CHAPTER 2 LITERATURE STUDY

2.1 INTRODUCTION

Chapter 1 of this thesis described the need for the investigation. The specific objectives of this work were defined and the general areas of investigation were detailed with regard to the requirement for finding ways to increase the energy efficiency of shafts in the design phase of projects. With respect to improving this efficiency, the energy losses resulting from the flow of air through shafts were highlighted as being worthy of further investigation.

To ensure that these areas were effectively evaluated, a literature review was undertaken. This review concentrated on the following general topics:

1. *Measurement*: The various measurements that have been undertaken are discussed and the results are evaluated against current theory.
2. *Theory*: The theory currently available for the evaluation of the pressure drops in shaft systems is evaluated and its efficacy is commented on.
3. *Computational fluid dynamics*: The efficacy of using this analysis technique for further evaluation is commented on.

2.2 MEASUREMENT

A comprehensive search of the available literature on the actual resistance of shafts was completed and the pertinent papers are discussed here. Most of these tests were completed circa 1960. At this time the shape of shafts was in the process of changing from rectangular to circular. One of the primary drivers for this change was the increased difficulty being experienced by engineers in ensuring that sufficient ventilation was supplied to the mine workings. It is intriguing to note that the primary driver for the tests was to confirm that the pressure losses would still allow ventilation to be distributed and not specifically to ensure that the overall shaft complex operated efficiently.

It will also be noted that while some shafts were themselves measured, a number of the tests were carried out using scale models of shafts. It is therefore prudent first to evaluate the efficacy of using scale models to draw conclusions on the resistance of shaft systems.

2.2.1 Efficacy of the Use of Scale Models

The use of scale models depends primarily on the use of dimensional analysis in order to understand the importance of certain parameters in the system being considered. A definition was supplied by Pankhurst (1964): "The dimensions of physical quantities can be manipulated algebraically and the results can be interpreted to provide a great deal of information about the physical processes involved in the situation considered."

Unless the geometry of the systems has no effect on the physical situation to be evaluated, the first requirement of a scale model is that it should be geometrically similar to the actual system being evaluated, i.e. the distance between any two points in the modelled system must bear a constant ratio to the distance between the corresponding two points in the original system. This constant ratio is called the 'geometrical factor'.

Similarly, we define the kinematic similarity (i.e. when velocities are involved) by the condition that the velocity at any point in the one system bears a constant ratio to the velocity at the corresponding point in the other system. This is called the 'velocity scale factor'.

Various other factors, such as elastic similarity, thermal similarity, etc., are all defined in a similar fashion but are not pertinent to this discussion.

The limitations of this technique must also be highlighted. Although this technique is powerful and allows a meaningful comparison of scale models with full-scale systems, it must be emphasised that this is only valid as long as the system does not require extrapolation beyond the ranges of the dimensionless parameters defined in the tests. Within these ranges, the dimensional analysis provides the required scale factors, but it provides no information whatsoever about the way in which a given non-dimensional coefficient varies with the dimensionless parameter on which it depends. As a result the specific parameters are allowed to vary and those to which the scale factors will apply must be chosen with care.

As will be discussed below, a number of the measurements carried out and used in the evaluation of shaft resistances were done on scale models (Chasteau, 1962). The two models generally referred to are the 1.981 m (78 inch) model and the 0305 m (12 inch) scale models which were operated by the CSIR. These models were constructed in the horizontal plane and were both configured to allow the flow in them to achieve a fully developed profile before the typical shaft obstructions interrupted this flow. Care was taken to ensure that the mechanical scaling factors for the models and shafts were carefully correlated before tests began. However, as a result of practical limitations, the maximum airflow achieved in these models was half of that generally found in a typical shaft configuration. This had a direct effect on the Reynolds number used in the tests and raises some concern as to the extrapolation of the results.

In order to try and define the extent to which the data from this scale model could be used, various shaft configurations were tested by Chasteau (1962) and the results compared. These tests showed little correlation. In the 0.305 m (12 inch) model, the test showed little agreement even to standard pipe values. The tested values were lower than expected and the results showed that the test flow was potentially not fully developed.

The results also showed that it is perhaps generally better to use direct drag measurements to determine the effect of the resistance of buntons than to use the pressure drop. This has the advantage of removing the pipe wall roughness considerations from the overall measurements. When compared with full-scale shafts, the scaling up of the Reynolds number may be an inaccurate procedure even if the effect of wall roughness can be taken into account. The differences between the two scale models seems to be primarily a result of the difference in wall friction effects. The direct drag measurements do correlate satisfactorily.

In spite of these shortcomings, which show that direct correlation of the results may yield inaccurate results upon calculation, the tests completed are sufficient to demonstrate the empirical direction that should be taken to reduce shaft resistances.

2.2.2 Measured Data Discussions, Results and Conclusions

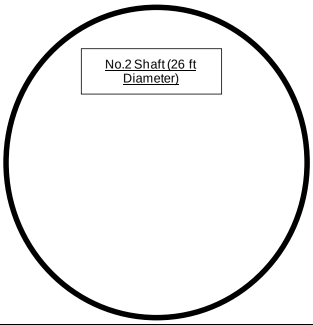
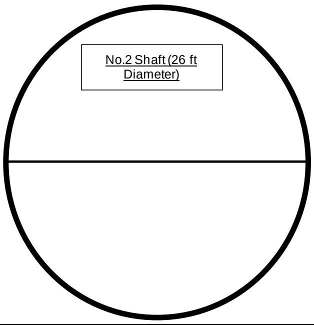
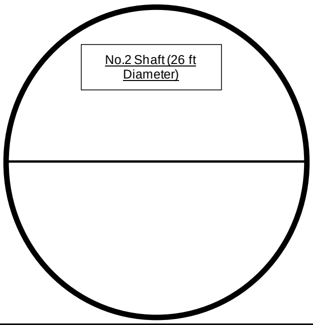
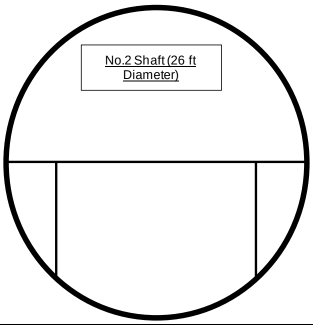
In 1957, scale model tests were carried out on the configurations being included in the design of Harmony Gold Mining Company's No. 2 and No. 3 shafts (Martinson, 1957). These tests were undertaken at the time specifically because the shafts in question were installing equipment that was novel. It was therefore decided that to obtain an accurate result for the resistance each of the shafts offered to the air flowing through them, it would be necessary to subject the arrangement to scale model tests. These tests went further than the standard measurement of the shaft configuration. To gain an understanding of the overall effect of each of the pieces of equipment that were to be installed in the shaft, tests were conducted as equipment was added to the scale model.

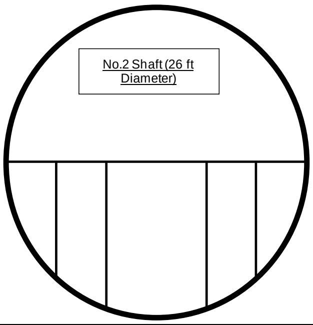
The basic requirements for scale models were adhered to:

1. The scale model must be geometrically similar to the original shaft for which it is being used to predict losses.
2. Dynamically similar conditions between the flow conditions in the model and the shaft must exist, i.e. the air velocity in the model duct must be equal to the air velocity in the full-size shaft, multiplied by the chosen scale ratio.

The scale factors that were used are 1:12.9 for the No. 2 shaft and 1:12 for the No. 3 shaft. The details of these calculations can be found in Appendix C. A summary of the various tests completed for the Harmony No. 2 shaft is given in Table 2-1. This table shows the various shaft configurations that were tested in the scale model. The Chezy-Darcy friction factor that was calculated from the measurement of these models is shown for both shafts in Figure 2-1.

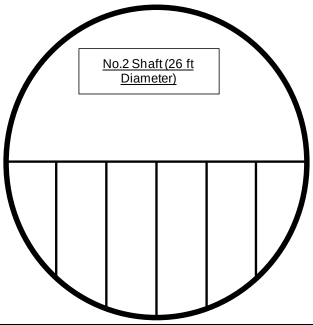
Table 2-1: No. 2 shaft (7.92 m (26 ft) diameter)

	Test Number 1 No buntons No buntons
	Test Number 2 Bunton at 9.144 m (30 foot) centres
	Test Number 3 Buntons at 4.572 m (15 foot) centres
	Test Number 4 Buntons at 4.572 m (15 foot) centres



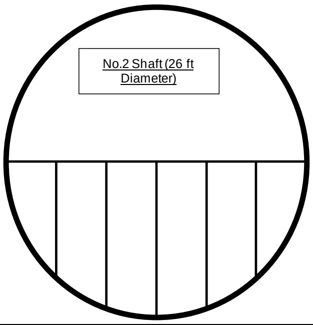
Test Number 5

Buntons at 4.572 m (15 foot) centres



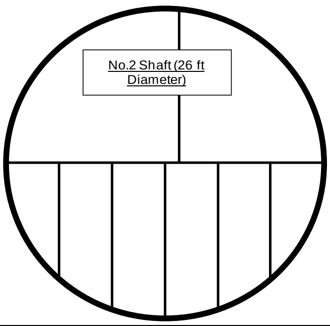
Test Number 6

Bunton at 9.144 m (30 foot) centres



Test Number 7

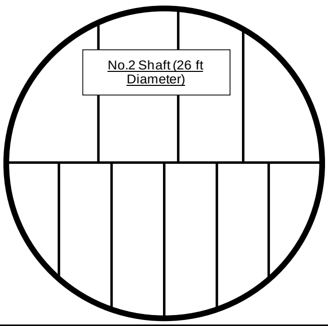
Buntons at 4.572 m (15 foot) centres



Test Number 8

Buntons at 4.572 m (15 foot) centres

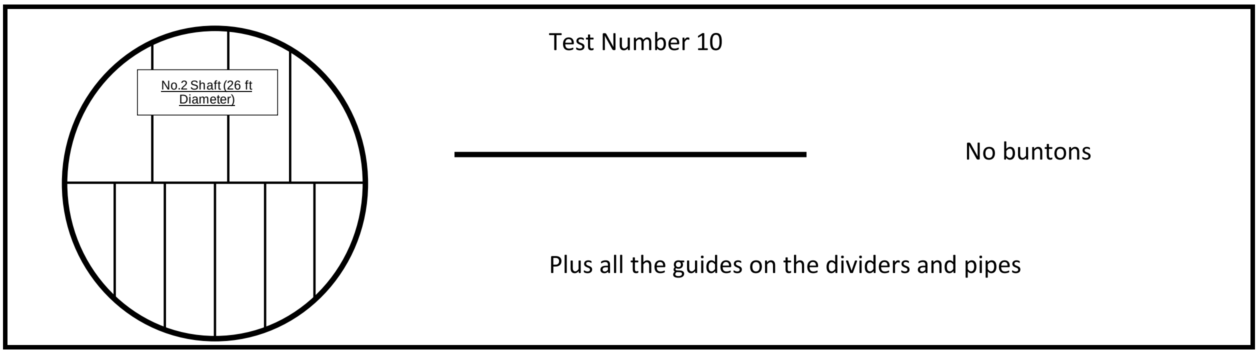
Plus all the guides on the dividers



Test Number 9

Buntons at 4.572 m (15 foot) centres

Plus all the guides on the dividers



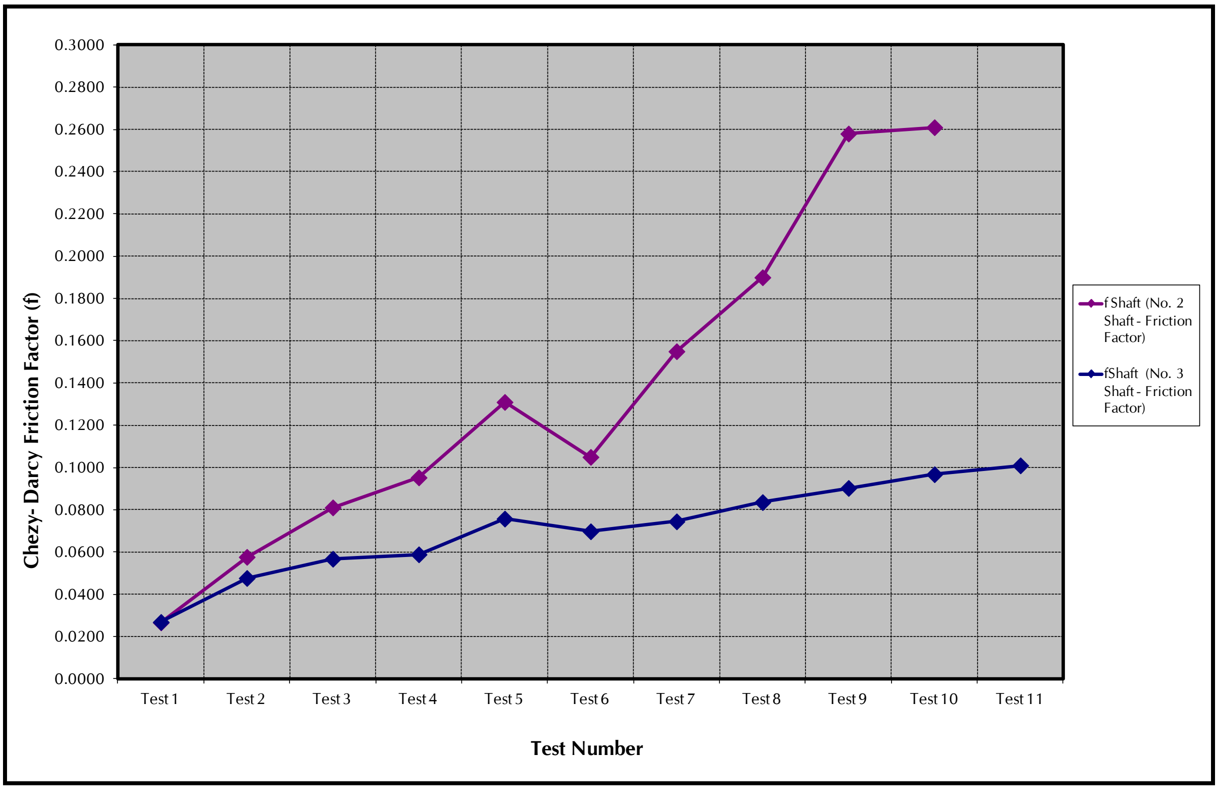


Figure 2-1: **Chezy-Darcy friction factors for Harmony No. 2 and No. 3 shaft scale model tests**

The tests with this scale model were carried out with Reynolds numbers between 500 000 and 900 000. There are some anomalies in the data. The following general comments are applicable to the data evaluated here:

1 The inconsistencies remarked on are particularly apparent for the resistance values obtained for the individual members in No. 2 shaft. The differences in the profiles do not appear to account for the variations in the measured resistances. It was postulated by the author that the changes are due to changes in the velocity profile in the shaft as additional members were added to the shaft cross-section. These differences were also

noted in the test results from No. 3 shaft. It would therefore be advisable to treat the individual resistance values with caution if they are to be applied to other shafts.

2 The few longitudinal spacing tests carried out do not provide sufficient data with which to establish any relationship between the shaft resistance and the spacing of the shaft supports. Although these data do demonstrate that increasing the distance between bunton centres has an effect on the shaft resistance, this also asymptotes at approximately 4.572 m (15 foot) centres for the one bunton configuration tested.

3 These tests did confirm that the Chezy-Darcy friction factor is largely independent of the Reynolds number, which is as expected.

4 The data measured from this experiment were analysed in accordance with current theory. The results of this analysis can be found in Appendix C. The calculations show that there is some correlation with the current theory for the prediction of pressure losses in shafts, but this agreement is not consistent. The difference between the calculated resistance and the measured resistance is consistently approximately 30%. This may be attributed to a number of factors:

- A number of the parameters need to be assumed from standard tables (e.g. the drag coefficients, the velocity profile of the test section, etc.).
- There is limited knowledge on the actual scaled system used for the tests other than the broad description. Thus ensuring that the correct values were used for the required parameters was challenging.

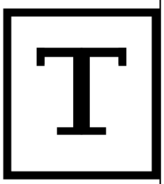
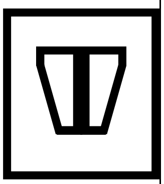
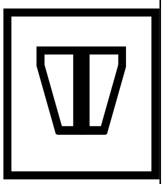
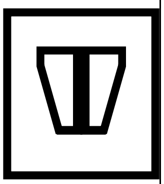
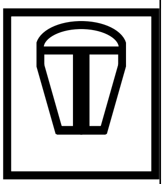
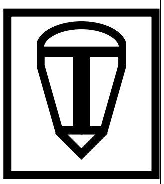
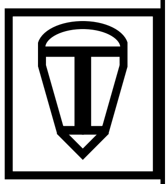
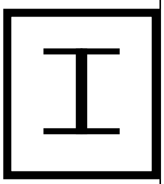
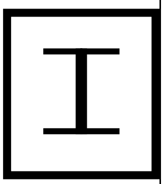
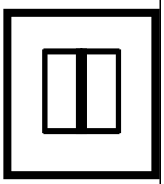
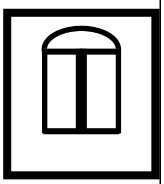
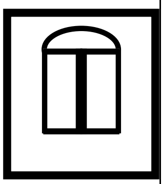
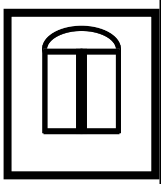
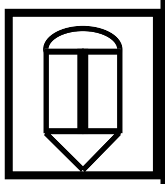
This was the first recorded instance of the use of a scale model to test the resistance of a shaft and it is thus expected that there will be some anomalies that will require clarification. The test did, however, achieve its goal in that the shafts in question were shown to be able to support the required ventilation and this proved to be correct.

In 1959, Chasteau conducted some basic tests on the Pioneer Shafts of the Buffelsfontein Gold Mine. In this instance some measurements were taken on the shaft itself and these were compared with the results obtained using a scale model test rig. It was a horizontal test rig 1.9812 m (78 inches) in diameter, which resulted in scale ratio of 1:4. The steelwork was manufactured from plywood, including the radii of the buntons. The tests were conducted at relatively low Reynolds numbers. The results from the scale test did not compare favourably with those from the shaft itself. This difference was attributed to the particularly difficult conditions encountered in the shaft during the tests. These comparisons were made with the final test configurations.

However, the scale test did evaluate the different bunton shapes. These were changed sequentially for the different tests and allowed meaningful comparisons to be made. The initial bunton shapes were standard RSJ sections and modified T sections. These were modified until the overall shape being evaluated was similar to a streamlined bunton connection. These bunton shape changes are depicted in Table 2-2.

The measured results were compared with current theory; the details of these calculations can be found in Appendix C. These calculations showed varying correlation with the measured results. These differences are in some part attributed to the assumptions that were made of the drag coefficients for the various bunton shapes. The tests showed clearly that the streamlined bunton sections offered approximately half the resistance offered by the un-streamlined sections.

Table 2-2: Pioneer shaft bunton shape changes

Primary bunton shapes						
Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
						
Secondary bunton shapes						
						
Measured friction resistances of the shaft configuration for the various tests						
0.381	0.255	0.210	0.198	0.168	0.159	0.152
Note Each test considers the primary and the secondary buntons together.						

The following general comments should be noted on the tests conducted for Pioneer shaft.

i The actual free air velocity measured was very low in comparison with the velocities usually found in shafts.

ii The general analysis of the system is only to depict how best to reduce the friction of the shaft; in this it was successful. However, the data are insufficient to draw more than general conclusions about the behaviour of the airflow around the buntons.

iii The correlation between the measured and calculated figures is strongly dependent on the complexity of the bunton shape being considered.

These two initial tests showed the way forward with respect to both potential shaft layouts and the shape of the bunton to be used for the shaft steelwork. Neither of the papers (Martinson, 1957; Chasteau, 1962) dealt with the placement and efficacy of the services within the shaft or the overall effect of the cage movement within the shaft. In addition, while these results provide general guidance as to the layout and the bunton shapes, neither of these parameters can be used in more than general terms for the analysis of additional shafts.

Graves (1961) noted that before the 1960s, all shafts were rectangular and were designed for the transport of men and materials alone. However, when the energy costs became important and it became increasingly difficult to move ventilation air underground, the shaft resistance to the ventilation air was considered. Graves felt this was worth highlighting in order to emphasise the importance of changing only one parameter at a time in order to obtain the best results. In this instance significant savings were accrued from modifications to the buntons, as well as the use of round shafts. The extent to which each of these changes contributed to these reductions was never ascertained.

In this regard (i.e. the evaluation of rectangular shafts) the effect of changing the equipment in a rectangular shaft was monitored Botha and Taussig (1961). The equipment in this shaft was changed in the following ways:

1 Old worn timber sets were replaced with steel sets.

2 Existing steel ventilation piping was used to facilitate the carrying of additional downcast air in a timbered rectangular shaft.

3 The effect of placing half-round caps on the buntons was evaluated.

4 The effect of removing some of the buntons in a shaft was evaluated. This was possible as the hoisting speed was reduced.

5 The Chezy-Darcy friction factors for wood, smooth steel and galvanised iron piping in vertical shafts was evaluated.

The shafts were tested but not in detail due to the limited shaft time available. The emphasis was put on getting enough data of sufficiently good quality which could be used on a relative basis.

The following particulars were noted from the tests:

i It was noted that replacing old timber in shafts with un-streamlined buntons had no beneficial effect.

ii The large-diameter smooth pipe did help to increase the air-carrying capacity of the shaft without increasing the power consumption.

iii The half-round caps that were placed on the buntons in the concrete-lined shafts did reduce the shaft resistance by approximately 30%.

iv It was possible to remove every second or third bunton and this reduced the shaft resistance by between 25 and 40%. The original bunton spacing was 3.048 m (10 ft).

All the changes discussed here are strongly dependent on the velocity of the ventilation air and therefore the required outcome for a specific shaft may require different methodologies and analyses. The nature of the tests was such that the data presented could not be relied on for detailed analysis, but it was hoped they would provide a useful summary. The overall reduction effect is consistent with those found in other shafts.

The next test took the understanding of the resistances shafts offer to ventilation air to another level. In this instance, the resistance that the Vaal Reefs No. 1 shaft offers to the air flowing through it was measured by Quilliam et al. (1961). This is a dry shaft divided into five compartments. Various tests were conducted in the shaft and on the levels to obtain measurements that would allow the calculation of the shaft resistance. However, the details of the tests and the observations made were not included in the paper. It was stated that during the tests the ventilation fans were baffled in order to vary the velocity of the air in the shaft. These variations in velocity showed that there was a significant difference in the resistance in the lower Reynolds number range, but that this difference was reduced once the higher Reynolds numbers were used.

Once the above tests had been completed, Chasteau (1961) set up the scale model to be similar to the Vaal Reefs shaft in order to verify the measured data. The same scale arrangement was used as for the Pioneer shaft discussed above. In addition to this, a 1.981 m (78 inch) wind tunnel and the 0.305 m (12 inch) wind tunnel were used. These tunnels had scale ratios of 1:1,393 and 1:24 respectively. Once again, as the scale models were equipped, the buntons were increasingly streamlined and the differences measured. In both of these models the data showed significant scatter when lower Reynolds numbers were used for the testing. Although the resistance at these lower velocities was also noted to be lower, this scatter was attributed to the inadequacies of the instrumentation used. At high Reynolds numbers, i.e. $1.2x10^5$ for the 1.981 m (78 inch) model and $2.5x10^5$ for the 0.305 m (12 inch) model, the Chezy-Darcy friction factor calculated from the data became constant. In addition, in the sections of the wind tunnel that had no 'equipment' installed, it was noted that the results were very similar to those of the full-scale shaft measured.

The data were also plotted against the mean air velocity in the scale models. This showed a much better correlation to the shaft measurement than the Reynolds number, prompting speculation from the author that this was perhaps a better way to depict the results. It was also recommended that, in order to understand the air flow in the mine shaft more fully, the turbulence characteristics of the models and the mine shaft needed to be better correlated. In spite of this there was good agreement between the shaft test results and those of the scale model.

These tests and comparisons provided additional insight into the working of the shaft system. However, there are a number of questions that the tests still did not consider:

i An increase in the turbulence of the scaled systems from 1% to 3% resulted in an increase in the drag coefficient from 1.27 to 1.33. This highlighted the individual nature of shafts as the majority of the turbulence experienced by the shaft ventilation air is induced by the structure within the shaft. It also emphasised the importance of ensuring the accuracy of the various coefficients used for the theoretical evaluation. (in this instance, the intensity of turbulence encountered is measured by the non dimensional number N, where

$$\mathrm{Re} = \frac{\rho\,D\,U}{\mu} = \frac{\rho\,D\,U}{\rho\,l\,v} = N$$

Where:

Re	-	Reynolds Number
ρ	-	density
D	-	diameter
μ	-	dynamic viscocity
l	-	mixing lenght
v	-	component of turbulent velocity at right angles to the mean speed U
N	-	non dimensional number for turbulent flow equivalent to the Re number in laminar flow

ii The results from the two wind tunnels agreed reasonably well for Reynolds numbers of 400 000, but this agreement was closer for buntons that were further apart.

iii The resistance of the shaft only was evaluated, and of the shaft and the equipment in it. No attempt was made to evaluate the effect that the age of the shaft and the age of the skips might have on the resistance of the shaft.

iv The aim of the general analysis of the systems was only to depict how best to reduce the friction of the shaft; in this it was successful. However, the data are insufficient to draw more than general conclusions about the behaviour of the airflow around the buntons.

v There seems to be a linear relationship between the increase in the bunton spacing and the resistance of the shaft.

The measured results were compared with current theory and the details of these calculations can be found in Appendix C. These calculations showed varying degrees of correlation with the measured results, with one measurement showing a significant difference. The average percentage difference is approximately 50%. It is thought that these differences are a result of the assumptions made for the drag coefficients for the various bunton shapes that had to be estimated. This is thought to be one of the primary reasons for the discrepancies between the calculations and the measured results. However, as was noted by Chasteau (1961), perhaps some portion of these differences could be accounted for by the lack of adequate instrumentation, especially where the lower Reynolds numbers were used.

At this stage of the progress in determining the actual resistances of shaft systems, we have a number of scale model tests, none of which were verified with field tests. Graves (1962) helped to fill this gap by testing three shafts to determine their actual resistance to airflow. The basic characteristics of each of these shafts are listed in Table 2-3.

Table 2-3: Tests on downcast shafts

Description	Shaft No. 1	Shaft No. 2	Shaft No. 3
Name	President Brand No. 3	Vaal Reefs No. 2	Western Deep Levels No. 3
Bunton type	AirSave	Squashed pipe	Squashed pipe
Coefficient of drag	$C_D = 1.55$	$C_D = 1.25$	$C_D = 1.25$
Shaft depth	1 219.2 m	1 493.2 m	1 592.9 m
Bunton spacing	4.572 m	6.10 m	6.10 m
Velocity of air in shaft (free air velocity)	12.93 m/s	10.19 m/s	10.10 m/s

All the shafts had pipes and cables in them, but not in significant quantities. All the cages being used in the shaft were parked on the bank during the tests and the air was entrained in the shaft below this level, resulting in the measurement of an unobstructed shaft.

The results of these tests were tabulated and conclusions were presented by the author (Chasteau, 1961). These are:

1 The resistance of the slim (0.102 m (4 inch) wide) hexagonal buntons is appreciably less than that of the rather thicker (0.152 m (6 inch) wide) rounded buntons.

2 The wider vertical spacing of the bunton sets results in a reduction of the shaft resistance.

3 The 0.152 m (6 inch) squashed pipe buntons used show a lower resistance than the semi-streamlined buntons.

4 It is concluded that the streamlined buntons do in fact reduce the airflow resistance by some 50% over the standard I sections.

The measured results were compared with current theory. The details of these calculations can be found in Appendix C. These calculations again showed varying amounts of correlation with the measured results, with one measurement showing a significant difference. The average percentage difference is approximately 50%. It is thought that these differences are a result of the assumptions that were made in determining the drag coefficients for the various bunton shapes. In addition, no information was made available about additional inclusions in the shaft, such as levels and intermediate pump station levels, all of which would have an effect on the measured shaft resistances.

Although this paper does not deal with the dynamic aspects of the resistance losses and does not evaluate actual shaft configurations, up to this time this was the most complete set of results that had been compiled for the evaluation of shaft resistance. However, the measurements were only taken at the top and bottom of the shaft and no attempt was made to identify the progressive resistance of the shaft. This could also be one of the factors that resulted in the difference between the theoretical calculations and the results from the research work, as none of the effects of the station steelwork or the stations themselves was taken into account.

Nevertheless, the data presented here once again provide empirical evidence as to the validity of the design of shaft systems using more streamlined bunton sets. Martinson (1962) notes that as a result of the work completed on the resistance of shafts, the use of RSJ as buntons and dividers in shafts had been scrapped. This scrapping was matched by an increase in the bunton spacing for the same reason, namely to reduce the resistance of the shaft. He also noted that both the 'airsave' bunton and the 'squashed pipe' bunton significantly reduced the resistance of the shaft, but cautioned against the statement that the actual resistance of the 'airflow' bunton was higher than that of the 'squashed pipe' version, as this statement was based on observations made on two different shafts without an effective evaluation of other variables. He recommended that these buntons should first be tested in similar conditions before such statements were made.

In an attempt to quantify the actual effect of the various systems in the shaft, Chasteau and Kemp (1962) conducted a series of tests on a scale model. The initial tests showed that the increased streamlining of buntons reduced the shaft resistance. Although this was not new, additional variations in the shaft configuration also showed that streamlining the central portion of the shaft cross-section had the most significant effect on the overall shaft resistance. It was noted as well that the most significant reduction occurred when I sections were converted to streamlined sections. There was, however, little difference when tails were added to this configuration.

These tests were also the first to consider the contribution made by the cables and pipes to the resistance of the overall shaft. Removing the cables resulted in a reduction of 10% and removing the pipes and the associated brackets an additional 11%. Lambrechts and Deacon (1962) built further on this work by testing the changes in shaft resistance in a shaft while it was being rehabilitated, i.e. with the rough wall smoothed and the bunton and guides in the shaft removed. In this instance, the shaft resistance was reduced by 87% when the buntons, guides and associated connections were removed. An additional 50% reduction in the shaft resistance was noted once the rough wall had been smoothed.

Casati and Martinson (1962) also added to this growing database by using a model to measure the effect that bunton spacing had on the overall resistance of the shaft. This test showed that the resistance of the shaft equipment was significantly higher than that of the shaft wall. The test also showed a reduction in the shaft resistance as the bunton spacing was increased.

Casati and Martinson (1962) also did tests on a different model. In this instance the No. 4 shaft at City Deep Mine was modelled. This is a circular shaft. One result of interest from this test was that the lined portion of the shaft showed a resistance of approximately 40% less than that of the unlined portion. Another interesting result was that the addition of various pipes and cables decreased the resistance of the shaft. No reason was proposed for this anomaly and no additional investigations were made at this time. Once again no effort was made to evaluate the effect of the shaft cages on the shaft resistance.

In this regard some anomalies were noted in ventilation pressure and energy surveys at Freddies Consolidated Mine Limited (Unsted and Benecke, 1978). There were large variations in absolute pressure, sometimes accompanied by airflow reversals. These reversals were traced back to the passage of the large cage in the downcast shaft at No. 3 shaft.

To establish how this occurred, barometers were placed at the bank of No. 3 and No. 1 shafts and on 53 level of the same shaft. It was noted that the barometric pressure was considerably lower when the cage was below the observation point than when above it. In addition, the barometric pressure fluctuations at No. 1 and No. 3 shafts were 'in phase' and these phases were linked to the position of the cage in No. 3 shaft. No. 1 and No. 3 shafts are approximately 4 500 m apart and these pressure variations were instantaneously transmitted throughout the ventilation system. This was due partly to the high velocities present in these shafts. An air flow velocity of 18.9 m/s was present in No. 3 shaft and this increased to approximately 25.4 m/s when the cage was in the shaft.

In order to effectively evaluated the response of the ventilation flow in a shaft to cages moving through the shaft a study was undertaken by Ruglen and Wilson (Ruglen and Wilson, 1978). In this paper various shaft and haulage configurations were evaluated, including the effect of conveyances on ventilation flow in a shaft. One of the most significant findings was the large effect that the inclusion of ribs had on the overall resistance that the conveyance offered to ventilation flow through the shaft. The importance of keeping the cages doors closed while moving the conveyance through the shaft was also noted. While little data was included in this report, it was noted that reduction in the losses around the cage could be reduced by as much as 50% for a cage with a shaft blockage of 30%, but that this reduced to 40% for the blockage of 50%. The optimum size of fitting size of fairing was found to be between 0.3 and 0.35 times the width of the cage.

2.2.3 Significance of Available Data

All these tests provide valuable empirical data, as well as valuable direction as to the way in which the design of shaft systems should proceed. There is a definite trend towards the following criteria for shaft design at this point:

i Buntons and guides should be streamlined.

ii Shaft walls should be lined.

iii Buntons should be spaced as far apart as possible.

iv In addition, it is important to ensure that the velocity profile in any test section is as close to that of the shaft as possible.

Up to this point, however, no definitive data are available on the actual manner in which the above systems should be designed. This is primarily a result of the difficulty in measuring the actual resistances of installed shafts and, once measured, of the high requirements in terms of time and cost to adapt their configuration for additional tests. This led to the use of scale models. The accuracy of such models and concerns surrounding their use and results have been described.

In addition, there is no reference to the quantification of the results in accordance with the procedure presented by Bromilov (1960). The calculations performed during this research project are based on the work presented by Bromilov (1960) and latterly McPherson (1987), and there is little correlation between these and the tests carried out.

Finally, although the manner in which the various measurements were taken is recorded, little information is available from the actual data measured and, other than the reference by Chateau (1961) to the accuracy of the instrumentation and its placement, no comment is made on this.

One of the objectives in reviewing these papers was to try and find additional data to calibrate a computational model. In this instance the difficulties associated with the measurement of shaft resistances were highlighted, particularly with regard to ensuring that sufficient time is allowed in the shaft to complete such measurements.

It was also noted that the horizontal test chamber (Chasteau, 1962) showed little reduction in the shaft resistances when pipes and cables were introduced. Other papers to note this was that presented by Casati and Martinson (1962). This reduction was also noted by Bromilov (1960) and this highlights the danger of using scale models without fully understanding their ramifications.

The effects of the uniqueness of each shaft layout, the resultant effect on the turbulence of the shaft and its effect on the measured coefficient of drag were also highlighted by Chasteau (1961). As a result of the general lack of information available on the shafts and models being tested, the various methods available for testing shaft resistances accurately are discussed below.

The investigation of fairings on the shaft conveyance is worthy of investigation as these can also result in reductions in the overall losses experiences by the shaft.

2.2.4 Methods of Testing Shaft Pressures

The actual manner in which the measurements were taken for the various tests should be considered when evaluating the current results. The shaft measurements discussed above used different techniques for measuring the pressure and free air velocity at various points in the shaft. Three recognised techniques are used to evaluate the resistance of a shaft:

1 Density method

2 Full volume–Reduced volume method

3 Trailing hose method

Bareza and Martinson (1961) commented on the efficacy of using these methods for the measurement of shaft systems and these comments are discussed here to highlight the fact that when systems with large vertical differences (i.e. shaft systems) are tested, there are often parameters that normally would not cause concern but that suddenly become very important to control if accurate measurements are to be achieved.

1 *Density method*: The pressures at the top and bottom of the shaft are measured. The pressure at the bottom of the shaft is then compared with the calculated pressure that should occur at the shaft bottom, assuming the shaft was frictionless. This method requires some calculation and it is therefore an indirect method of measurement.

2 *Full volume–Reduced volume method*: This is based on the fact that the pressure loss in any given section of an airway is a function of the flow rate and of the mean density only. This method is useful because of its simplicity, but to obtain good results it is better used in areas where the difference in the flow rate is large. This is also an indirect method of measurement.

3 *Trailing hose method*: When this method is used, density correction must be applied to obtain the correct value (Barenbrug, 1962). If this is not done, the error can become significant when pressure is evaluated over the length of a shaft. This is, however, a direct measurement system, albeit one given to inaccuracy due to the long vertical differences between each of the measurement points.

Density method

In order for this method to apply, it is assumed that the density of the fluid varies linearly with the elevation. This assumption is of particular importance when evaluating the theoretical term over large elevation differences where the assumption of linearity may not apply.

An examination that was conducted by Hemp (1975) showed that the assumptions noted above did provide reasonably accurate results but that there were also a number of cases where this was not true. To try and achieve better accuracies, Hemp suggested a two-pronged: approach:

i Recognise the assumption that conditions along an airway are perhaps not valid.

ii Use a method for correcting the pressure survey results to allow for departure from the assumption.

A method is supplied to test the accuracy of the calculations, but this has not gained general acceptance. In order to ensure, as far as is practically possible, the accuracy of the planned tests, this calculation must be completed for steady-state tests to verify the testing procedure. However, the act of correcting data could also corrupt the reason for the measurement, which is to ascertain the extent of the pressure losses that occur during the dynamic conditions of the cage movement, and it will thus not be used once the procedure has been confirmed.

Suffice it to say that when the experimental procedure is designed it must take cognisance of these potential inaccuracies and ensure that the requirements to avoid them are met. Although it should be noted that there are problems associated with this indirect measurement method, these problems can be overcome by proper design of the survey.

Full volume–Reduced volume method

This survey method involves measuring the barometric pressure, as well as the wet bulb and dry bulb temperatures at the two ends of the survey. These measurements are taken during the full flow condition and during the reduced flow condition.

This method has advantages. However, to be able to calculate the pressure drop over an operating shaft, it is not possible to reduce the volume of air flowing through it without affecting the production of the shaft. This method will therefore not be considered further here.

Trailing hose method

The principle of this method is straightforward. A hose is laid along the length of the airway and a suitable pressure differential measuring device is attached to either end. If the airway is horizontal, then the differential pressure is equal to the friction pressure loss. In a vertical airway this is not identical, but calculations can be used to find the friction pressure loss.

This method has its advantages and disadvantages, all of which can be corrected. For example, care must be taken to ensure that the psychrometric properties in the hose are the same at difference elevations. This is most easily taken care of by ensuring that there is no moisture in the hose and that the conditions are such that condensation does not occur. This method has one primary disadvantage, namely the physical length of the hose and the logistics of laying a trailing hose in a shaft more than 1 000 m long. This method will therefore not be considered further here.

Kemp (1962) investigated these methods of measurement and commented specifically on the use of the trailing hose method of resistance measurement. He noted that the use of the trailing hose resulted in error owing to the differences between the density of the air in the shaft and the air in the manometer tubes. This effect increases as the length of the trailing hose increases. This concern can be overcome by ensuring that the air in the manometer is at the same temperature as the shaft air. In addition, the hose should be well ventilated with the shaft air to ensure consistent moisture content before the tests are started.

2.3 DESIGN CONSIDERATIONS

Any discussion on the design of shaft systems and their evaluation with respect to the resistance they offer would not be complete without discussing the work contributed by Bromilov (1960). Bromilov separated the resistances for the various items in a shaft system in order to evaluate each of these items separately. The sum of the resistances offered by each of these items listed below results in the calculation of the total shaft resistance:

1 Shaft walls

2 Shaft fittings (buntons, guides, pipes, etc.)

3 Cages and/ or skips

The base assumption of this work is that the resistance offered by each of these items is independent of the resistance offered by the others. In the context of the work produced by Bromilov, each of these will be discussed separately because the analysis techniques for each differ.

Shaft walls

The resistance of the shaft wall is calculated using factors available for standard pipe theory for skin Chezy-Darcy friction factor of the wall or the duct wall. These Chezy-Darcy friction factors allow the calculation of the resistance of this item based on its size, the roughness expected of the wall and the flow of air through it. The limitation of this theory is that it can give conservative results when very rough walls are included in the calculation.

Guides, pipes and cables

It was noted that fittings such as these may actually reduce the resistance in a shaft. Nevertheless, the resistance they offer is estimated by subtracting the area of these fittings from the area of the shaft to obtain an increased air velocity. To calculate the resistance offered by fittings such as flanges, the free area used for the calculation of the increased velocity is reduced by the amount that the flanges reduce the overall area available.

It should be noted that no attempt is made to quantify the potential decrease in the shaft resistance as a result of the inclusion of these items or to quantify the additional turbulence that would occur as a result of the inclusion of discontinuities such as the flanges. It was, however, postulated that the reduction in resistance is based on the reduction of the swirl in the shaft.

Buntons

The calculation of the resistance that the buntons offer the airstream is based on the drag that the bunton would experience. This drag is defined as follows (McPherson, 1987): “A body placed in an airstream is acted on by forces due to the movement of the air past it. The force on the body that is parallel to the airstream is known as the drag and is proportional to the approach velocity to that body and of the air and frontal area of the body presented to the airflow”.

One of the limiting assumptions for this theory to apply is that the airflow past a set of buntons is not affected by the presence of the buntons upstream. To estimate this effect, the calculation includes for the use of an interference factor, which is calculated based on the distance between subsequent sets of buntons.

Cages and skips

The calculation of this is based on work by Stevenson (1956). Stevenson used a horizontal duct of circular cross-section in which he placed cages of various configurations and sizes, and measured the response of the airstream to these. The resistance that these offer to the airstream has been included in Bromilov’s calculation via the use of various factors applied to the cage based on its shape, size and length.

It was interesting to note that Stevenson also investigate the use of fairings. The judicious use of these resulted in the measured resistance of the cage reducing, in some instances by more than half. The application of this work does, however, assume that the cages are sufficiently far apart such that any disturbances they apply to the airflow will not affect the other conveyances.

2.3.2 General Discussion

At the time, Bromilov’s work was the first attempt to calculate the actual resistance offered by shaft systems. Following this work, Van Wyk (1961) presented a paper which discussed the design requirements of shaft systems with the respective resistances a shaft would be expected to offer. Van Wyk did not refer to Bromilov’s work, but the conclusions reached were similar. He produced a table comparing the unit cost of each of the bunton shapes with the resistance they offered to the flow of air in the shaft. However, before one can have a meaningful discussion on the most cost-effective system to be installed in a shaft, it is necessary to have a better understanding of the current shaft steelwork design theory of shaft systems.

The current design theory and understanding of the ideal bunton and guide connection holds that shaft system should be designed so that the buntons are as flexible as possible and the guides as rigid as possible. This arrangement offers the best configuration for the support of the conveyances as they move in the shaft and the constraint of the conveyances within their travel paths. This requirement is fortunate as the more slender buntons have a significant advantage for the flow of ventilation, and the cross-section of the guides that is generally presented to the flow is minimal.

Rope guides should also be considered in the design of shaft systems as they present the smallest cross-section to the airflow. However, the large space requirements between the conveyances in such a shaft and between the conveyances and the sidewall are such that a large shaft is required to accommodate a number of conveyances. There is also the complication in multi-level mines that each of the conveyances to be used must be constrained at each of the levels that the cage serves. This generally requires construction of a system that will protrude into the shaft, thus creating a potential safety risk to the operators of the shaft. Any constraint in this regard will also have an effect on the cycle times of the conveyances.

In shallow mines, the portion of total capital cost apportioned to shaft sinking is relatively small. This cost increases substantially as the shafts are sunk to deeper levels. It is therefore important to utilise this capital expenditure as efficiently as possible. This means that a shaft must be designed to permit maximum hoisting while still allowing the maximum ventilation through the shaft. There are basically three ways to reduce the resistance of the shaft during the design phase. These are:

1 Improve the aerodynamic shape of the obstructions.

2 Reduce the frontal area of the obstruction.

3 Increase the space between the obstructions.

A fourth way will be examined in this thesis, and that is optimising the layout of the cages, skips, guides and services in such a way as to minimise the overall resistance offered by the shaft.

Knowing the interaction between these options is important, and Van Wyk's paper highlights some of the more significant concerns in this regard.

Once the aerodynamics have been considered, the only other methods left for reducing the shaft resistance are to reduce the frontal area of the shaft fitting and to increase the spacing between the buntons. These methods must be considered in conjunction with the alignment of the shaft. If the shaft can be correctly aligned, then it is possible to reduce the strength the buntons needed and the number of buntons can be reduced.

With regard to increasing the bunton spacing, it must be noted that with the improvement of the aerodynamics of the buntons, the effect of increasing the bunton spacing becomes less pronounced (Martinson, 1962). The use of these buntons must, however, be considered in conjunction with the complications they introduce, with respect to both the installation and maintenance of the shaft. Once these criteria have been optimised, the auxiliary services become important.

In conclusion, Van Wyk felt that the contribution of the shape of the bunton to the shaft resistances had reached a point where it could now be considered fully developed. He proposed that the emphasis now be placed on the design considerations.

In this paper, Van Wyk highlighted the specific design concerns that the shaft engineer had to consider. However, no theory other than the broad terms described above was included. In addition, all the comments he made were with respect to static installed systems. He did not comment on the resistance offered by the cages or the specific placement of the services and how these placements could affect the shaft resistance.

Bromilov's (1960) work was further built on by McPherson (1987). In this work McPherson simplified and metricated the calculation of shaft resistances. He also introduced the concept of 'rational resistance'. In this representation the resistance depends only upon the airway geometry and roughness, and is independent of air density.

In addition, he proposed the use of the Colebrook-White equation for the derivation of the shaft Chezy-Darcy friction factor. This equation is based on the Moody chart for the Chezy-Darcy friction factor and is consistent with the work Bromilov presented. The use of this equation does allow the mathematical evaluation of the shaft lining in the more conventional manner.

The theory used in McPherson's paper was consistent with that proposed by Bromilov. He also evaluated the results from Stevenson's tests and included these in the evaluation of the resistances offered by conveyances in the shaft. In this paper McPherson did not add significantly to the store of knowledge available for the calculation of shaft resistances, but he did simplify its application.

In conjunction with the work by McPherson, Wallace and Rogers (1987) conducted a survey of the shafts currently being used around the world and how they were configured. In this survey, questionnaires were sent to various mining companies. A total of sixteen mining operations participated in the survey with a total of 37 shafts. In this survey the following information was supplied:

1 *Coefficient of fill (C_f)*: This is the percentage of area that a conveyance occupies in a shaft.

- 23 shafts had a C_f of less than 20%.
- 8 shafts had a C_f greater than 50%, all of which were men and materials downcast shafts with a single conveyance.

The trend is therefore that men and materials shafts have a greater C_f while hoisting shafts have a lower C_f. In addition, it was generally noted that as the shafts became deeper, the C_f was lower.

2 *Free air velocity*: This is the velocity of the ventilation flow in the free area of the shafts.

- The most common free air velocity was 5 to 7.5 m/s. (Approximately half of the men and material shafts were in this range.)

- The highest free air velocity was 17.85 m/s.

The modified theory put forward by McPherson (1987) was evaluated by Deen (1991). Deen's specific aim was to define the resistances of shafts and to validate these calculations based on the theory. The shafts chosen for this study varied in size, shape, depth and general fitting arrangements. This work included the review of a rectangular shaft. Deen achieved very good accuracy when comparing his calculated resistances with those calculated using the current theory. The accuracy on three of the shafts was to less than a 5% difference and the difference was 11.8% for the final shaft.

In this exercise, the comparison showed good congruity between the theory and the results. Unfortunately, no information was supplied on how the tests were done, or the assumptions used for the basis of the calculation or the detailed comparison of the results.

In the evaluation of the theory discussed above, all the calculations require that a good database be available for evaluation of the various resistances. In this regard, Fytas and Gagnon (2008) compiled a database of ventilation factors obtained from various mines in the Quebec province of Canada. The reason for undertaking this exercise was increasing concern that the current Atkinson friction factors were based on historical factors obtained from old workings. It was argued that these factors were no longer applicable as a result of advances in mining layouts and techniques. In the compilation of these figures, 137 Atkinson friction factors were measured in 10 underground mines. Unfortunately, no shaft resistances were measured. However, good data were supplied from current mining operations and it was possible to compare the resultant Atkinson friction factors with the historical data. These data showed that small reductions in the measured Atkinson friction factors were possible when compared with the older data.

Fytas and Gagnon's (2008) paper did highlight the importance of ensuring that the Atkinson friction factors used in any evaluation are appropriate to that application.

The design of any system must, however, be undertaken with full cognisance of the capital and operating cost ramifications of any decision. In this regard, there are several costs that influence the size and equipping of shaft systems, namely:

- The total ventilation air that the shaft is required to accommodate
- The cost of the shaft and its equipment
- The limitation of the velocity of the air passing through the shaft
- The size of the equipment to be carried through the shaft (i.e. skips, services, cages, etc).

The general operating costs for ventilation systems have not changed. Barenbrug (1961) noted that:

> "As is often the case in engineering plants, a high capital outlay could result in low operating costs, or low capital outlay in high operating costs and in the ventilation of mine, the same principles hold good. Large diameter shafts with large capital outlay usually result in smaller fan power requirements whilst for the same volume small diameter shafts require large fan power because of the high resistance to airflow. There is thus for a certain volume of air a size of shaft which will give the lowest total cost".

In this regard he noted that the operating costs with respect to a shaft are dependent on

1 the volume and mass of the air transported

2 the density of that volume

3 the length of the shaft

4 the perimeter of the shaft

5 the area of the shaft

6 the overall Chezy-Darcy friction factor of the shaft

7 the mean density of air in shaft

8 the power cost per unit

9 the fan efficiency and the maintenance cost of the fans.

Prince (1961) noted particularly that the shaft is a wasting asset and that for the increase in capital to be used in the sinking of a shaft to be useful, it should be evaluated against the borrowed capital rate to evaluate the actual return on capital. Uhlmann (1961) noted that a more correct criterion for the most economical size (of shaft) is that point at which the percentage return on increased capital expenditure is equal to the rate of interest that the client can obtain on alternative investments or which he would have to pay for borrowing the extra capital. This point must be noted as the overall requirement for the sinking of a shaft is to make a gain on the overall capital investment. This is entirely consistent with the approach suggested by McPherson (1993).

Wells (1973) also emphasised the importance of incorporating the operating costs of the shaft with the overall capital required to build the shaft. The specific emphasis of the design to reduce the resistance of the shaft is correctly based on the fact that the cost of power to overcome the internal resistance to the flow of air through a shaft will live with the mine for its full lifespan. In this regard Wells recommended that the design of shaft parameters that affect the resistance of the shaft should be very carefully considered when designing the internal configuration of a shaft. The additional expense incurred in the construction stage is generally negligible when compared with the benefits that will accrue for the rest of the life of the mine. Some of the more important parameters are listed below:

- Arrangement of shaft steelwork
- Spacing of buntons
- Streamlining of bunton cross-section
- Alternative methods of guiding conveyances (i.e. stub buntons, rope guides, etc.)
- Smooth concrete lining
- Widening of shaft at station elevations
- Bank bypass (independent ventilation inlet)
- Long narrow conveyances
- Scientifically designed ventilation inlets or outlets from the shaft (i.e. splitter blades)
- Fairings to streamline conveyances
- Evase design

This requirement to design efficient shafts goes hand in hand with the requirement to contain the operating costs of the mine. To contain these costs it is necessary that the ventilation engineer on the mine should understand fully the resistance factor within that mine. Once this is achieved, specific steps can be taken to control and improve the overall resistance. Krishna (1992) noted that it is of vital importance that the mine ventilation planning be integrated with the overall mine production and layout planning. This is especially true of the shaft system as decisions affecting this system can have a significant effect on the overall power consumption of the mine. Although deficiencies in the design of these systems can be easily overcome by increasing the pressure that the main ventilation fan can accommodate, this pressure is dissipated in the shaft system and cannot be used to ventilate the mine. It should also be borne in mind that the relationship between power and airflow is cubic, and the cost of these increases is substantially more than the linear value of the increase.

Seeber (2002) also emphasised this point. He noted that through the generation of the Atkinson friction (K) factor, mine operators have a viable means of assessing the impact that ventilation costs have on their operations. The relationship between the pressure drop in the system and the energy required to overcome that pressure drop is a simple mathematical process, providing the mine operator has a good understanding of a ventilation system's resistance characteristics.

2.3.3 Significance of Available Data

The theory described in this section allows for the complete mathematical design of a shaft system with respect to the resistance that the shaft will offer to air flowing through it, but some critical questions regarding this analysis remain unanswered. These concerns are:

1. As the duty required of shafts increases and they are used to transport more services underground, the actual effect of the shaft fittings needs to be quantified. This is especially applicable when it is considered that both Bromilov (1960) and McPherson (1987) commented on the potential decrease of the shaft resistance through the judicious placement of these. In addition, the effect of the connections of the fittings (i.e. pipe flanges, cable brackets) needs to be evaluated so that an explicit solution can be derived.
2. The effect that conveyances have on the resistance of the shaft needs to be more explicitly quantified. This is especially important when the behaviour of large conveyances is considered, with respect to both the forces they apply on the shaft steelwork and the resistance they offer to the ventilation air.
3. The effect that the shaft steelwork has on the ventilation air has been quantified based on the drag resistance it offers to the airflow. In addition, it is noted that the further away the buntons are from each other, the better. Although this had been proven, the actual effect of these on each other required quantification.

The maintenance of shaft systems must be optimised such that it takes as little time in the shaft as possible. In the evaluation of these systems cognisance should also be taken of more recent trends in shaft system design, specifically the general increases in design air velocities. Biffi et al. (2006) noted that although equipped shafts inherently present a higher frictional resistance to airflow, they are also designed for higher air velocities.

The free air velocities in equipped shafts may be as high as 12 m/s and air velocities of up to 22 m/s may be tolerated in unequipped shafts, although some of the free air velocities in South African shaft are higher. These velocities are higher than those recommended by McPherson and are indicative of the requirement to make capital assets such as the shaft work as hard as possible to service the mine’s general requirements.

2.4 COMPUTATIONAL FLUID DYNAMICS

Computational fluid dynamics (CFD) was proposed as a method to help further the understanding of shaft resistances. The first instance of the use of this technique in mining was by Wala et al. (1993). One of the objectives of this paper was to show how CFD simulations can be used to study the airflow across the main airways of a mine ventilation system. In particular, the flow through the transition zone between the upcast shaft and the main fan ductwork was investigated.

2.4.1 General Discussion

Although CFD has many advantages, it does not completely eliminate the need for experimental results, which are still needed to validate numerical solutions. The transition piece was developed and the results collated with tests conducted on site. In this regard favorable comparisons between simulations and measurements supported the use of the software package CFD2000 as a tool for the design and planning of fan ductwork configurations. This is one of the few applications of CFD to design and verify practical ventilation problems. Wala et al.'s (1997) study showed good correlation between the modeled data and that which was measured. The CFD technique used in this instance was therefore validated.

In a similar vein, Meyer and Marx (1993) used CFD to evaluate the design of a fan drift–mine shaft intersection. In this work, Star-CD was used to create a CFD model of this intersection. A number of options were evaluated with respect to the geometry of this intersection. The results of the analysis demonstrated that savings could be achieved by adhering to certain ratios when defining the fan drift geometry. The finite volume mesh for this model was created using the SIMPLE algorithm and the turbulent model used was k–epsilon. The economics of the potential reduction in pressure losses were also evaluated.

This work and that described above was found to be some of the earliest work using CFD to resolve engineering issues on mines.

In 1995, Brunner et al. described a number of problems they had solved using advanced CFD techniques. The most useful was their finding that the mesh generation at this point had developed to the extent of allowing relative movement of the meshes, enabling the simulation of multiple moving bodies. In these examples, trains moving through openings were evaluated and the specific geometry of the opening through which they were moving was evaluated. These models were created using the Fluent software. The models assumed incompressible fluid, and radiation and heat conduction were neglected in their evaluation. The result of this analysis showed the importance of 'flaring' the opening in order to reduce the pressure losses through these openings.

To explore the potential for using CFD modelling in mines, Wala et al. (1997) used CFD techniques to model the flow of air between a shaft and the main ventilation fans of a mine. These modelled results were compared with those from work completed in 1995 on measuring the flow characteristics between these points. The model assumed incompressible airflow and specified steady-state, turbulent, single-phase flow. The effects of body forces and heat transfer were considered to be small and were not taken into consideration. This exercise showed favourable comparisons between the data and the measured results.

Additional work was done by Graig (2001) on the CFD evaluation of the drag coefficient on buntons of various shapes. A number of difference geometries were evaluated using a 2D model generated using Fluent v5.5 software and a velocity of 5 m/s. This analysis produced coefficients of drag that differ significantly from those used by McPherson (1987). However, as was noted by the author, there are several concerns with the data presented, the first being that the Reynolds number used would be significantly lower than that experienced in a shaft (Re = 5e4, whereas a typical shaft configuration has an Re = 3e6). In addition, the technique used assumed fully turbulent flow and the transition from laminar to turbulent flow was not noted. This problem is not unique to this analysis and has produced results that are less than 50% of the overall published figures for the coefficient of drag. This work did highlight the complexities of calculating the specific drag coefficient for various bunton configurations.

In 2007 a validation study was carried out by Wala et al. (2007). In this work a comparison was made between a scale model test and a CFD model of this test. The area modelled was the flow of ventilation air in a heading created by a continuous miner. The work consisted of the following:

1 Design and build a scale ventilation model of the area under consideration.

2 Measure the response of the model to the flow of air through it.

3 Develop a CFD model of the same area.

4 Compare the experimental results with those of the CFD model.

In this regard a 3D steady-state incompressible solution for the Navier-Stokes equation with species transport without chemical reaction was performed. The results showed significant correlation between the measured and the modelled airflow, with sufficient accuracy to allow the prediction of the airflow. This analysis, however, only considered an empty heading and did not include the equipment and other obstructions that would typically be found in such a heading. This is thought to be one of the first attempts to validate actual measurements with those of a CFD model.

In 2008 Jade and Sastry also carried out a comparison between the use of CFD modelling and measured results. In this instance, two-way junction splits were considered. Once again incompressible steady-state viscous flow was considered. This comparison again showed a good correlation between the predicted characteristics and the measured results. These results were also compared with results in the available literature for loss coefficient between these points. The literature results agreed with the modelled data for smooth-walled duct flow. However, although the correlation between the model and the measurements for rough walls was consistent, the literature prediction of losses for rough walls was not accurate. This finding was expected.

In spite of the lack of shaft applications for CFD, the technique has been used extensively in the evaluation of problems similar to the shaft resistance concern. Berkoe and Lane (2000) noted that CFD is typically used for modelling continuous processes and systems. The software utilises a 'CAD-like' model-building interface, advanced numerical methods and state-of-the-art graphics visualisation. CFD eliminates the need for typical assumptions, such as equilibrium, plug flow, averaged quantities, heat transfer coefficients, etc., because the physical domain is replicated in the form of a computerised 'prototype'.

A typical CFD simulation begins with a CAD rendering of the geometry, adds physical and fluid properties, and then specifies natural system boundary conditions. By changing these parameters appropriately, countless 'what-if' questions can be answered quickly. One of the most important uses of CFD is to compare alternatives and to view the effects of upset conditions. It is therefore best used as a design tool and is particularly useful when it is important to know how the variables – temperature, pressure, concentration/composition, and velocity – change throughout the computational domain, in space and time.

2.4.2 Significance of Available Data

Although little information is available on the use of CFD in the evaluation of shaft systems, the evaluations that have been completed indicate that this tool is worth investigating for the evaluation of shaft resistances.

It is not proposed to evaluate the specific drag characteristics noted by Craig (2001). Rather it is proposed to use the technique to model significant portions of the shaft system which will produce a better understanding of the inter-related nature of the various effects.

2.5 SUMMARY AND CONCLUSIONS – CHAPTER 2

This section summarises the most important conclusions from this chapter.

2.5.1 Measurement

- The main findings were:
  - All shafts should be lined to reduce the roughness of the shaft walls as much as is practically possible.
  - Buntons and guides should be streamlined and should be placed as far apart as possible.

  - It is important to ensure that the velocity profile and Reynolds number in any test section are as close to those of the shaft as possible.

- The above general guidelines were recommended in the majority of the papers reviewed. However, no definitive data are available on the actual manner in which the above systems should be designed.
- None of the papers noted above included any quantification of the results in accordance with the procedure presented by Bromilov (1960).
- Care must be taken when reviewing the results from this chapter because, although the manner in which the various measurements were taken is recorded, little information is available on the actual data measured and the details of the instrumentation used.
- One of the objectives of reviewing these papers was to try and find additional data to calibrate a computational model. In this instance the difficulties associated with the measurement of shaft resistances was highlighted, particularly with respect to ensuring that sufficient time is allowed in the shaft to complete these measurements.
- It was also noted that the horizontal test chamber showed little reduction in the shaft resistances when pipes and cables were introduced.
- The uniqueness of each shaft layout and the resultant effect on the turbulence of the shaft and, in turn, its effect on the measured coefficient of drag were highlighted.

2.5.2 Design

- The theory described in this section allows the complete mathematical design of a shaft system with respect to the resistance that the shaft will offer to air flowing through it, but some critical questions with respect to this analysis remain unanswered:
  - As the duty required of shafts increases and they are used to transport more services underground, the actual effect of the shaft fittings needs to be quantified.
  - The effect that conveyances have on the resistance of the shaft needs to be more explicitly quantified.
- The effect that the shaft steelwork has on the ventilation air has been quantified based on the drag resistance it offers to the airflow. In addition, it is noted that the further the buntons are away from each other the better.
- The maintenance of shaft systems must be optimised such that it takes as little time in the shaft as possible.

- Air velocities in equipped shafts may be as high as 12 m/s and air velocities of up to 22 m/s may be tolerated in unequipped shafts.

2.5.3 CFD

Although there is little data available on the use of CFD in the evaluation of shaft systems, the evaluations that have been completed indicate that this tool is worth investigating for the evaluation of shaft resistances.

It is not proposed to evaluate the specific drag characteristics that were noted by Craig (2001). Rather it is proposed to use the technique to model significant portions of the shaft system, which will produce a better understanding of the inter-related nature of the various effects.