CHAPTER 6 COLLATION OF ALL RESULTS

6.1 GENERAL

This section considers all the results from the work presented in the previous chapters. It is only possible to compare the results from simulations T10, T11, T12, T13, T14 and T15. The other simulations all considered only portions of the shaft which it was not possible to test independently.

The results from simulation T10 will be considered first.

Table 6-1: CFD simulation No. T10 – Shaft barrel and buntons and pipes including flanges

	14 Shaft	11 Shaft	1 Shaft	11C Shaft	12N Shaft
Simulation No. T10					
Pressure loss calculated from theory (Pa)	612.5	584.0	276.1	671.5	266.0
Pressure loss calculated from CFD (Pa)	615.3	537.0	209.2	425.3	88.5
Pressure loss from measurements (Pa)	891.1	721.3	248.1	752.4	917.6

The results in Table 6-1 are considered separately as simulation No. T10 is the only test that assumed that there is nothing in the shaft except the fittings. As can be seen from this analysis, there is a substantial difference between the measured data and those of both the theoretical calculations and the CFD analysis, the specifics of this have been discussed in section 4.2.1. The concern regarding the estimation of the coefficient of drag has already been discussed. Suffice it to say that there is consistency between the CFD data and the theory, albeit for different reasons.

Table 6-2: CFD simulations Nos T11, T12, T13, T14 and T15

	14 Shaft	11 Shaft	1 Shaft	11C Shaft	12N Shaft
Simulation No. T11 – Shaft barrel and buntons and pipes including flanges and skip 1					
Pressure loss calculated from theory (Pa)	706.1	638.2	310.0	-	331.7
Pressure loss calculated from CFD (Pa)	618.7	541.0	211.1	-	94.0
Pressure loss from measurements (Pa)	897.5	756.3	231.4	-	866.0
Simulation No. T12 – Shaft barrel and buntons and pipes including flanges and skip 2					
Pressure loss calculated from theory (Pa)	706.1	638.2	309.9	-	377.0
Pressure loss calculated from CFD (Pa)	618.6	541.1	211.1	-	93.9
Pressure loss from measurements (Pa)	897.5	756.3	231.4	-	866.0
Simulation No. T13 – Shaft barrel and buntons and pipes including flanges and man cage 1					
Pressure loss calculated from theory (Pa)	649.5	630.6	285.1	713.8	-
Pressure loss calculated from CFD (Pa)	647.7	568.0	215.0	444.8	-
Pressure loss from measurements (Pa)	930.0	796.3	242.0	856.1	-

	14 Shaft	11 Shaft	1 Shaft	11C Shaft	12N Shaft
Simulation No. T14 – Shaft barrel and buntons and pipes including flanges and man cage 2					
Pressure loss calculated from theory (Pa)	649.5	-	285.1	-	-
Pressure loss calculated from CFD (Pa)	634.6	-	214.9	-	-
Simulation No. 15 – Shaft barrel and buntons and pipes including flanges and service cage					
Pressure loss calculated from theory (Pa)	652.2	-	285.0	719.7	-
Pressure loss calculated from CFD (Pa)	627.8	-	214.7	426.8	-
Pressure loss from measurements (Pa)	891.1	-	216.8	752.4	-

As can be seen from Table 6-2 and as has been noted before, there is good correlation between the theoretical calculation and the CFD analysis. However, there is consistently poor correlation between the measured results and both the theoretical and CFD results.

It is interesting to note that this does not apply to the 1 shaft tests. This is the only shaft that did not use the airflow buntons. This would seem to add strength to the concern raised above about the accuracy of the drag coefficient data used for the theoretical calculations.

The discrepancies noted in 12N shaft have been discussed previously in this thesis and will not be re-evaluated here.

The differences noted between the other shafts and the data above do, however, highlight the potential differences that arise when evaluating complex systems from the theoretical perspective. It is not possible to include the effects of various items such as imperfections between the lining rings, the inclusion of slinging points in the shaft, large cable pocket installations, intermediate pump stations and other shaft openings. The differences noted above are attributed to these as well as the other inaccuracies noted above.

This also highlights the importance of ensuring that there is sufficient capacity in any designed system to accommodate future requirements, which it is not possible to anticipate in the design phase. In this instance the data indicates that the allowance should be of the order of a 30% increase should be made.

One of the variables that was not measured against time for the duration of the test was the velocity of the ventilation air within the shaft. This can make a significant contribution to the overall pressure losses calculated and should be measured in future tests.

6.2 SUMMARY AND CONCLUSIONS

The following specific points can be made from the collation of all the results:

1. There is not a reasonable correlation between the results from the theoretical calculations and the results of the CFD simulations in the initial tests. There is however good correlation between the theoretical calculations and the results of the CFD simulations in the tests evaluating the complete shaft. The specific conclusions which can be drawn form this are discussed in Section 8.2.

2. There is not a good correlation between the measured data and the theoretical or CFD results. These differences are in part attributed to imperfect installations such as the kerb ring during installation, as well as to the mid-shaft cable pockets, cable installation attachments and other miscellaneous items that can be found in the shafts. These differences do highlight the importance of understanding the limitation of any theoretical analysis when comparing it with a physical installation.

3. It is important to note that, once the theoretical analysis has been completed, an additional factor should be added to ensure that the non-homogenous imperfections of any installation can be effectively accommodated. This factor is shown to be of the order of 30%.

CHAPTER 7 ECONOMIC EVALUATION OF SHAFT OPTIONS

7.1 SUMMARY OF OPTIONS

To ensure that the recommendations made in this work are valid, a number of additional options were evaluated using the CFD technique described above. The following specific scenarios were evaluated on a typical shaft system:

1. Bunton arrangements
   - Shaft bunton arrangement with airflow buntons
   - Shaft bunton arrangement with streamlined buntons
   - Shaft bunton arrangement with square buntons
   - Shaft bunton arrangement with I-beam buntons
2. Piping placement (This option will be completed with airflow buntons.)
   - Piping placed in same place along edge of shaft
   - Piping placed near centre of shaft
   - Piping distributed around shaft
   - Option with the least resistance, including flanges
3. Cage fill factors (This option will be completed with airflow buntons.)
   - Cage C_f = 10%
   - Cage C_f = 20%
   - Cage C_f = 30%
   - Cage C_f = 40%
   - Cage C_f = 50%
   - Cage C_f = 30% (cage with fairings at top of cage)
   - Cage C_f = 30% (cage with fairings at bottom of cage)
   - Cage C_f = 30% (cage with fairings at top and bottom of cage)

The above options were evaluated and the pressure losses over the shaft length were calculated. The dimensions used for the shaft are as follows:

- Shaft diameter: 9 m
- Shaft depth: 2 000 m
- Ventilation velocity: 10 m/s

The basic fan power required to deliver the flow rate and the calculated pressure, as well as the overall costs for the power to deliver this were calculated. This cost for the power requirement was used to evaluate the current and potential costs of the options under consideration.

The cross-section of the shaft is shown in Figure 7-1.

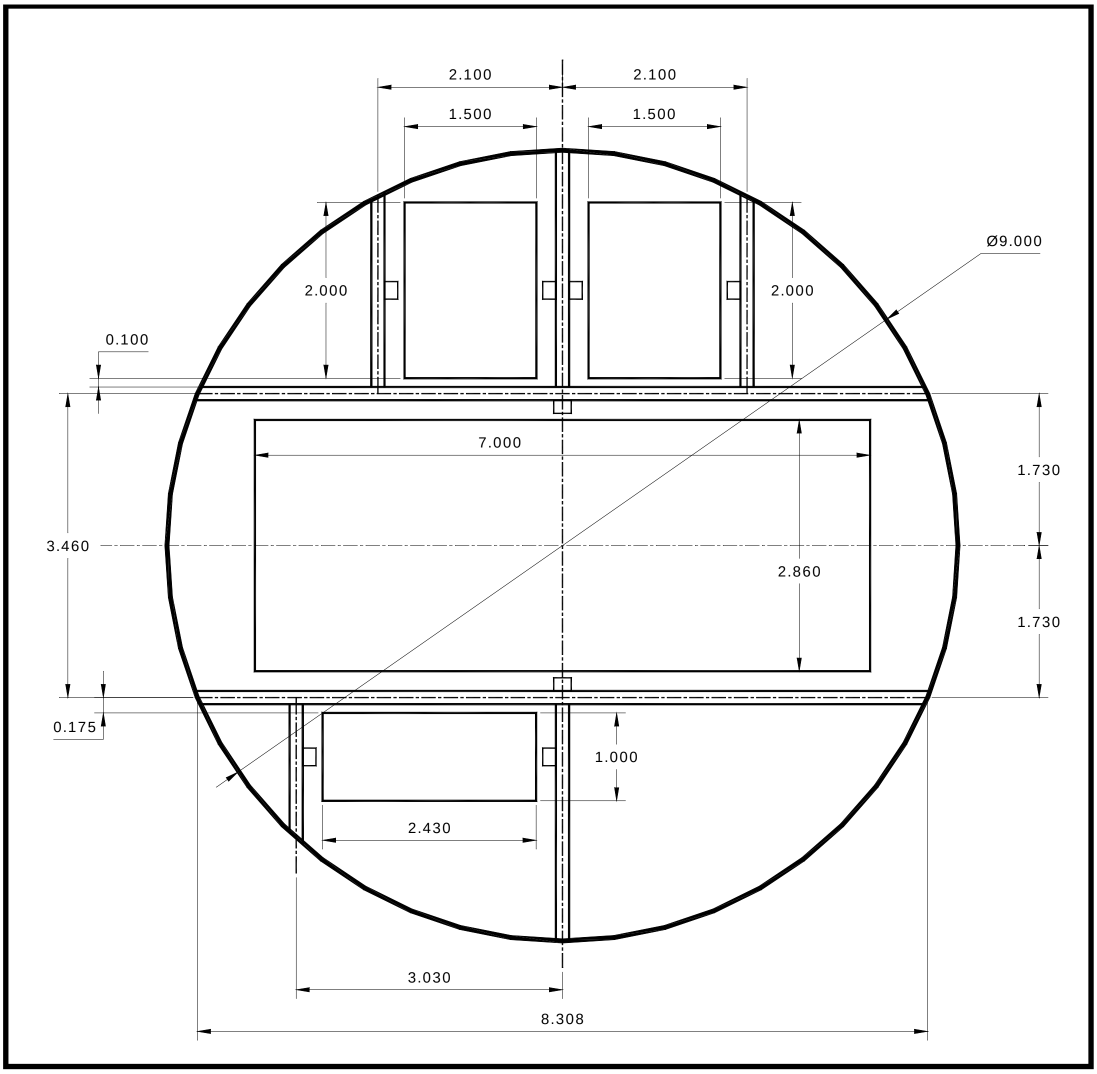

Figure 7-1: Typical cross-section

A summary of the results is given in Table 7-1, Table 7-2 and Table 7-3. An estimate is also made of the operating costs for 20 years based on an inflation rate of 12% per annum for the electrical costs.

It should be noted that this is well below the anticipated increased noted in section 1. These values are then discounted at 7% per annum to achieve and effective present cost.

7.2 SUMMARY OF RESULTS

7.2.1 Bunton Shapes

Table 7-1: CFD simulation for piping placement

Item	Description	Shaft P_{Loss}	Estimated total annualised cost	% Differences	Estimated capital cost	Estimated current annual savings	Savings over 20 years
1.01	Airflow buntons	822	R3,908,773	1.00 (Baseline)	R8 965 440	–	–
1.02	Streamlined buntons	774	R3,716,566	0.95	R8 965 440	R192 206	-R 5 738 460
1.03	Square buntons	1,608	R7,058,823	1.81	R8 229 640	R3 150 051	R94 046 991
1.04	I-beam buntons	1 324	R5,932,280	1.52	R7 471 200	R2 023 507	R60 413 237
Note : % Differences, this is a difference when compared to the option chosen as the baseline (this option is shown as (Baseline)							

As can be seen from Table 7-1, a significant saving can be made through the judicious choice of the bunton shape. This varies from 52% to 81% of the fan power costs as a direct result of the resistance the shaft offers to the flow of air through it. A small decrease in these costs was also not for the Streamlined buntons of 5%.

7.2.2 Piping Arrangements

Table 7-2: CFD simulation for piping arrangements

Item	Description	Shaft P_{Loss}	Estimated total annualised cost	% Differences	Estimated current annual savings	Savings over 20 years
2.01	Piping along shaft edge	856.7	R4 047 589	1.11	R405 769	R12 114 528
2.02	Piping away from shaft edge	819.3	R3 898 095	1.07	R 256 275	R7 651 281
2.03	Piping distributed around shaft	755.3	R3 641 819	1.00 (Baseline)	–	R -
2.04	Distributed piping with flange	866.7	R4 087 632	1.12	R445 812	R13 310 040
Note : % Differences, this is a difference when compared to the option chosen as the baseline (this option is shown as (Baseline)						

This result shows that the judicious placement of the piping in the shaft can have a significant effect on the resistance in the shaft. This saving can be between 7% and 12% of the total resistance experienced in the shaft. The results also show that, once the most efficient position has been chosen for the piping, the use of flanges to join the pipes can increase the cost of supplying air to the mine by approximately 12%.

7.2.3 Coefficient of Fill and Cage Configurations

Table 7-3: CFD simulation for varying cage fill factors

Item	Description	Shaft P_{Loss}	Estimated total annualised cost	% Differences	Estimated current annual savings	Savings over 20 years
3.01	C_f = 10%	1 780.3	R7 746 095	0.31	R-17 197 073	R-513 430 817
3.02	C_f = 20%	3 293.3	R13 804 763	0.55	R-11 138 405	R-332 544 979
3.03	C_f = 30%	6 075.0	R24 943 168	1.00 (Baseline)	–	R -
3.04	C_f = 40%	11 966.0	R48 532 709	1.95	R23 589 540	R704 282 448
3.05	C_f = 50%	17 306.0	R69 915 639	2.80	R44 972 470	R1 342 684 978
3.06	C_f = 30% (fairings on top)	3 706.2	R15 458 139	1.00 (Baseline)	–	R -
3.07	C_f = 30% (fairings on bottom)	6 051.4	R24 848 827	1.63	R9 390 688	R280 365 636
3.08	C_f = 30% (fairings on top and bottom)	4 172.7	R17 325 986	1.13	R1 867 846	R55 765 881
Note : % Differences, this is a difference when compared to the option chosen as the baseline (this option is shown as (Baseline)						

Although the overall savings here seem to be significant when the coefficient of fill of the cage decreases, it must be remembered from the previous conclusions that these losses can be avoided by the judicious design of level take-off configurations since the pressure losses shown here are most apparent when the cage is blocking the shaft. However, these data will give guidance as to the overall effect that could occur should this not be the case.

The most significant results of this analysis are the savings that can be achieved by the addition of fairings on the cage (of the order to 30%). This potential saving is not sufficient in itself to justify wholesale changes in the design of conveyances. However, if such a change is required for safety reasons, it provides a way in which this can be achieved while also achieving savings. This safety concern arises from the possibility that falling objects in the shaft may penetrate the roof of the cage; a fairing of this nature will help to deflect such objects.

It can also be seen that these results are broadly consistent which those noted by Ruglen and Wilson (Ruglen and Wilson, 1978). The negligible reduction of the calculated pressure losses of the conveyance as a result of the bottom fairing was also discussed in this paper. This is as a result of the fact that these would have to excessively long to affect the streamlines apparent with fully developed flow. The effect of the small fairing could however have the effect of increasing the effective length of the conveyance, thus increasing the total resistance offered by the conveyance. However it is important to note that conveyance will move up and down, so the fact that this fairing does not indeed add to the overall resistance is important to note.

7.3 SUMMARY AND CONCLUSIONS

The following specific points can be made from the collation of all the economic data.

1 The shape of the buntons is important in meeting the requirement to reduce the pressure drop in the shaft as much as is possible.

2 The placement of the piping in the shaft and the use of flanged piping can have a significant deleterious effect on the pressure drops in the shaft.

3 The addition of fairings to a cage can have a positive effect on the pressure drops that are apparent in a shaft. However, although this effect may be significant, it must be borne in mind that the overall effect of the cage on shaft pressure drops arises from the blockage it applies to the shaft. This can be mitigated more effectively by designing conveyance stop points to ensure that the ventilation air can flow around the cage with ease.

CHAPTER 8 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1 SUMMARY

As a result of the rising electrical energy costs in South Africa, a method was sought to reduce the overall electrical consumption of typical shaft systems. To achieve this, the first step was to analyse a typical shaft system and to determine what areas required the most energy to operate.

A typical shaft configuration was analysed and the primary energy consumers were identified. The ventilation fans for this system were found to consume a total of 15% of the total energy of the shaft system. It was calculated that more than 50% of this energy is consumed by the shaft itself, more specifically by the pressure losses that occur in the shaft as the ventilation air passes through it. This area was deemed worthy of additional evaluation. To complete this evaluation, the following steps were undertaken:

1 Literature study

2 Definition of the objectives

3 Evaluation of current shaft configurations

4 Detailed analysis

5 CFD simulation of the shaft system

6 Economic evaluation

A comprehensive search was done to find literature on the evaluation of shaft resistances. The literature review in Chapter 2 discussed the manner in which the shafts have been designed and provided invaluable information with respect to the way the current shaft configurations have been achieved.

In this regard, it is interesting to note that the driver for understanding and then reducing the resistance that the shaft offers to ventilation air was the need to get ventilation air underground. Most of this work was completed circa 1960 and it is during this period that the most useful work was done. Very little has been done in this area since then. McPherson (1987) formalised the approach for designing shafts to reduce resistances but did not undertake further research. A number of papers discussing tests that had been conducted on shaft systems were evaluated. These provided the basis for the methodology used here in measuring the shaft systems under consideration in this work.

Some CFD work was completed by Anglo American (Craig, 2001), but the driver for this was to find ways to optimise the design of the shaft steelwork. Interest in this work has more recently picked up again as the cost of electrical energy has increased and this is apparent in the papers published more recently.

Once the literature study had been completed and the work that has been done was understood, the next phase was to conduct some measurements on existing shafts. A number of shafts were evaluated at Impala Platinum. All these shafts were more than 10 years old. Although this was not ideal, it could not be avoided as none of the new-generation shafts had been commissioned at the time of writing.

These shafts did, however, provide a good spectrum against which to complete the initial tests. The following shafts were tested:

1 Impala 14 shaft

2 Impala 11 shaft

3 Impala 1 shaft

4 Impala 11C shaft

5 Impala 12N shaft

These shafts were all subjected to the testing described in Chapter 3. These tests consisted of placing data loggers in the shafts to take the environmental measurements. The results were collated against the measurements obtained from equipment placed on the winders of the shaft. The combination of these measurements showed the pressure drops in the shaft in relation to the movement of the conveyances within the shaft.

The testing of the shafts was completed over approximately 2 years. This long period was a result of various problems with the equipment being used and the availability of the shafts. The Impala Platinum ventilation personnel and the engineers on the various shafts were very helpful in this regard.

Once the data had been gathered and collated, they were all graphed against the same time scale such that the movement of the conveyance could be compared against the various pressure drops. These results were collated and the results tabulated in graphs which can be found in Appendices D, E, F, G and H.

Once this testing had been completed, the results were compared with those from a detailed theoretical analysis using the currently available techniques.

The detailed analysis and the measurements were then compared with the results obtained from CFD simulations. These simulations were completed using the STAR CCM+ computational fluid dynamics software.

One of the advantages of this sort of simulation was that the simulation models could be built and run incrementally. This allowed the evaluation of the various components within the shaft with respect to their contribution to the overall pressure losses experienced by the shaft.

The initial evaluation of the cost of sinking a shaft with respect to its diameter is shown in Figure 1-11. Discussions with mine personnel and shaft-sinking professionals resulted in the installation and maintenance costs not being included in this analysis. This is because these costs are considered to be the same no matter what bunton shape is used.

Shaft maintenance generally occurs during the weekly shaft inspections and is the same no matter which buntons are chosen. The only potential difference is the face that is presented to the ventilation airflow, as this is the face on which muck and other deleterious material collect. The use of a flat bunton could, if the shaft is not maintained correctly, give rise to more corrosion as the material does not naturally flow off this as would happen with the rounded face. This difference is not considered sufficient to result in any cost differential, assuming that the maintenance is done consistently.

The installation time for buntons depends primarily on the work that is done to provide accurately jigged and connected buntons at the installation stage. These operations take as long to do for any bunton shape and will therefore also not result in a cost differential between the options.

The operating costs are evaluated as the electricity required to operate the ventilation fans. These costs are also evaluated over a 20-year cycle. The capital cost is added to this amount to provide an overall cost of ownership.

The installation and maintenance cost for the piping is not considered a cost differential here and is therefore not included in the analysis. This includes the flanges and/or other pipe connectors that could be used.

8.2 CONCLUSIONS

8.2.1 Conclusions from Perusal of the Test Data

The following conclusions can be drawn from a perusal of the measured data:

1. There is little or no pressure loss associated with the movement of the cages. There was a small pressure increase in the tests for 1, 11 and 11C shafts. These pressure spikes were of short duration and lagged the passing of cages. The tests for 14 Shaft showed a general

increase in the resistance seen in the shaft during the periods when the skips were moving consistently between the shaft top and bottom. Neither of these findings was consistent with the theory.

2 There was also a significant difference between the measured pressures and the calculated pressures for the shafts, this was discussed in Section 6.2. The 12N shaft data were, however, so different as not to be useful. This difference is attributed to the placement of the pressure measurement devices in the shaft and will not be considered further here.

3 There was little congruence between the current theory and the and the measured data. The calculation of the pressure drop associated with the buntons using this theory is dependent on the availability of accurate data to define the coefficient of drag (C_d) of the buntons. As has been shown above, the buntons contribute the most significant portion of the overall pressure losses in a shaft system. The drag coefficient's (C_d) of the buntons as listed by McPherson have been calculated from various date associated with measurement of pressure losses in shafts (as listed in the right hand column of Table 3-1). The specific conclusion deriving from this analysis in conjunction with the CFD analysis is discussed in section 8.2.2.

4 The effects of a cage moving in the shaft can be ignored unless

i the constant movement of conveyances in the shaft is sufficiently regular such that the blockage in the shaft needs be considered. (This is mostly apparent in long shafts where the ventilation is introduced only in the lower level.)

ii the coefficient of fill (C_f) in a shaft of the cage is close to 30% of the free-flow area in the shaft. (The exact C_f at which this occurs is not known. This cross-over point should be evaluated using CFD analysis.)

One of the issues that should be considered in evaluating these data is that, should any of the conveyances remain stationary at a particular level for a length of time, the overall resistance seen in the shaft will increase. This emphasises the need to ensure that the stations are designed in such a way as to allow the ventilation air to bypass the conveyance without a significant pressure loss occurring.

8.2.2 General Conclusions from the Analysis

All the shaft configurations discussed were analysed with respect to the current theory available for the evaluation of the shaft system, as well as the being subjected to a detailed CFD analysis.

In order to break down the various contributors to the overall shaft resistance, both the theory and the CFD model were used to analyse the shaft as it was built up. This analysis started with the bare shaft cross-section and sequentially included the complete bunton and piping sets and, finally, each of the conveyances. At each step of this process, it is possible to subtract the values obtained for the resistance offered by the wall or the buntons and thus to calculate specific figures for the resistance of individual sets. This approach to the overall evaluation yielded some interesting results.

1 The current theory does not provide sufficiently accuracy to design new shafts which differ from the current shaft configuration. It has been shown that this theory is does not provide the necessary definition to allow the shaft parameters to be varied and to provide accurate results based on these variations. In addition, the calculation of the pressure drop associated with the buntons using this theory is dependent on the availability of accurate data to define the coefficient of drag (C_d) of the buntons. If this is not the case, differences between the measured values and the calculated values are to be expected. This conclusion is valid only if it is assumed that the interference factor used for the calculation of the shaft resistance is accurate.

i As the shaft was built up and the buntons and pipes were added, there was little correlation between the theoretical pressure losses and those predicted by the CFD analysis. This continued until a point was reached, as the piping was being added in its various configurations, when the resistance predicted by the CFD analysis equalled that of the theoretical analysis. The conclusion that was reached was that the inter-related nature of the equipment in the shaft increased the total resistance of the shaft by some 30%. This finding has two specific outcomes:

ii The theoretical approach to the evaluation of shaft resistances, which consists of arithmetic adding the Chezy-Darcy friction factors for the various items in the shaft and then using the total Chezy-Darcy friction factor to calculate the shaft resistance, is incorrect. Although the final values for the theory and the CFD analysis agree to within 5–15%, the actual make up of the shaft resistance is not as the theory predicts. This conclusion was alluded to by Martinson (1957), however the data gathered was not sufficient to allow for a meaningful comparison.

iii The inter-related effect of the fittings in the shaft is stronger than was initially anticipated. In order that shaft be designed in a manner which will limit the shaft resistance, the dynamic consideration of the shaft with respect to the turbulent ventilation flow needs to be considered in detail. Should the current theory be used without this consideration being taken in to account, changes could be made to reduce the shaft resistance that are either incorrect or could not have as significant an effect as was originally thought. The emphasis should rather be placed on creating free-flowing channels and using bunton spaces and pipe configurations that facilitate flow and limit turbulence as far as is practically possible.

2 One of the areas that was considered worthy of further investigation was the manner in which the resistance of piping in the shaft was calculated. The piping was therefore modelled, initially at its pipe diameter, then at the flange diameter, as is required by the theory, and finally at the pipe diameter with flanges, which has not been done before. There was not a significant increase between resistances calculated by the CFD simulations using the piping at each of the diameters (less than 1%). However, when the piping was introduced with flanges there was a significant increase in the resistance (the piping in a bare shaft showed an increase of 20%, while the piping in a shaft with the buntons showed an increase of 10%.). This is a significant increase and more than sufficient to warrant avoiding the use of flanges in a shaft and avoiding any discontinuities in the piping as far as practically possible.

3 The drag coefficient (C_D) calculated from the CFD analysis for comparison with the theory showed little agreement. The CFD-derived drag coefficient was significantly lower than that used in the available literature. This discrepancy reduced considerably when the interference factor was included in the calculation. Chasteau (1961) noted that the measured drag coefficient was different depending on the surrounding turbulence in the shaft. This was found to be correct. This does also give rise to some concern about the approach of the current theory as it seems that the appropriate drag coefficient for each shaft could differ depending on its configuration and velocity.

4 In addition, for the initial simulations in 11 shaft and 12N shaft (i.e. the simulations that considered only the pipe in the shaft at the pipe diameter), a small decrease in the shaft resistance was noted. This decrease was commented on by Bromilov (1960), but it did disappear when the pipe was made larger and the flanges introduced. This shows that perhaps the piping does having a smoothing effect on the ventilation flow.

5 In the even that more detail work is required for the evaluation of the resistance of shaft, both for the more detailed analysis of current shaft configurations as well as the analysis of future shaft. In this instance it is recommended that the configurations be evaluated using CFD techniques.

8.2.3 Conclusions from the Economic Evaluation

8.2.3.1 Buntons

Various bunton shapes were evaluated, with the following conclusions:

i Aerofoil bunton shape (most cost-effective bunton shape to use based on the electrical consumption of the ventilation fans)

ii Airflow bunton shape (+5% (from aerofoil shape))

iii I–section buntons (+57% (from aerofoil shape))

iv Rectangular buntons (+86% (from aerofoil shape))

It should be noted that the capital costs for the aerofoil and airflow buntons are approximately equal, while the I-beam bunton is 17% more costs effective than the aerofoil and the rectangular bunton is 8% more cost effective.

8.2.3.2 Pipes

Three pipe positions were evaluated: first pipes placed along the side of the shaft, then placed near the shaft centre and finally dispersed around the shaft. The final costs were evaluated with the best option chosen from these three positions (i.e. the option that results in the least resistance to flow), and flanges were added.

The overall finding from cheapest to the most expensive is:

i Piping distributed around the shaft

ii Piping aligned in the middle of the shaft (+7% from distributed option)

iii Piping aligned at the shaft edge (+11% from distributed option)

Finally, should the piping be distributed around the shaft, but with flanges used as the pipe connection, the cost is +12% from the distributed option.

8.2.3.3 Cages

As can be seen from Table 7-2, the relationship between shaft resistance as a result of the size of the cage and the coefficient of fill for the cage is exponential.

Although the overall savings here seem to be significant, it must be remembered from the previous conclusions that these losses can be avoided by the judicious design of level take-off configuration. However, these data will provide a guide as to the overall effect that could occur should this not be the case (C_f = 30% (0), C_f = 50% (280% higher than C_f = 30%). It is also interesting to note that inclusion of fairings does have an effect on the resistance offered by the cage (39%).

The most significant results of this analysis are the savings that can be achieved by the addition of fairings on the cage. This potential saving is not sufficient in itself to justify wholesale changes in the design of conveyances. However, if such a change is required for safety reasons, it provides a way in which this can be achieved while also achieving savings. This safety concern arises from the possibility that falling objects in the shaft may penetrate the roof of conveyance; a fairing of this nature will help to deflect such objects.

8.3 SUGGESTIONS FOR FURTHER WORK

No work of this nature would be complete without considering the deficiencies of the results presented and the suggested direction for future work.

One of the more concerning and recurring themes of this work is the consistent reference to empirical data obtained more than 50 years ago. Of most concern are the values defined for the drag coefficient. It is suggested that the pertinent bunton shapes be subjected to a detailed experimental and CFD analysis to confirm this data..

The significant difference between the measurement results from the physical tests and those calculated from both the theory and the CFD analysis is a cause for concern. The best way to resolve this would be to find a shaft with a shorter section that could be properly surveyed and then subject it to tests similar to those described above. The technology for such a survey is available but there should be strong emphasis on the need to install instrumentation in the shaft itself to minimise potential losses. A way should also be found to consistently measure the ventilation velocity of the shaft over the same period in which the tests are completed.