n is the number of repeat trials. B was chosen to be less than 2 pct. Given this and the standard deviation, the required sample size can be computed. Since the standard deviation is unknown, a priori; it was necessary to establish a range of probable values of s, before a value of n could be determined.

This range of values was established by collecting data at mine 4, and applying a subset of the measurement methods shown in table 2. In all cases, a large sample, greater than 60 repeat trials, was collected. The standard deviation of various random subsets of the data was computed and the behavior of the standard deviation as the consistency of the subsets changed was observed. Data from a study by Thimons (31) were examined in a similar fashion (mine 5). The results of the mine 4 data were compared to those for Thimons' data (mine 5) and found to be almost identical. Given the differences under which these two different sets of data were collected, this result allowed a range for the standard deviation to be selected, with some assurance that it would not differ radically among different mines.

The results indicated that each measurement method experiment should be repeated at least 25 to 30 times, in experiments involving the vane anemometer, thermogauge, and the air draft sensor. Experiments involving oil of wintergreen or smoke tubes would require a substantially greater number of repeat trials to attain a sampling accuracy of 98 to 99 pct. Additional analysis indicated that the bound on the error of estimation could be held to less than 5 pct, if 25 to 30 repeat trials were performed. Given the nature of these last two devices, this level of sampling accuracy was deemed acceptable. Consequently, the decision was made to repeat each measurement experiment a minimum of 30 times for each velocity range at each mine.

It should be noted that the sample size necessary to achieve a desired level of sampling accuracy is not the same as the absolute accuracy of the data, which must also account for the accuracy of the control station instruments.

EXPERIMENTAL APPARATUS

The control station was established in each mine so that the true volume flow rate could be determined. An airtight stopping was constructed across the aircourse where the experimentation occurred (fig. 1). A pitot-tube array assembly was an integral part of the control stopping. During an experiment, readings from the pitot-tube array, barometer, and wet and dry bulb thermometers were recorded frequently. This information allows an accurate calculation of the true volume flow rate. The analytical procedures for treating the data are described in the "Data Analysis" section, while the balance of this section deals with the equipment.

The two pitot-tube arrays had a guaranteed accuracy to within 1.0 pct. The larger diameter (54 in) unit was designed for the higher flow rates, the smaller one (24 in) was designed for lower flow rates. An integral part of these arrays was an hexal air straightener.

The total and static pressure heads in the array were measured, using a manometer connected to the array in the standard manner, which allowed direct reading of the velocity head. A commercially available manometer was selected for its mine-worthiness and accuracy to within 1.0 pct.

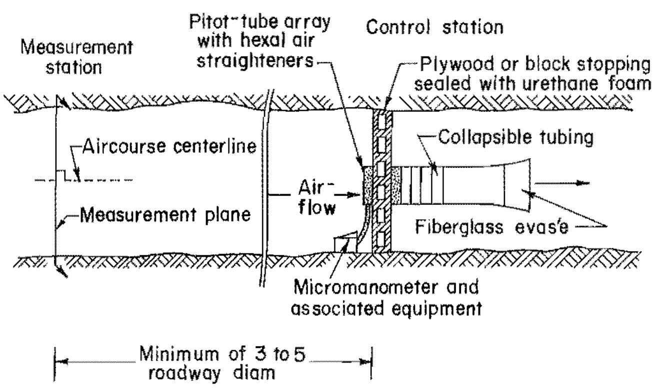

FIGURE 1. - Diagram of the control station arrangement for in-mine experiments.

An engineer's barometer and a sling psychrometer were used to collect data necessary for computation of the air density. The former was accurate to within 5 pct and the latter to within 1.0 pct.

The air velocity measurement devices used in this study included the following:

- o Ball-bearing low-speed vane anemometers, with NBS calibration curves.
- o Hand-held vortex shedding anemometers (air draft sensor).[6]
- o Heat transfer anemometer, with manufacturer calibration curves.

Smoke tubes and oil of wintergreen (methyl salicylate) were also utilized in air velocity measurement methods. Two types of smoke tubes were utilized for comparability of results. Reagent-grade methyl salicylate was used with an aerosol propellant for the oil of wintergreen method.

The accurate determination of the cross-sectional area of the aircourse at the measurement station was a key factor. The area of the pitot-tube array at the control station was easily measured. A photographic method was selected to determine the area of the mine opening at the measurement station.

Two different methods were used to mark the perimeter of the aircourse at the measurement station. The first suite of

[6]The vortex shedding anemometer works on the following concept. When a fluid flows past an obstruction or strut, turbulence is created. Above a minimum velocity this turbulence assumes a regular pattern of vortexes. These vortexes separate or shed from the strut and travel downstream in a fixed predictable pattern. The number of vortexes shed downstream of the strut per unit time is proportional to fluid flow rate. This vortex frequency is detected using an ultrasonic beam that is transmitted through the vortex pattern downstream of the passing vortexes. This modulated signal is then processed through simple signal conditioning electronics, resulting in a pulse output signal at a frequency directly proportional to the fluid flowrate.

equipment for this purpose consisted of a laser and an equatorial telescope mount with a right-angle prism, both designed for mounting on heavy-duty tripods. The laser was beamed in such a way as to establish an airway center line.[7] The right-angle prism was then held in the laser beam and rotated 360° with the equatorial mount which, in turn, scribed a plane on the roof, ribs, and floor of the mine with the refracted beam. This plane was exactly perpendicular to the air flow. A photograph of this plane was taken and subsequently planimetered for a precise area determination. Reflective tape, fastened around the plane's perimeter, increased the visibility of the cross section in the photograph, and a calibration plate of known size provided a reference area.

After the start of this project, an alternative method of marking the perimeter was utilized--a photoprofile apparatus. Essentially, this device is a projector that casts a plane of light that may be photographed, yielding a white line around the perimeter against a black background. It is powered by a standard miner's cap lamp battery and provides a 1.000 m^2 reference in the photograph area. Horizontal and vertical alignment is made by eye rather than by gravity or any other auxiliary method. However, geometrical analysis has shown that for small angles, the resultant error in apparent area is negligible. This method was used successfully at two mines.

EXPERIMENTAL PROCEDURES

Aircourses selected, and the specific locations therein, for execution of the experiments had the following characteristics:

- o Free of obstructions.
- o All crosscuts and draw points were sealed.
- o Free of bends within 10 roadway diameters upstream and 10 roadway diameters downstream of measurement and control stations.
- o Airways were not exceptionally smooth or lined.
- o Removed from production and related activities that could cause unpredictable fluctuations in the airflow.

The control station was always located five roadway diameters downstream of the measurement station to eliminate the cushioning and funneling effects of the control stopping on the measurement station. During a preliminary trip to each mine, the candidate sites were monitored over a full shift to detect any changes in flow that occurred as a result of mining activity. Smoke tubes were also utilized to detect any leakage or abnormal flow patterns that could introduce error into the experiments.

The control station configuration is shown in figure 1. The control stopping was a wooden frame covered by plywood and completely sealed with urethane foam. A circular opening was cut in the plywood sheets, before their attachment to the wooden frame, to accept the pitot-tube array. The array was then mounted in the opening. The perimeter interface between the control stopping and the array was sealed with foam. A 20-ft length of collapsible tubing was attached to the array, on the exit side, using band clamps. The stopping was checked for leakage every shift and the hexal straighteners of the array were checked for excessive dust accumulation periodically. Since the stations were always located in intake aircourses, dust problems were minimal.

The control station apparatus, described previously, was located near the control stopping and was used to record the parameters required in the true volume calculations. These data were recorded by an observer every 5 to 10 min.

All velocity experiments were conducted by three engineers with substantial experience in the use of devices prior to the actual field program. All repeat trials of an experiment were performed by the same operator to eliminate variability.

The following general comments apply to all experiments at all mines:

[7] Two geometric centroids are located in an airway 50 to 100 ft apart; connecting these points with the laser beam locates the centerline.

o The operator always stood in the measurement plane with the measurement device extended at arm's length.

o All single-point measurements were taken at the geometric center of the airway.

o All traverse method measurements were taken through the same path; traverse speeds were limited to a maximum of 30 fpm.

A set of data collection forms were developed for use in all experiments to insure a complete record of the experiment, and to facilitate encoding of the data for computer analysis.

DATA ANALYSIS

An analytical program was developed to provide summaries of the collected data which utilized statistical measures, and to address the major issues of this study.

One unique aspect of this investigation was the establishment of a control station where the volume flow rate could be accurately determined and used as a basis for comparison against all other measurements. The true volume flow rate at the control station is

$$V_{true}(t) = v_{true}(t)\,A_p, \qquad (1)$$

where $v_{true}(t) = 1{,}098\,\frac{H_v(t)}{W(t)}$

= true air velocity,

$H_v(t)$ = velocity head across the pitot tube array,

$W(t)$ = air density,

A_p = cross-sectional area of the pitot tube array,

and t = time of each measurement.

All variables were recorded and analyzed as a function of time, but for simplicity the time dependency is not shown in the balance of the equations.

The measured volume flow rate using the vane anemometer is given by

$$V_{meas} = v_{meas}A, \qquad (2)$$

where v_{meas} = measured air velocity

$= \frac{DR}{\Delta t} \times f_I$,

DR = device reading (anemometer),

Δt = elapsed time during reading,

f_I = instrument calibration factor,

and A = cross-sectional area of the mine opening where the reading was taken.

For each point in time corresponding to a device reading, a correlation factor is computed as

$$cf = \frac{V_{true}}{V_{meas}}. \qquad (3)$$

Thirty measurements (samples) were taken for each measurement method, e.g., single-point centerline or continuous traverse. Using equation 3, 30 correction factors were calculated, and then the statistics were computed. Since the data are normally distributed, the mean, $\bar{X}$, and standard deviation are defined as

$$\bar{X} = \frac{1}{N}\sum_{i=1}^{N} cf_i, \qquad (4)$$

$$S = \frac{1}{N-1}\sum_{i=1}^{N}[(cf_i - \bar{X})^2], \qquad (5)$$

where N = number of samples (equal to 30 for this study),

cf_i = 1 of the 30 correction factors calculated from equation 3,

and $\bar{X}$ = mean correction factor.

The evaluation of equation 2, specifically the measured velocity, depends upon the device used. As shown, equation 2 is appropriate for single point or continuous traverses. If the measurement method is a fixed point traverse, then the measured velocity is computed as

$$v_{meas} = \frac{1}{G} f_i \sum_{g=1}^{G} \frac{DR_g}{\Delta t_g}, \tag{6}$$

where G = the number of fixed points in the grid,

f_i = instrument calibration factor,

DR = device reading for the gth grid point,

and Δt_g = time elapsed during reading for the gth point.

Devices that have a scale reading directly in feet per minute, such as the air draft sensor, are operated on in equation 2 by modifying the reading to

$$v_{meas} = DR \times f_i. \tag{7}$$

Finally, smoke tubes and oil of wintergreen methods are treated in equation 2 as

$$v_{meas} = X/\Delta t, \tag{8}$$

where X = distance traveled by cloud

and Δt = travel time of cloud.

The aforementioned equations allow the correction factors to be computed. The appropriate application of the computed correction factors requires consideration of other things, one of which is accuracy. Essentially the accuracy of the correction factors determined has two components. The first is the accuracy of the velocity measurement using the devices included in the study. Statistically it has been determined that most readings had a sampling accuracy of better than 2 pct. The second component deals with the accuracy of the control station value, i.e., the true volume. The elements of the control station such as the pitot tube array, the manometer and so forth were not calibrated and certified against secondary standards. Consequently, their absolute accuracy is unknown, except that it is believed to lie within the accuracy stated by the manufacturer. Most of the equipment at the control station had stated accuracies of ±1 pct. The worst case accuracy for the true volume computation would occur if the inaccuracy of each device added or subtracted together. In this situation the computed true volume flow rate would approach ±5 pct of the calculated value. This is not likely. Usually some errors add, while others subtract, thereby yielding a better overall accuracy than predicted by the worst case.

Correction factor summaries for the data in this study are given in tables 3, 4, and 5. The accuracy shown is the sampling accuracy. In a worst case an additional ±5 pct error would have to be considered, although the absolute accuracy of the control station was probably closer to 2 pct. The appropriate use of correction factors goes beyond a mathematical statement of accuracy and is discussed in the following section.

RECOMMENDATIONS FOR MEASUREMENT OF AIR VELOCITY

The practical measurement of air velocity is based on the need to define airflows in the mine. Statutory requirements and the needs of the mine's ventilation engineers normally dictate general locations for and the frequency of measurements. The person making the measurement is often faced with one or more of the following issues:

- What influence will the measurement observer have on the final reading?

o The measurement must be taken at an adverse location, such as a bend or intersection; what factor can be used to correct the reading?

o Would a different instrument or measurement method improve the accuracy of the reading?

o What correction factor should be applied to determine the average volume flow rate?

OPERATOR INFLUENCE

The person taking the measurement can dramatically impact the quality of the measurement depending upon his/her proximity to the instrument, as well as his/her technique. In general, stickheld or remote placement of the measurement device will yield better results than when the device is handheld. The best results

TABLE 3. - Summary of correction factors (cf's) for mine 1, true velocity at 62, 187, and 340 fpm

Method	62 fpm			187 fpm			340 fpm		
	cf	Accuracy,[1] pct	Range	cf	Accuracy,[1] pct	Range	cf	Accuracy,[1] pct	Range
1.........	0.76	±6	0.71-0.81	0.72	±6	0.68-0.76	0.68	±6	0.64-0.72
2.........	.73	±6	.69- .78	.78	±6	.74- .83	.76	±7	.71- .81
3.........	.78	±6	.73- .83	.83	±6	.78- .87	.79	±5	.75- .84
4.........	.78	±7	.73- .84	.83	±6	.79- .88	.78	±6	.74- .83
5.........	.81	±6	.76- .86	.94	±6	.88- .99	.89	±6	.84- .94
6.........	.74	±6	.70- .79	.82	±6	.77- .87	.77	±6	.73- .82
7.........	.84	±6	.79- .89	.95	±6	.89-1.01	.88	±6	.82- .93
10........	.79	±6	.74- .84	.88	±6	.82- .93	.84	±6	.78- .89
11........	.87	±6	.81- .93	.95	±6	.90-1.01	.90	±6	.84- .95
21........	.88	±17	.73-1.03	.91	±7	.85- .97	.61	±6	.58- .65
22........	NAp	NAp	NAp	NAp	NAp	NAp	.77	±6	.72- .82
27........	.64	±11	.57- .71	.82	±6	.77- .87	.73	±8	.67- .79
28........	.85	±7	.79- .91	.91	±6	.86- .97	NAp	NAp	NAp
31........	.73	±12	.65- .82	.96	±10	.87-1.06	NAp	NAp	NAp
32........	.74	±10	.66- .81	.94	±9	.86-1.03	NAp	NAp	NAp
41........	.60	±8	.56- .65	.67	±10	.60- .73	.69	±12	.61- .77
42........	.63	±7	.59- .68	.72	±8	.66- .77	.72	±8	.66- .78
43........	.65	±7	.60- .69	.71	±7	.66- .75	.72	±8	.66- .78
44........	.70	±8	.65- .76	.80	±9	.73- .86	.74	±9	.68- .81
50........	.78	±9	.71- .84	NAp	NAp	NAp	NAp	NAp	NAp
51........	NAp	NAp	NAp	.90	±9	.83- .98	.91	±7	.84- .97

NAp Not applicable, no readings taken.
[1]99-pct confidence level.

TABLE 4. - Summary of correction factors (cf's) for mine 2, true velocity at 35 fpm

Method	cf	Accuracy,[1] pct	Range	Method	cf	Accuracy,[1] pct	Range
1...........	0.74	±12	0.65-0.83	31..........	0.74	±19	0.60-0.88
2...........	.70	±10	.63- .77	32..........	.92	±17	.76-1.07
3...........	.81	±12	.71- .91	41..........	.50	±14	.43- .57
5...........	.56	±7	.52- .60	42..........	.49	±9	.45- .54
7...........	.54	±10	.48- .59	43..........	.46	±11	.41- .52
11..........	.51	±8	.47- .56	44..........	.66	±14	.57- .75
21..........	1.77	±22	1.38-2.16				

[1]99-pct confidence level.

TABLE 5. - Summary of correction factors (cf's) for mine 3, true velocity at 52, 93, 135, and 650 fpm

Method	52 fpm			93 fpm[2]			93 fpm[3]		
	cf	Accuracy,[1] pct	Range	cf	Accuracy,[1] pct	Range	cf	Accuracy,[1] pct	Range
1.........	0.92	±9	0.84-1.00	0.87	±7	0.81-0.93	0.82	±7	0.76-0.88
2.........	.89	±9	.81- .97	.92	±7	.86- .98	.93	±7	.87-1.00
3.........	.94	±8	.87-1.01	.96	±7	.90-1.03	NAp	NAp	NAp
4.........	.78	±8	.72- .85	.89	±7	.83- .95	.88	±7	.82- .93
5.........	.91	±6	.85- .97	.90	±7	.84- .96	.94	±7	.88-1.00
6.........	.91	±8	.84- .98	.87	±6	.81- .92	.91	±7	.85- .90
7.........	.92	±7	.86- .99	.89	±6	.84- .95	.97	±7	.91-1.03
10........	.70	±8	.65- .76	.86	±7	.80- .92	.83	±7	.78- .88
11........	.88	±7	.81- .94	.89	±7	.83- .95	.92	±7	.85- .98
21........	1.16	±15	.98-1.33	.84	±7	.78- .90	.90	±9	.82- .99
27........	.48	±8	.44- .52	.84	±7	.78- .90	.80	±7	.74- .85
28........	1.02	±8	.94-1.09	1.04	±7	.96-1.11	1.01	±7	.94-1.08
31........	.98	±10	.81-1.15	.85	±9	.78- .93	NAp	Nap	Nap
32........	1.07	±17	.88-1.25	.92	±14	.79-1.05	NAp	NAp	NAp
41........	.85	±12	.75- .95	.79	±10	.72- .87	NAp	NAp	NAp
42........	.84	±12	.75- .95	.82	±9	.75- .90	NAp	NAp	NAp
43........	.86	±10	.77- .95	.81	±8	.75- .87	NAp	NAp	NAp
44........	1.10	±12	.96-1.23	.89	±10	.88- .97	NAp	NAp	NAp
50........	.80	±11	.71- .89	NAp	NAp	NAp	.85	±10	.77- .94
51........	NAp	NAp	NAp	NAp	NAp	NAp	.82	±10	.73- .90
52........	NA	NA	NA	NA	NA	NA	NA	NA	NA

Method	135 fpm			650 fpm		
	cf	Accuracy,[1] pct	Range	cf	Accuracy,[1] pct	Range
1.........	0.85	±6	0.79-0.90	0.90	±6	0.85-0.95
2.........	.89	±7	.83- .95	1.06	±6	1.00-1.12
3.........	.92	±7	.85- .98	1.12	±6	1.06-1.19
4.........	.89	±6	.84- .94	1.07	±7	.99-1.15
5.........	.95	±6	.90-1.01	1.10	±7	1.03-1.10
6.........	.89	±6	.83- .94	.96	±6	.90-1.01
7.........	.97	±6	.91-1.03	1.13	±7	1.06-1.20
10........	.87	±6	.82- .93	.96	±6	.90-1.01
11........	.96	±6	.90-1.02	1.05	±6	.99-1.12
21........	.84	±7	.78- .90	.84	±7	.79- .90
27........	.89	±6	.84- .95	.89	±6	.84- .95
28........	.96	±6	.90-1.02	.91	±6	.85- .96
31........	.92	±10	.83-1.01	NAp	NAp	NAp
32........	1.01	±10	.91-1.12	NAp	NAp	NAp
41........	.81	±9	.74- .89	NAp	NAp	NAp
42........	.87	±9	.80- .95	NAp	NAp	NAp
43........	.86	±8	.79- .93	NAp	NAp	NAp
44........	.94	±11	.84-1.04	NAp	NAp	NAp
50........	.97	±10	.88-1.07	NAp	NAp	NAp
51........	.96	±8	.89-1.04	1.10	±8	1.02-1.10
52........	NAp	NAp	NAp	1.10	±7	1.02-1.10

NA Not available. NAp Not applicable, no readings taken.
[1]99-pct confidence level. [2]Field team observer 1. [3]Field team observer 2.

were achieved in this study by holding the device straight out to the side of the observer's body and just slightly upstream. All things being equal, the readings obtained by two different observers are likely to be different. In this study, two different observers made a series of measurements at the same site. The resulting data differed by 1 to 2 pct, even though the observers both used the same equipment and proper technique.

Certain conditions can increase the importance of the operator's influence. At lower velocities, proximity effects are accentuated and the operator's technique becomes more important. If the device has to be moved during the measurement, as in a traverse, precautions must be exercised to keep it perpendicular to the airflow. The proximity of the observer to the device should remain constant, although this is problematic in practice.

In general, if good technique is practiced the resulting error will be negligible when compared with other error sources.

LOCATION SELECTION

The location of an air velocity measurement within the mine is usually determined by a statutory or engineering requirement. Often, these locations are less than ideal in that the airflow is partially obstructed by a roof fall, equipment, or timber sets, or is altered by a nearby bend, intersection, and so forth. It would be convenient in these cases to have a correction factor that would correct for the error introduced by the obstruction. This correction factor would be used in addition to the correction factor that transforms the measured velocity to average velocity. It would also be desirable to establish criteria for site selection under these less than ideal conditions. For example, a helpful criterion would specify the minimum downstream distance at which a measurement can be made from an obstruction, which is blocking a certain percentage of the airflow, and yield a result which had an acceptable level of error.

As indicated earlier, the use of factors to correct readings taken at adverse locations has been heavily investigated, but there is so much disagreement among investigators that it is difficult to use the reported factors. Experiences during this study have led to the conclusion that such factors are useless for general application. They tend to be valid for only one specific situation in a given mine, and only at one specific velocity. Any attempt to generalize them is futile. The reason lies in the behavior of isovels (flow patterns) and the influence of these isovels on the measurement. This phenomenon is explored later.

Given that generalized factors cannot be employed to correct readings taken at adverse locations, the initial site selection becomes even more important. Based on the results of this investigation and the literature review, the following site selection guidelines are presented:

- Measurements made at locations near obstructions or changes in the aircourse will adversely affect measurement accuracy and should be avoided when at all possible.
- The downstream effects of obstructions or changes are much more pronounced than upstream effects. Consequently, measurements should be obtained on the upstream side of the obstruction or change.
- In the event that measurements must be made between two different obstructions or changes, and it is impossible to get the recommended distances upstream or downstream of either, optimum results will be obtained by selecting a measurement point between the two which is one-third of this distance upstream of the second obstruction and two-thirds of the distance downstream from the first obstruction as encountered in the normal direction of airflow.
- Measurements should always be made at a minimum distance of 3 roadway diameters upstream of an obstruction and 10 roadway diameters downstream of an obstruction. If any doubt exists, these distances should be increased.
- Smoke tubes are a useful tool for detecting unusual air patterns.

Measurements should not be made in locations where the smoke reveals large vortexes; maximum flow near the roof, ribs, or floor; or splitting of the air within the aircourse.

- o At less than ideal locations, measurement accuracy can be substantially improved by performing a timed-point traverse rather than a single-point measurement.
- o The construction of an artificial measurement station may be justified in locations where measurements are made frequently, but where the airway characteristics, such as timber sets may be a constant source of error.

MEASUREMENT METHODS AND DEVICES

Each measurement method and associated measurement device offer certain advantages and usually one or more disadvantages. The relative nature of these will, of course, depend on the individual requirements of those performing the measurements. Here the methods and devices are compared in terms of the following attributes:

- o Initial cost.
- o Calibration and maintenance.
- o General application.
- o Susceptibility to operator influence.
- o Accuracy.

The following devices are included:

- o Vane anemometer.
- o Smoke tubes.
- o Oil of wintergreen.
- o Thermogauge (prototype thermoanemometer).
- o Vortex shedding anemometer.

The following methods are included:

- o Single point centerline.
- o Continuous traverse.
- o Timed-point traverse.

In the case of vane anemometers, the method of support, i.e., handheld, stickheld, or remote, are also analyzed. For smoke type measurements, the influence of the cloud measurement point and the distance between operators are also examined.

The initial cost of the different measurement devices is not a major concern since all are less than $1,000 and costs do not vary by more than a few hundred dollars. The smoke tube and oil of wintergreen measurement devices are approximately two orders of magnitude cheaper initially.

Calibration and maintenance are not of concern with the smoke tube and the oil of wintergreen devices. The vane anemometer, however, is susceptible to damage of the vanes and should be frequently calibrated (at least after every 60 days of use). The vortex shedding anemometer has no moving parts and is not as susceptible to damage; calibration once every 6 months should suffice. The prototype thermoanemometer is also not susceptible to damage, but dust must be removed from the sensing tube before a measurement is performed.

The general application attributes include the following:

- o Ease of use.
- o Number of people required to perform a measurement.
- o The need for secondary calculations.

All of the devices included in this study are relatively easy to use and require little training time. The vortex shedding prototype anemometer and thermoanemometer both have digital readouts which make it slightly easier to obtain accurate readings.

Both the vortex shedding anemometer and thermoanemometer measurements can be accomplished by one person. A second person is required to perform timing measurements with the vane anemometer, if maximum accuracy is to be achieved. Both the smoke tube and oil of wintergreen devices demand two people.

The vortex shedding anemometer is the only device that does not require secondary calculations, as it is a direct reading device. The thermoanemometer and vane anemometer readings must be converted, using a calibration curve. Smoke tube and oil of wintergreen measurements require simple arithmetic calculations involving the travel distance and elapsed time. Certain devices lend themselves better to certain applications. The smoke and oil of wintergreen tests are particularly suited to low velocity flows (less than 50 fpm), for which a device such as the vane anemometer no longer provides accurate readings.[8] The convenience of direct reading combined with the durability of the vortex shedding device might make it more appealing to certain users, although the uncertainties surrounding its use in a turbulent atmosphere may subject the results to some question as to accuracy.

The evaluation attribute is the susceptibility of a particular measurement device and method to operator influence. To address this issue, the correction factors and raw data sets obtained from each of the measurement methods and devices were analyzed using one-way analysis of variance tests, where data sets existed with multiple observers. Although several duplicate data sets were collected where all conditions were identical with the exception of the observer, these duplicate tests were not performed over all velocity ranges, so no attempt was made to determine whether operator influences became more or less critical at different velocities.

The analysis of variance tests were conducted utilizing a 95-pct and a 99-pct confidence interval. It was found that the operator influence was significant in all tests involving handheld measurement devices. For example, for vane anemometer single-point centerline measurements conducted with the anemometer handheld, stickheld, and remote, in the handheld measurement, operator influence was significant, whereas in the other two it was not significant.

Similar results were obtained for all other measurements with the exception of the smoke tube and oil of wintergreen where operator influence was found to be negligible. This, in itself, is an important finding. However, it is not possible to determine the maximum error that might result because of operator technique since these techniques could be so highly variable. It should be noted in these experiments that the different operators were utilizing proper technique, and that the accuracy differences were less than 1 to 2 pct in all cases. However, statistical significance was established as previously described.

The final point of evaluation, accuracy, is based solely on the results of the experimental investigation and the computed correction factors. The statistical accuracy is used to compare the methods and devices.

Because of the device's operating characteristics, the maximum accuracy achievable with it will depend on the velocity range. Thus, the free stream velocity in which the ball-bearing vane anemometer is useful is limited by the friction of the ball-bearing drive mechanism. Similarly, certain sampling methods are limited by the free stream velocity. The continuous traverse utilizing a mechanical response device, such as the ball-bearing vane anemometer, will be subject to larger errors at lower velocities if the traverse speed of the device is not reduced proportionately. The accuracies found for the devices and methods included in this study are shown in table 6.

Analysis of the data obtained reveals some interesting results.

o The ball-bearing vane anemometer yields the most accurate results through the widest range of conditions.

o For specific velocity ranges, certain devices can be selected over others to yield increased accuracy of the measurement. For example, the vortex shedding anemometer and the vane anemometer should not be used in flows where the free stream velocity is less than 62 fpm; the smoke tube, however, yields measurements of acceptable accuracy in this range. The prototype thermoanemometer did not perform more accurately in these low-speed flows than any of the other devices, although it was specifically designed for use in low-speed flows.

o The oil of wintergreen method did not provide satisfactory results in flows less than 135 fpm because of its operational characteristic, i.e., the oil of wintergreen droplets precipitated out of the airstream causing increased errors.

[8]Oil of wintergreen should not be used to measure velocity in a belt entry because the odor travels with the belt, which may have a higher velocity than the airflow.

TABLE 6. - Comparative accuracy of different air velocity determination methods, percent

Average velocity.......................fpm..	35	52	62	93	135	187	340	650
VANE ANEMOMETER								
Centerline:								
Handheld.................................	±5	±4	±1	±2	±2	±1	±2	±1
Stickheld................................	±7	±3	±1	±2	±2	±1	±1	±1
Remote operator..........................	NAp	±3	±2	±2	±1	±1	±1	±2
Continuous traverse:								
Handheld.................................	±2	±1	±1	±2	±1	±1	±1	±2
Stickheld................................	NAp	±3	±1	±1	±1	±1	±1	±1
Split traverse:								
Handheld.................................	±5	±2	±1	±1	±1	±1	±1	±2
Stickheld................................	NAp	±3	±1	±2	±1	±1	±1	±1
Timed-point traverse:								
Handheld.................................	±3	±2	±1	±2	±1	±1	±1	±1
Stickheld................................	±17	±10	±12	±2	±2	±2	±1	±2
VORTEX SHEDDING ANEMOMETER								
Centerline: Handheld.......................	NAp	±3	±6	±2	±1	±1	±3	±1
Continuous traverse: 2 min.................	NAp	±3	±2	±2	±1	±1	NAp	±1
THERMOANEMOMETER								
Centerline:								
Handheld.................................	±14	±13	±7	±4	±5	±5	NAp	NAp
Remote operator..........................	±12	±12	±5	±9	±5	±4	NAp	NAp
SMOKE TUBE								
Centerline:								
Leading edge, 10 ft......................	±9	±7	±3	±5	±4	±5	±7	NAp
Leading edge, 20 ft......................	±4	±7	±2	±4	±4	±3	±3	NAp
Leading edge, 30 ft......................	±6	±5	±2	±3	±3	±2	±3	NAp
Cloud center, 20 ft......................	±9	±7	±4	±5	±6	±4	±4	NAp
OIL OF WINTERGREEN								
50 ft....................................	NAp	±6	±4	NAp	±5	NAp	NAp	±3
100 ft...................................	NAp	NAp	NAp	NAp	±3	±4	±2	NAp

NAp Not applicable, no readings taken.

It did, however, yield accurate measurements in the velocity range of 135 to 340 fpm.

o At velocities greater than 135 fpm, all devices performed at an acceptable level of accuracy.

CORRECTION FACTORS

The volume flow rate of air in an aircourse is the product of the average measured velocity and the cross-sectional area of the aircourse where the velocity was measured. If this cross-sectional area or measurement plane is representative of the aircourse and is not located near any obstructions or changes in the aircourse, then an accurate volume flow rate can be obtained, if the measured and average velocities are equal. However, most devices do not measure the average velocity. Rather, one or more points in the measurement plane are sampled, i.e., a velocity measurement is made, and then this point(s) is mathematically manipulated to obtain a number that is called the average velocity.

The justification for this mathematical transformation is an *a priori* knowledge of the isovel or flow pattern. In this sense, the velocity measurement method (centerline, single point, multipoint traverse with a linear grid, multipoint traverse with a log grid, etc.) can be viewed as a sampling scheme. It is well known from mathematical sampling theory that a few samples can be used to approximate the behavior or characteristics of the population of all values in the sample space, provided that sampling is performed in accord with theorems or practices that utilize an *a priori* knowledge of the population. In this case, the population is simply the set of all point velocities that define the airstream.

The published correction factors span a large range and are often so contradictory that it is difficult to apply them. The correction factors obtained in the course of this study often appear contradictory and also span a large range for similar methods and velocity ranges. Extensive parametric analyses were unable to develop any functional relationships between the following variables and the resulting correction factor:

- Velocity range.
- Measurement device characteristics.
- Rubbing surface characteristics.
- Cross-sectional area.
- Aircourse height-to-width ratio.
- Air density.

Factor analysis, which is often helpful when functional relationships cannot be developed on the variable, was conducted without success. A graphic analysis was somewhat helpful in defining the problem.

Data for the construction of isovels were collected at each measurement plane and then plotted. The resulting isovels, some of which are shown in figure 2, are enlightening. It was mathematically found that the application of different sampling schemes to a particular isovel would result in very different results. It was also found that isovels for different velocity ranges changed unpredictably, as shown in figure 3. The following conclusions were developed from the graphic analysis:

- Multipoint traverse methods will yield the most accurate results for the

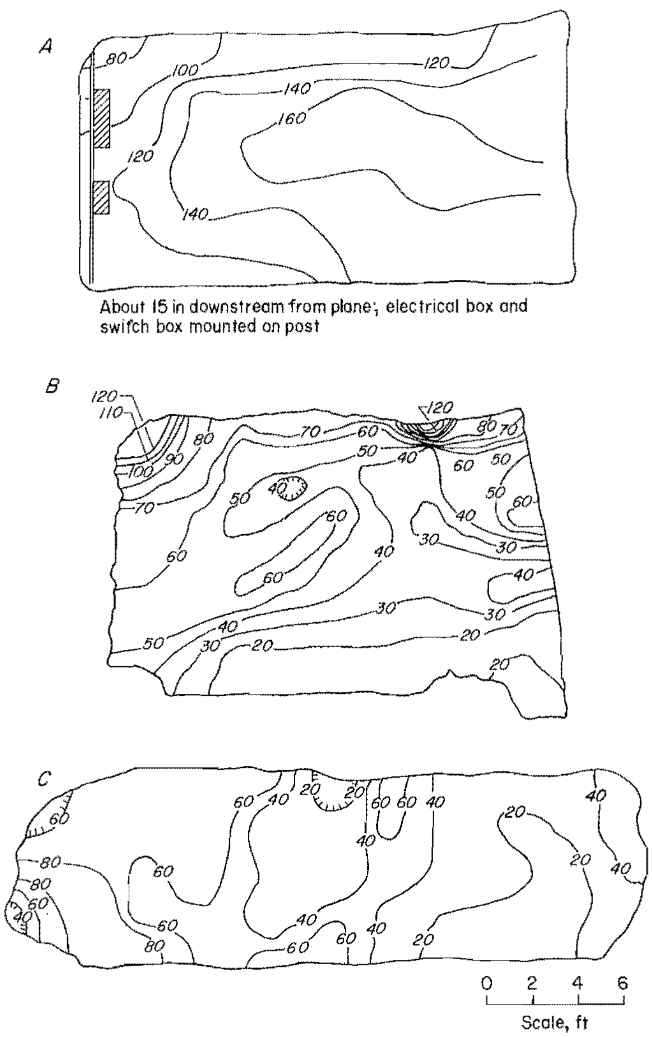

FIGURE 2. - Isovels at measurement plane. *A*, mine 1, V = 180 fpm; *B*, mine 2, V = 35 fpm; mine 3, V = 52 fpm.

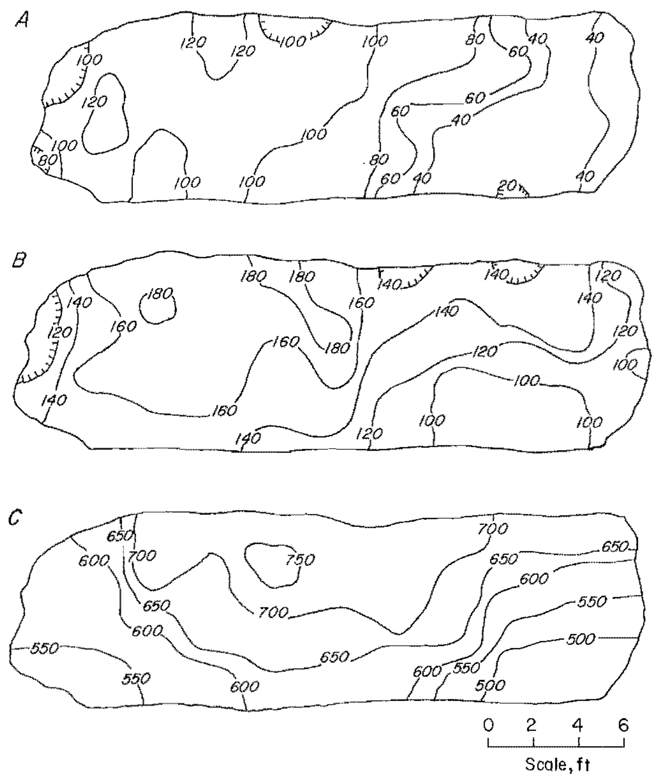

FIGURE 3. - Mine 3 isovels at measurement plane. *A*, V = 93 fpm; *B*, V = 135 fpm; *C*, V = 650 fpm.

largest range of mine aircourse characteristics and velocity ranges.

o Although the reported correction factors in the literature vary widely and are sometimes contradictory, they are probably appropriate and representative of the mines in which the experiments were conducted.

o Generalization of correction factors is therefore hampered by their site-specific nature, which is not easily quantifiable.

o A table of generally applicable correction factors is feasible if the accuracy limitations are recognized, and the resulting measurements are used with this in mind.

Air velocity measurements are taken in mines to satisfy statutory requirements and to support mine planning activities. In a coal mine, for instance, these measurements are taken throughout the mine at intervals that range from minutes to weeks, based on 30 CFR requirements. These measurements are being made and will continue to be made independent of this research project and its results. Despite any shortcomings in the application of generalized correction factors, the industry needs such factors for routine ventilation work. Therefore, an attempt has been made to develop a generalized correction-factor table. As indicated previously, such an effort is difficult to justify technically based on the site-specific characteristic of correction factors.

A set of correction factors directly relating to the experiments conducted is given in table 7. These correction factors represent the values recorded at different mines and at the indicated air velocities. The appropriate correction factor for any given pair (measured velocity, measurement method) can be obtained by interpolating between velocity ranges for the method selected.

An alternative approach is to fit a quadratic curve through the data for correction factors to establish generalized (velocity-dependent) correction factors. The regression equation is

$$cf = a + bV + cV^2, \quad (9)$$

TABLE 7. - Summary of correction factors, by velocity, for different measurement methods

Method	Air velocity, fpm								Mean value over all velocities
	35[1]	52[2]	62[3]	93[2]	135[2]	187[3]	340[3]	650[2]	
1	0.74	0.92	0.76	0.87	0.85	0.72	0.68	0.90	0.81
2	.70	.89	.73	.92	.89	.78	.76	1.06	.85
3	.81	.94	.78	.96	.92	.83	.79	1.12	.89
4	NAp	.78	.78	.89	.89	.83	.78	1.07	.86
5	.56	.91	.81	.90	.95	.94	.89	1.10	.89
6	NAp	.91	.74	.87	.89	.82	.77	.96	.86
7	.54	.92	.84	.89	.97	.95	.88	1.13	.90
10	NAp	.70	.79	.86	.87	.88	.84	.96	.84
11	.51	.88	.87	.89	.96	.95	.90	1.05	.88
21	1.77	1.16	.88	.84	.84	.91	.61	.84	.96
27	NAp	.48	.64	.84	.89	.82	.73	.89	.76
28	NAp	1.02	.85	1.04	.96	.91	NAp	.91	.96
31	.74	.98	.73	.85	.92	.96	NAp	NAp	.86
32	.92	1.07	.74	.92	1.01	.94	NAp	NAp	.93
41	.50	.85	.60	.79	.81	.67	.69	NAp	.70
42	.49	.84	.63	.82	.87	.72	.72	NAp	.73
43	.46	.86	.65	.81	.86	.71	.72	NAp	.72
44	.66	1.10	.70	.89	.94	.80	.74	NAp	.83
50	NAp	.80	.78	NAp	.97	NAp	NAp	NAp	.85
51	NAp	NAp	NAp	NAp	.96	.90	.91	1.10	.94

NAp Not applicable, no readings taken. [1]Mine 2. [2]Mine 3. [3]Mine 1.

where cf = correction factor,

V = measured air velocity,

and a,b,c = coefficients.

Table 8 lists coefficients a, b, and c. The last column in table 8 is an indication of the range of expected error associated with the measurement technique and use of the quadratic equation for estimating the correction factor. This is the ratio of the standard deviation of the measurements from the quadratic estimator in equation 9 to the measured mean correction factor (last column in table 7) for each measurement method.

The large error range shown in table 8 is a reflection of the site-specific nature of correction factors, and the consequent difficulty in generalizing. Since this table is based on curve fitting to the collected data, its general applicability is subject to debate.

MONITORING SYSTEMS AND AIR VELOCITY SENSING

Mine monitoring systems offer considerable potential to improve mine safety and productivity. Currently, several coal mines are using environmental monitoring systems to monitor airflows in belt entries so that this belt air can be used to ventilate the working place. Many of the problems associated with air velocity monitoring are common to air velocity measurements made with conventional instruments such as vane anemometers.

The location of a fixed point velocity sensor must be selected with the same considerations as for standard velocity measurements. The constraints imposed on the fixed point sensor are more rigorous, however, because it is capable of measuring the airflow at only one point. Whereas timed-point traverses are recommended for certain adverse locations when using conventional instruments, this is not an option for fixed-point monitors.

Once a suitable location has been established within the airway, the fixed-point sensor must be installed. Two considerations dictate that the sensor be

TABLE 8. - Coefficients for generalized correction factors, by method, using the quadratic equation

Method	Points in analysis	Coefficients of equation 1			Mean error, pct
		a	b	c	
1	9	0.833	-9.96×10^{-4}	1.55×10^{-6}	8.4
2	9	.855	-4.39×10^{-4}	1.12×10^{-6}	10.7
3	8	.915	-7.23×10^{-4}	1.57×10^{-6}	8.3
4	8	.869	-4.92×10^{-4}	1.20×10^{-6}	6.5
5	9	.764	$+9.53 \times 10^{-4}$	-7.27×10^{-7}	12.3
6	8	.910	-7.13×10^{-4}	1.198×10^{-6}	7.1
7	9	.777	$+8.87 \times 10^{-4}$	-5.92×10^{-7}	13.7
10	8	.764	$+5.24 \times 10^{-4}$	-3.68×10^{-7}	5.9
11	9	.737	$+1.25 \times 10^{-3}$	-1.25×10^{-6}	13.5
21	9	1.420	-4.62×10^{-3}	$+5.79 \times 10^{-6}$	24.0
27	8	.634	$+1.03 \times 10^{-3}$	-1.04×10^{-6}	15.9
28	7	.998	-3.58×10^{-4}	$+3.40 \times 10^{-7}$	6.9
31	6	.750	$+1.36 \times 10^{-3}$	-1.24×10^{-6}	10.3
32	6	.909	$+1.96 \times 10^{-4}$	4.79×10^{-7}	11.8
41	7	.576	$+2.01 \times 10^{-3}$	-5.07×10^{-6}	16.4
42	7	.539	$+2.95 \times 10^{-3}$	-7.27×10^{-6}	15.4
43	7	.542	$+2.85 \times 10^{-3}$	-7.02×10^{-6}	16.9
44	7	.762	$+1.53 \times 10^{-3}$	-4.80×10^{-6}	17.4
50	4	.822	-1.72×10^{-3}	$+2.09 \times 10^{-5}$	1.4
51	5	.877	-1.43×10^{-5}	$+5.39 \times 10^{-7}$	5.3

suspended near the center of the airway. The first consideration deals with turbulence profiles in the airway; the second relates to changes in the isovels, and hence the correction factor, as air velocity changes.

TURBULENCE

A fluid flow is said to be laminar if it is free from rapid and random fluctuations. Under certain conditions, the laminar flow can become unstable, go through some transition stage, and become turbulent. The turbulent flow is characterized by the rapid and random change of velocity at a given point. There are several different theories on the origin of turbulence in laminar flows (14). In a general sense, it is known that the linear dimensions of the system, the mechanical properties of the fluid, and the wavelength of disturbances in the flow are relevant to the formation of a turbulent flow. A dimensionless quantity known as the Reynolds number and the size (wavelength) of a disturbance have been used successfully to predict turbulent flows.

The Reynolds number for mine flows can range from about 4×10^3 to well over 4×10^6, with typical values in the range of 4×10^5. Laminar flow in a mine will cease if the Reynolds number exceeds 2,000. It can be assumed that mine flows are always turbulent. This, of course, is a desirable characteristic since mixing of the flow is greatly enhanced, thereby facilitating dilution and removal of noxious and toxic gases and dusts in the mine environment.

Air-speed measurement in turbulent flows can be rather problematic. The devices commonly used to measure air speed are calibrated in laminar flows. Additionally, mine ventilation engineers have not determined the nature of the turbulent flow found in underground mines. It is known that turbulent flows can cause erroneous readings in measurements taken with vane anemometers (1). The use of fixed-point velocity sensors in turbulent flows is especially questionable, since most fixed-point sensors operate on a vortex-shedding principle suitable for laminar flows.

A full experimental characterization of turbulent flows was beyond the scope of this study. However an experimental program was developed and turbulence data were collected in one mine. A limited group of wind tunnel tests were implemented to identify the effect of mine-like turbulence on a fixed-point velocity sensor that operated on the vortex shedding principle. The results of this preliminary work suggested that mine turbulence could be a problem, in that sensor readings could be 50 pct greater than the true value. Additional research is needed to better define the extent of the problem and possible solutions.

Another finding of this limited investigation into turbulence was the location aspect. In all cases, minimum turbulence intensity occurred near the center of the airway. Historically, monitoring system sensors in coal mines have been mounted near the rib, on a post installed specifically for that purpose. It was found that the airstream perturbations around the post, near the rib, resulted in significant levels of turbulence. Accordingly it would be prudent to avoid this type of placement, at least until the resulting errors are better defined.

CORRECTION FACTORS

The fixed-point sensor, like the vane anemometer, measures the velocity at one point, not the average velocity needed to compute volume flow rate. Thus a correction factor is needed. A recommended procedure for determining this correction factor is given by Kohler (14). As discussed previously in this report, the isovel, and hence the correction factor, changes whenever the mean air velocity changes. Under normal circumstances, fixed-point sensors can be very useful in allowing personnel on the surface to assess conditions underground. However, under abnormal conditions, the air velocity will probably be different from when the sensor was installed, so that the sensor readings will be erroneous. This effect can be minimized by placing the sensor near the center of the airway, where isovel changes are usually less, and hence correction factor changes are smaller. A minimal change in correction factor translates directly to a reduced error.

CONCLUSIONS

This investigation has addressed the development and use of correction factors for air velocity measurements and the establishment of location guidelines for making measurements. Long-standing problems in this area, contributed in large part by the disagreements within the technical literature, have been resolved.

Guidelines for selecting suitable locations for making air velocity measurements have been defined and must be strictly applied. Otherwise results will be erroneous. The use of factors to correct for adverse locations is not technically justified. In fact, a strong case has been made against the use of such factors.

Correction factors are useful to convert instrument readings to average values; a set of correction factors has been developed and is presented in this report. As in previous investigations, the correction factors developed here appear to diverge and are not always consistent with intuitive expectations. In contrast with the approaches taken in previous investigations, this fact was recognized and analyzed. It was found that computed correction factors are extremely site-specific, and specific to a velocity range. Accordingly, it is difficult to generalize tables of correction factors. Although it was impossible to establish a general mathematical relationship that would be useful to predict a correction factor given mine-specific information, the reason for diversity in correction factor tables was explained, and related to the isovel.

It was found that accurate measurements could be obtained with most of the methods examined, although timed-point traverses tended to be more accurate in most situations. Accuracy requirements for mine ventilation applications are not well defined, but it appears that an accuracy of ±20 pct is satisfactory, based on current practice, thus permitting the use of correction factors. An examination of accuracy requirements would be useful and should be considered for future work in this area.

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APPENDIX.--LITERATURE REVIEW

An exhaustive search was made of literature dealing with mine air velocity measurements or related topics, using the *Engineering Index*, and computerized literature data bases. At the conclusion of the literature search, copies had been obtained for all available publications on mine air velocity measurement, from 1900 to 1980. These publications were reviewed and analyzed within the objectives of this investigation. Specifically the following topics were emphasized:

- o Site selection criteria.
- o Correction factors.
- o Area measurement.
- o Instrument characteristics and operator methodology.

The published material provides an interesting historical perspective on the artful development of mine ventilation measurements. It was also helpful in establishing the nature of the experimental investigations that were performed during this study. Beyond that, the published literature is of minimal value, and must be interpreted carefully for several reasons.

First, the published reports often contain little or no information about the experiment design, making it impossible to assess the validity of the work. Second, information on the experimental site is often sketchy. Parameters such as velocity range, aircourse characteristics, and so forth are sometimes unreported. Third, the use of proper controls was usually absent. Instead, repeatability (precision) was incorrectly used as a true velocity, rather than accuracy. Finally, many of the published recommendations appear as some undefined blend of personal experience and scientific fact.

The selection of a suitable site is often addressed in the literature. It was recognized by the earliest researchers that obstructions, bends, intersections, and so forth, modify the airflow, and as such, measurements should not be taken near those places. Most investigators made recommendations for selecting sites, while a few proposed correction factors to account for airstream perturbations. Table A-1 summarizes site selection guidelines found in the literature.

The literature is even more profuse in the area of correction factors, with significant variation in suggested correction factors (table A-2).

The instrument characteristics and operator's methodology affects the accuracy of the velocity measurement. Several investigators have examined the influence of the following factors:

- o Instrument support method.
- o Operator position.
- o Measurement method.
- o Instrument orientation.
- o Timing technique.

A complete review of the literature in this area is given by Kohler and English (15).[1]

The method of supporting an instrument in the airstream, to take a measurement, affects the reading. The extent of the effect will depend upon the instrument used and the characteristics of the airstream. Schubauer and Adams (26) examined the effect of instrument support on measurement accuracy (table A-3).

The operator's position and proximity to the instrument while the measurement is being taken has been extensively investigated, with mixed results. An example of this proximity effect is shown in figure A-1, based on the work of Boshkov and Amontree (4). Typical effects of operator position, compiled from the results of Boshkov and Amontree (4) and Swirles and Hinsley (30) are shown in table A-4. In general, two different operators, using the same instrument at the same location, can obtain readings that differ significantly (20 pct).

The measurement method, e.g., single-point or multiple-point traverse, will affect the accuracy of the measurement. As discussed before, these measurements are usually taken to allow the computation of an *average* value. Obviously the reading obtained from a single point in

[1] Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

TABLE A-1. - Summary of location guidelines given in the literature

Reference	Requirements and recommendations	Upstream	Downstream
7........	Use lined airway..............................	30 ft.......	30 ft.
32.......	Use straight airway (at least 150 ft from long-wall face if in return).	75 ft.......	15 ft.
6........	Use uniform airway, at least 5 to 6 roadway diameters in length.	4 to 5 diameters.	1 diameter.
8........	Use "regular" airway...........................	20 yd.......	NA.
11.......	Use uniform airway; use smoke to find uneven velocities.	2 diameters.	1 diameter.
16.......	Use artificial station, at least 15 to 20 ft long, tapered inlet and outlet. Station should be 6 to 8 times long as wide.	NA..........	6 ft.
17.......	Theoretical requirements for fully established duct flow--not established for mines.	50 to 100 diameters.	NA.
18, 20...	1,000 ft of straight section required "a considerable distance from any disturbance."	NA..........	NA.
19.......	Use artificial station 10 to 20 ft long with tapered entrance (exit was abrupt).	NA..........	4 to 5 ft.
21.......	Use canvas lining in 100 ft of airway, with point traverse.	50 ft.......	50 ft.
22.......	Avoid obstruction; zone of no flow may exist downstream.	NA..........	NA.
24.......	Use uniform airway.............................	5 or 6 diameters.	NA.
27.......	Use "regular" airway, straight and uniform.....	...do.......	NA.
28.......	Stay at least 5 roadway diameters from bend and 0.5 m upstream from an irregular area (such as the end of the station).	NA..........	NA.
30.......	Use "clear section"............................	6 diameters.	NA.
33.......	Use straight section...........................	NA..........	NA.

NA Not available.

the airstream will not, in most cases, be the same as the true average velocity. An attempt to reduce the error, and convert the reading to an average value, is made with correction factors.

If a continuous traverse is used, measurement error may be introduced if the traverse speed is too large. A number of investigators have found a good correspondence between traverse speed and error. The effects of traverse speed established by Swirles and Hinsley (30), and shown in figure A-2, agree with other researchers in that (1) overestimation of the airspeed tends to increase with traverse speed; (2) this effect becomes more pronounced at lower air velocities.

The literature for cross-sectional area measurement in mines is not as profuse as for the other topics. Notwithstanding, the following eight different recommended

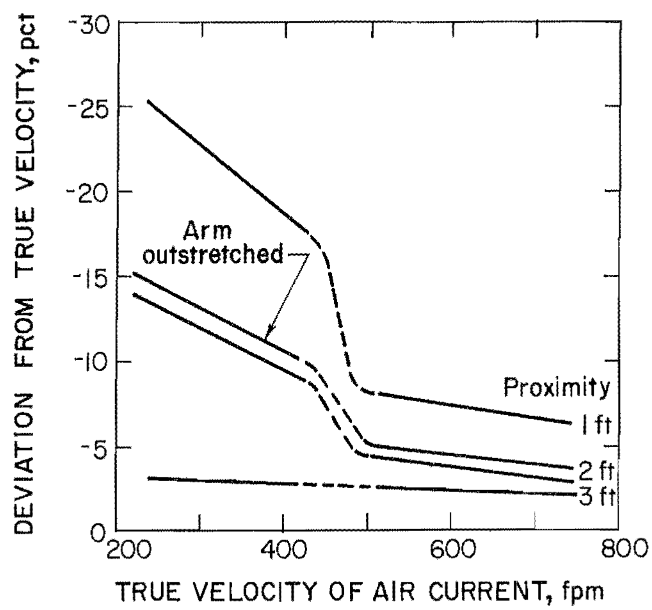

FIGURE A-1. - Effects of operator proximity on anemometer readings (operator to side) (4).

TABLE A-2. - Summary of correction factors given in the literature

Reference	Method	Correction factor	Location and/or guideline
7.....	Anemometer, point..	0.80	Center point.
	...do..............	1.00	0.14 roadway width from rib.
2.....	...do..............	[1].80	Center point.
3.....	...do..............	.85	Center of regulator openings.
	Anemometer, continuous traverse.	1.00	Regulator; deduct 0.5 ft^2 from area for arm.
	...do..............	1.00	Airway; deduct 4.0 ft^2 from area for body.
	Smoke..............	.80	Point of maximum velocity (not necessarily at center).
5.....	Anemometer, point..	0.70- .73	Center point (recommended, not verified).
	...do..............	.80	Center point, timbered airway (recommended, not verified).
6.....	...do..............	.90	Center point.
8.....	...do..............	.88- .94	Center point; av.--0.91, low--0.71.
9.....	...do..............	1.00	"D-6 position"; 1/6 roadway width from rib.
10....	...do..............	.7	Point of maximum velocity, airway.
	...do..............	.8	Point of maximum velocity, stope.
	Smoke..............	.65- .85	Point of maximum velocity, av. several measurements.
	...do..............	.80	Recommended for common use; within 5 pct error.
11....	...do..............	.80	Av. measurements from several random points.
12....	Anemometer, point..	.85	Center point.
13....	Smoke..............	[2]1/1.1	Quarterpoints over 25-ft distance; av. several measurements at each point, then av. results.
20....	...do..............	.90	Quarterpoints.
	...do..............	.80	Center point (for higher velocities).
	Anemometer, point..	.78- .82	Center point (1949).
	...do..............	.80	Center point (1935).
	...do..............	1.00	1/7 roadway width from rib.
	...do..............	.65- .90	Center point of irregular entries.
	...do..............	.75-1.0	Center--constriction (low), expansion (high).
	Anemometer, continuous traverse.	.85- .90	In airway of 35- to 45-ft^2 area.
	...do..............	.88- .92	In airways of approximately 80-ft^2 area.
	...do..............	.90- .93	In airways greater than 100 ft^2.
	Anemometer, precise traverse.	.95	For 16-point traverse in doorframes.
	...do..............	1.00	NA.

See explanatory notes at end of table.

TABLE A-2. - Summary of correction factors given in the literature--Continued

Reference	Method	Correction factor	Location and/or guideline
19....	Anemometer, point..	0.82-0.88	Center point, lagged crosscut.
	...do..............	.63- .65	Center point, narrow rock crosscut.
	...do..............	.65- .73	Center point, larger crosscut (88 to 96 ft^2).
	...do..............	[3]1/1.10-1/1.17	Center point, shafts.
	Anemometer, continuous traverse.	.90- .91	Hand-held anemometer.
	...do..............	.96- .98	Shaft-held anemometer.
	Anemometer, precise traverse.	.94- .95	20 points in airway at 1 location.
	...do..............	.89- .82	20 points in airway at new location.
	Anemometer, continuous traverse.	1.11	Timber sets, loosely lagged, straight airway.
	...do..............	.97	Timber sets, tightly sealed, slightly curved airway.
	...do..............	1.01-1.04	Timber sets, tightly sealed, straight airway.
	...do..............	1.02	Recommended factor for timber sets.
	...do..............	.77- .83	Irregular rock, untimbered, area 41 to 46 ft^2.
	...do..............	.98-1.01	Timbered (not sets), lagged, straight airway.
22....	NA.................	NA	In low flow, point of maximum velocity is below the center point.
23....	Smoke..............	.80- .95	Center point.
	...do..............	.90	Quarterpoints, average of all 4.
24....	Anemometer, point..	1.0	1/7 to 1/3 roadway width from rib.
	...do..............	Variable	Center point; varies with Reynolds number.
25....	Smoke..............	.90	Quarterpoints; av. 3 measurements; good below 120 fpm.
27....	Anemometer, point..	.84- .90	Center point.
28....	...do..............	.75- .80	Point of maximum velocity; V = Vmax.
	...do..............	.95	Doorway center point if doorway area <1/2 airway area.
	Anemometer, continuous traverse.	.95	Hand traverse, large regulator.
	...do..............	.90	Hand traverse, small regulator.
29....	Anemometer, point..	.924	Center point, model mine shaft.
31....	...do..............	.80- .85	Center point (cited industry standard).
	...do..............	.76	Center point, remotely controlled.
	...do..............	.73	Center point, rod held.
	...do..............	.67	Center point, hand held.
	Smoke..............	.74	Center point.
	Scent..............	.67	NA.

NA Not available. [1]4/5. [2]0.91. [3]0.91-0.85.

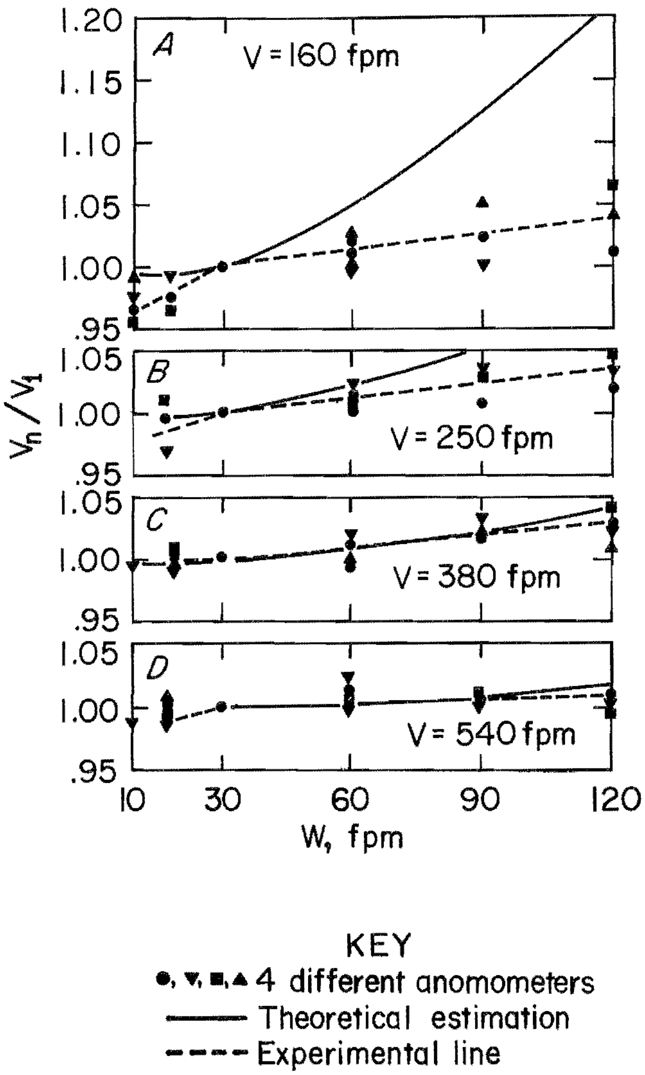

FIGURE A-2. - Effects of traverse speed on anemometer readings at various velocities, where W = traverse speed, V = average velocity of airflow, and V_n/V_1 = ratio of measured velocity to true velocity (30).

area measurement techniques can be found in the litterature:

- o Vertical and horizontal taping.
- o Vertical and horizontal offsets.
- o Simpson's rule.
- o Diagonal offset.
- o Spiked protractor.
- o Profilograph.
- o Full circle protractor (Craven sunflower).
- o Photographic.

TABLE A-3. - Resulting errors in velocity measurement for different methods of vane anemometer support (26), percent

Support method	Error range at 400 to 1,600 fpm
Rod..................	0
Plate..................	3.3- 5.6
Hand 1 (holding anemometer top)..........	15.9-18.1
Hand 2 (clutching top hasp)................	11.8-18.1
Hand 3 (holding handle in base).............	9.6-14.6

TABLE A-4. - Summary of error ranges for different operator positions, percent

Operator positions, ft	Reference 4	Reference 30	
		Operator to side	Operator downstream
Absent.....	0	0	0
5..........	NA	1- 7	1- 5
4..........	NA	2- 8	1-10
3..........	2- 4	2- 8	5-15
2..........	4-14	4-12	10-22
1..........	7-24	9-27	20-50

NA Not available.

A vertical and horizontal tape measurement is the most prevalent method of area determination; the airway is assumed to be of rectangular cross section. While this method is the simplest and fastest, it tends to be the least accurate. The most accurate method is the photographic. The airway cross section is photographed and the print is planimetered to determine the area of the opening. The other methods are attempts at improving the accuracy of vertical and horizontal taping without the use of a camera. While they are interesting they probably have little use today. A summary of these methods is given in table A-5, and a more complete review of each method is given by Kohler and English (15).

TABLE A-5. - Summary of area measurement techniques given in the literature

	Description
DIRECT MEASUREMENT	
Horizontal and vertical taping.	Area equals height times width; several heights and/or widths may be averaged.
Simpson's rule.........	Application of known mathematical law after measuring a set number of strips of constant width.
Triangulation (by segments).	Divide area into smaller triangles and measure two known sides and the included angle of all triangles.
Craven sunflower.......	Divide area into circle segments of equal arc and measure all radii.
SECTION REPRODUCTION	
Offsets: Horizontal and vertical diagonal from a frame.	Measure a baseline and measure offsets from it; use information to plot a scale area for planimetering.
Radii: Protractor, Craven sunflower, plane table.	Measure various radii and the angles between them; use information to plot a scale area for planimetering.
Triangulation (by points).	Measure distances from two points to various points on airway; use information to plot scale area for planimetering.
Profilography and pantography.	Obtain cross-sectional diagram directly without plotting points and planimeter.
PHOTOGRAPHIC	
Photographic...........	Planimeter photographs or projection.

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