Comparison of barometer pressure surveys with other measuring techniques for determining frictional pressure loss in shafts

R. Ruckman
Mine Ventilation Services, Inc., Clovis, California, USA

J. Bowling
Mine Ventilation Services, Inc., Clovis, California, USA

ABSTRACT: During ventilation surveys, differential pressure measurements are typically conducted with either the barometer (or altimeter) technique or the gauge-and-tube method. Over the course of the past two decades Mine Ventilation Services, Inc. has conducted numerous pressure surveys using both techniques. This paper discusses the relative accuracy of a barometer pressure survey for quantifying shaft frictional pressure loss compared with other methods. The other methods include the gauge-and-tube technique to measure pressure as well as reducing pressure differentials using Kirchhoff's Laws to compare against a barometer survey. The results and relative accuracies of the pressure survey methods and associated instruments are presented and discussed. The comparative pressure data analyzed are representative of typical mine ventilation survey conditions and were obtained from historical ventilation survey records. The theory behind, assumptions required for, and challenges associated with barometric pressure surveys of shafts are examined. The merits of barometer surveys vis-à-vis other methods for determining shaft pressure loss are also discussed.

1 Introduction

With advancements in technology, modeling of ventilation systems is an integral tool to assist in evaluation and future projections for engineers. Engineers have two methods to develop a ventilation model; by using either theoretical data or measured data. Theoretical model development is acceptable and, for future modeling, necessary; however, measured data can incorporate irregularities which exist in any ventilation system. To develop a model from measured data, the accuracy of the measured data is important when collecting airflows and pressure differentials. Emphasis is generally placed on accurate measurement of airflow quantities; historically methods and technologies for airflow measurements have been heavily examined. However, frictional pressure differentials are required to quantify the airway resistances through the system but are not typically required for daily operations. As the methodologies for various techniques to obtain frictional differential pressures have been studied, the accuracies in the data obtained have not been comparatively examined.

2 Methodology of Measurements

There are various techniques to measure frictional pressure differentials through a mine. The techniques typically used are the barometer (altimeter) survey and the gauge-and-tube survey. The procedures, advantages and disadvantages of both measurement techniques are described in "Measurement of Frictional Pressure Differentials during a Ventilation Survey" (Prosser, B.S. 2004). A summary of the techniques used to measure the frictional pressure differentials and measured data reduction are discussed in the following sections.

3 Measurement Technique 1- Barometric Survey

Barometric surveys may be used to determine frictional pressure differentials and the field data collected can be measured using either of two techniques. The techniques are the Roving method and the Leapfrogging method. The Roving method can be performed with one person and the use of a surface barometer which continuously or incrementally records a stationary surface/atmospheric barometric pressure. The roving barometer is used to conduct corresponding barometric pressure measurements underground throughout the mine. The barometric pressure measurements obtained with the roving barometer are then corrected for changes in the atmospheric pressure throughout the day based on the surface barometer readings. The Roving method assumes that the barometric pressures in the mine and on the surface fluctuate simultaneously. The inherent weakness attributed to this assumption can be mitigated using the Leapfrogging method. The Leapfrogging method entails two measurement teams simultaneously conducting barometric pressure readings at two varying locations underground. This method does not require a surface barometer. The Leapfrogging method is more accurate than the Roving method but requires instrumentation with accuracy and precision and constant communication between the two teams (Prosser, B.S. 2004). For the purpose of a shaft differential pressure measurement, often one of the measurement locations for the barometer is on the surface at the shaft collar. In this case, both methods involve simultaneous measurements in the atmosphere and at an underground location (shaft station).

The theoretical reduction of the barometric survey can be interpreted with three different methods used to calculate the frictional pressure differentials. The three methods used to calculate the frictional pressure differentials are described in the following sections.

3.1 Method 1 – Direct Application of the Steady Flow Energy Equation

McPherson derives Method 1 in *Subsurface Ventilation Engineering* (McPherson 2009, Section 2.3). The calculations to obtain the frictional pressure differential based on the measured barometric pressure survey are detailed as follows. The Steady Flow Equation (Equation 1) is used to calculate the work done against friction as the air travels between two measurement stations.

$$F_{1,2} = \frac{u_1^2 - u_2^2}{2} + (Z_1 - Z_2)g - R(T_2 - T_1)\frac{\ln(P_2/P_1)}{\ln(T_2/T_1)} \qquad (1)$$

Where:
$F_{1,2}$ = Work done against friction (J/kg)
u = Air velocity at the barometer location (m/s)
Z = Elevation of barometer location (m)
g = Gravitational acceleration (9.81 m/s^2)
R = Mean gas constant (J/kg K)
T = Absolute temperature (K)
P = Barometric pressure (kPa)

The work calculated with the Steady Flow Equation is converted to a frictional pressure differential using Equation 2.

$$p_{1,2} = \rho_a F_{1,2} \qquad (2)$$

Where:
$p_{1,2}$ = Frictional pressure differential (Pa)
ρ_a = Average density of air between two stations (kg/m^3)

When the two underground barometric pressure measurements are not conducted simultaneously, it is necessary to apply a correction to the one of the two barometric pressure measurements to incorporate changes in the surface atmospheric barometer. It is that assumed a series of polytrophic processes link the surface barometer to the roving barometer underground though the application of a correction derived from Equation 3.

$$P'_1 = \Delta P_c \frac{P_1}{P_c} \qquad (3)$$

Where:
P'_1 = Updated barometric pressure at Station 1 (kPa)
P_1 = Measured barometric pressure at Station 1 (kPa)
ΔP_c = Change in surface atmospheric pressure (kPa)
P_c = Surface atmospheric pressure measured at the corresponding time as Station 1 measurement (kPa)

3.2 Method 2 – Mine Ventilation Society of South Africa (MVSSA)

The Mine Ventilation Society of South Africa recommends the *Environmental Engineering in South African Mines* (Burrows, J. et al 1989, Chapter 6) approach to calculate the frictional pressure differential as derived in Equation 4.

$$p_{1,2} = -(P_2 - P_1) - g\int wdZ \qquad (4)$$

Where:
$\int wdZ$ = Theoretical increase in pressure (Pa)

The difficulty with Equation 4 is evaluating the integral term for the change in air density as a function of depth. A series of measurement locations can be established between the measurement stations; however, this can result in an excessive quantity of data reductions. Therefore, an assumption is made that the density varies linearly with elevation, as given in Equation 5.

$$\int wdZ = \frac{1}{2}(\rho_1 + \rho_2)(Z_1 - Z_2) \qquad (5)$$

The error with this assumption is particularly severe when the elevation change exceeds 300 meters (m). Additionally, this method assumes the airflow quantity at each measurement location is representative of the airway in between each location. This assumption may be valid in certain cases, but is not correct in the case of a complex network (Prosser, B.S. 2004).

3.3 Method 3 – Exact Density Solution – Hall (1981)

Hall derives an exact solution for barometric pressure measurements which uses a density analysis, similar to the MVSSA method in *Mine Ventilation Engineering* (Hall, C.J. 1981, Chapter 8). For this method a frictionless pressure is determined using Equation 6.

$$P_{2calc} = P_2\left(\frac{2P_1 + Dg\rho_1}{2P_2 - Dg\rho_2}\right) \qquad (6)$$

Where:
P_{2calc} = Frictionless pressure (kPa)
D = Depth below datum (m)

The frictional pressure differential attributed to friction, shock, and increases in kinetic energy is derived using Equation 7.

$$p_{1,2} = P_{2calc} - P_2 \qquad (7)$$

4 Measurement Technique 2 – Gauge-and-Tube

The gauge-and-tube method can accurately determine frictional pressure differentials through airways. The gauge-and-tube method (or trailing hose technique) allows for direct measurements of frictional pressure differentials using a digital manometer or magnehelic gauge connected to a length of tubing. Typically 6 mm diameter nylon tubing is used. One end of the tube is lowered down the shaft from the upper station or collar. The manometer is configured with one pressure port open to the station air or atmosphere and the other port connected to the tube. Without a Pitot tube, the differential pressure measured is the static pressure loss. Measuring from outside the shaft collar or through a building wall effectively includes the shock losses in the differential pressure measurement, which is sufficient for the purpose of modeling. An example of a measurement of frictional pressure loss through an upcasting shaft is shown on Figure 1. An average measurement of the total pressure between the two stations is determined. The gauge-and-tube method is independent of minor changes in elevation, psychrometric parameters, or air velocity. The method can accurately measure frictional pressure losses down to 1 Pa.

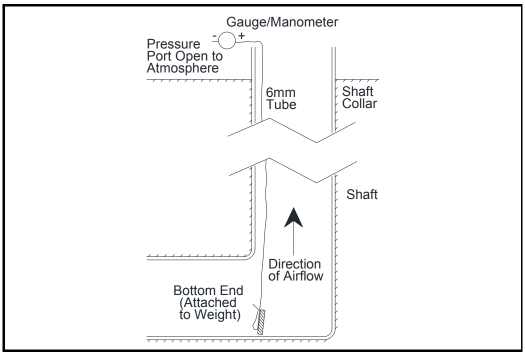

Figure 1. Illustration of Gauge-and-Tube Method for Measuring Pressure Loss in an Upcasting Shaft.

For maximally accurate frictional pressure loss calculation in a shaft or other airway, the psychrometric properties of the air in the tube and in the airway should be considered. In practice, the temperature and moisture content (thus density) of the air in the tube differs somewhat from the air in the airway. When using Pitot tubes in a drift, allowing the tube to pressurize upstream and settle allows the tube to be filled with drift air, assumed to have the same psychrometric properties (equal temperature, pressure, density). Since a Pitot tube is not used in a shaft differential pressure measurement, the tube should be allowed to equalize temperature and pressure for some time prior to measuring a differential pressure. A correction factor is necessary as the air in the measurement tube is stationary, and not affected by friction, which results in a slightly higher pressure inside of the tube than exists in the airway (McPherson 2009, Section 6.3). The correction is approximated from the total energy equation by removing the nearly negligible kinetic energy term. The corrected shaft pressure equation for a measurement of an upcasting shaft from the top is given as Equation 8 (Hinsley 1962).

$$p_{shaft(UC)} = \Delta P_{top} - \varepsilon \approx \Delta P_{top}\left(1 + \frac{\Delta Z g \rho_{top}}{2P_{top}}\right) \tag{8}$$

Where:
$p_{shaft(UC)}$ = Corrected differential pressure over the upcasting shaft (Pa)
ΔP_{top} = Differential pressure measured at top of shaft (Pa)
ε = Error in measured pressure (Pa)
ΔZ = Vertical distance of tube (shaft depth) (m)
g = Acceleration due to gravity (m/s^2)
ρ_{top} = Air density measured at top of shaft (kg/m^3)
P_{top} = Barometric pressure measured at top of shaft (Pa)

Similar correction equations can be derived for both upcasting and downcasting shafts and the gauge at the top or bottom (Hinsley 1962). For shafts up to 300 m in depth the error term is sufficiently small ($\varepsilon < \sim 2.5\%$); however, a correction factor should be used for shaft measurements over roughly 300 m. The correction for elevation differences is insignificant for measurements along horizontal or near-horizontal airways.

5 Kirchhoff’s Second Law

Frictional pressure differentials can be determined using Kirchhoff’s second law where direct measurements cannot be conducted using either a barometer survey or gauge-and-tube. Kirchhoff’s second law is applied to ventilation networks where the algebraic sum of all pressure drops around a closed path, or mesh, in the network must be zero, having taken into account the effects of fans and ventilating pressures as derived in Equation 9 (McPherson 2009, Section 7.2.1).

$$\sum(p - p_f) - NVP = 0 \tag{9}$$

Where:
p = Frictional pressure drop (Pa)
p_f = Rise in total pressure across a fan (Pa)
NVP = Natural Ventilation Pressure (Pa)

6 Comparative Analyses Based on Measured Results

Mine Ventilation Service, Inc. (MVS) engineers have utilized all of the methods previously described to determine the frictional pressure loss through mine airways and shafts. The following section discusses the barometer survey data gathered by MVS and the variances when compared to the gauge-and-tube method and application of Kirchhoff’s second law. The data were collected from various mines worldwide, but for the comparative analyses the frictional pressure losses were evaluated at standard air density of 1.2 kg/m^3.

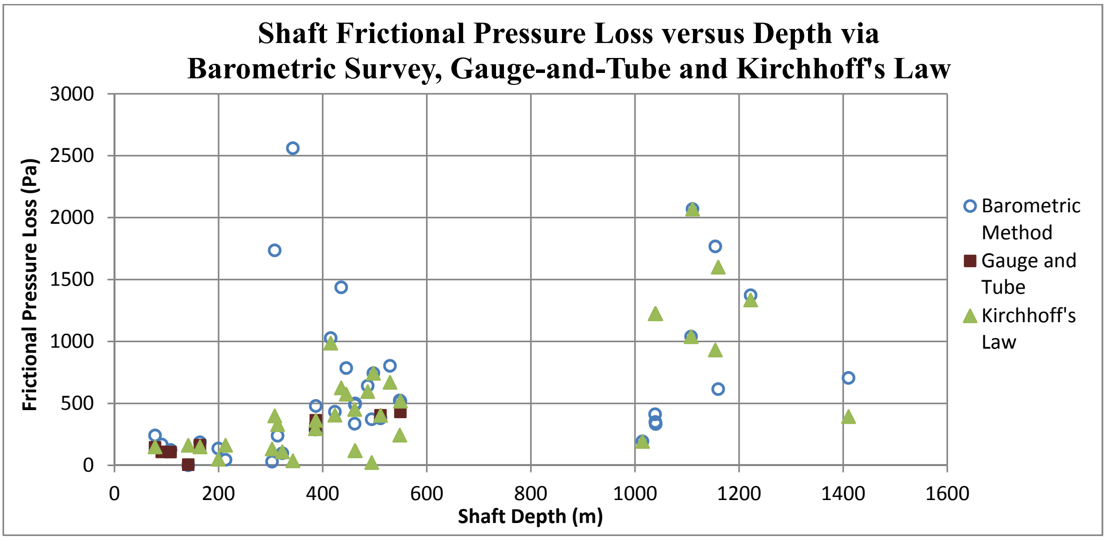

Figure 2. Shaft Frictional Pressure Loss versus Depth by Measurement/Calculation Method.

MVS engineers conducted over 50 barometer surveys and gauge-and-tube measurements of ventilation shafts at 14 underground mines to determine the frictional pressure losses. In addition, Kirchhoff's second law was used to calculate the frictional pressure loss where direct measurements through the ventilation shafts could not be performed. When Kirchhoff's Law was utilized to determine the frictional pressure loss in a shaft, the frictional pressure losses through the main airways excluding the shaft were measured with the gauge-and-tube technique where accessible and shaft pressures were calculated via loop closure difference. A plot of the measured and calculated pressure losses versus depth considered in this analysis is presented as Figure 2.

Using the data collected by MVS engineers, the barometer measurements were compared to the gauge-and-tube method and the frictional pressure loss values calculated using Kirchhoff's second law. The gauge-and-tube method and the Kirchhoff's second law values were compared to the barometer measurements based on the depth of the shaft. The data were grouped into four sets by depth: shafts less than 100 m, 101 m to 300 m, 301 m to 500 m, 501 m to 1000 m, and greater than 1000 m. No gauge-and-tube measurements were performed for shaft depths greater than 600 m. The measurements were evaluated to determine the average percent variance from the barometer measurements based on the depth of the shaft. Figure 3 illustrates the average percent difference by which the gauge-and-tube method and Kirchhoff's second law frictional pressure losses vary from the barometer measurements.

Based on the results presented on Figure 3 it can be determined that barometer measurements for shafts less than 100 m in length have a high variance between gauge-and-tube measurements and results calculated through the application of Kirchhoff's second law. As the depth exceeds 100 m, the direct measurements obtained with gauge-and-tube are typically within 15% of the barometer measurements. Barometer measurements are affected by the accuracy of data used in the calculations, specifically accurate elevations. Barometer measurements between 101 m and 300 m are likely to have a large percent variance, on average exceeding 100%, between the frictional pressure loss calculated using Kirchhoff's law. In several of the cases the barometric measurements with shaft lengths between 301 m – 500 m, data were omitted because the elevations used in the barometer survey were approximated (accurate surveyed elevations were unavailable), resulting in significantly varying pressure losses. With the approximated elevations, the gauge-and-tube measurements vary an average of 76% from the barometer data. With data based on estimated elevations omitted, the gauge-and-tube and barometer data vary by approximately 14% as shown on Figure 3.

The barometer survey measurements were compared to the gauge-and-tube measurements and the frictional pressure losses determined using Kirchhoff's second law. The resulting pressure differentials were compared based on the percent variance between both the gauge-and-tube measurements and Kirchhoff's second law from the barometer survey measurements. The comparative results of the barometer survey measurements are shown on Figure 4. The results show approximately 60% of gauge-and-tube measurements will vary by less than 25% from the barometer survey measurements. However, in approximately 10% of measurements the gauge-and-tube measurement results vary by more than 100% from the barometer survey values. In the cases where the gauge-and-tube measurements vary by more than 100% from the measured pressure differentials were noted to be less than 50 Pa.

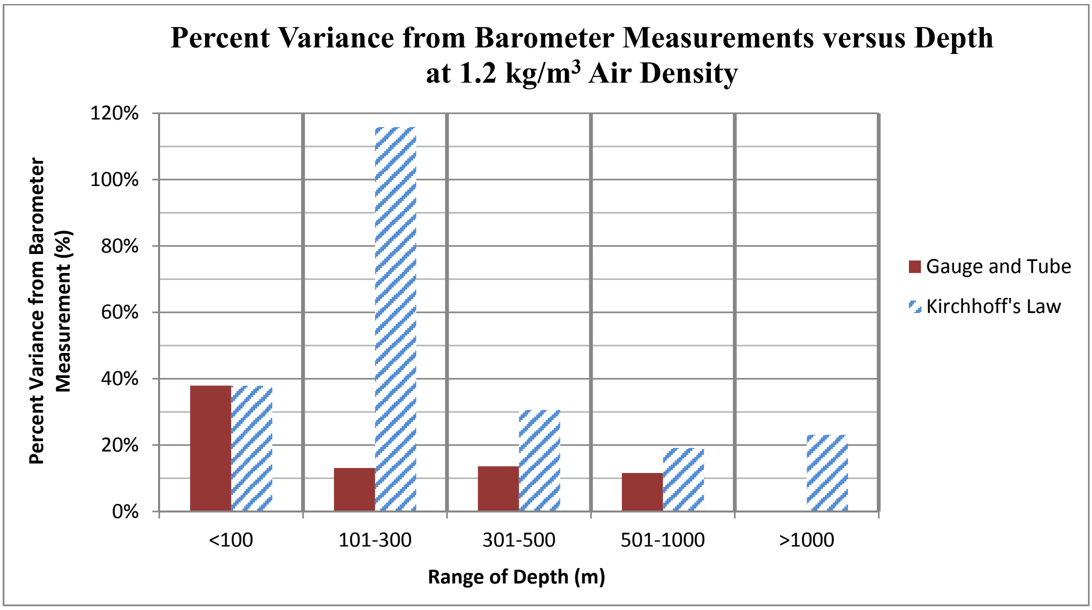

Figure 3. Average Percent Variance of Gauge-and-Tube Method and Kirchhoff's Law from Barometer Measurements.

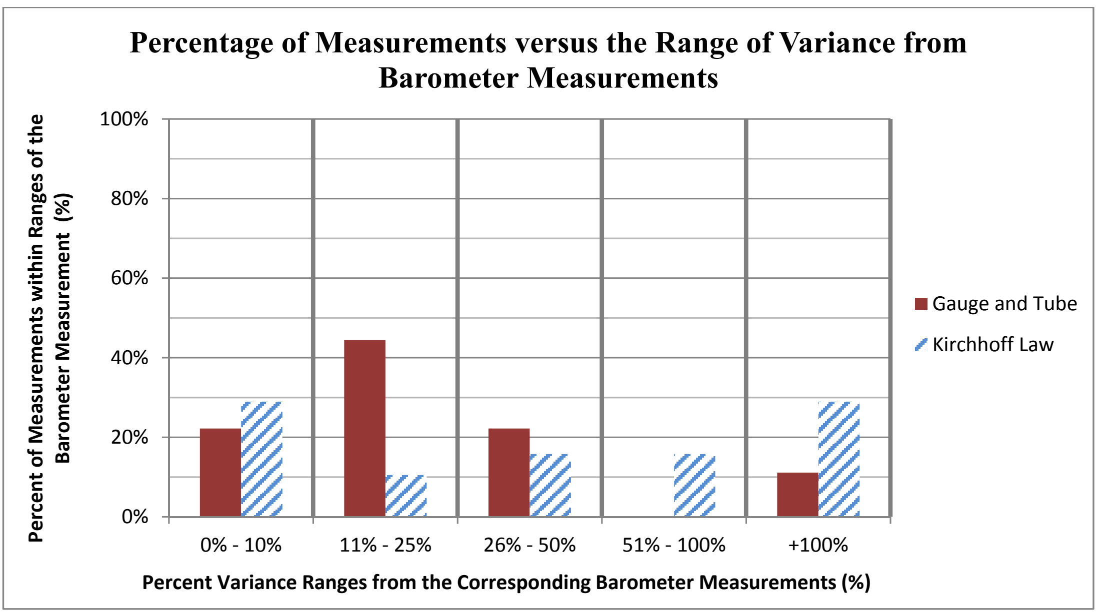

Figure 4. Percent Variance of Gauge-and-Tube Measurements and Kirchhoff's Second Law Results from Barometer Measurements.

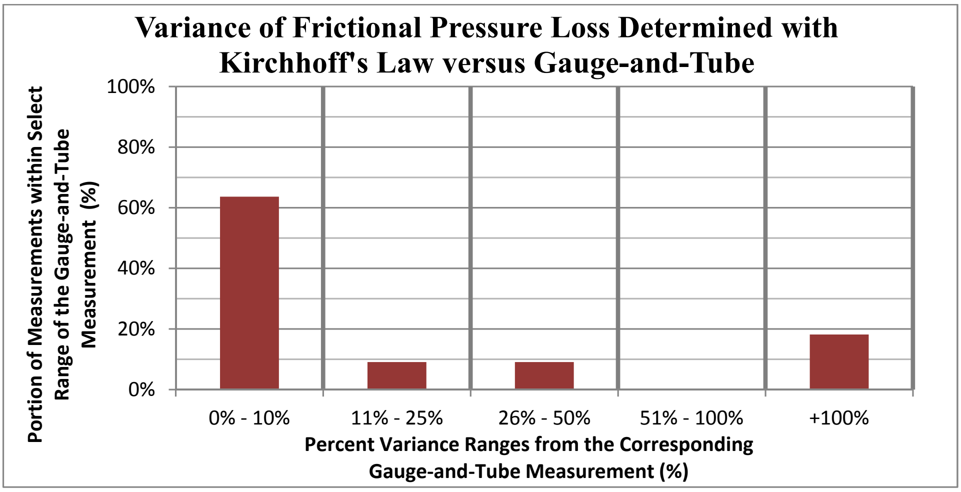

Figure 5. Percent Variance between Gauge-and-Tube Measurements and Kirchhoff's Second Law Results.

Based on the analyses, where direct measurements were conducted, the resulting frictional differential pressures exhibit less percent variance from the barometer measurements than the calculated Kirchhoff's law results compared to the barometer measurements. As shown on Figure 4, approximately 30% of the calculated results using Kirchhoff's second law result in less than 10% variance from the barometer measurement. However, the results also show that approximately 30% of the calculated results vary more than 100% from the barometer measurement.

An analysis was performed to evaluate the gauge-and-tube method compared to frictional pressure differential calculated using Kirchhoff's second law. The results of the comparison are shown on Figure 5. Based on the measured and calculated results, approximately 65% of the gauge-and-tube measurements are within 10% of the calculated pressure differentials using Kirchhoff's second law. It was noted, where the measured and calculated frictional pressure differentials exceeded 100% variance, the shafts measured included active hoisting systems for either personnel or materials. While measurements can be performed on active hoisting shafts, there is an increased chance for discrepancies in the actual pressure differentials.

7 Conclusions

Both the barometer survey and gauge-and-tube measurement techniques produce reasonable results for the purpose of conducting a pressure survey through a shaft. The data showed that the vertical elevation difference between measurement stations for a barometer survey will affect the accuracy of a measurement. If the vertical elevation difference is less than 100 meters between points, the results could vary up to 40% from directly measured results. However, as the range in depth increases, the percent variance between barometer survey and gauge-and-tube measurements decreases. When the barometer survey measurements were compared to the frictional pressure losses calculated using Kirchhoff's second law, the results were similar: as the depth increased, the percent variance decreased, especially for shaft depths exceeding 300 meters.

All methods can be utilized for determination of frictional pressure losses through shafts, though measurements should be preferred to calculation by difference, especially when a pressure loop cannot be closed via a ramp system to surface. Multiple estimated pressure branches in a loop compounds errors in measurements and estimation. The data suggest that barometer and gauge-and-tube measurements will have similar results for most conditions, but can vary significantly over short (<100 m) shaft depths, where total measured pressure loss is less than 50 Pa or where accurate elevations are not available. For medium to longer (>300 m) shafts, all measurement methods tend to converge to similar values, though gauge-and-tube measurement becomes increasingly more difficult due to the length of the shaft and tube required to obtain the measurement.

8 References

Burrows, J. et al 1989. *Environmental Engineering in South African Mines*. The Mine Ventilation Society of South Africa.

Hall, C.J. 1981. *Mine Ventilation Engineering*. Society of Mining Engineers of the American Institute of Mining, Metallurgical and Petroleum Engineers, Inc. New York, New York.

Hartman, H.L. et al 1997. *Mine Ventilation and Air Conditioning, 3rd Edition*. Wiley-Interscience Publication.

Hinsley, F.B. 1962. "The Assessment of Energy and Pressure Losses Due to Airflow in Shafts, Airways, and Mine Circuits", *The Mining Engineer*. Col:121, pp. 761-777.

McPherson, M.J., 2009, *Subsurface Ventilation Engineering*. Clovis, California: Mine Ventilation Services, Inc.

Mine Ventilation Services, Inc., Internal Records, 1995-2011.

Prosser, B.S. and Loomis, I.M. 2004. "Measurement of Frictional Pressure Differentials During a Ventilation Survey", 10th US Mine Ventilation Symposium. pp. 59-66.