Performance and Acceptance Testing of Main Mine Ventilation Fans

D J Brake[1]

ABSTRACT

In most underground mines, the ventilation system is a significant portion of the total mine capital and operating cost and the largest consumer of underground electrical power. The effectiveness of the ventilation system has a major bearing on the safety, health, comfort and morale of underground personnel, and has a critical role in meeting production targets and therefore business revenue. Perhaps the most important component of the primary ventilation system is the primary fan. Correct performance testing of the primary fan during the warranty period is important not only to ensure the mine has obtained the asset that it paid for and can therefore deliver on the fan's crucial safety and economic role in the future of the mine, and to provide a justification for releasing final performance warranty payments to the supplier, but also to provide a benchmark or baseline against which to assess future performance issues. As there are at least three potential international standards available to measure fan performance, there has been considerable confusion regarding which of these to use for testing primary mine fans, and also the correct allowances and tolerances to use. This paper provides guidance on which standards to use for different applications, how the standards should be interpreted, what allowances and tolerances are reasonable, and other important issues to be resolved with the fan supplier prior to making a contract award. The paper also discusses practical issues and methodology for *in situ* primary fan performance testing.

INTRODUCTION

According to ISO 13348, the energy usage by all fans worldwide has been calculated as nearly 20 per cent of total global energy demand. A new primary fan installation in a major mine will cost millions of dollars; perhaps as much as $20 M if the ventilation shaft itself is included in the cost. The productivity, operating cost and safety of the mine is also heavily dependent on the effectiveness of the primary ventilation system, especially the main fans. Performance testing of primary fans, particularly newly purchased fans, is therefore of critical importance. For many years, Australia used the British Standard BS 848 (1980) for main fan performance and acceptance testing. This standard was replaced in the early 2000s with various international standards, particularly ISO5801, ISO5802 and ISO13348. There are overlaps and inconsistencies between these standards which have created problems with specifying and interpreting fan acceptance testing criteria in the context of underground mines.

Performance testing of fans, especially the main (primary) fans, is important for several reasons:

- performance testing is a statutory requirement in most jurisdictions
- assuming the fan duty has been correctly established and specified, performance testing ensures the mine will be able to meet its current and future ventilation requirements and hence supports the health, safety, production and cost targets of the operation
- for newly purchased fans with a performance warranty, performance testing ensures the mine has 'got what it paid for' and therefore provides an auditable basis for releasing any financial performance bonds to the supplier
- it provides a benchmark or baseline against which any future changes (especially performance decrements) in the primary fan output can be assessed, which is very important for fault finding and repair or refurbishment of the fan, or even for diagnosing other problems in the primary ventilation system unrelated to the fan (such as build-up or sloughing in the shaft, or ground falls in underground primary airways).

SPECIFICATION OF THE PRIMARY FAN

Developing the correct specification for a primary fan is a critical activity and one which needs considerable thought. Putting aside the commercial issues, there are three technical aspects to this:

1. determining the fan duty which will almost always change over its life and should therefore be described more accurately as a range of fan duties, or a duty envelope
2. other important specification issues such as the configuration of the fan (axial or centrifugal or mixed flow, single or twin, directly mounted or via elbow), its operating environment (corrosion, erosion, noise), etc
3. performance testing of the fan.

Determining the fan duty over its life

Surprisingly, this is an aspect of the fan specification that is often done badly and has major potential to adversely constrain the mine into its future. The author is aware of

1. FAusIMM(CP), Director, Mine Ventilation Australia, 12 Flinders Parade, Sandgate Qld 4017. Email: rick.brake@mvaust.com.au

situations where the specified fan duty has been vastly different to the actual requirement resulting in a fan that is fundamentally unsuited to the application. The reasons for this usually fall into one of two categories:

1. Badly executed ventilation design, either incompetently completed or because the underlying mine design (on which the ventilation design was based) was itself incompetently completed. In this author's experience, the underlying causes have usually been either excessively optimistic assumptions or failing to consider the fan duty over the full operating life of the fan.
2. Changes to the key ventilation design criteria after the fan duty was determined. For example, there has been a significant change in required production rate, mining method or geographical spread of the operation which has been agreed by senior management without first checking the impacts on the primary ventilation system.

It is therefore very important that the 'basis of design' on which the ventilation system has been specified is thoroughly tested, challenged and validated before the fan duty goes to tender. The ventilation design needs to be robust without being excessively over-engineered. However, the fact that there are so few mines where 'the ventilation system is over-designed' does indicate that in most cases, the ventilation system has been specified from the start with very little spare capacity, and in many cases, can never deliver what the operating mine will actually require once it becomes an 'as built'. Once the primary ventilation system has been designed, procedures need to be put into place so that proposed changes to key assumptions are properly considered before being implemented.

Other key technical issues in fan specification

Stachulak and Mackinnon (2002) provide an excellent discussion regarding many important practical aspects of selecting a suitable primary fan for a mine. These are not further discussed here except to clarify the following.

Fan duties are usually determined by ventilation modelling (eg Ventsim Visual™). So, for example, if Ventsim is used to model a mine and the fan is to be on the surface of an exhaust shaft, then the reference point (plane) for the fan duty is the collar of the exhaust shaft as the modelling only includes pressure losses to this point. It is very important that the specification is clear that this is the reference plane for the fan duty. Any losses associated with the shaft collar, or any transition pieces or bends, etc above the collar, are losses that must be incorporated into the fan curve *by the manufacturer*.

For mine fans, the fan curve (including fan efficiency) that should be 'guaranteed' is the fan static pressure (FSP) curve referenced to the location where the system pressure modelled by the client finished. Some fan manufacturers provide only fan total pressure (FTP) curves. It is best to insist on FSP curve, shaft power and fan static efficiency at the reference plane. If this is not provided, the FTP curve must be converted to an FSP curve by deducting the fan velocity pressure (FVP) from the FTP at each flow, where the FVP is the calculated value at the fan *outlet* (eg evasé outlet) based on true outlet airflow (at outlet density) and gross outlet area without any allowance for any internal fairings, etc (ISO 5802 clause 3.1.12, AMCA 210 clause 3.1.3). The fan FSP curve must then be recalculated at the agreed reference plane (eg shaft collar) by deducting total (not static) pressure loss between reference plane and fan inlet, based on the tendered above-collar pressure loss at the duty flow, recalculated for each fan curve flow. Fan efficiencies and shaft power will also need to be adjusted to those applicable to the reference plane. This can be done by noting or calculating fan shaft power at each flow, and using airpower defined as $FSP_{collar} \times Flow_{collar}$ with FSP efficiency at collar = shaft power/ $FSP_{collar} \times Flow_{collar}$.

The easiest way to avoid all this complexity is to ensure that the fan duty and the fan curves are specified as being FSP at the shaft collar! For exhausting fans (the usual case), this means the negative total pressure at the shaft collar.

A further point to note is that a main fan installation on a mine often uses twin fans in parallel. This provides some residual capacity if one fan were to fail or be offline. However, the second fan is not a backup; the 'duty' specified by the ventilation modelling requires both fans to be operating at any given time. It is important to note that the resistance of the above-collar part of the installation will be much higher if one fan is operating compared to when two fans are operating. Therefore a fan curve based on both fans operating, even if the reference plane is the shaft collar, cannot be 'halved' to test each fan individually.

Performance testing

There are two key concerns mine ventilation practitioners have regarding performance testing:

1. What standard and criteria should be used to assess fan performance?
2. The practical issues of conducting the fan performance test and interpreting the results.

These two matters are the subject of the remainder of this paper.

FAN PERFORMANCE TEST STANDARDS

Most fans manufactured in the world are small: ceiling fans, car, domestic, commercial and industrial air conditioner fans and cooling fans for consumer goods such as computers, etc. These fans can be tested relatively easily and their efficiency is often not critical. By contrast, primary fans in mines are often large and major power consumers at least relative to the underground power load. Large mine fans are also 'field erected', ie they are so large that they are first run in a fully assembled state only after being erected at the mine. They must therefore be tested '*in situ*' rather than at the fan manufacturer's factory.

Until quite recently, primary mine fans in Australia were almost always tested against the 1980 edition of the British Standard 848 (BS 848). The reasons for this were that there was no Australian standard suitable for testing of large '*in situ*' mine fans. BS 848 was also a simple standard to use.

North America generally uses the US Air Movement and Control Association (AMCA) test standards; however, these have never been popular in Australia and are not 'picked up' by Standards Australia, who almost always link Australian standards to ISO standards, where these are available.

In the past 15 years, the ISO has issued three new standards that impact on fan testing.[2] These are:

1. ISO 5801 (2007): *Industrial fans – Performance testing using standardized airways*. Originally issued 1997. Note that the corresponding Australian Standard (AS ISO 5801–2004) references the 2004 version of the ISO, *not* the more recent 2007 version.

2. In fact, this technical committee has issued more standards than these, including ISO 12759 *Fans – Efficiency classification for fans*, first issued in 2010. However, the other standards (typically dealing with mechanical safety, noise levels, jet fans, vibration levels and air curtain fans) are not relevant to main mine fan testing.

2. ISO 5802 (2001): *Industrial fans – Performance testing in situ*. This is the original and still the current edition.
3. ISO 13348 (2008): *Industrial Fans – Tolerances, Methods of Conversion and Technical Data Presentation*. Originally issued 2006 and revised in 2007 and then 2008.

These three standards are very long, very comprehensive, very technical and very complex. The intention to make them as general as possible also makes them difficult to understand and interpret. Unfortunately they also have some internal inconsistencies and, at times, contradict one another on some important points. In some cases, these standards also call up one another on particular matters, eg ISO 5802 references ISO 5801 in its clause 10.4.

All three of these ISO standards were developed by the same Technical Committee (TC 117) and its subcommittees. The secretariat for TC 117 is the British Standards Institute. There are 17 'participating' countries on this committee (including Australia via its proxy *Standards Australia* and the USA via its proxy the *American National Standards Institute [ANSI]*) and a further 20 'observing' countries. Publication (of a draft ISO) as an International Standard requires approval by at least 75 per cent of the member bodies casting a vote.

In most cases, International Standards are adopted as Australian standards without alteration. For example, ISO 5801 is also released as 'AS ISO 5801—2004'. The following is from the preamble to the Australian version of ISO 5801:

> *This Australian Standard was prepared by Committee ME-013, Industrial Fans. It was approved on behalf of the Council of Standards Australia on 5 February 2004 and published on 16 April 2004. The following are represented on Committee ME-013:*
>
> *Airconditioning and Refrigeration Equipment Manufacturers Association of Australia*
>
> *Australian Chamber of Commerce and Industry*
>
> *Australian Industry Group*
>
> *Australian Institute of Refrigeration Air Conditioning and Heating*
>
> *Institution of Engineers Australia*

As few (if any) mine ventilation practitioners are members of any of the above bodies, nor is the AusIMM, the *mine ventilation community does not have any input into these important standards*.

Finally, note that ISO 5801 is the only one of the above three ISO standards that has been taken up by Australia at this point, and has a corresponding Australian standards number. ISO 5802 and ISO 13348 have not yet been adopted by Standards Australia. Since ISO 5801 is not intended for *in situ* fan testing, Australia *technically still has no standard for fan testing relevant to main mine fans*.

ERRORS AND UNCERTAINTIES IN TEST MEASUREMENTS

The true absolute performance of any fan is unknown and unknowable. It can only be estimated by measurements which are subject to uncertainty. Under International Standards, uncertainties are expressed at the 95 per cent confidence level, which implies that, out of a large number of measurements having a normal distribution, 95 per cent will be within the limits specified with 2.5 per cent being above the top limit and 2.5 per cent being below the bottom limit.

The sources of these measurement uncertainties are set out in ISO 13348 clause 5.3 as follows (author's emphasis):

> *This International Standard acknowledges that there are two different sources of uncertainty influencing performance tests.*
>
> ***Design and manufacturing processes*** *have inherent dimensional uncertainties leading to deviations of important mechanical dimensions from the target value. This, again, will lead to inevitable deviations in performance data …*
>
> ***Limitations in the measuring accuracy of the instruments used, and deviations from the standardized test-duct arrangements according to ISO 5801****, will influence the confidence that can be applied to the uncertainty of the resulting characteristic values, such as capacity, fan pressure, power consumption, speed and sound power level. These values, being measured independently by different instruments, will have errors that are unrelated and, as such, their influence on test results shall be considered independently.*
>
> *These tolerances are not limited to the errors of the instruments or the test arrangement employed. They also allow for human error associated with the reading of the instruments and the interpolation of intermediate values. This is particularly relevant for large fans, where the difficulty in achieving standardized test arrangements may be the largest source of error.*
>
> *Measuring uncertainties shall be considered differently from manufacturing tolerances …*
>
> *Zero or exclusively positive tolerances can neither be supported in theory or practice and are not recommended …*

A good discussion of some of the sources of these errors is also given in papers by Lownie (2008) and Stachulak and Mackinnon (2002).

The separation of total tolerance (uncertainty) into manufacturer's tolerance (uncertainty) and measurement tolerance (uncertainty) is a change from fan testing in the past. In the 1980 version of BS 848, manufacturers' tolerances and measurement tolerances were both recognised as being relevant, but were combined into a single measure of tolerance in the Class A, B and C system. For example, BS 848 (1980) clause 16.1 states:

> *… The expected range of this manufacturing variation shall be added to the uncertainty of measurement to determine the minimum tolerance required for a performance specification. Such tolerances are not specified in this standard but some recommendations concerning their use are given in Appendix A.*

ISO 5801

ISO 5801 was designed to test fans using 'standardised airways' (ie standardised inlet and outlet duct conditions) using 'common parts' (pieces of duct). The required inlet and outlet conditions for fan testing were quite restrictive. Basically, the standard is intended for factory ('works') testing of fans, not *in situ* testing. In this sense, it failed to provide a suitable platform for testing of most mine fans, which is usually only attempted once the fan has been erected on site. However, it should be noted that some mine operators, particularly overseas, do require 'works' testing of a main fan before it is bought to site, or where this is not practical, a test of a scale model (Stachulak and Mackinnon, 2002). This is expensive and difficult and the test procedure (being standardised) does not take into account the 'system effects' at the individual mine site fan location, which can be extremely important. However, it does allow the aerodynamics of the fan itself to be established accurately in a controlled environment and the option for such testing should not be discounted.

ISO 5802

To overcome the limitations of ISO 5801, ISO 5802 was issued and provided with extensive tables covering a wide variety of different inlet and outlet conditions during fan testing in real-world conditions. It was therefore an attempt to provide for *in situ* testing.

Since *in situ* fans are mounted in different ways in real-world applications, ISO 5802 deviates from ISO 5801 by classifying fans according to one of four different types of installations, being effectively: unducted, blowing, exhausting and in-line. Test procedures vary for these different applications.

For test purposes, ISO 5802 also distinguishes between fans *with* adjustment devices (eg variable pitch, VIVs, VS drive) and those *without* such devices. Most mine primary fans do have 'adjustment devices'.

During testing of fans *without* adjustment devices, the system resistance must be varied so that three measurement points are obtained that bracket the contractual duty, with one point being 85 - 90 per cent of duty volume, one being 110 - 115 per cent of duty volume, and the other being 97 - 103 per cent of duty volume. This is similar to the 1980 BS 848. Once these three points were measured, they could be used to draw the 'as built' fan curve at least in the vicinity of the duty point. The duty system resistance drawn through the duty point on the tendered fan curve would then intersect the 'as built' fan curve at the so called *most probable operating point*. The discrepancy between this point and the contact duty point (the *characteristic error*) then determined whether the fan passed or failed the performance test.

During testing of fans *with* adjustment devices, both the fan *and* system resistance are required to be adjusted so that the values of both fan pressure and flow are within four per cent of the duty flow. For example, fan RPM and system resistance would both be varied to achieve this. Additional measurement points to bracket the duty are then obtained by adjusting the system resistance as for the fans without adjustment devices. The *most probable operating point* and the *characteristic error* are then determined as above.

This highlights a very important point: for a fan to be tested to ISO 5802 not only must its inlet and outlet conditions fall within one of the specific situations listed in the standard (not always practical in mines) but *three test points* bracketing the *contracted fan duty* MUST be obtained.

ISO 5802 clause 10.1 does go on to state:

> *Where it is impossible to comply strictly with the recommendations of this International Standard, some modifications may be agreed between manufacturer and purchaser, but in such cases it should be understood that the accuracy of the results is likely to be affected.*

In effect, this gives the parties the freedom to adjust the procedure away from the standard by mutual consent, but effectively also then states that the results can only be used if both parties are in agreement, which is not very satisfactory if there is a dispute. To avoid this problem, the use of ISO 5802 puts great emphasis on the parties to develop a comprehensive test procedure prior to awarding a contract, as agreement after an award is likely to be problematic.

There is a further important point (and limitation) about ISO 5802; it is NOT intended to test an entire fan curve (ie the full range of the curve). So, for example, if the mine has specified a fan duty of 400 m^3/s at 3.0 kPa fan collar total pressure, then this (and only this) duty is what can be tested. This presents two potential (but not uncommon) problems:

1. What if the mine cannot in practice alter the system resistance to get this close to the contracted duty? Or if the test party cannot be given sufficient time by the mine operators to obtain the necessary three test points? It may (probably will) be necessary to obtain four or five test points to get three that conform strictly to the tight requirements of the standard.
2. What if the mine duty has been incorrectly estimated? Is there any point testing the fan at a duty which it will no longer ever be required to achieve? If not, how can the fan be 'acceptance' tested at other points on its curve, away from the contracted duty given that ISO 5802 will not allow this with prior agreement?

As an example, consider a mine that specifies a fan to have a duty of 150 m^3/s at 3.5 kPa but when installed, the measured values are 190 m^3/s at 2.0 kPa. This is a big discrepancy but it does happen. If, once the fan is operational, the mine believes it is never going to run the fan at 3.5 kPa, is there much point testing it at this duty? But if the performance test specifies the use of ISO 5802, this high pressure duty is the only value that the fan supplier is required to meet. Perhaps even more importantly, if the fan is running at 190 m^3/s at 2.0 kPa, the actual mine resistance is 0.055 Ns^2/m^8. The contractual duty resistance for 150 m^3/s at 3.5 kPa is 0.156 Ns^2/m^8. To set up the mine to test the fan at 3.5 kPa will require the fan flow to be reduced to 150 m^3/s (as the fan must remain on its curve). At 150 m^3/s, the mine pressure loss at the current mine resistance will be $150^2 \times 0.055 = 1240$ Pa. This means an *artificial resistance* creating an additional 3500 - 1240 = 2260 Pa must be created in the main return to the fan. This artificial resistance will require the main return to be reduced in opening size to about 3.8 m^2. If the main return is (say) 5.5 m × 5.5 m (30 m^2), this requires almost completely closing off the main mine exhaust (to about ten per cent of its normal value). The load on the temporary regulator will be about 10 t force. This is extremely difficult to do both safely and quickly (and then it has to be readjusted four or five times to get the required three test points) and the 'low flow' with the fan throttled will certainly impact adversely on the mine operation for the duration of the test, which is likely to be at least six hours per test point or 18 hours for three test points, assuming only three test points are needed and none have to be repeated which is rarely the case.

This is one reason why, in this author's opinion, ISO 5802 is not generally a reliable standard to call up in contract specification documents, at least as the sole standard to be relied upon and it is for this reason that ISO 13348 was developed and issued. However, there are some aspects to ISO 5802 that are relevant to mine fan testing, particularly relating to *how* pressure, flow and power measurements are taken and *how* measurement tolerances should be established.

In this regard, the measurement of pressure and flow should be reasonably familiar to experienced competent ventilation engineers or fan manufacturers (Table 1). However, the most difficult acceptance criterion to meet is usually fan efficiency, which requires accurate measurement of fan shaft power. Several methods are acceptable in the standard, but the most relevant for mines is usually an integrating watt-hour meter and a timing device such as a stop watch. Alternately, electrical input power can be calculated from line voltage, line current and power factor. Either method will provide

TABLE 1

Data that needs to be collected to measure each test point against the fan curve (exhausting fans).

Parameter	How collected/produced
Fan inlet air density, kg/m^3	Barometric pressure outside the fan plus static pressure across the fan wall at the Pitot traverse location
Fan inlet airflow, m^3/s	Velocity pressure (VP) traverse at shaft collar with even flow conditions (low variation in VP) and known cross-sectional area
Fan static pressure	Total pressure (TP) traverse at shaft collar (exhausting fans)
Number of traverse lines and sample points on the lines for VP and TP	ISO 5802 section 8.4
Impeller speed	Tachometer on impeller shaft if possible, else some other agreed method
Inlet power	Watt-hour metre and stop watch or other agreed method

the input power to the motor. Assuming the motor has a test certificate, it is then possible to accurately estimate the motor output (ie fan shaft input) power using the motor efficiency on the motor test certificate at that load. Additional useful information in this regard is also available in Chapter 13 of Fan Engineering (Howden Group Ltd, 1999b).

ISO 5802 also stipulates, for example, certain maximum measurement variations to be achieved in the total or velocity pressure profiles during Pitot traverses.

Once these measurements are taken and meet the criteria, the fan laws are used to adjust the raw measurements to the fan curve density and fan curve speed, etc, ie to bring the measured points to the contractual (fan curve) reference conditions.

As noted earlier, the 'fan inlet' should have been defined in the tender invitation as the shaft collar (assuming this is the end point of the ventilation modelling). In the unfortunate case where the tendered duty is not at the shaft collar, then an agreed adjustment for the pressure loss between the collar and the 'fan inlet' is required, and the airflow will also need to be adjusted to the air density at the fan inlet, not the shaft collar.

Providing measurement techniques and locations are conducted in accordance with ISO5802, the standard states that the measurement uncertainties for most mine fans should be as shown in Table 2. Note that the measured parameters also need to be adjusted or at least checked for the compressibility coefficient. This is particularly important when the measured values (flow, pressure, power) at the measured RPM and density need to be adjusted significantly to meet the curve RPM or density. In this case, the compressibility coefficient can affect the recalculated values by as much as a percentage point or more, which is very significant when the allowable tolerances are only in the same order of magnitude.

ISO 13348

ISO13348 is the most recent of the standards and was issued because the Technical Committee saw significant shortcomings and gaps in the two other extant standards. ISO 13348 therefore helps to put the three fan test standards into their respective categories as stated here:

> *5.5.3.2 Agreements in performance testing*
>
> *5.5.3.2.1 When the customer specification calls for measurements to be carried out to verify compliance with the contractual data, it shall be agreed as to how this is carried out. The options are as follows:*
>
> *a) performance testing according to ISO 5801, ISO 13347-1 and ISO 14694;*
>
> *b) performance testing using a geometrically similar model, according to the standards detailed above and converting, using the fan laws (see 7.1 and ISO 5801:1997, 15.1);*
>
> *c) performance testing on-site according to ISO 5802, noting that this introduces additional uncertainties and also that, where inlet and outlet connections to the fan are not straight, an unknown system effect factor should be considered.*

Taken as a whole, the purpose of ISO 13348 is to cover the circumstances where ISO 5802 cannot be applied due to *in situ* circumstances, or due to the actual fan duty lying well away from the nominated duty, or where a wide range of the fan curve needs to be tested. ISO 13348 also provides more flexibility for fan manufacturer and purchaser by providing four different grades of manufacturer's tolerances. Whilst manufacturer's tolerances are allowed (and even required) in ISO 5802, little guidance is given in what values are appropriate; this is remedied in ISO 13348.

TABLE 2

Summary of typical measurement uncertainties (tolerances) applicable for most main mine fans.
Note that measurement uncertainties must be adjusted where the fans actual measured speed is not at the curve speed.

Measurement	Uncertainty (measurement tolerance)	Comment
Volumetric flow	±3%	Measured using a Pitot tube traverse in regularly shaped airway
Fan velocity (dynamic) pressure	±4%	
Fan (total) pressure	±1.5%	According to installation type and FVP, as per ISO 5802 Figure 29. Where FVP is small compared to FTP (the normal case for mine primary fans), the FTP measurement uncertainty is typically about ±1.5 per cent for all installation types found in mines (B, C and D).
Fan characteristic error	See ISO 5802 Figure 30	The difference in the actual flow at the system duty resistance, versus the duty flow
Input power	±2%	Assuming watt-hour metre readings, see ISO 5802 clause 10.5.8
Fan efficiency	Typically about three per cent for main mine fans	Varies according to the fan characteristic uncertainty (the characteristic error divided by the duty flow) and the ratio of FVP to FTP, determined as per ISO 5802 Figure 31. The value of three per cent applies where the FVP is small compared to FTP, and the fan is tested somewhere near its duty point.

The four recommended manufacturing tolerance grades are shown in Table 3, but note that these only apply where the fan curve efficiency at the test point is at least 90 per cent of the 'stated best efficiency'. The actual manufacturing tolerance values applicable to each grade are shown in Table 4.

Where the test point curve efficiency will lie outside 90 per cent of the *best* (highest) efficiency on the curve, then lower (more generous) tolerances must be applied. These are shown in Table 5.

Effectively Table 5 is stating that if a mine operator buys a fan with a certain duty point, the manufacturer must only guarantee the contractual tolerance grade in the portion of the fan curve that lies within 90 per cent of optimum efficiency. The manufacturer is *not* guaranteeing the whole fan curve to that accuracy. Since most manufacturers will select a fan that has its optimum efficiency at the nominated duty point (if there is only one duty point), this means the fan curve is only guaranteed to the contractual tolerance class near the contract duty. Outside this region on the fan curve (in both directions), the allowable 'manufacturing tolerance' becomes larger and larger. See ISO 13348 Figures 3 and 5.

The 'manufacturer's' tolerances are then drawn around the contractual fan curve as per ISO 13348 Figure 5. The different regions of the fan curve with different tolerances based on the fan efficiency on that part of the curve are clearly visible. The measured points then have the measurement tolerances created around each point also as per ISO 13348 Figure 4 and 5. It should be noted that the measurement *tolerances* (not only the measured *values*) need to be mathematically adjusted if the fan is not at its curve speed.

ISO 13348 recommends the fan test meets criteria for: Volume flow, Fan pressure, Fan shaft power, Fan efficiency, and Fan noise level. The fan then is acceptable if the uncertainty envelope in *all* of the contractual performance criteria overlaps the fan curve manufacturer's tolerance zone. If the fan fails to meet any one of the contractual performance criteria, then it has failed the acceptance test. Of course, the fan may also pass in some portions of the fan curve, and fail in others.

It is also important to note that an acceptance criteria-based on power by itself will *not* ensure an efficient fan. The fan input (or shaft) power manufacturer's tolerance is basically to ensure the fan motor and associated electrical equipment are not overloaded. From Table 4, a fan could meet AN2 by being 2.5 per cent low on both flow and pressure (5.2 per cent low on airpower) and meet the AN2 criteria for power (being three per cent high on power). The fan efficiency is therefore approximately 7.5 per cent 'low'. It should be clear that if the fan was tested solely on flow, pressure and power, it could pass, when in fact it should fail on efficiency. In general, fan efficiency is the most difficult criteria to meet; however, since it can only be calculated with an accurate measurement of power, it is also often one of the most difficult measurements to obtain reliably and are therefore frequently ignored.

For comparison, the acceptance criteria for the earlier fan test standard BS 848 and ISO13348 are shown in Table 6.

It may appear there are some similarities between BS 848 and ISO 13348. Whilst this is true, there are some very important differences. BS 848 did not provide any tolerances for fan pressures. This is because BS 848 was designed to test a single duty point only, and since a fan can only operate on its system resistance curve, then by specifying a volume tolerance, BS 848 was also effectively specifying a pressure tolerance according to $P=RQ^2$. BS 848 also did not specify an efficiency tolerance for Class C fans, as it was assumed that this class would only be used in situations where fan efficiency was not important (although avoiding excessive fan

TABLE 4

Partial extract from ISO 13348 Table 2: Manufacturing tolerance grades.

Parameter	Tolerance grade				Additional information
	AN1	AN2	AN3	AN4	
Volume flow rate	±1%	±2.5%	±5%	±10%	
Fan pressure	±1%	±2.5%	±5%	±10%	
Power	+2%	+3%	+8%	+16%	Negative deviations permissible
Efficiency	-1%	-2%	-5%	-12%	Positive deviations permissible

TABLE 5

Manufacturer's tolerance grade applicable to different portions of the fan curve.

Nominated manufacturer's tolerance		AN1	AN2	AN3	AN4
Actual applicable tolerance for points on the curve with this efficiency	>90%	AN1	AN2	AN3	AN4
	80 to 90%	AN2	AN3	AN4	AN4
	60 to 80%	AN3	AN4	AN4	AN4
	<60%	AN4	AN4	AN4	AN4

TABLE 3

Extract from ISO 13348 Table 1: Guide for fan 'air and noise' tolerance grades 1 to 4.

Tolerance grade (air and noise)	Typical application	Material of, and manufacturing processes used for, major aerodynamic components	Approximate minimum power[a] (kW)
AN1	Mining (eg main fan), process engineering, power stations (eg exhaust fan), wind tunnels, tunnels, etc	Machine in some places, case (high accuracy)	>500
AN2	Mining, power stations, wind tunnels, runnels, process engineering, air conditioning	Sheet or plastic material, partly machine, cast (medium accuracy)	>50
AN3	Process engineering, air conditioning, industrial fans, tunnels, power station fans and industrial fans for harsh (abrasive or corrosive) conditions	Sheet material, cast (medium to low accuracy), special surface protection (eg hot dip galvanising, moulded plastics)	>10
AN4	Process engineering, ships fans, agriculture, small fans, power station fans and industrial fans for harsh (abrasive or corrosive) conditions	Sheet material, special surface protection (eg rubber coating), moulded or extruded plastics	-

a. For each class, a recommendation has been given only for the lower power limit; an upper limit is not essential. For example, even if the power is greater than 500 kW, any one of the grades may be assigned.

TABLE 6

Indicative comparison of BS 848 (1980) and ISO 13348. Note that the tolerances in BS 848 (1980) included both manufacturing and measurement tolerances whereas the ISO 13348 values below are for manufacturing tolerances only. The measurement tolerances for ISO 13348 are additional to those below with indicative values for typical main mine fans shown in Table 1.

	ISO 13348 manufacturing only				BS 848 manufacturing plus measurement		
	AN1	AN2	AN3	AN4	Class A	Class B	Class C
Volume	±1%	±2.5%	±5%	±10%	-2.5%	-5%	-7.5%
Power	+2%	+3%	+8%	+16%	+7%	+10%	+15%
Efficiency	-1%	-2%	-5%	-12%	-2%	-3%	N/A
Fan pressure	±1%	±2.5%	±5%	±10%	N/A	N/A	N/A

power was still important). By contrast, ISO 13348 requires a manufacturer's tolerance envelope to be drawn around the complete fan curve, so that at any point on the curve, both a volume and pressure tolerance is required. There are also differences between the way the efficiency pass/fail criteria was assessed for BS 848 versus ISO 13348.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are made regarding main mine fan testing. All of these points should be discussed and agreed with the supplier prior to awarding a contract to supply the fan:

- Main fans should be performance tested to ensure the mine has received the fan that it paid for, to keep tenderers 'honest' in terms of their technical offers which protects the tendering process generally, to provide an audit trail prior to release of contract performance guarantee retention monies and to provide a baseline against which the fan's future performance (and the primary ventilation system's performance) can be assessed.
- Specified main fan duty(ies) should correspond exactly to the 'end point' of the ventilation model (ie the exact location of the fixed quantity in the model which gives rise to the duty pressure). In most cases, this will be the top of the surface ventilation raise. Any pressure losses above this point must be taken into account by the fan supplier.
- Fan curves *must* be provided as fan static pressure referenced to that same location.
- Main fans should be tested as soon as possible after commissioning.
- The test should be conducted by an agreed, experienced independent third party with representatives from both the mine owner and the fan supplier in attendance.
- Prior to awarding the contract to supply the fan, the test procedure should be carefully detailed. It should also state (with completed worked examples) how the measured data will be converted into final test results (especially how power and efficiency will be calculated) and agree beforehand on the specific measurement tolerances and manufacturers' tolerances that will apply.
- In almost all cases, the appropriate test standard to reference for *in situ* main mine fan testing is ISO 13348. This, in turn, will reference test procedures and measurement tolerances from ISO 5802. However, the manufacturers' tolerances and overall pass/fail criteria should be adopted from ISO 13348.
- ISO 5802 by itself is only suitable for fan testing if one (or a small number) of fan duties is specified, the mine is certain that it can (and will) adjust the mine resistance on the test dates to provide three points closely bracketing each duty, and the rest of the fan curve is irrelevant to the future of the mine.
- ISO 5802 and ISO 13348 have not been adopted (to this time) by Standards Australia.
- ISO 5801 is only suitable for 'works' (factory) testing, not *in situ* testing.
- In testing to ISO 13348, at least three points should be tested on the fan curve: one near the top, one near the bottom and the third near the expected duty. Alternately, the region of the fan curve which the manufacturer is guaranteeing needs to be explicitly stated and agreed.
- Choose the ISO 13348 manufacturer's tolerance grade carefully. Specifying an unnecessarily high grade will increase the capital cost of the fan for potentially no additional value. The same is true for specifications that require 'zero negative tolerances'. A ±2.5 per cent allowance on flow and pressure will not impact negatively on most mine operations so that the AN2 is the most appropriate standard for most main mine fans, assuming the nominated fan duty is near the optimum curve efficiency, which is almost always the case.
- Note that this tolerance is only required to be met in the near-peak efficiency portion of the fan curve; the manufacturer's tolerance (allowance) will vary up and down the fan curve in accordance with Table 4. However, it is important to understand that specifying an AN2 tolerance (-2.5 per cent on flow and pressure) will automatically trigger AN3 (-5 per cent) and AN4 (-10 per cent) tolerances on less efficient regions of the fan curve. Understanding this is particularly important if the fan may or will be required to operate over a wide range of its fan curve over its operating life.
- Measurement uncertainties must also be agreed before awarding the contract. ISO 5802 provides good guidance in what these measurement uncertainties should be. Recommended values for main mine fans are shown in Table 2 of this paper. Achieving these uncertainties requires considerable thought to be put into where and how the various measurements will be obtained *prior* to awarding the fan supply contract, eg the Pitot traverse plane, the ability to measure impeller speed and electrical input power, obtaining motor test certificates, etc.
- There is little point in insisting on very tight manufacturer's tolerances if the fan measurement uncertainties are going to be high. What is the point in insisting on AN1 manufacturer's tolerance (one per cent tolerance on flow and pressure) if the fan test set-up is so poor that pressures and flows can only be tested to (say) four per cent measurement tolerance?
- All test equipment should have suitable range and accuracy, and must have current calibration certificates;

manometers should be the averaging type and if the expected velocity pressures will be very different to total pressures (often the case), then a 'low range' manometer should be obtained to measure velocity pressures accurately. The high range manometer is used to measure total (and static) pressures.

- Correct application of the fan laws is vital. A good reference is Howden Group Ltd (1999a) or McPherson (2009).
- The shape and size of the duct at the Pitot traverse plane should be carefully checked, and any nearby upstream or downstream obstructions (eg shaft collar lip) assessed for impact on the measurement site. This should be done prior to awarding the contract, and then during the *in situ* test to confirm the arrangements.
- If the shaft is an exhaust and is carrying liquid water in the airstream at the Pitot traverse plane, then obtaining accurate measurements can be difficult as the Pitot tube will block very quickly resulting in unreliable readings.
- Where the main fan installation consists of two fans operating together to meet the duty, then the test procedure can only be conducted with both fans operating at the same speed and blade/VIV setting, etc *or* the fan manufacturer must provide separate curves for single fan operation.
- 'Pass/fail' criteria need to be clearly agreed and cover all potential outcomes, eg:
  - if the fan being tested passes on two measured points but fails on the third, or
  - if two identical fans subject to the performance test are tested and one 'passes' but the other 'fails'
  - if the fan passes on some criteria (pressure, flow, power, noise) but fails on others (efficiency)
  - if the fan passes on some portions of the fan curve, but fails in other regions.

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