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APPLICATION OF VENTSIM TO LOW PRESSURE GAS DRAINAGE AND HIGH PRESSURE NITROGEN RETICULATION SYSTEMS

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ABSTRACT This paper outlines a methodology employed to apply Ventsim ventilation modelling software to gas drainage and nitrogen injection systems. Use of the software to account for compressible flow, specified gas compositions and the resistance of conduits of various dimensions makes it suitable for both ventilation circuits and gas reticulation systems. Unlike mine ventilation circuits, in gas drainage systems it is necessary to specify flow rates arising from gas pre drainage holes as these are dependent on gas reservoir properties. This requires a mass flow balance to be obtained between underground gas drainage holes and that reporting to surface pump(s). In nitrogen injection systems it is convenient to create an interface between the gas drainage reticulation system and the mine workings which in turn is connected to the ventilation system. However, it is also possible to keep the two systems separate for simplicity and tuning. The results of applying these strategies to an operating gas pre drainage system are described. These provide the "as built" pipe friction factors obtained by matching the model results to observed differential pressures. The Pike River re-entry nitrogen injection system has also been modelled. This uses the same principles as the negative pressure gas drainage models but with high positive pressures of up to 1,000 kPa (10bar).

BACKGROUND THEORY

The mathematical theory describing frictional losses in gas reticulation systems is provided by, amongst others, McPherson, (1993) and Boxho, *et al*., (2009). In summary, the calculation proceeds as follows;

1. Calculate the "rationale "resistance of the pipe from dimensions and wall roughness factor. This being the physical resistance of the pipe without a correction for density.
2. For a defined gas composition, calculate the gas constant (J/(kg.K)) and density from which the mass flow rate (kg/s) can be calculated for a given gas flow rate (m^3/s at specified temperature and pressure).
3. Calculate the change in pressure due to frictional losses using gas laws corrected for compression or expansion of the gas mixture.

The form of the final equation for pressure loss in a horizontal pipe with compression is shown in Equation 1 with that for the rational resistance in Equation 2.

$\frac{P_1^2 - P_2^2}{2} = M^2 . R.T.r_t$ Eqn.1	$r_t = \frac{64.f.L}{2.\pi^2.d^5}$ Eqn.2
where, P_1 and P_2 = absolute pressures at the start and end of the pipe, (Pa) M = mass flow rate of the gas mixture, (kg/s) R = gas constant for the gas mixture, (J/(kg.K))	T = absolute temperature, (K) r_t = rationale resistance of the pipe, (m^{-4}) f = dimensionless friction factor L = pipe length (m) d = pipe diameter (m)

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For design of gas reticulation systems, as with Atkinson's equation for frictional losses in ventilation systems, the following issues need to be considered;

1. Resistance is inversely proportional to the pipe diameter to the fifth power i.e. small changes in diameter have a profound effect on frictional losses. Appropriate sizing of pipes is critical.
2. For pipes under negative pressure, increasing suction pressure decreases absolute pressure in the pipe resulting in a reduction in density and a consequential increase in volumetric flow rate i.e. the volumetric flow rate increases with increasing suction. The opposite is the case in a pressurised system which is why injection pipes are significantly smaller than drainage pipes.
3. The frictional loss is proportional to the square of the mass flow rate i.e. double mass flow rate results in four times the frictional loss. Other than limiting flow rates in a single pipe this also means that installing parallel pipes, or ring mains, provides a reduction in resistance inversely proportional to the square of the number of parallel paths.

These calculations can be undertaken using a spreadsheet approach but are now also provided for in Ventsim models. It is recommended that both methods are employed to double check results prior to selecting critical infrastructure of this type.

VENTSIM SETTINGS

Due to the low flow rates and high pressure differentials occurring in gas drainage or nitrogen injection systems, compared to those in ventilation circuits, it is necessary to modify Ventsim simulation settings to avoid simulation errors. The custom settings to change are shown in Table 1:. These are mainly focused on increasing simulation precision, even if the simulation time increases.

Table 1: Ventsim settings for gas reticulation

Ventsim Setting	Comment
Presets	
Resistance (at 1.2 kg/m^3)	for items such as bends or valves, leakage path air to hole collar and pipe joints
Friction factor (at 1.2 kg/m^3)	for each pipe diameter only use custom for individual pipes as a last resort
Layers Air Type	one for each pipe diameter for faster editing as a group
Gas mixtures	set for hole collars or nitrogen plant outlet (note ambient intake will be fresh air)
Simulation - Airflow	
Allowable error	0.001 m^3/s for 1.0 l/s
Compressible flow	Yes
Convergence limit	0.100 m^3/s or lower if pressure excess problem on convergence
Density adjust friction factors	Yes
Density adjust pre set resistance	Yes
Maximum simulation pressure	set 10 x maximum e.g. for gas drainage +1,000 kPa for N2 injection 10,000 kPa
Use Natural Ventilation Pressure	optional if 3D model
Simulation - Gas	
Use gas density for air simulation	Yes
Simulation - Environment	
Pressure	for ambient or seam intake or NP (101.3 kPa)
Temperature	for ambient or seam intake or NT (20^{O}C)
System Settings	
Use mass flow	Yes or No depending on preference. Mass flow is easier to balance.

Important note on Ventsim releases – the gas density calculation algorithms in Ventsim for high pressure conditions were updated for revision 5.1.2.2 or later. Earlier revisions of Ventsim may fail to simulate high pressure systems described in this paper.

ESTABLISHING A GAS RETICULATION MODEL

In both negative pressure gas drainage or positive pressure nitrogen injection systems it is necessary to fix flow intake or outlet rates as they will be dictated either by gas emission rates in gas drainage systems or valve settings in nitrogen injection systems. Furthermore, gas composition at intake points (boreholes or nitrogen plant outlet) must be pre-set. The recommended strategy for establishing a gas reticulation model is as follows (this creates a separate system unlike Ventsim's duct builder tool):

1. All reticulation system entry or exit points must be connected to the surface or alternatively, for nitrogen injection, the pipe outlet can be connected to the ventilation model. This provides a means of sizing pipes with or without the complexity of connecting to the ventilation part of the model.
2. All entry or exit points, except two, must be fixed flow or have an equivalent fan curve applied to them. It is convenient to use mass flow for this balance as values are independent of temperature or pressure.
3. There must be one entry or exit point to the reticulation system that is not a fixed or a fan/pump branch. This avoids potential conflicts in the Ventsim mesh selection routine. The easiest strategy is to use one very high resistance branch that allows free mesh selection but does not lead to errors or high leakage rates.
4. For gas drainage systems, the inbye pipe range pressure will be that applied to hole collars. This is set by having a single inbye input branch with a specified fixed pressure drop, for example -5.0 kPa for collar pressures of that value. For nitrogen injection systems, the pipe pressure is set by an inbye pressure loss representing a control valve(s).
5. All entry points, that are not fresh air, must have the gas composition specified. Entry points to gas drainage systems that are leakage paths with fresh air will result in dilution of the gas mixture in the pipe. It is therefore necessary to run an "air" then "gas" then "air" simulation sequence to obtain the correct result.
6. It is recommended that airway type and airway friction factor pre-sets are established so that changes to the whole circuit can be made by changing a single value. This is useful when attempting to match the model to observed values. Unless survey results are very detailed, this is all that will be available in any event.

To set a model up without knowing actual losses in the system, the suggested range of friction factors for "clean" pipes is shown in Table 2 and shock losses for pipe fittings in Table 3. Actual pipe resistances will then be very much dependent on the degree of obstruction to due accumulation of water or drill fines.

Table 2: Friction factors for clean pipes

	Poly pipe		**Galvanised pipe (welded)**			
e mm	0.01	0.1	0.5	1.0	**1.5**	2.0
Diam mm	k Ns/m^4	k Ns/m^4	k Ns/m^4	k Ns/m^4	**k Ns/m^4**	k Ns/m^5
100	0.0018	0.0029	0.0046	0.0057	**0.0065**	0.0073
200	0.0016	0.0025	0.0037	0.0046	**0.0052**	0.0057
400	0.0014	0.0022	0.0031	0.0037	**0.0042**	0.0046
600	0.0013	0.0020	0.0028	0.0033	**0.0037**	0.0040
800	0.0013	0.0019	0.0026	0.0031	**0.0035**	0.0037

Table 3: Notional shock loss factors for pipe fittings

Item	X	Item	X
Tee, Flanged, Dividing Line Flow	0.2	Globe Valve, Fully Open	10
Tee, Threaded, Dividing Line Flow	0.9	Angle Valve, Fully Open	2
Tee, Flanged, Dividing Branched Flow	1	Gate Valve, Fully Open	0.2
Tee, Threaded , Dividing Branch Flow	2	Gate Valve, 1/4 Closed	0.3
Union, Threaded	0.08	Gate Valve, 1/2 Closed	2.1
Elbow, Flanged Regular 90°	0.3	Gate Valve, 3/4 Closed	17
Elbow, Threaded Regular 90°	1.5	Swing Check Valve, Forward Flow	2
Elbow, Threaded Regular 45°	0.4	Ball Valve, Fully Open	0.1
Elbow, Flanged Long Radius 90°	0.2	Ball Valve, 1/3 Closed	5.5
Elbow, Threaded Long Radius 90°	0.7	Ball Valve, 2/3 Closed	200
Elbow, Flanged Long Radius 45°	0.2	Diaphragm Valve, Open	2.3
Return Bend, Flanged 180°	0.2	Diaphragm Valve, Half Open	4.3
Return Bend, Threaded 180°	1.5	Diaphragm Valve, 1/4 Open	21

https://www.engineeringtoolbox.com/minor-loss-coefficients-pipes-d_626.html

DISPLAYING PIPES

A problem arises when attempting to display small diameter pipes on a mine model involving normal airway dimensions and scale of the mine e.g. a 400 mm x 3.0 km long pipe will not display clearly while viewing an overall mine layout.

One solution to this problem is to create a shadow of the pipe system as follows, Figure 1:

1. Create an “Air Type” called “pipe shadow” or similar.
2. Select a colour similar to the pipes but with some degree of contrast.
3. Duplicate then group then exclude the entire reticulation system.
4. Select the excluded group and make some visible size (e.g. 2.0 m wide x 0.5 m high) then offset 0.5 m below the actual reticulation system.

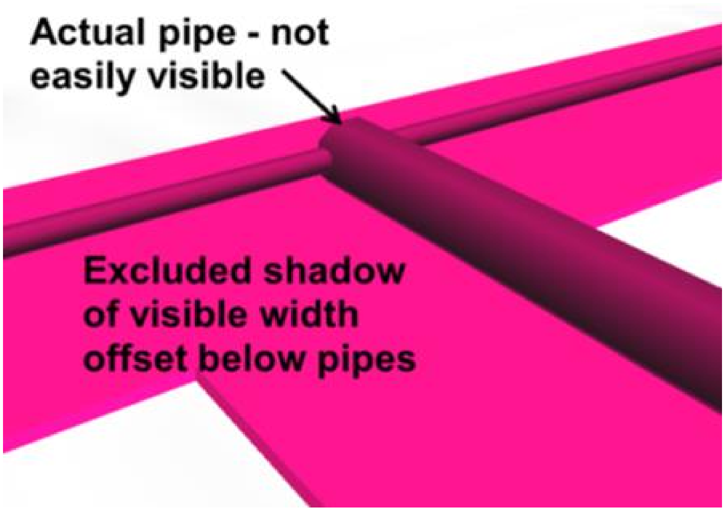


Figure 1: Displaying pipes using excluded airway shadows

The shadow ”Air Type” can then be turned on or off as required and has no effect on the model.

DISPLAYING RETICULATION FITTINGS AND DEVICES

Pipe fittings (e.g. water traps or valves) can be shown by establishing a zero resistance pre-set resistance and assigning an icon. This is a particularly useful strategy for all Ventsim models to show where infrastructure is located, Figure 2. That is, the icon is shown but has no effect on simulation results.

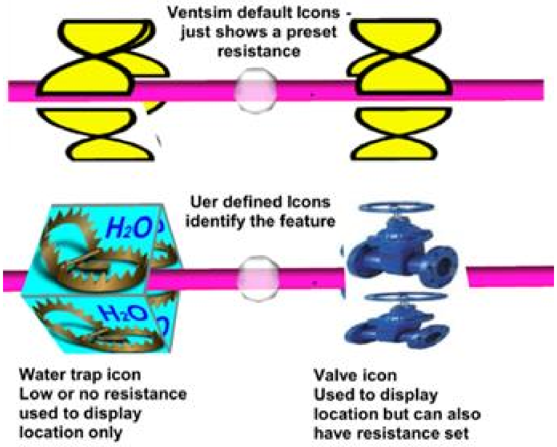
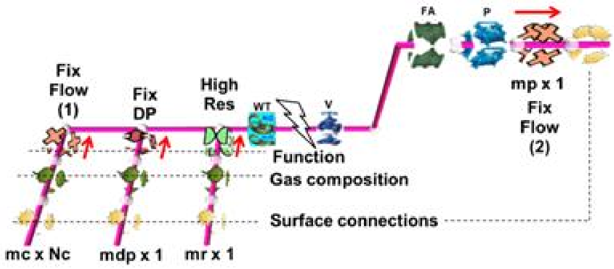


Figure 2: Examples of preset resistance icon pictures for clarity

GENERIC CONFIGURATION OF RETICULATION MODELS

The recommended method for establishing gas drainage system input points is to use multiple short fixed length airways, Figure 3 at each entry point. The first section is connected to the surface and has the gas composition specified. This provides the NTP entry density and gas properties at hole collars. The second is the fixed flow rate or the inbye fixed pressure drop which sets the individual hole flow rate or collar pressure. The third provides a monitoring point with a single value; otherwise the reported data value will be the branch average.



WT-Water trap, V-Valve, FA-Flame arrestor, P-Pumps

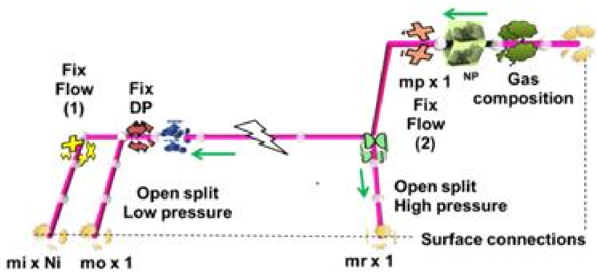
Figure 3: Gas drainage system (generic schematic)

The mass balance for the system is then determined by the sum of fixed hole collar flow rates which will be determined by that of the total reporting to the surface pump station minus that through leakage paths or the single high resistance branch for mesh selection, Table 4.

Table 3: Mass Balance and icons for a gas drainage system

Gas Drainage Feature	Mass Flow kg/s	Number In Circuit	Comment
Fix flow (1)	mc	Nc	One for each collar or set of holes
Fix DP	mdp	1	Fix collar DP e.g. -5,000 Pa
High res	mr	1	Open split (Q = (DP/R)^n) very low flow
Fix flow (2)	mp	1	Pump flow mp = mr + mdp + mc x Nc

For nitrogen injection systems, the recommended strategy is to set an NTP flow or mass flow rate (at a set composition) into the plant from surface pressure then set the back pressure by applying fixed pressure drops to the end of pipes where control valves will, in reality, be located, as shown in Figure 4. Again, a single very high resistance branch is used to provide a theoretical open split for mesh selection.



NP-Nitrogen plant

Figure 4: Nitrogen Injection circuit (generic schematic)

This model shows nitrogen pipes discharging to atmosphere for the purpose of sizing pipes. However, they can also be connected to the mine's ventilation model to predict inertisation times.

The mass balance for the system is then determined by the sum of fixed hole collar flow rates which will be determined by that of the total flow rate provided by the nitrogen plant distributed to outlet points, Table 4.

Table 4: Mass balance and icons for a nitrogen injection system

Feature	Mass Flow kg/s	Number In Circuit	Comment
Fix flow (1)	mc	Nc	One for each injection point except one
Open split	mo	1	Open split on low pressure side
Fix DP	mdp	1	Fix back pressure on reticulatin system
High res	mr	1	Open split (Q = (DP/R)^n) very low flow
Fix flow (2)	mp	1	N2 plant flow mp = mr + mo + mi x Ni

APPLICATION TO A GAS DRAINAGE SYSTEM

The modelling strategy for gas drainage systems described above has been applied to a mine's gas drainage system for which flow rates, gas composition and pipe pressure differentials were measured. The purpose of the analysis was to assess the need to increase the pipe diameter in the reticulation system for inbye extension.

The geometry and characteristics of the current gas reticulation system together with the Ventsim model results are shown in Figure 5. The main issues were as follows;

1. At a flow rate of about 1.5 m^3/s NTP at 85% CH_4, the inbye mains pipe had a pressure differential of about -4.1 kPa and the pump inlet pressure was -15 kPa.
2. An allowance of 20 kPa back pressure on the pump outlet was also made to allow for delivery of gas to gas utilisation and methane destruction infrastructure.
3. The existing mains 450 mm pipe was at about 5.0 km from the pump station borehole. The plan was to extend this by up to 6.0 km inbye for a potential life of mine (LoM) length of 11 km.
4. The success of pre and post drainage strategies meant that the plan flow rate for future gas drainage requirements was to be increased to 3.0m^3/s NTP mixed 85% CH_4 at up to -30 kPa pump inlet pressure.
5. Recognising that the 450 mm pipe could not meet LoM gas drainage requirements, the main question to be addressed was what pipe size would be appropriate?

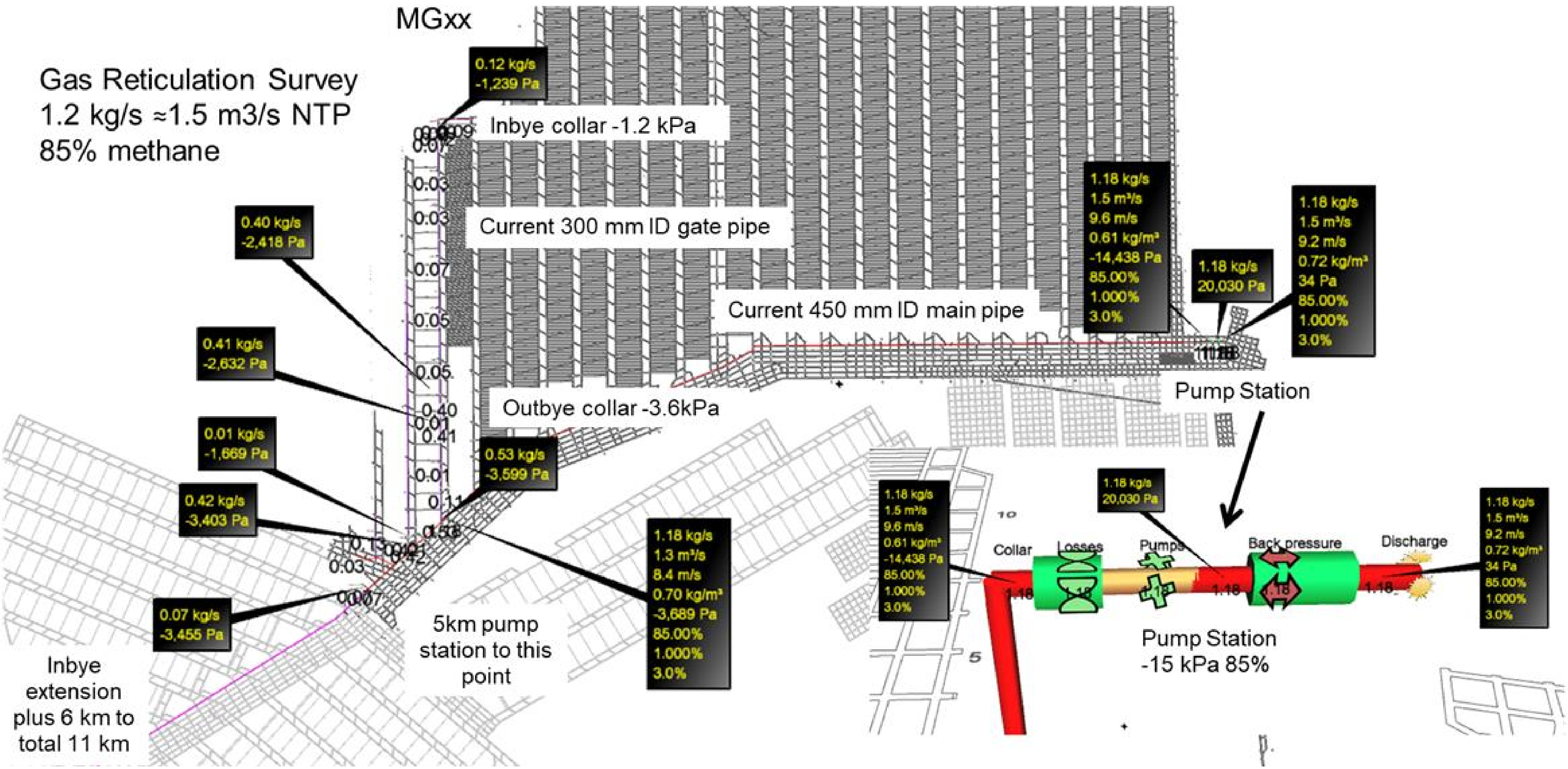


Figure 5: Ventsim model of existing gas reticulation system

A survey of all flow rates and pressures for individual drilling stubs was undertaken by the mine to determine the distribution of gas flow rates and pressure losses in the system. For example, the flow rate and pressure differential profile of MGxx is shown in Figure 6. This type of information is invaluable for tuning any type of Ventsim model.

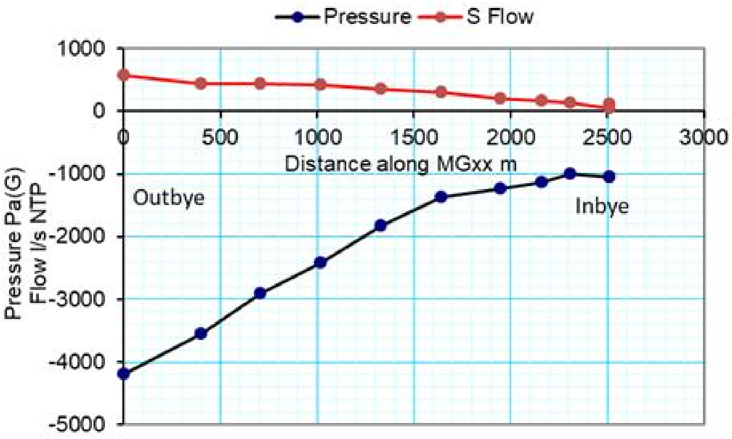


Figure 6: Observed frictional loss and flow rates MGxx

Once the reticulation system was set up in Ventsim with the gas flow balance described by the survey, the pre-set pipe resistance was modified to match observed pressure differentials. This strategy determined an effective friction factor for installed pipes (including fill and valves) of 0.0055 Ns^2/m^4 or about 20% higher than for a clean pipe. Of course, any significant accumulation of water or drilling fines in a single pipe could completely change the result.

DESIGN OUTCOMES

The tuned model was then extended to 11 km and the flow rate increased to 3.0 m^3/s NTP 85% CH_4 at the inbye gates. The model was then run using pre-set “Air Types” for pipe diameters of 600 mm to 900 mm but with the pre-set pipe friction factor set to that obtained by matching observed flow and pressure data. The outcome, for a base case of 3.0 m^3/s NTP at 85% CH_4 and 4.2 m^3/s NTP at 60% CH_4, was that a 750 mm pipe would be required for extension to 11 km, Figure 7. This would include replacing the existing 450 mm diameter pipe with a pipe of similar diameter. The mine has now commenced with installation of 750 mm pipes.

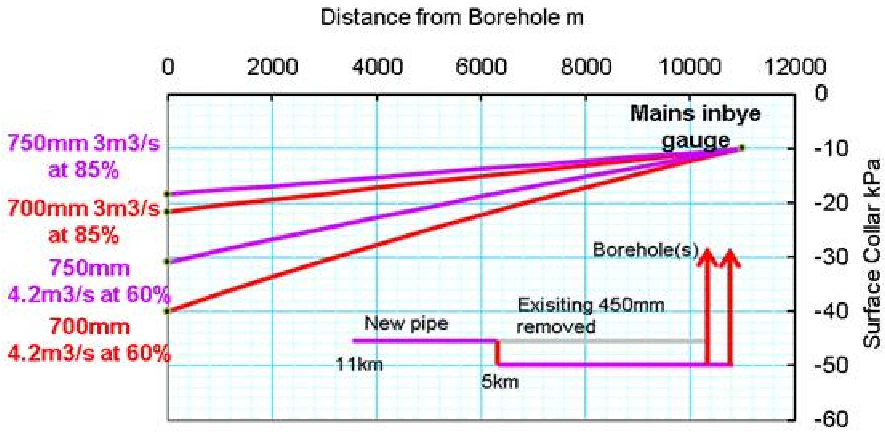


Figure 7: Gas reticulation characteristics to 11 km

For general design of gas drainage systems operating at low pressures (50 to 70kPa (abs)), this analysis provided a limiting pipe velocity of about 14 m/s. For example, and in round numbers, 3.0 m^3/s NTP would be about 6.0 m^3/s at 50 kPa (abs) which would require a 738 mm pipe for 14 m/s at the pump inlet.

APPLICATION TO PIKE RIVER RE ENTRY NITROGEN INJECTION SYSTEM

Important qualification – the Pike River Recovery Agency (PRRA) has given permission to use the following information for this paper under its policy of openness and transparency. This information, analysis and design outcomes are preliminary, subject to further work and risk assessment. Not all, if any, of this work will necessarily be employed in the re entry process.

Following a methane explosion in 2010 in which 29 miners were killed, Pike River coal mine is currently sealed. Other than some variations adjacent to the portal seal during periods of rising barometric pressure, the mine's atmosphere is now more than 90% methane. As part of the proposed re-entry of the drift, to be undertaken sometime in 2019 for forensic examination purposes (PRRA, 2018), the plan is to initially displace methane with nitrogen then maintain nitrogen injection to the body of the mine while the drift is recovered in an atmosphere compliant with explosion risk zone 1 (ERZ1) standards and as shown in Figure 8.

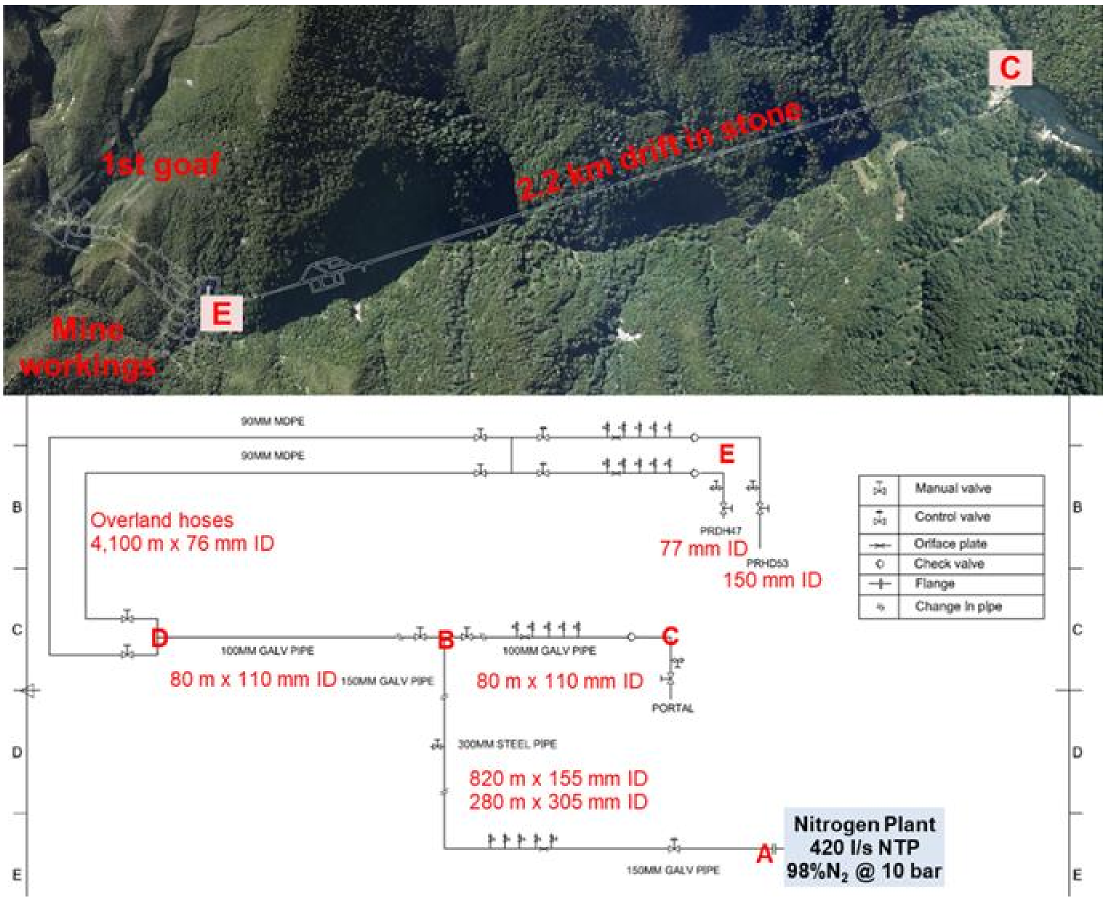


Figure 8: Pike River Mine Re-entry nitrogen reticulation system and surface topography

The nitrogen reticulation system, Figure 8, comprises the following;

1. A membrane nitrogen plant delivering up to 420 l/s NTP at 98%N_2 at up to 10bar (point A). There are also three back up cryogenic units.

2. Galvanised steel pipe (110 mm to 305 mm ID) from amenities to the portal area (points A – B – C). This provides for nitrogen injection to flush the drift.
3. Approximately 4.1 km of twin 90 mm (76 mm ID) hoses to the injection borehole collars at an elevation approximately 400 m above the portal, points D to E. Due to the steep terrain, these will be installed by ground crew after being dropped in by helicopter. It is therefore essential that they be sized appropriately.
4. Two injection boreholes (141 m x 77 mm ID and 98 m x 150 mm ID) into the coal workings. These provide for nitrogen injection into the coal mine workings to maintain an inert atmosphere during re-entry to the drift.

The purpose of the modelling exercise was as follows;

1. To demonstrate that two rather than one 4.1 km hose was required to connect the plant to holes into the workings.
2. To estimate what the purge times would be (using dynamic gas simulation)
3. To provide a graphical representation for explanation of the injection strategy to other interested parties.

The model employed included a normal 3D representation of the mine to scale combined with a schematic representation of the nitrogen reticulation system, Figure 9. In this case, the exit points from the injection holes were connected to the mine's ventilation model using dummy low resistance pipes. A spreadsheet approach was also employed to check outcomes of this analysis.

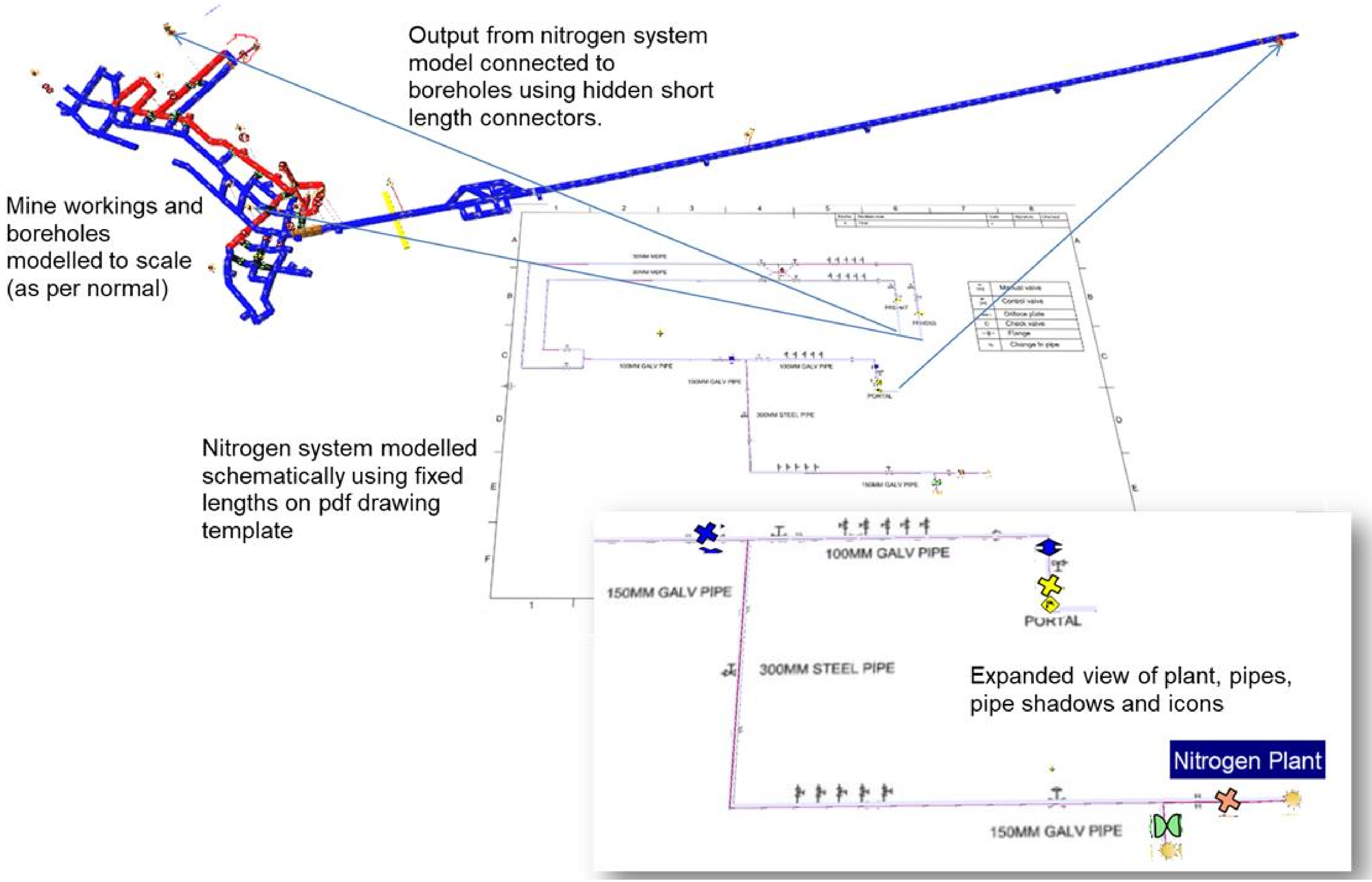
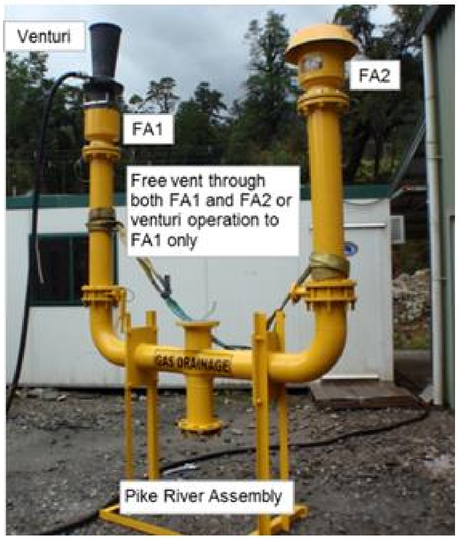


Figure 9: Combination of mine scale and nitrogen system schematic in a single ventsim model

A point to note when modelling gas drainage or nitrogen injection systems is that the characteristics of flame arrestors may not follow the square law. This could be significant when considering flow rates through venturi assemblies without applying venturi pressure i.e. under natural buoyancy.

The previously used Pike River venturi assembly, Figure 10, was found to follow a $P \alpha Q^{1.8}$ relationship with new 150mm flame arrestors following a $P \alpha Q^{1.5}$. This is due to transitional flow regimes through the flame arrestor packing. This relationship can be included in the Ventsim presets.



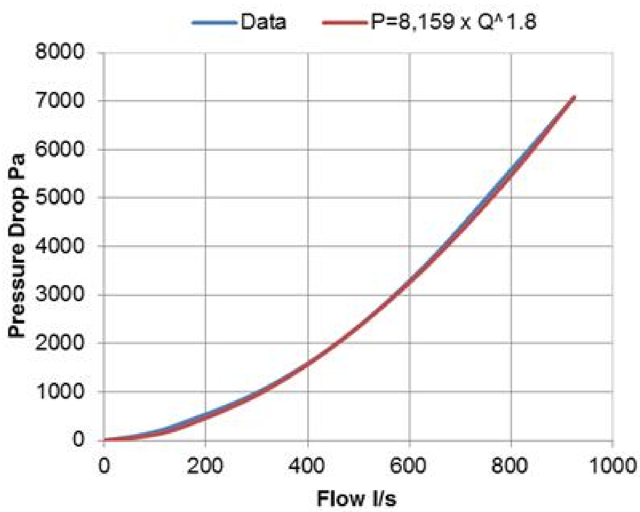


Figure 10: Venturi assembly and flame arrestor characteristics

DESIGN OUTCOMES

This model, together with crosschecks with spreadsheet calculations, provided the following design outcomes:

1. Two 4.1 km 90 mm nitrogen pipes will be required to deliver full plant capacity to the mine working's injection boreholes at less than 4 bar (400 kPa). This analysis also provided a planning value of approximately 300 l/s NTP through a single pipe should the other fail.
2. Two additional 150 mm boreholes will be required, one for increased injection capacity to the mine workings and another for increased exhaust capacity.
3. Drift purge times could vary between 2 and 7 days depending on the status of additional holes and degree of connectivity between the drift and workings through a fall of ground at the top of the drift.

Currently, the model is conceptual and subject to tuning to observed conditions as the re-entry process proceeds. In this respect, nitrogen injection to the portal commenced on 12th December 2018 and, as at 14th December 2018, successfully purged the drift (<3.0% CH_4 and <2% O_2) so far as the 140 m point in preparation for the first phase of re-entry.

CONCLUSIONS

This work demonstrates that Ventsim can be used to model gas reticulation systems at pressures significantly higher and lower than normal mine ventilation systems. Results are consistent with those from spreadsheets based on conventional, and well tested, calculation methods.

Application of Ventsim software to gas reticulation systems aids in decision making with respect to pipe sizing and pressure control. It also provides a means of documenting the location and status of gas drainage infrastructure for ongoing system management.

Unlike pure ventilation models, in which ventilation flow rates are determined by fan characteristics and regulator settings, it is necessary to pre determine gas flow rates and take a "fixed flow" approach to modelling of both gas drainage and nitrogen reticulation systems i.e. assume that valves will be altered as or when required to modify gas flow rates. The main outcomes for design purposes are the resultant pipe losses and operating pressures being dependent on pipe diameters employed together with location and settings of valves.

A further use for Ventsim models is the application of pictures to fixed resistance icons so that infrastructure can be located on the plans or model without necessarily being used for calculation purposes. This provides a means of planning and communicating infrastructure locations.

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