Quality Assurance Standards for Mine Ventilation Models and Ventilation Planning

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ABSTRACT

Most mine ventilation engineers are involved in ventilation planning and design in some capacity. Ventilation modelling software used by a competent experienced ventilation engineer is extremely useful in developing good ventilation designs by allowing assessment of a wide range of potential options. Unfortunately, ventilation modelling undertaken by persons who do not have sufficient experience or knowledge usually results in a façade that covers up a fundamentally unsatisfactory design. Ventilation models are produced for a wide variety of purposes including: fault-finding of a problem area in a mine and options analysis for resolution of such problems; a complete review or optimisation exercise of an entire mine's ventilation system; or a much longer life-of-mine type of study. Models can be intended as the basis for studies with diverse purposes such as primary shaft or airway sizing, primary fan specification, examining re-entry times after blasting, resolving leakage or recirculation, or investigating the impact of fires or underground climate or cooling requirements. The concepts of 'materiality' and 'fitness for purpose' are essential to developing or using a ventilation model and serious mistakes have been made in wrongly using a ventilation model for purposes for which it was never intended, often because it is simply the most recent model on the mine site. Mistakes at this level often translate into faulty ventilation strategies and inefficient or ineffective use of scarce capital for ventilation projects. Validating a ventilation model is a time-consuming and expensive process and not every model must (or even should) be fully validated to meet the objectives at that time. This paper discusses the application of quality assurance in ventilation planning with particular respect to the 'basis of design' (BOD) as well as the standards for validating a ventilation model. It also provides a recommended way of dealing with non-conformances in measured versus modelled values of critical parameters in the model.

INTRODUCTION

Developing a high quality ventilation strategy that will be safe and effective in an underground mine whilst having the lowest net present cost (ie adding most value) is not a trivial undertaking. All too frequently the answer is seen to be in 'the ventilation model'. As ventilation modelling tools have become more sophisticated and the outputs more colourful, it is easy to confuse substance with style.

A ventilation model can, in the right circumstances, be produced in only a day or two. However, the model is not an end in itself; in all cases it is the means to an end, which is to solve a ventilation problem or assess a new or modified ventilation design. In this sense, the model is only as good as the validity of the data on which it has been built and the process that has been used in its development.

In this author's experience, there are three areas in which the ventilation design process fails because of failure to:

1. understand the scope, battery limits or deliverables of the exercise; recommendations in this regard have already been presented (Brake, 2008)
2. obtain or use the appropriate inputs and assumptions for the study or to understand the correct ventilation operating standards that need to be achieved by the design
3. develop a valid (ie accurate) ventilation model(s).

In addition, the use of a ventilation designer with insufficient skill or experience is a major contributing factor to the above three problems. However, this is not always the case. Often the mine design or operating staff do not understand the impact of certain design or operating practices on the ventilation system. If the wrong questions are asked by the ventilation engineer, or the right questions are not asked (two different situations), then it is possible even for competent persons to arrive at a design that is unsatisfactory, but which may not be recognised until the mine has spent millions of dollars adopting the system.

In this respect, there are two particular quality assurance (QA) issues that ventilation engineers needs to be familiar with. These are:

1. how to validate a ventilation model
2. how to prepare a basis of design (BOD) for a ventilation design.

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The process of validating a ventilation model refers to the QA process, which ensures the model will give reliable predictions of the performance of the ventilation system, either 'as built' or at some future point in time. However, a valid ventilation model does not necessarily mean a good or optimised ventilation design. This comes about by careful and comprehensive definition of the inputs to the ventilation BOD as well as the knowledge and experience of the ventilation engineer.

These two facets of the design process will be discussed separately.

VENTILATION MODEL VALIDATION

It is very high-risk to use a ventilation model that has not been validated (effectively 'certified as free of material errors') as an input to decisions that may involve millions of dollars in capital or operating costs, or may either support (or compromise) critical future mine production, or may result in serious occupational health and safety (OH&S) consequences relating to dust, gases, fires, etc.

For this reason, only properly validated ventilation models should be used for major planning exercises and any model validation should have a documented paper trail back to original source documents that show all these measurements or justify all the key assumptions. In other words, the model must be an auditable document.

For a model to meet these criteria, it must correlate with more than just the measured airflows. In fact, a high correlation between measured airflows and modelled airflows can often cover up an invalid model!

The reason for this is that any model can be adjusted, massaged or fudged so that it reflects measured airflows. This is often done with the best of intentions and can be achieved by adjusting friction factors or shock losses or airway dimensions or lengths or regulator settings, etc. In addition, during audits this author has often found compensating errors such as an incorrect fan curve being used with incorrect shock losses but still producing a 'correlated' airflow. Therefore, to assume that a good airflow (volume) correlation means that the model is valid can and often does cover up fundamental underlying problems such as: incorrect fan curves (wrong fan type) or blade or variable inlet vanes (VIV) angles or impeller speed, incorrect air density, incorrect friction factors, shock losses or fixed resistances or fixed flows or airway lengths, shapes or dimensions, flow reversals or missing airways or incorrectly modelled regulators or leakage or recirculation paths.

The issue is that a massaged model or one with compensating errors will look correct and may in fact be fully satisfactory for examining minor ventilation changes to the network, ie whilst it is only being used for assessing minor or incremental changes then it may be fit for purpose. There may therefore even be confidence on-site in 'the ventilation model'. However, if such a model is then used to examine wholesale or major changes to the network (eg reversals of airflow through main airways, new major airways, blocking off existing main airways, new major fans or fan relocations, significant changes in existing fan duties requiring higher or lower pressure/flow, etc) then it can give very incorrect results that may not be detected until the changes are made, which may be after the expense of thousands or millions of dollars and have potential consequences on production schedules and the like. This author is therefore very reluctant to accept any ventilation model 'as is', without any validation process being conducted.

In fact, it is better to have a ventilation model that *doesn't* reflect measured airflows quite as well, but has a better overall correlation with all of the above, than one that has been massaged to indicate a good airflow correlation but for which none of the other important correlations have been checked.

Therefore, for a ventilation model to be considered to be valid, it should meet the requirements in Table 1. Where any criteria cannot meet the standard, the risk must be assessed via simple sensitivity analysis to ensure the model will still be 'fit for purpose' *with the non-compliance* and if not, the measurements and/or the model are further examined to bring the criteria into compliance with the standard. Note that getting a good correlation between actual and model values will require using compressible airflow and, in some cases[1], taking natural ventilation pressure into account.

In Table 1, 'major' is undefined but refers to selecting a sufficiently representative sample of high airflow airways dispersed throughout the entire mine. What is sufficient will depend on the size of the mine and the extent of the ventilation circuit. However, as a general rule, the following airflows and differential pressures should be checked.

Airflows:

- all regulators and circuit (district or booster) fans (as well as primary fans)
- the entry and exit of air into and out of ventilation districts or major splits.

Differential pressures:

- all mine primary and circuit (district or booster) fans
- all regulators and most other ventilation controls which, if they did not exist, would result in a significant short-circuit between intakes and returns.

In practice, any airflow split that is carrying more than (say) five per cent of the total airflow or more than 4 m/s should probably be checked. In some cases, it can be useful to categorise ventilation measurement stations in a system using the criteria in Table 2.

The above validation criteria is true for all ventilation modelling software. With respect to Ventsim™, the following specific checks are also recommended:

- Key airways are named according to the mine's local naming conventions; 'show data' set up to hide clutter.
- Levels set up with elevations.
- User-defined presets set up under tools>settings. This should include above-collar losses for surface fans unless these are already included by the manufacturer in the fan curve.
- No 'custom' values for friction losses, resistances or shock losses or airway types/sizes are used at all in Ventsim™; all such values should be set up as 'presets' as this makes global changes and auditing of the model much easier and more robust.
- User-defined settings configured especially surface elevation, surface barometric pressure and surface temperatures. Ensure these are giving the correct surface intake air density during modelling.
- 'Prevent direction change' is turned on for critical airways as this will create a run-time warning for the user if a major airway 'wants' to change direction.
- Airway sizes/shapes checked by sorting high to low in spreadsheet view.
- Airway cross-sectional areas checked (too high or low) by sorting in spreadsheet view.

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1. Mines that have large voids (eg open stopes) especially if these voids have significant vertical height and carry significant airflow at low wind speeds in hot or cold strata.

TABLE 1

Key validation criteria for a ventilation model.

Criteria	Standard
'Fit for purpose'/objectives of model.	A clear statement of the purpose of the model once it is validated. Ventilation model validation can be an extensive and costly process and it is not always essential for the entire model to be validated. However, if this is not the case, then it clearly needs to be stated and incorporated into the associated file note. With Ventsim™, it is possible to include any such notes in the 'title note' or 'file memo'.
Criteria for model validation agreed.	The pass/fail criteria for ventilation model validation has been completed and agreed with the mine's technical and management representatives. Recommended criteria are listed in this table.
A basis of design has been agreed.	The basis of design covers all the important ventilation standards and planning and operating practices that will be used for this mine during the period covered by the ventilation model.
Primary ventilation survey completed either during or immediately prior to the ventilation model validation.	Where the mine already exists, a 'routine' primary ventilation survey of flows and primary fan duties should be completed as part of the model validation, or immediately before the validation starts. The primary ventilation (fans, regulators, etc) circuit during the survey must be set to operate as per the desired circuit in the ventilation model, ie primary ventilation survey cannot be from a period when the mine was fundamentally different, or primary fans were different, etc. This survey should also measure pressure differences across a representative selection of ventilation controls (ventilation doors and walls), as well as the open area and pressure drop across all drop board regulators (DBRs). Short-circuits and major leakage paths (eg open stopes, open passes, open caves or goafs) should be identified.
Pressure losses in major (see text) airways especially shafts (usually using a barometric pressure survey).	Actuals should be within ten per cent of modelled values or 150 Pa, whichever is the lower. Where barometric pressures cannot readily be used to determine specific airway resistances, the raw barometric pressure values should be compared to the modelled values. These should also be within 200 Pa. Note that compressible airflow and natural ventilation pressure must both be used in the model.
Pressure differentials across major (see text) ventilation controls (usually using a manometer survey).	Actuals should we within 15 per cent of modelled values or 150 Pa, whichever is the higher.
Airflows in major (see text) airways (those carrying more than five per cent of total mine airflow, or minimum of 50 m^3/s).	Actuals should we within ten per cent of modelled values or 20 m^3/s, whichever is the higher.
Airflows in all airways.	Ideally within 10 m^3/s and preferably within 20 m^3/s of modelled values.
Correct direction of airflows and correct direction of pressure differences across all but insignificant airways or controls.	Even if the magnitudes of flows or pressures are in error, the direction of flow and pressure should be correct.
Correct number and location of all fans and their make, model, blade solidity, blade/VIV setting, impeller speed (rev/min), density. Correct fan pieces (bellmouth, transition pieces, bends, evasés). Original copies of all fan curves must be found and checked.	All fans, but especially those moving more than ten per cent of total mine airflow, or minimum of 50 m^3/s. In addition, any fan that is bolted onto a wall, or which has duct going through a wall, must be included.
Pressures and flows through fans are measured correctly and matched to fan curves. Note that a fan must operate on its curve. If it doesn't then either the curve is incorrect or the fan measurements are incorrect. Fan total pressure (FTP) curves should be used in modelling, with a specific resistance added to account for non-useful fan pressure (eg losses in the evasé, or inlet losses or evasé losses).	Measured pressures and flows should be within three per cent of the fan curve. If they are not, then the difference must be investigated. Potential issues are noted above and would include extra losses in adaptors, dampers, erosion on fan blades, etc.
Correct handling of above-collar pressure losses (eg elbows, transitions, adaptors).	Where the fan curve provided by the manufacturer already includes above-collar losses in the fan curve, and the above-collar arrangement has not been changed, then no allowance is required. However, where the above-collar loss has not been included in the fan curve by the manufacturer, or the nature of the above-collar elbow, etc has changed since the curve was issued, then the above-collar loss must be measured and set up as a user-defined preset for that fan installation.
Correct location, type and leakage through ventilation control devices (including regulators).	A realistic allowance for leakage through ventilation controls must be made. All regulators should be set up as 'orifices' (true m^2 open area) not fixed resistances. Where possible, photographs should be taken of each control and these should be kept with the audit documents. (In Ventsim™, it is possible to take photos of each vent control, vent door, fan, or other vent-related device and then 'drag and drop' the photo onto the airway in Ventsim™. This will then put the photo onto the airway and also into the box on the 'notes' tab in the EDIT dialog.)
Correct modelling of leakage, short-circuiting and/or recirculation (if it exists) through old workings, caved zones, goafs or other voids (including stopes).	A realistic allowance for leakage through old workings, caved zones, goafs or stopes must be made.
Consistent use of shock losses and friction factors.	Friction factors and shock losses from comparable known airways should be used, or measured *in situ*. Similar airways (eg raise borers) should have the same friction factors. Similar airway shocks (obstructions, etc) should use the same shock loss factors. However, shock losses should only be applied in airways that are either dedicated for ventilation, or have wind speeds more than 6 m/s. Do not use equivalent lengths in lieu of shock loss factors as these need to be manually recalculated if the airway size is changed.

TABLE 1
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Criteria	Standard
Nil or carefully justified and documented use of 'fixed flows', 'fixed pressures', 'fixed lengths' and 'fixed direction'.	For 'as built' models, there should be no fixed flows, fixed pressures and 'fixed lengths' and 'fixed direction' should only be used where unavoidable. For models where the fans have not yet been purchased, fixed flows are acceptable, but should be replaced once budget prices and fan curves are provided. Where there is any doubt about the accuracy of the location or length of the airways, the survey 'as built' should be imported as a reference graphic and overlaid on the ventilation model and carefully checked.
Correct length, dimensions, connections, shape and 'wall type' of the air routes in all important circuits.	It is important to not rely on anecdotal data here. All airways in the primary ventilation circuit and major district circuits should be carefully checked for these values and an audit trail established.
Consideration of the impact of mine depth on air density for modelling and fan curves. Air density used in fan curves should also be consistent with air density used in the airway pressure loss modelling.	Compressible air modelling should be used. Fan curves in the ventilation fan database should be carefully checked to ensure the air density is as per the manufacturer's fan curve. Ventsim Visual™ will automatically adjust these to the local air density in the particular airway. Fan rev/min must also be checked.
Consideration of the impacts of natural ventilation pressure (usually only an issue in mines with refrigeration, or mines with large differences in the surface elevation of their intakes and exhausts, or in large areas underground that have very low flows such as large stopes, caves or open goafs).	Natural ventilation pressure must be turned 'ON' for fire modelling or temperature modelling especially if refrigeration plants are in use.
Wet-bulb (WB) temperatures.	Assuming a temperature model has been developed. (Note: in most cases, only the summer design condition should be compared to actuals. This means actual measurements need to be during the peak summer condition.) WB predictions within 1°C of actual. Total heat pickup in the mine within ten per cent of modelled value.

TABLE 2
A classification system for ventilation measurement stations.

Category	Description	Basis of measurement
Category A	Critical measurements that are diagnostic in terms of primary ventilation circuit fault-finding or Ventsim™ modelling.	Based on anemometer traverse and surveyed airway cross-sectional areas. Checked every three months maximum.
Category B	Important measurements for local ventilation circuits. This would probably also apply to fixed installations such as workshops, magazines, fuel bays, etc.	Based on centre (spot) readings and surveyed airway areas. A centre point correction factor should be established specific to each location. Checked every six months maximum.
Category C	Interim or short-term ventilation measurements for local circuits or short-term situations.	Based on centre (spot) readings and airway areas found using tape measures or 'Distomat' devices. Checked as required, which could be as much as daily for daily operational issues in a problem area, or as infrequently as annually for low importance but not completely irrelevant readings. Ideally centre point correction factors would be developed for each specific location, but as these are frequently changing, this is not essential.

- Friction factors checked by sorting in spreadsheet view. Also check the use of the density-adjust checkboxes in EDIT dialog box.
- Compressibility and natural ventilation pressure turned on/off as appropriate (compressibility should always be turned on).
- Check for any fans with *only* fan static pressure curves (all fans should have fan total pressure curves).
- Check for multiple or duplicate airways (two or more parallel airways set up to show as single airways in the model).
- Primary and secondary layers set up.
- Airway type colour-coding defined.
- User-defined views identified and set up to include *all* future submodels (eg future stages of mine life). Views should include critical parameters such as volume, wind speed, wet bulb as well as critical directions of airflows. Note that the appropriate use of 'favourite' data types allows user-defined data types such as airflow combined with wet bulb temperature.
- User-defined model stages (options) are set up.
- Maximum and minimum airflows and wind speeds and air direction checked especially on key airways including ramps, travelways, ladderways and exhaust shafts (eg for potential for water blanketing). Note: set up a user-defined view for each check so it is easy to cycle through these views.
- Fans clearly named in fan database and correct fans placed in network at correct locations.
- Fans operating with correct rev/min, blade/VIV angle, air density, blade solidity.
- Fan duties checked for excessive pressure/flow and position on the fan curves. Also for 'auto-close', 'rev/min' and other boxes.
- Auxiliary fans placed/provided for including self-closing dampers and duct resistances (especially where fans are bolted into walls or have ducts passing through walls).
- Where ducts are in the model, check if leakage must be modelled accurately.
- Compile a list of ventilation controls and fans used in the model. Check practicality of controls at each location. Hint: name any airway with a vent control (except simple walls or bulkheads) so it is easy to compile this list.
- Evasés, fan bends, bellmouths correctly placed (if not already included in fan curves).

- Shock losses applied (check these by sorting in spreadsheet view). Do not use equivalent lengths for reasons noted above.
- Fixed flows should be converted (eventually) to resistances or fans. Resistances of drop board regulators or other openings (eg cracked brows or passes) should be input as orifice openings (m^2 open area), or resistance values (Ns^2/m^8) not 'regulator per cent'.
- Circuits checked for continuity (unconnected or wrongly connected nodes, etc). Can check using 'contaminant simulation' using a fixed concentration source on surface airways and also dynamic modelling. Search for single or double loose ends.
- Use spreadsheet view and also the 'financial simulator' on a global basis to check for 'high cost' airways.
- Model checked for recirculation using the 'Recirculation finder'.
- Check airway densities (sort in spreadsheet view).
- Model checked for sensitivities and robustness to changes in schedule or design.
- Use edit>find and check most of the items in these menus (for correctness).
- Check the model against its *basis of design* for any inconsistencies.
- Re-entry times checked for typical development and production blasts.
- Heat loads checked and temperatures checked (if required).
- Check for excess surface entries (ie airways incorrectly marked as being 'surface' airways), airways incorrectly marked as 'close end', airways incorrectly marked as 'exclude', duplicate airways, flow reversals, fixed lengths.
- Check for custom (ie not preset) resistances, friction factors, shock losses. Custom values should be converted to 'presets' or (for resistances) to orifices (m^2 openings).
- Check for at least one open (unregulated) split in each ventilation district or circuit.
- Check impact of fires on first and second means of egress and also entrapment/refuge stations.
- Key parameters (total mine flow, flows in key airways, fan pressures, etc) summarised and compared between options for any inconsistencies. This should not only include parameters under *run*>*summary* but also key airflows and fan pressures, etc.
- File clearly named and can be identified in final report. Notes stored within file.
- File secured using a password to prevent accidental changes

VENTILATION BASIS OF DESIGN

As noted earlier, a ventilation model may be valid in the sense that it accurately predicts how the network will perform, but the ventilation design/strategy itself may nevertheless still be seriously flawed. In this author's experience, there are two reasons for this:

1. the ventilation designer does not have the knowledge or experience to develop a sound design, or
2. the inputs used in the design are incorrect.

Peer review, especially when the peer reviewer is involved in the design from an early stage, is a helpful process to avoid the former of these two problems. Peer review is also a very helpful mentoring tool much like the traditional artisans' approach to developing skill and competency in the apprentice.

However, for experienced ventilation designers, the latter of the above points is of most concern. One reason is that the mine planning engineers or senior management often only have a vague understanding themselves of how some important details of the mine will work, or they have conflicting understandings of these (between design and operations). In many cases, even senior mine planning engineers and operating managers have only a rudimentary understanding of ventilation, and in some cases, quite erroneous understandings. Therefore producing an auditable ventilation BOD, whilst it can often be a lengthy process, is a remarkably effective way to ensure all stakeholders are under the same understanding of how the mine will operate, and what ventilation standards will be achieved in that operation. This author has had many experiences where the process of producing the ventilation BOD has drawn out critically important disagreements between key persons in the mine design and operations, which has meant that these *can* be resolved before the design is finalised. In many cases, without a detailed and explicit BOD, the problems would not have been recognised even after the ventilation design had been completed and approved, until operations actually commenced under the new design, when the problems with some of the details would have then become apparent.

A small example of the sorts of key inputs that may *not* be agreed include:

TABLE 3
Example of a ventilation basis of design.

Parameter	Value(s)		
Purpose of this design	Review the cooling strategy and cooling loads to provide technical information for the tender specification for the refrigeration plant		
Animation file and software	v86d_150122 [InTouch]		
DXF file	v86_fxs_141126_2_no_gc_drill		
Date	August 2019		
Graphic	{Refers to sufficient representative screen shots showing the mine at these particular stages}		
Reason for choice of milestone/stage	All major underground ramps completed; ore handling system commissioned; mine operating at 3.5 Mt/a (achieved in Q4 2017) (Crusher commissioned Q3 2017; shaft commissioned 2016).		
Ventilation standards	{Documentation on what will be the ventilation standards for this mine at this stage in its life}		
Materials handling (t/a)	Trucked to surface	Orepasses (shaft)	Trucked internally
Ore	800 kt/a rate	2.8 Mt/a rate	Nil
Waste	500 kt/a rate	200 kt/a rate	Nil

TABLE 3
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Mining method	Low rise transverse sub-level open stope and longitudinal benching with footwall drives and RARs on each level			
Airflow estimate based on benchmarking for chilled air (unchilled air)				
Principal changes in primary circuits between milestones	Not applicable (only one milestone)			
Filling method	Paste			
Ramp vent strategy	Top down with open RARs on some working levels and near ramp bottom			
Vent wall construction (to estimate leakage)	High quality ventilation walls (leakage 1 m^3/s at 1 kPa across wall)			
Ramp system	A	B	C	D
Active development levels per ramp	4	4	0	1
Active ramp faces in addition to development levels	0	0	0	1
Active production levels per ramp (drilling, bogging)	1	3	7	1
Total active levels needing vent	5	7	7	3
Trucks TH551, 515 kW (no, Tier)	3 (1)	2 (1)	3 (1)	2 (1)
Load-haul dumps (LHDs) 621 production and development 352 kW (no, Tier)	3 (2)	1 (2)	3 (2)	0
LHD haulage level LH621 (345 kW), (no, Tier)	3 (2)			
Airflow allowance per level	35 m^3/s. Based on 330 kW LHD at 0.05 = 16.5 m^3/s at the face. Allowing for 30 per cent leakage in a duct means 23.6 m^3/s into the fan. Allowing 30 per cent for the fan to not recirculate, means 31 m^3/s into the level, rounded up to 35 m^3/s. Note this does not allow for multiple headings with fresh air, nor for trucks.			
Litres diesel consumed underground orebody (trucks and LHDs)	160 000 L/month assumed on ten sources, ie average of 22.2 L/h+20 per cent margin = 26.7 L/h = equiv engine of 84 kW			
Litres diesel consumed underground LHD haulage	8.5 hr/shift × 2 shift/day × 3 LHD maximum × 40 L/hr = 2040 L/day = 28.3 L/h = equivalent engine of 89 kW			
T.km per month	Trucks (290 000); orebody LHDs (60 000) (excludes haulage level)			
Auxiliary fan/duct combinations	For ducts up to 300 m serving LHD only, single 55 kW 1.2 Φ fan feeding single 1.2 Φ duct or twin 1.067 Φ ducts (or combination of these). No trucks. For ramp face (truck and LHD), twin 110 kW 1.4 Φ fan feeding twin 1.2 Φ ducts (one to face, one to S/P). Only 1 truck. Only 1 face.			
Maximum duct lengths production areas	300 m			
Trucks off-ramp?	Only in level access immediately off the ramp. No trucks on the levels.			
Ore handling in the orebody	Eight orepasses in total of which only four are in use in 2019. However, this Ventsim™ model allows for top exhaust on five passes simultaneously. In {date}, total ore production is rate of 3.5 Mt/a of which roughly 2.6 Mt/a goes through the passes and is hoisted, with the remainder (roughly 0.9 Mt/a) going via trucks to surface. Main passes 3.8 m Φ r/b; smaller passes 3.8 × 3.8 m D&B. Main orepasses will be tipping into on two levels or more at any time. When a finger into an orepass is not in use, it will be securely plugged. Orepasses that are in use will have 15 m^3/s top exhaust.			
Main crusher level haulage operation	Three diesel LHDs operating on peak shifts (average 2.3 LHDs) No chutes 6 min cycle time per LHD back to the tipples Maximum distance of any ventilation split on the haulage is 420 m, which means if the haulage is 30 m^2 and carries 30 m^3/s (wind speed = 1 m/s), it will clear on average every seven minutes.			
Policy regarding working downwind of LHDs in their dust/gas/heat	We will not allow persons without air-conditioned cabins to work downwind of LHD (producing dust, heat, DPM, gases).			
Policy regarding trucks on levels	Not allowed. Level ventilation designed for LHDs only.			
Underground fixed infrastructure (magazines, fuel bays, stores, workshops, crushers, cribrooms, etc), effectively anywhere where there are persons working, or combustibles stored	Workshop (xx L) Fuel bay (xx L, near current workshop) Magazine (xx L, precursor explosives only) Two emulsion bays (xx L and yy L) Cribroom (within workshop) Tyre bay (within workshop) Stores (within workshop)			
Method of production blasting (eg tight or reverse blasting)	Void against h/w and blast away from stope access			

TABLE 3
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Largest production blasts (typical)	80 000 t
Method of initiating production blasts	Remote firing.
Stopes short circuiting (when)	Brow remains closed until stope is nearing empty so no short-circuiting till remote loading in progress. Then once stope is emptied, fill wall constructed on lower level so no short-circuiting.
	When stope is emptied, fill walls go up. Top level needs vehicle access through wall. Will use Nixon flap or similar.
When remote LHD used	Only at end of stope, ie stope not drawn empty till end of life
Independent firing? Locations?	No
Re-entry issues/times, etc	Production blasting twice per day Development blasting twice per day Re-entry time allowance is 45 minutes (shift change time)
Underground electrical power excluding winders, surface exhaust fans	6.5 (say 7) MW (assume 14 loads each 500 kW all sensible)
Explosives consumption	115 t/month (production) plus 100 t/month (development). Not all heat enters ventilation air.
Cement consumption	5600 t/month but not all heat enters ventilation air
Groundwater produced at average depth (mbs)	50 L/s at 400 mbs (virgin rock temperature (VRT) is 31.5)
Total heat on each active level heat from explosives, cement, groundwater (without diesels)	250 kW (see note 1 [not provided here])
Working in heat protocols	Min 0.5 m/s WS if wet-bulb (WB) > 25. Work/rest cycling if WB>30 for persons working outside air conditioning.
Strata gases	None
Threshold limit values for gases and dusts, except diesel particulate matter (DPM)	As per Australian NOHSC standards. Adjustment for non-standard rosters as per Western Australia approved guideline.
DPM	This vent design cannot meet DPM limits using airflow dilution alone. Needs Tier 2 engines with clean fuel (<50 ppm) and DP filters to comply.
Toxic dusts (silica, lead, coal, other)	None
Explosive dusts (sulfide dust explosions)	None
Spontaneous combustion	None
Cost power, $/kW-hr	$0.05/kW-hr
Non-air-conditioned vehicles?	All development and production LHDs and trucks have air conditioning
Second means egress including dedicated raise or shared	Ladderway to all production levels (parallel escape system to each ramp. Ladderways are in the RAR system. Maximum wind speed 10 m/s (36 k/h). See note 2 (not provided here).
Fire refuge	All persons 30-min belt-worn self-contained self-rescuer (SCSR); max 750 m from any working place to secure fresh air base or 36-hour rated refuge chamber ('secure' meaning the fresh air raise has uncontaminated fresh air even in event of mine fire taking out underground power (but not surface fans)).
Emergency warning systems	Stench gas at intake portals only not at intake shafts, manually activated
Policy on refuge chambers (RC) and fresh air bases (FAB)	FAB or RC Max 750 m spacing. FAB is 'secure' so remains fresh air even if power lost to underground or part. RC is rated 36-hour standalone. Size and number for double normal persons in that feeder zone.
Policy on SCSRs	30 min belt-worn all persons underground
Policy on 'inbye' workers heavy vehicles	No person working inbye truck or LHD without either second escape, refuge chamber or FAB
Surface rainfall	See
Surface design wet blub temperature (°C)	23.0
Surface coincident design dry bulb temperature (°C)	32.0
Surface Baro P (kPa)	99.8
Underground temperature limits	30° WB where persons are working outside a/c cabins; hence 30° WB reject temp is the overall limit where persons may be outside a/c cabins. No limit for persons working inside a/c cabins. Ramp temps to not exceed 28° (allowing +2° for heat pickup between ramp and face, hence 30° WB on levels fed from the ramp).
Airflow allowance for diesel equipment	0.05 m^3/s per kW rated diesel engine power (target) at the diesel workplace.
Water to diesel ratio (fraction)	8
Diesel calorific value	34 MJ/L
Diesel quality	50 ppm S maximum

TABLE 3
Cont …

Strata heat on levels	See note 3 (not provided here)	
Diesel heat load	Based on predicted fuel burn + 20 per cent	
Elevation of mine above sea level	880 m (collar of hoisting shaft)	
Rock thermal properties		
Near surface VRT (°C)	27.5	
Geothermal gradient, °C/100 m depth	1.0	
How handle strata heat	See note 4 (not provided here)	
Rock density (kg/m^3) [host, not ore]	2700	
Rock specific heat (J/(kg.°C) [host, not ore]	800	
Rock thermal diffusivity (m^2/s × 10^{-6}) [host, not ore]	Calculated from above	
Rock thermal conductivity (W/(m.°C) [host, not ore]	1.8	
Rock wetness (fraction)	0.15	
Airways	Size (m wide × m high)	Friction factor (Ns^{2}m^{-4})
Crusher, north, central and southern surface exhausts	4.5 m Φ r/b	0.004
Southern, central and 'refrigerated' surface intakes	4.1 m Φ r/b	0.004
Haulage shaft size, furniture, usage	8 m Φ concrete lined rope guides no routine man riding (Maryann for maintenance and emergency)	0.010
Footwall drives	5 × 5 arched drill and blast (D&B)	0.010
Ore drives	5 × 5 D&B	0.010
Internal RAR, drop raise/raise bored	4.5 × 4.5 D&B or 4.5 Φ r/b	0.010, 0.004 1.1 m Φ laddertube in 4.5 m Φ raise bore: 0.006 Ns^2/m^{-4} 1.1 m Φ laddertube in 4.5 × 4.5 D&B raise: 0.015 Ns^2/m^{-4} Max WS for ladderways 10 m/s
Internal FAR	4.5 × 4.5 D&B or 4.1 Φ r/b	0.010, 0.004
Declines	5.5 × 6 arched D&B	0.010
Conveyor drives	6.5 × 5.5 arched D&B	0.020
Ventilation duct	Various	0.004
Shock loss policy	Ventsim™ autoshock feature	

- how many workplaces need to be ventilated at any time to achieve operational flexibility and targets
- whether persons will need to be working inbye (downwind) of a production loader
- what the operating temperature limits are for persons outside air-conditioned cabins.

The actual items to be included in a ventilation BOD will vary with the particular circumstances of the mine or the ventilation design. However, Table 3 is an example of such a BOD. It is not suggested that the actual values in this BOD should be adopted at all operations. Note that the BOD *must* also (within the body of or attached to the BOD) include *all* the supporting documentation that is required for the audit trail (omitted from this example for brevity).

CONCLUSIONS

There are four key elements to obtaining high quality 'fit for purpose' ventilation designs:

1. A good understanding of the scope, battery limits, exclusions and deliverables from the work. These need to be critically reviewed before the study commences as sometimes the restriction of the scope of the design may so impact on the design that it renders any conclusions unsound or at least heavily 'non-optimum'.
2. A documented BOD, which ensures all the necessary inputs (factual and assumptions) are agreed, the standards for the resulting ventilation operations are agreed, and an auditable paper trail is established for every key 'ventilation driver' within the BOD.
3. A validated ventilation model. Again, this must be an easily auditable document that can be clearly referenced back to the BOD or ventilation measurements audits.
4. Competent, skilled ventilation engineers in the design development process. Achieving this is a separate matter to the content of this paper, but it is clear that no amount of process or standards, by itself, will result in an optimised ventilation design if the designer does not have the skills or experience to do a high quality job.

Templates have been provided for ventilation model validation and the BOD. These are not prescriptive as they will need to be adjusted for specific circumstances depending on the scope of the work; however, they provide examples of what is required.

REFERENCES

Brake, D J, 2008. A protocol and standard for mine ventilation studies, in *Proceedings 12th US/North American Mine Ventilation Symposium 2008* (ed: K G Wallace), pp 3–11 (University of Nevada: Reno).