Auxiliary ventilation design – why and how mines waste so much power on inferior systems

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ABSTRACT

There has been a strong trend over the past decade in hard rock mines towards the use of very high powered auxiliary (or secondary) fans; in many mines, the installed power for the secondary ventilation system now exceeds that of the primary ventilation system. This also reflects the trend to use two-stage auxiliary fans pushing air into a single 'trunk' duct that in turn splits into multiple branches with multiple outlets feeding multiple workplaces. This often produces a poor result in terms of face flows due to the high resistance, high leakage and badly managed duct outlets, as well as high fan capital and operating (power) costs, which in turn also results in a higher cost for the underground power reticulation/distribution systems. This paper explores the reasons why this trend exists and what ventilation practitioners can do to utilise less expensive systems that simultaneously deliver better workplace conditions. It includes a case study.

INTRODUCTION

There is a widely-held belief in the mining community that more fan power in a ducted ventilation system will produce more airflow. However, in most cases, this is either not true in any practical sense, or is a very expensive way to achieve an increase, in both capital and operating costs.

Combined with this erroneous belief is the trend towards the using of single 'trunk' duct with multiple branches, each with an outlet in a different heading. The concept is that when a heading is not in use, the outlet to that heading can be closed off by constricting the duct, and so the headings that do need air can continue to receive the flow they need.

This paper will address the problems with both of these matters and recommend the correct way to be designing auxiliary (secondary) ventilation ducted systems.

THEORY

One of the most basic ventilation equations (McPherson, 2008) is:

$$p = R\,Q^2 = k\,C\,L\,Q^2 \,/\, A^3 \qquad (1)$$

Where:

p is the pressure loss in the airway or duct (Pa)
k is the friction factor ($N.s^2/m^4$ or kg/m^3)
C is the circumference (m)
L is the length (m)
Q is the volumetric flow (m^3/s)
A is the cross-sectional area (m^2)

And a second fundamental equation (McPherson, 2008) is:

$$P = p\,Q/1000 \qquad (2)$$

Where:

P is air power (kW), which is directly related to fan shaft (input) power (kW) which in turn is directly related to electrical power consumed (kW)

In Equation 1, C is proportional to the airway diameter (d) and A is proportional to the square of the airway diameter, therefore for any given value of flow (Q), the pressure loss is inversely proportional to the fifth power of the airway diameter. Since airpower is also proportional to pressure loss (for any given flow), it follows that airpower is also inversely proportional to the fifth power of the airway diameter.

Similarly, airpower is also proportional to the cube of flow, for any given duct configuration.

The practical consequences of these relationships for secondary ventilation systems are that:

- For any given duct type, length and diameter, a doubling of fan power will increase the flow by 26 per cent. However, the fan pressure will also increase by 1.26^2 or about 60 per cent. This increase in fan pressure (and hence pressure in the duct) will increase the leakage, often disproportionately to the increase in pressure (because leakage areas such as holes or splits or open joins grow larger with higher pressure, especially on flexible duct) so that the net increase in flow at the duct outlet(s) will inevitably be less than 26 per cent.
- For any given duct type and length, an increase in duct diameter from (say) 1.2 m to 1.4 m (17 per cent) will reduce the required fan power by more than half (for the same delivered flow), or alternately will allow a 29 per cent increase inflow for the same power.

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- The combined resistance of two airways in parallel is one quarter that of the single airway, so that installing two identical ducts in parallel (each carrying half the required flow) provides the same total flow to the outlets at 25 per cent of the fan power to achieve the same flow using one duct.

A corollary of this is that a two-stage fan will generally only increase the volume flow in a duct by a very modest amount. Consider these common single (Figure 1) and two stage (Figure 2) fans. The important thing to note is that the two stage fan curve does not achieve a higher flow than a single fan, ie the curve does not shift to the right at all. It is true that for any given resistance, the two stage fan will move 'down' its fan curve compared to the single fan, but the likely increase in flow is usually small. An example is shown in Figure 3. The 2-stage fan curve is d-e-f and it is assumed (at this point) that each stage develops half the pressure and that there are no additional losses when one stage is off. The single-stage curve is therefore a-b-c. If the duct length is short, the resistance is low (say curve w-x) and the single-stage fan might operate at point a (44 m^3/s). If 44 m^3/s is 'not enough' and we turn the second stage on, the operating point moves to d (49 m^3/s). In terms of electrical power consumption, operating one stage will consume 97 kW and operating two stages will consume 160 kW. This means that at a site power cost of (say) \$0.20 per kWh, the first 44 m^3/s is costing the mine \$110 000 per annum or \$3860 per m^3/s per annum, and the next 5 m^3/s is costing the mine \$144 000 per annum or \$22 000 per m^3/s per annum. This is a highly ineffective and expensive way to achieve an extra 5 m^3/s! If the duct resistance is much higher (curve r-s), then the flow increase achieved by running two stages is 7 m^3/s (from b to e) but this strategy remains a very expensive way to increase the flow by a paltry 7 m^3/s.

In practice, there are additional complications in this analysis (discussed later) but the basic principal remains. Adding fan pressure in series in an expensive and generally ineffective way to achieve additional flow through a duct.

WHY DOES THIS TREND EXIST?

A strong argument could be made that the trend towards high powered fans, and also the trend towards single trunk ducts with branches, is due to the rise in the use of contract mining companies to undertake underground development.

Consider the situation of the secondary ventilation from the contractor's point of view.

When a contractor buys an auxiliary fan, he or she is able to pass on the capital cost (mostly or often entirely) to the mine owner (the principal). The contractor also does not pay for electrical power which is often (per annum) many times the cost of a brand new fan. For example, the cost of a new twin 110 kW 1.4 m Φ fan (a common fan in Australia), with

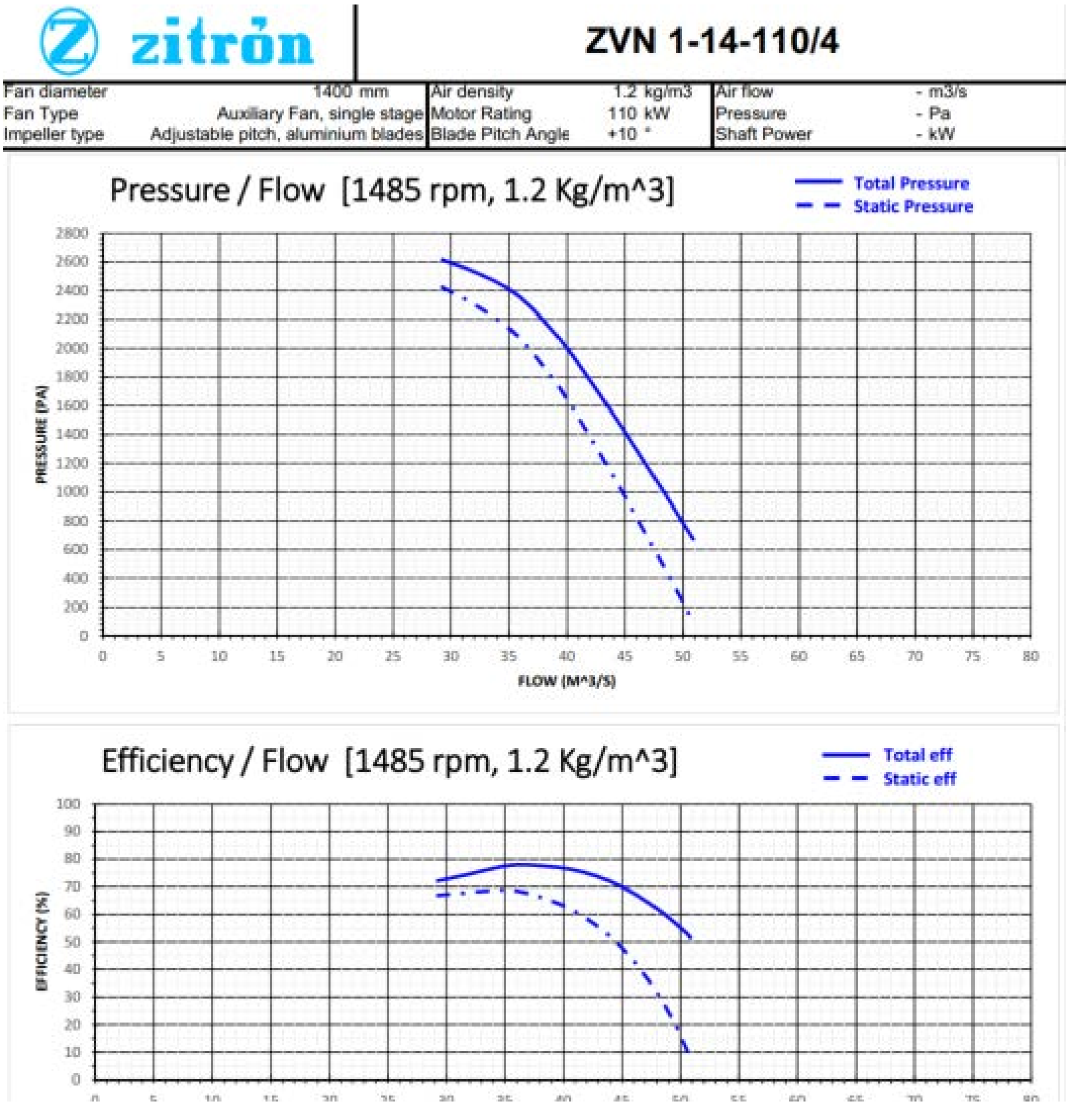

FIG 1 – Single 110 kW fan curve (source: Zitron).

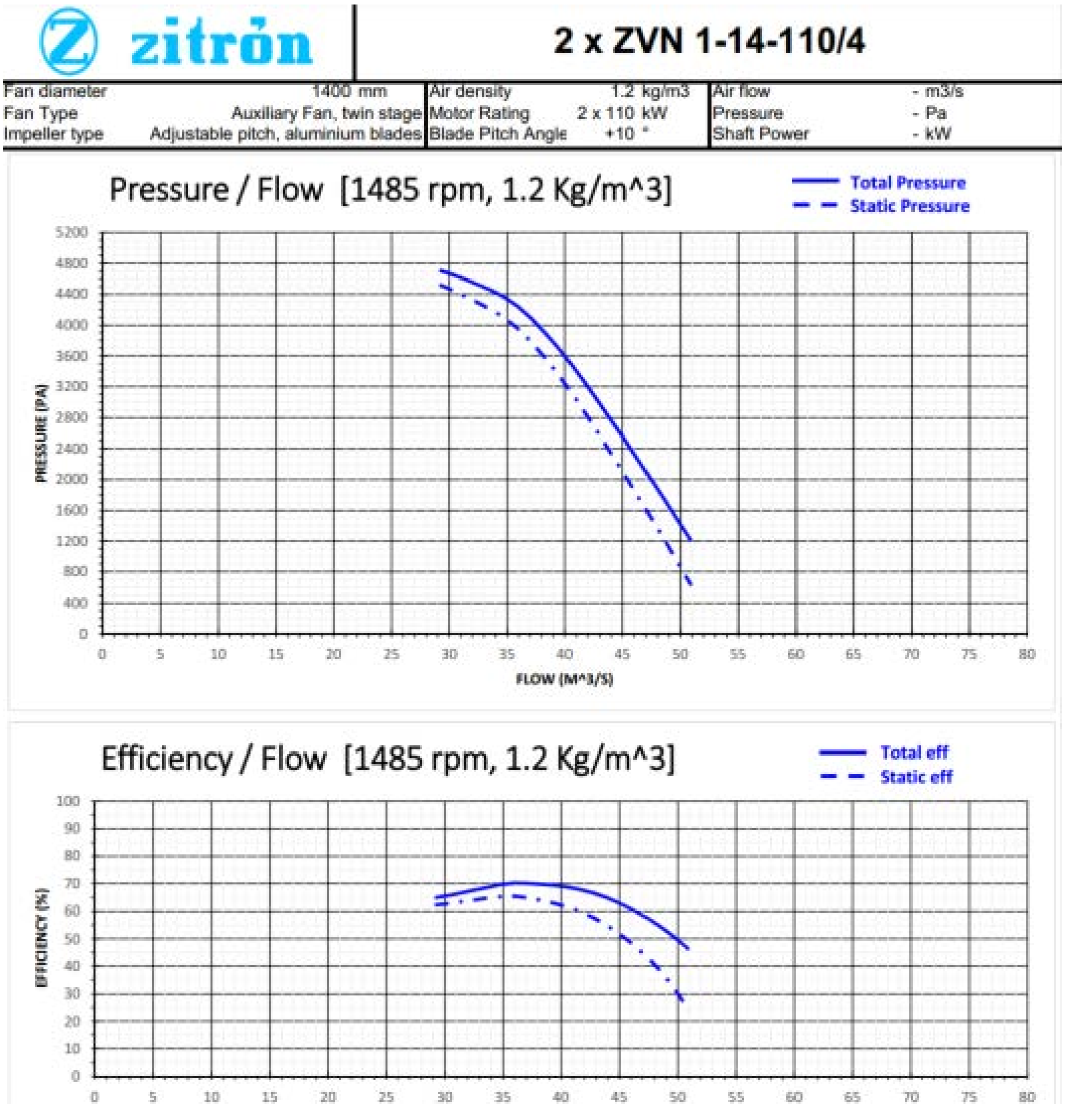

FIG 2 – Twin 110 kW fan curve (source: Zitron).

silencers and DOL fan starters, is about $70 000. For a mine where the site power cost is $0.20 per kWh, this fan at full load (say 220 kW) is costing about $390 000 per annum to operate (more than five times its new capital cost) and this is in power costs alone. And the contractor does not pay for underground power *reticulation* costs (ie providing substations and extending the underground power reticulation system), which can also be substantial. But from the contractor's business perspective, he is far better off over-sizing the fans (nil risk) and then knows (or believes) his secondary ventilation will never be undersized irrespective of what job the client wants done, rather than correctly sizing the fans and ducts. He buys twin stage fans (often with only a single integrated electrical fan starter) and then, if necessary, runs 'only one stage' which is quite inefficient as the other stage has to push through the non-operating stage (driving it as a turbine, see later discussion). In addition, this means these two-stage fans with single starter cabinets can never be 'split' (the fans often can be split, but the starters cannot).

In a schedule of rates mining contract, usually all 'secondary ventilation' costs are to the contractor's account so he wants to put in one duct rather than two because it is cheaper to install one duct and cheaper to maintain one duct — especially if this one duct is undersized for the job. Another problem is that using one duct means more outlets from that duct are needed to support any given number of faces (outlets often supposedly tied off when not in use). This is also a problem as there is frequently much leakage through all these tied-off outlets. Plus each of these branching tees has a shock loss so the duct resistance is also higher.

The contractor also wants to put the truck as close to the tramming LHD as possible to reduce the LHD tramming distance and this puts more strain on the ventilation system as it means the heading needs more air further 'inbye' (closer to its outlets) than if there was just the LHD to ventilate. Plus, in some cases, the contractor may want to stack up trucks in a queue to keep the LHD busy so the jumbo can get back into the face as soon as possible. It is not uncommon to hear the reply that because some of the trucks are only 'idling', the legal airflow requirement (eg in WA) should not apply to those trucks.

In some cases, since fan movement costs are also to the contractor's account, he prefers to run with longer ducts rather than to move the fans, which means fans are not advanced as quickly or as often as they could be.

This is aggravated by the use of large diameter fans with silencers as the backs of the development must be 'stripped' above standard height to fit these fans in, which means large fans often cannot be moved to 'unplanned' locations once the services have been run due to the downtime and potential damage that would be incurred by the required stripping.

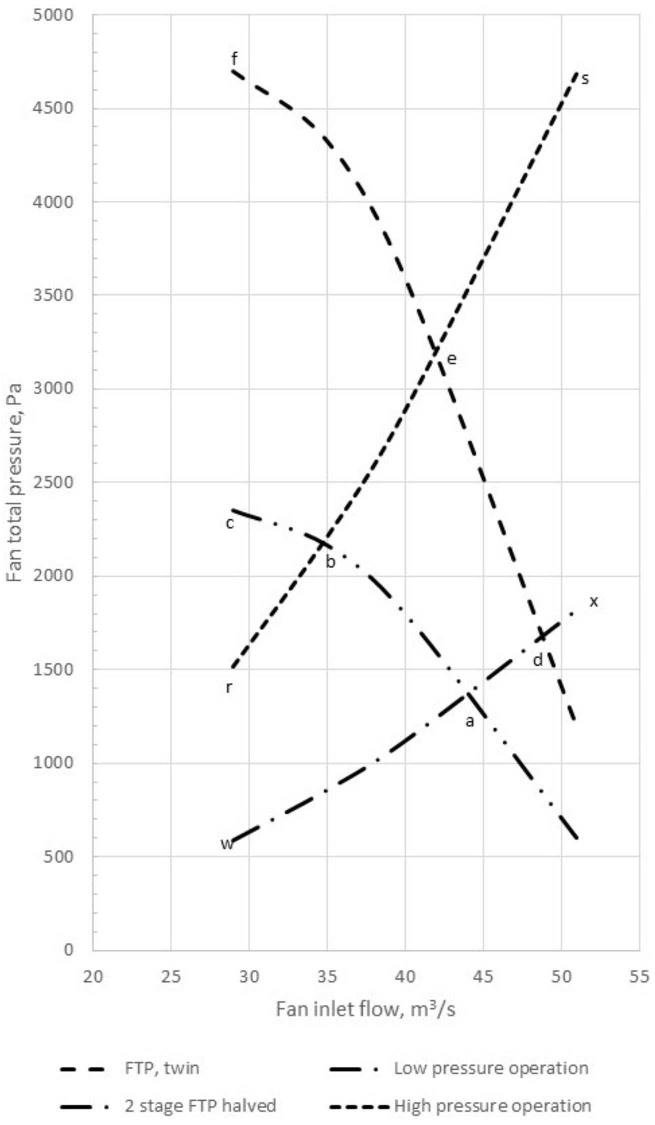

FIG 3 – Turning on a second stage is an expensive and inefficient way to achieve more flow.

Further, since holding duct inventory on-site costs (the contractor) money (in working capital), often the contractor holds only a few types of duct pieces on-site, so that duct arrangements are suboptimal because they must use whatever is available rather than 'the right piece for the job'.

Unfortunately, the client is the loser in all these arrangements as the contractor's interests do not align with the principal's (which, since the principal has freely entered into the contract, is hardly the fault of the contractor). But the net result is that the mine ends up paying far more than necessary for conditions than are frequently poor and in some cases, illegal.

And then add to this scenario the fact that a generation of mining engineers has now grown up with this system of secondary ventilation, and accepts it as normal, and the problems of this style of ventilation have then also propagated into mines that do their own development.

REGULATOR'S CONCERNS ABOUT SECONDARY VENTILATION

Apart from costs, there are important safety and regulatory issues with poor secondary ventilation design and operation. A good summary of many of the 'things that are going wrong' with secondary ventilation installations in Australian hard rock mines is given in the Western Australian Regulator's Safety Bulletin No 95 (Anon, 2011) which identifies (*in part*):

- fan characteristics not properly assessed for the diameter and length of ventilation ducting required
- inadequate consideration of the regulatory requirements for ventilation standards at truck loading stockpiles in declines and on operating levels
- shift supervisors not aware of ventilation standards with regard to velocities and quantities of air
- use of single fans to ventilate multiple headings.

The reader is referred to the full text of this important safety bulletin.

CASE EXAMPLE

Consider the situation where a mine needs to ventilate a blind development heading 'off ramp' that will require a duct up to 400 m long (eg a level cross-cut and footwall drive) with the largest diesel load in the heading being a 350 kW LHD (needing 17.5 m^3/s at the duct outlet under typical Australian design rules). This author has often seen this arrangement being ventilated with a twin 110 kW fan or twin 90 kW fan feeding a single 1.4 m or even 1.2 m diameter duct. The smaller duct is often used with the 1.4 m diameter fan because the off-ramp development is mined lower (often 5 m high) compared to the ramp. When the heading (and hence duct) is short, the operation justifies this to itself by planning to 'save power' by running only one stage of the two stage fan.

Now consider an alternative situation in which the operation uses a single 55 kW fan with 1.4 m or 1.2 m diameter duct for the same job. The results are shown in Table 1. Further details of the fans are shown in Table 2. In practice, this table uses a single fan curve for a single stage fan, ie assumes no losses when a two-stage fan is operated with only one stage so that the true cost for the single-stage options in this table will be higher than shown (as discussed later).

This table also shows the theoretically ideal fan for these scenarios, based on 75 per cent fan efficiency and 95 per cent motor efficiency.

This table assumes that this heading must be ventilated by fan and duct for its entire working life which is taken as being 28 months, with two months at 40 m duct length, two months at 250 m duct length and the remaining 24 months at full 400 m length. This means that it is the 'final' length of the duct (and the corresponding power requirement) that is far more important in terms of overall ventilation cost for this level than the earlier periods which is usually the case.

The lifetime power cost for the secondary ventilation for this one level is shown in Table 3 and as a percentage of the twin 110 kW with 1.2 m Φ duct in Table 4.

It is obvious that there is a vast (order of magnitude) difference in power costs for these solutions.

A review of Table 2 shows many other advantages of smaller and/or lower power fans, including their much lower noise levels, lighter weight, smaller size and hence are easier to install into the back and cheaper in capital cost.

Also bear in mind that most noise regulations are written with respect to dBA and that a *doubling* of a noise level (measured as dBA) increases the value by 3 dBA. Hence a noise level that is 6 dBA above another noise level is four times noisier.

This case example examines only the issue of oversizing fans and undersizing ducts. It does not consider solutions that involve twin ducts, which, as noted above, require ¼ the fan power of a single duct solution, for any given duct size and

TABLE 1

Comparison based on same friction factor (0.00375 Ns^2/m^4) and leakage factor (264 mm^2/m^2) and unit power cost of $0.20 per kW-hr. Single stage fan operation assumes NIL losses through non-operating stage (not realistic as discussed in text). 'Perfect size' fan is the size required to deliver 17.5 m^3/s through one duct at 75 per cent fan efficiency and 95 per cent motor efficiency. All fans DOL(with pulse) start.

Fan		Single 110 kW 1.4 m Φ	Twin 110 kW 1.4 m Φ	Single 110 kW 1.4 m Φ	Twin 110 kW 1.4 m Φ	Single 55 kW 1.2 m Φ	Twin 55 kW 1.2 m Φ	Single 55 kW 1.2 m Φ	Twin 55 kW 1.2 m Φ	'Perfect sized' fan	'Perfect sized' fan
Duct diameter		1.4	1.4	1.2	1.2	1.4	1.4	1.2	1.2	1.2	1.4
Installed fan power		110 kW	220 kW	110 kW	220 kW	55 kW	110 kW	55 kW	110 kW		
Duct length/ duration	Duct length	Fan electrical power used (kW) Flow delivered (m^3/s) and Fan efficiency (FTP %)									
Level starting (2 months)	40 m	81 48.2 60%	140 50.7 46%	92 45.7 67%	155 49.1 51%	42 32.9 56%	82 33.8 45%	45 31.8 63%	85 33.2 47%	3 kW	1.5 kW
Level half way (2 months)	250 m	108 34.6 76%	185 39.1 61%	115 27.4 77%	217 33.0 69%	50 25.2 72%	95 27.3 55%	55 21.2 76%	104 24.3 61%	27 kW	11 kW
Level at stopping distance (24 months)	400 m	113 27.5 78%	197 31.8 65%	113 20.4 73%	225 25.3 70%	53 20.5 69%	98 22.7 57%	55 16.2 77%	108 19.3 65%	63 kW	25 kW

TABLE 2

Physical, noise and cost characteristics of some common fans used in hard rock mines (source: Zitron).

	Length (with silencer and inlet cone and adaptor)	Dia (max), with silencers	Weight, with silencers	Noise level, with silencers	Noise level, without silencers	Relative price with 1000 Volt DOL starters
Single 55 kW, 1.2 m	4340 mm	1485 mm	1670 kg	L_w = 98 dB(A) $L_{p,1m}$ = 80 dB(A)	L_w = 109 dB(A) $L_{p,1m}$ = 91 dB(A)	0.5
Twin 55 kW, 1.2 m	5790 mm	1485 mm	3120 kg	L_w = 101 dB(A) $L_{p,1m}$ = 83 dB(A)	L_w = 112 dB(A) $L_{p,1m}$ = 94 dB(A)	0.7
Single 110 kW, 1.4 m	4410 mm	1740 mm	2340 kg	L_w = 105 dB(A) $L_{p,1m}$ = 87 dB(A)	L_w = 114 dB(A) $L_{p,1m}$ = 96 dB(A)	0.6
Twin 110 kW, 1.4 m	5930 mm	1740 mm	3990 kg	L_w = 108 dB(A) $L_{p,1m}$ = 90 dB(A)	L_w = 117 dB(A) $L_{p,1m}$ = 99 dB(A)	1.0

L_w is the fan sound power level, $L_{p,1m}$ is the fan sound pressure level 1m × 90º Free Field. Noise with standard tubular silencers. Other silencers with higher insertion losses are available.

TABLE 3

Power costs in $1000 for the case study level over 28 months.

Fan/Duct	Single 110 kW	Twin 110 kW	Single 55 kW	Twin 55 kW	'Ideal fan'
1.4 m Φ duct	450	784	212	394	91
1.2 m Φ duct	456	896	222	433	229

TABLE 4

Power costs as percentage of twin 110 kW fan with 1.2 m Φ duct for the case study level.

Fan/Duct	Single 110 kW	Twin 110 kW	Single 55 kW	Twin 55 kW	'Ideal fan'
1.4 m Φ duct	50%	88%	24%	44%	10%
1.2 m Φ duct	51%	100%	25%	48%	26%

required airflow at the face. Twin duct solutions for this level would therefore reduce power requirements even further.

In terms of branching ducts, consider a 600 m long duct system with an outlet at 200 m, 400 m and 600 m. Each outlet delivers one third of the total fan flow. Ignoring leakage issues, 87 per cent of the pressure loss is in the first 200 m of duct (carrying all the flow), with 10 per cent of the pressure loss in the second 200 m, and only 3 per cent of the total pressure loss in the final 200 m. This indicates the problem with branching ducts as the system is largely constrained by the size of the first section of the duct, carrying all the flow. Obviously one method of reducing this impact is to use larger duct for at least the first section, but this is often not done, and is still not as good as a solution using two ducts.

The other problem with branching ducts is that they are, in effect, a parallel solution for ventilating headings as each heading gets its own 'split' of air from the fan. Whilst this is a laudable aim, if several outlets are open (or leaking), it is common to find the flow in each heading well below desirable values (minimum 0.5 m/s in each heading) and not infrequently below the legal requirement. For example it would be common to see a 1.4 m diameter fan pushing 45 m^3/s into a duct with three outlets receiving 10 m^3/s, 5 m^3/s and 7 m^3/s respectively. This results in poor working conditions. By contrast, pushing all the air to the end of the level (without use of branches) and then using small (even 15 kW) fans picking up the return air to ventilate individual headings with 15 m^3/s each can frequently double the effective flow reaching the operating headings (in this case, the most inbye heading would receive (say) 30 m^3/s and the other two headings 20 m^3/s each, for a total of 70 m^3/s, or more than three times the 'branching' solution).

Overall, the ventilation system is usually the largest consumer of electrical power in underground hard rock mines, and the principal point in these examples is that most hard rock mines could substantially reduce their power costs and power consumption (and greenhouse gas emissions) by improving the design of their secondary ventilation systems. Far too many mines have a 'one size fits all' approach to the secondary ventilation system. This has not always been the case and this author well remembers earlier times when large mines had a wide range of fans on-site and did take care with the selection of fans and ducts for each individual job, and were willing to change out fans as the development became longer etc In fact, the potential savings from correctly designing secondary ventilation system is likely to far outweigh the potential savings from 'ventilation on demand' and also provides a savings in capital costs, unlike VOD.

FURTHER ISSUES WITH TWO STAGE FANS OPERATING WITH ONE STAGE

Consider the twin 110 kW fan shown in Figure 4 which has curve d-e-f. Assume the system resistance (curve y-z) with both stages operating is at point d, which is well down the fan curve. When stage 2 is turned off, stage 1 will achieve about 40 per cent of the twin stage fan pressure, ie curve a-b-c and if the system resistance were to remain the same, the new operating point would be at a. However, in practice, the resistance seen by the stage 1 goes up (say to curve u-v), as it now has to drive the non-powered impeller. An indicative pressure loss to drive through this non-operating stage is around 1 velocity pressure which for this 1.4 m diameter fan at 35 m^3/s would be around 310 Pa which is about 15 per cent of the stage 1 pressure at that flow.

The net effect is that when the fan had two stages operating, it had a very comfortable margin to stall (the pressure difference between d and f, about 1500 Pa) whereas now with stage 2 'off', the margin to stall is very small (b to c, less than 100 Pa) and, if there is any wear on the blades or other issues, the fan may in fact now be in stall.

Now consider if the first stage is turned off leaving the second stage running. This stage 2 fan also sees the same additional resistance (curve u-v) due to the windmilling ('turbining') of the non-operating stage, but in addition it gets the poor air velocity distributions that the first stage fan now delivers to the inlet of the second stage operating fan. This inescapably further degrades the fan performance characteristic, indicatively to about 30 per cent of the 2-stage fan pressure (curve m-n) where its operating point would be n with a zero margin to stall, ie turning the first stage off may result in stage 2 operating in stall and it may not come out of stall even if stage 1 is restarted. If the stalled stage 2 stays stalled, this will result in both stages operating in a stalled condition.

If the fans are *contra*-rotating rather than *co*-rotating, then the stages usually have different numbers of blades, are set at different blade angles and there are no guide vanes between the stages. In this case, turning stage 1 off will result in stage 2 only achieving (indicatively) 20 per cent of the 2-stage fan pressure, ie curve p-q. It is clear that in this case, the operating impeller is now certainly in stall, and this is for a fan that, with both stages operating, is so far down its curve (operating point d) that it is relatively inefficient! And in practice, the second stage of a contra-rotating fan may obtain far less than 20 per cent of the 2-stage fan pressure when operating alone (Figure 5) – the reason being that this second stage often has a very low or even positive blade angle (opposite blade angle to stage 1) because there is already a major 'swirl' entering stage 2 from stage 1. But if there is no stage 1, then stage 2 achieves very little aerodynamic lift.

Now consider an alternative strategy (also Figure 4) where the fan is split and the second stage removed completely. The fan curve for a single stage 110 kW fan (from Figure 1) is h-i-j. The operating point at the system resistance is h and the pressure margin is h to j, which is about 300 Pa.

Each of the fans curves h-i-j, a-b-c, m-n and p-q are using a single 110 kW impeller but note the enormous difference in their performance! The operating cost difference between these strategies, even with the *same* 110 kW fan and duct and ignoring any potential damage due to possibly operating the fan in stall, is perhaps $100 000 per annum.

The point being that 2-stage fans are designed to operate with both stages running, and operating with only one stage running is at best very inefficient and at worst, potentially damaging the fan.

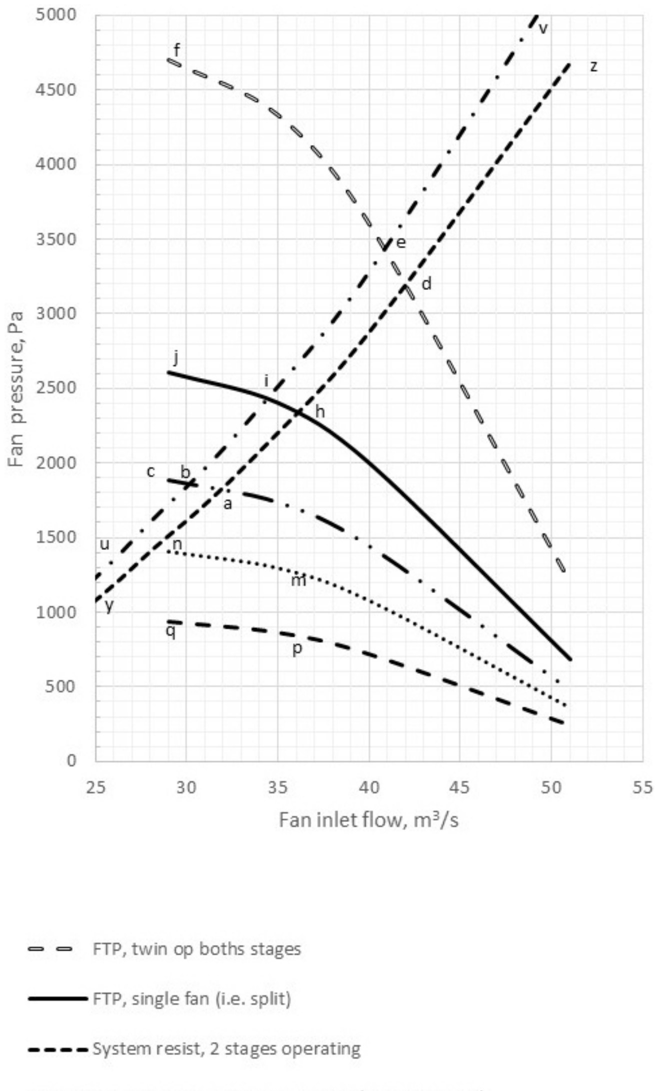

FIG 4 – The potential for a twin stage fan to go into stall when operating only one stage.

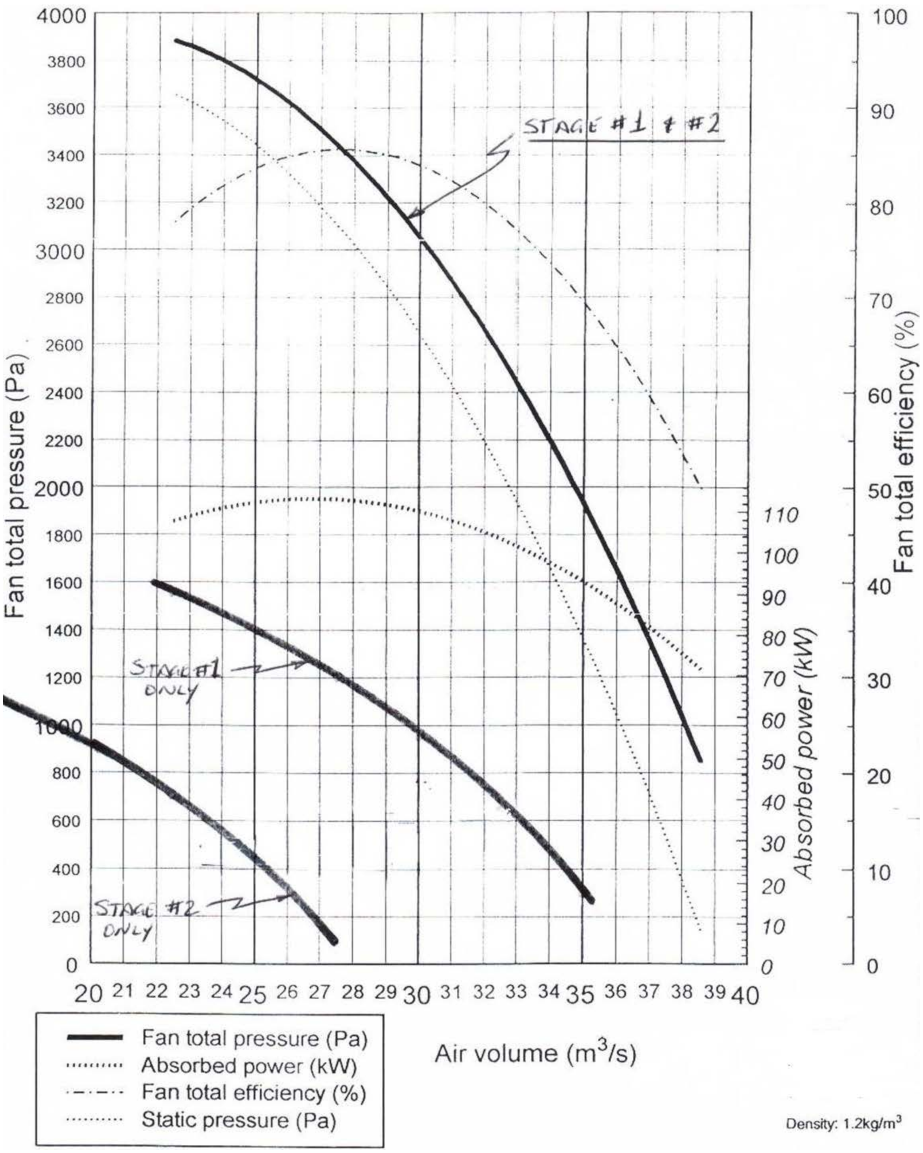

FIG 5 – Two stage contra-rotating fan (source: Anon, 1996).

It would be far better and cheaper to use a variable speed drive (VSD) for volume control rather than turning a stage off, even taking into account the high cost of 1000 volt variable voltage, variable frequency (VVVF) drives (a 55 kW 415 volt VSD is about $10 000 whereas the same VSD in 1000 volts is about $40 000).

SUMMARY AND CONCLUSIONS

In almost all practical cases, the solution to achieving more flow in a blind heading (or headings) is to either use a larger duct, or put in two (or more) ducts. In practice, two ducts will almost always be superior from a ventilation point of view to a single larger duct and may avoid the need to increase the development height to fit in a single larger duct.

Twin stage fans should only be used when single stage fans do not have the pressure capability for the job (ie where a single fan is approaching stall). Twin stage fans should not be used to achieve more volume flow. Remember that leakage coefficients for typical 'in service' duct do not remain constant as the duct experiences higher pressures as leakage paths open up.

If only one stage of a two stage fan is operating, it should be the first stage.

Under no circumstances should only one stage be running in a contra-rotating fan.

The mine will gain considerable additional flexibility by purchasing fans with individual starters, rather than a single cabinet with two starters. Similarly, purchasing fans that can be split (usually meaning co-rotating impellers, or contra-rotating impellers with special guide vane kits) will provide extra flexibility and avoid the need to run a two stage fan with only one stage operating.

Even where additional airflow is not required, these same solutions (larger ducts or dual ducts) will greatly reduce fan capital and operating costs, and electrical reticulation costs.

Smaller fans have many other advantages as well, including lower noise levels, smaller size, are more easily relocated, and are safer to handle (more manageable), and safer to lift and to hang from the back. Some of these advantages can be seen in the compilation in Table 2.

Fans operating at lower pressures (the usual outcome if larger duct is used for any given flow requirement) also means a lower wet bulb temperature increase from the fan motor into the duct air as the WB increase is directly proportional to the electrical power consumed, for any given flow.

Smaller fans can in many cases be hung from the back without additional stripping, which means the fans can be advanced more frequently and ducts kept shorter.

The use of variable speed drives should be considered for auxiliary fans especially high powered fans.

Consideration should be given to changing the agreement with contractors so they are back-charged for power used in secondary ventilation based on measured power consumed (which could easily be fitted to fan starters).

ACKNOWLEDGEMENTS

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