

# Maximizing Volumetric Efficiency for Ventilation Systems in Temporarily Reduced Flow Environments of Block Cave Mines

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There are times in a mine life when airflow may need to be temporarily reduced. This may be the result of maintenance/loss of a fan or air heater/cooler or shaft maintenance. Without proper planning mine operators can be underprepared for these events, and not know how to handle the off-normal operation of a sudden and prolonged temporary reduction in airflow. The complexity of the ventilation systems associated with a block cave mine require unique methodologies and actions to continue operations under reduced ventilation scenarios. By having a strategy in place, the available airflow can be redistributed to predetermined areas in the mine to lessen disruption to production, development, and cave operations. It is also imperative to recognize the safety impacts from the abridged ventilation system, such as the potential for airflow reversals in some areas of the mine, including fixed facilities and between levels. Maintaining legislative airflows can be challenging. It is vital to understand the impact on main and booster fans when the ventilation system is in a state of fluctuation. This paper provides suggestions in generating a plan for temporary reduced ventilation situations in a block cave mine, while maintaining safety and maximizing production. This plan was used in maximizing operations for reduced airflow situations at Oyu Tolgoi Mine.

Keywords: ventilation, planning, block cave, heating, cooling

## 1. Introduction

Airflow through the mine is critical to the health and safety of the workers in the underground and represents a multifaceted set of interactions. Reduced flow scenarios can be caused by maintenance or unplanned failure of fans, heaters and shaft/hoist infrastructure. With proper planning, disruption to mining activities can be minimized during periods of reduced airflow conditions. Lessening the impact in a block cave mine is important to maintain continuous cave movement or production and understand the proper trigger action response plan based on the scenario. The paper examines the effects of reduced air flow to the mine and developing a plan to reduce disruptions and maximize the use of the available airflow. This plan was developed from a study completed for off normal operations at the Oyu Tolgoi block cave mine located in Mongolia.

Oyu Tolgoi will utilize five shafts for ventilation, three intake and two exhaust and a dual decline conveyor and access tunnel (exhaust). Main ventilation infrastructure includes surface heater banks on the three intake shafts, Shaft #1, Shaft #2, Shaft #3 and surface exhaust fans on Shaft #4 and Shaft #5. Main underground booster fans are used for balancing footprint intake air to each side of the footprint, as well as a booster fan for pressurizing the declines as exhaust pathways. Outside temperatures at the mine can fall below -25 °C, which results in an airflow heating requirement for the intake shafts. A study was conducted on the Oyu Tolgoi life of mine ventilation system to evaluate the impact of loss of infrastructure under varying surface temperatures. Temperatures in the mine do not warrant refrigeration, but examples are given in this paper to provide a template for other operations to use. Figure 1 outlines the main ventilation infrastructure at Oyu Tolgoi.

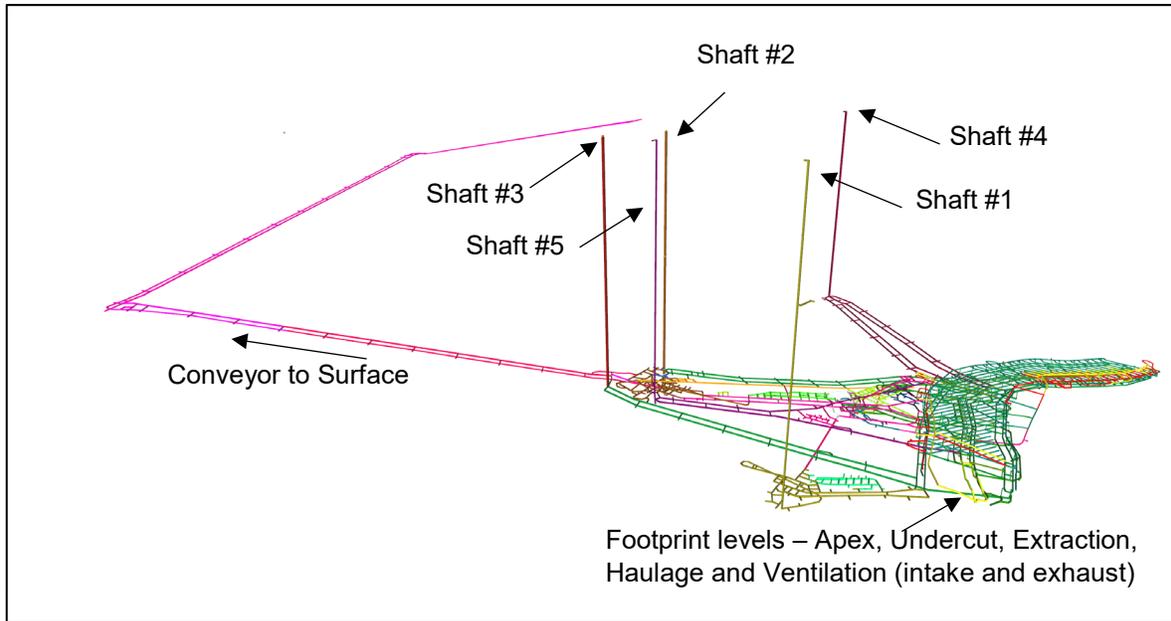


Figure 1. Oyu Tolgoi Lift 1 Mine Design.

## 2. Background information

The event of removing a fan or heater/cooler module does not need to equal a one to one loss in airflow. With proper planning, airflow delivery to the system can be maximized [1]. For Oyu Tolgoi, three surface fans are planned to operate in parallel at the collar of Shaft #5 and four in parallel at Shaft #4. As temperatures at the mine fall below freezing, two heater modules are planned for intake Shaft #2 and Shaft #3 and a single module for Shaft #1 with potential limited backup by using portable heaters.

### 2.1 Fan installations

Most block cave facilities require a large amount of airflow to be delivered through the mine likely requiring fans to be operated in parallel, providing the advantage that if one fan goes down, the other fan(s) may continue to operate. The potential impacts of a single fan failure are tempered by the operation of the fan relative to the performance curve. Once a fan has been dropped from the system, the overall pressure in the system will also decrease which will allow the remaining fans to operate at slightly higher airflows. By incorporating a greater number of fans in parallel, the effect of a loss of a single fan is less pronounced. An advantage of employing fans in parallel is that if one of them fails then the remaining fan(s) continue to supply a significant proportion of the original flow (up to 70% for two fans in parallel). In the example shown on Figure 2, if a fan ceases to operate, then the operating point for two fans in parallel falls along the resistance curve to the position of a single fan in operation, giving a significant portion of the original airflow [1].

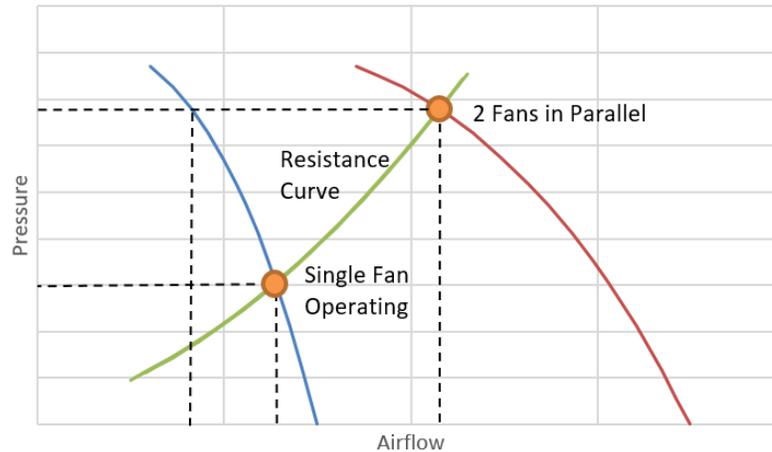


Figure 2. Characteristic curves for two fans operating in parallel.

## 2.2 Air heaters

Heater units being taken off-line during the winter months can create a significant problem. If the air is not heated to above freezing then there is a risk of either the shaft freezing (can compromise the structural integrity), or a build-up of ice in the headframe. If the mine is equipped with multiple heater modules and one is taken offline, then it may be possible to partially or completely make up the difference with other heating modules.

When heating is required, the amount of airflow that can be drawn down a fresh air shaft may be limited by two factors; outside air temperature, and air heater capacity. The air heater capacity should be designed for the maximum airflow required for the ventilation system combined with a designed minimum temperature rise. If there is not enough heating capacity available, then this may need to be throttled back. The design of the heater modules typically does not allow for the air velocity through the individual modules to be increased, rather, the temperature of the air leaving the remaining heater modules would need to be increased and mixed with the air by-passing the inoperable heater unit.

The heaters are designed for a certain airflow and temperature rise. For an equivalent heater energy input, a higher airflow quantity can be heated if the required temperature rise is less than the maximum design value. For example, a single heater module may be designed to heat a given airflow quantity by a set temperature rise, based on a minimum temperature. However, it could heat a greater airflow quantity if the air outside air temperature is higher than the minimum design point. An example air heater capacity airflow to temperature relationship is shown in Figure 3.

### Single Heater Unit Capacity

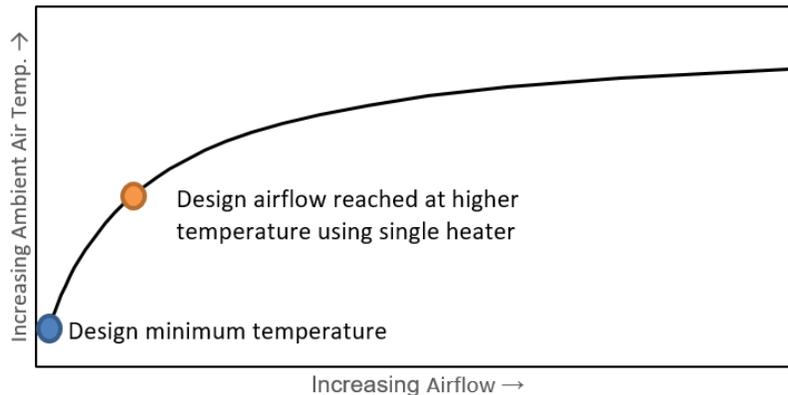


Figure 3. Theoretical heater capacity.

### 2.3 Bulk air coolers

Mines may also require surface air coolers to provide a reasonable working environment in the underground. There are many different configurations for bulk air cooling of mines. If more than one refrigeration module is installed at the main intakes to the mine, then the same theoretical adjustments can be made as surface air heaters, only inversed. As ambient temperatures fall below the designed maximum temperature, then hot air may be mixed in to account for loss of airflow if a cooler module is offline. An example bulk air cooler capacity airflow to temperature relationship is shown in Figure 4.

### Single Cooler Unit Capacity

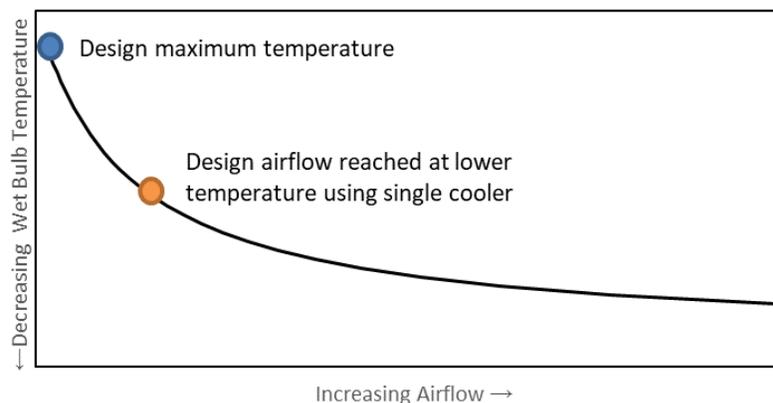


Figure 4. Theoretical cooler capacity.

### 2.4 Example calculation

Two heaters have a capacity of 10 MW each. Each heater is designed for a maximum duty of heating 300 m<sup>3</sup>/s of air from -25 °C to +2 °C, for a total of 600 m<sup>3</sup>/s of air entering a shaft. The air density is at 1.23 kg/m<sup>3</sup>. Assuming one heater module is rendered inoperable, a range of airflows can be determined for the working module based on the inlet temperature by using Equation 2 for the mass flow of air and equation 3 for heater capacity. The air heating is identified as the “applied” power without any allowance for efficiency. These values are plotted on Figure 5. Based on the figure, the original design airflow may be achieved when the inlet temperature is above -11 °C.

$$m_a = Q\rho \quad (1)$$

where:

$m_a$  = mass flow of air (kg/s)

$Q$  = quantity of air ( $m^3/s$ )

$\rho$  = density of air ( $kg/m^3$ )

McPherson [1].

$$q_a = m_a \times C_p \times \Delta T \quad (2)$$

where:

$q_a$  = heat/cooling capacity (W)

$C_p$  = specific heat of air ( $J/kg \text{ } ^\circ C$ )

$\Delta T$  = change in temperature ( $^\circ C$ )

McPherson [1].

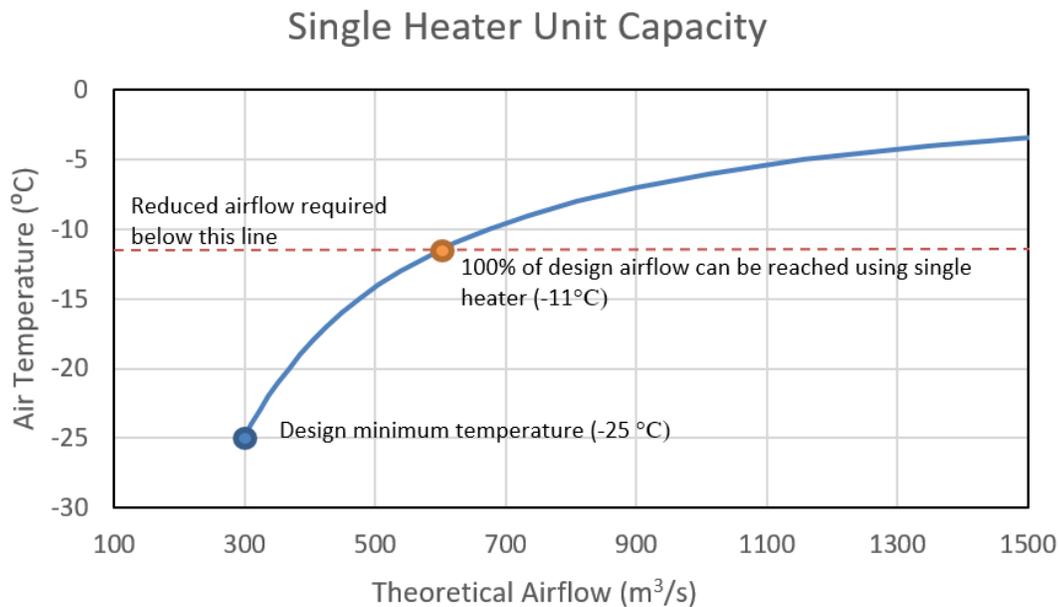


Figure 5. Example theoretical heater capacity for a 10 MW air heater.

### 3. Methodology

The following sections were founded on a study of the Oyu Tolgoi Mine to help generate an approach in developing a plan for reduced airflow scenarios. This method begins with ensuring accurate data is collected so that best decisions can be made to maximize the volumetric efficiency which is, the total amount of airflow in a ventilation system that is usefully employed at a working face or other location that requires airflow. The method also suggests an approach that can be conveyed to mine operators if the plan is implemented.

### 3.1 Step 1: Accurate ventilation model

An important tool in planning for future ventilation scenarios is an accurate ventilation model. For existing mines, the best method for developing a model is to use actual field measurements for both pressure and quantity along with the physical layout and characteristics of the airway profile. The ventilation model should be correlated to gathered field measurements. Manufacturers' fan curves should be adjusted to the measured conditions and placed in the model for every main and booster fan in the mine. This is a key component to determine the limits of the ventilation system. The ventilation study can only be as accurate as the data that is placed in the ventilation model.

At the time of the Oyu Tolgoi study, the mine was in its early development stages. Atkinson friction factors (k-factors) were used in the models to represent the resistances of the airways in the mine. The k-factors were based on measured resistances from mines with similar airway profiles, as measured field data is not yet possible. These models were used to represent the airflow distribution during six key development stages for the review with manufacturer's data from known infrastructure k-factor models.

### 3.2 Step 2: Determine reduced flow scenarios

A list of scenarios can be developed that may require a reduced airflow scenario at the mine. As every mine is unique, every list will be unique. Example reduced airflow scenarios can include maintenance/loss of a fan or air heater/cooler and during shaft maintenance. Other site-specific scenarios could also be generated.

An example flow chart is shown in Figure 6, for how the heater loss scenarios were developed for Oyu Tolgoi to test the resulting impact to the overall ventilation distribution. Similar charts were created for the loss of main surface fans and primary underground booster fans.

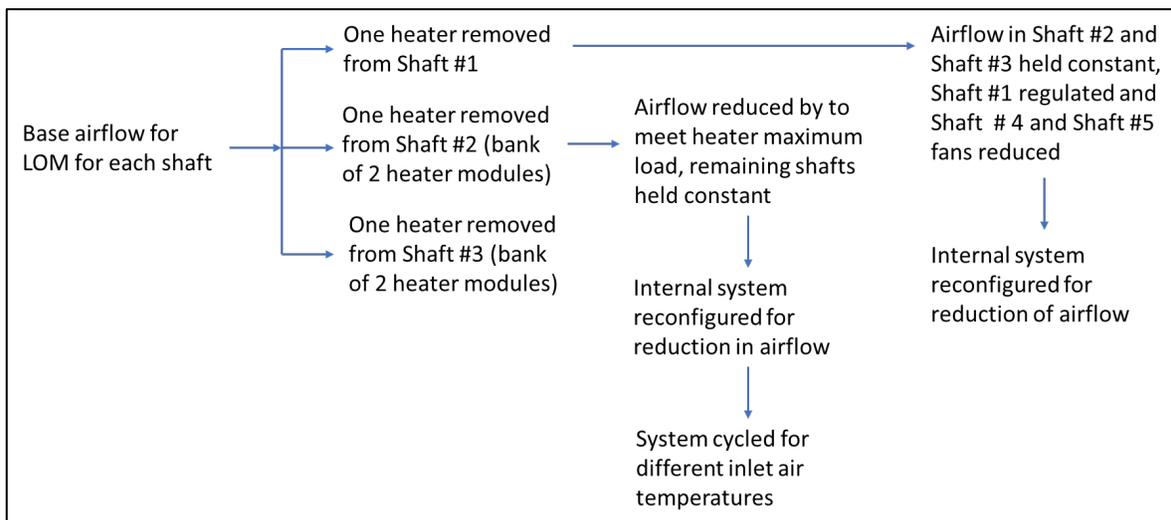


Figure 6. Example flow chart created for Oyu Tolgoi heater loss scenarios.

### 3.3 Step 3: Determine how effects of airflow reductions can be minimized

It may be possible to reduce airflow loss due to the availability of a fans, heaters, or air coolers depending on the scenario. The background information in this paper provides some of the theory to help make the determination on how minimizing losses can be achieved. Having multiple fans/heaters/coolers operating in parallel can increase the volume of airflow that can be recovered.

In the event of a fan failure, a portion of this lost airflow may be made up through remaining main fans. If the fans are fitted with Variable Frequency Drives (VFDs) then the operating speed of the remaining fan speeds could be increased to compensate. It is important to ensure that the fans stay

on the recommended manufacture's curve to not operate the fan in a stall condition. It is also important that the fan does not exceed the rated motor power to not overload the motor. It is important to remember that a loss of a single fan in a parallel setup does not result in an equivalent/equal loss in airflow; as the pressure decreases, the operating point will fall lower on the curve, increasing the airflow through the other fans in parallel.

For airflow reductions resulting from heater/cooler failure, airflow reduction may be minimized if the temperatures are above/below the respective design point for the module. A chart for available airflow at varying temperatures can be developed based on the module total heating/cooling capacity. This information should be provided during tender process, engineering phase, and handover phases. Plans should also be made on how the monitoring is performed either manually or by operator, as there is a complex set of variables that should be considered when making changes to the ventilation system.

The impacts from a temporary loss of the ventilation infrastructure could justify having spare infrastructure in place but not operating. Conversely, the study could show that spare infrastructure may not be needed if the operation can reasonably sustain a temporary reduction to flow.

Performance curves were digitized from the planned fans to be installed and input into the Oyu Tolgoi ventilation models. The purpose of using actual performance data is to determine the effects of turning main exhaust fans on/off and identifying how the system will react to each of the scenarios. Heater capacity airflow to temperature relationships were developed for each heater module to determine maximum airflows at varying temperatures.

#### **3.4 Step 4: Determine target airflows and areas that may have reduced flow**

It is imperative to identify operating requirements the mine's ventilation system. These can be legislated, guidelines, internal requirements or world-best-practice (minimum airflow maximum/minimum velocity, exposure limits, etc). These requirements need to be followed even in an off normal event. This often includes minimum airflows based on the operating motor power of diesel equipment and minimum air velocities where personnel are working.

Determine where the mining priorities are for the mine. Is it in production, development, or keeping the cave going? This can be used as a basis to close off airflow to less significant areas to the mine. Look at the number of open draw points that can be closed and at the potential to adjust airflow to the haulage level.

Depending on the priorities of the operation, reduce the number auxiliary ventilated areas and prevent access until normal operations resumes. Keep in mind that if reduced airflows are present in the mine, there is a potential for recirculation with auxiliary ventilated headings if not enough airflow passes the inlet of the auxiliary fan. To prevent recirculation, the recommended total quantity in the airway should be at least 50% more than the total intake into the auxiliary fan [2]. Alternatively, controlled recirculation could be considered if legislation permits and all risk factors have been taken into account, such as health and escape options in the event of a fire.

Airflow through fixed facilities may be a relatively easy area to change as they typically have adjustable regulators installed at the exhaust. It may be necessary to stop work in the area with reduced flow due to not meeting operating requirements and maintaining a safe work environment. It is also important to ensure flow to exhaust is maintained to minimize potentially contaminated air entering the intake airways.

Reducing the number of active drives is a quick way to reduce airflow used by the mine. Airflow on the haulage level may also be reduced when the number of trucks operating is reduced.

The minimum airflow for each LHD on the extraction levels at the Oyu Tolgoi mine is 15 m<sup>3</sup>/s based dilution of contaminants created by diesel equipment. The primary focus is distributing airflow

to the extraction level to maximize production. A list of possible changes to the Oyu Tolgoi ventilation system for reduced flow scenarios is as follows:

1. Adjustment of fans and heaters to increase airflow towards steady state conditions.
2. If heater modules are taken off line on Shaft #2 or Shaft #3, then doors in the shaft bottom area(s) are opened to equalize flow.
3. Reduction in airflow through the shops (work would need to stop in these areas and operator would need to examine how long this would could be sustainable).
4. Closing off airflow to development headings (also prevents recirculation of airflow in auxiliary systems).
5. Extraction drift regulators are closed with corresponding regulators on the haulage level.

### **3.5 Step 5: Model each scenario**

Model each reduced airflow scenario separately. Start with the scenarios that have the least amount of airflow reduction and work towards scenarios with higher reduced airflow. Begin by closing off the predetermined lower priority areas and continue to remove sections from the ventilation system until all target airflows and velocities are met. The results may even show that in some events, work in the mine should be stopped. Consider the safety aspects regarding airflow reversals and low airflow areas. An airflow reversal could result in fumes from shops entering the main airways or increase spread of fumes in the event of a fire. Low airflow areas could result in a build up of potentially poisonous gases such as carbon monoxide.

Listed below are some important notes to keep while completing the study:

1. List the steady state conditions for the system at normal operating conditions.
2. If using air heaters or coolers, consider varying inlet temperatures.
3. Determine the total change in mine flow.
4. Identify the difference in differential pressure on the ventilation infrastructure, including headframes, regulators and doors.
5. Determine if all fans are operating within the fan manufacturer's recommended range and not exceeding the installed motor power or in stall condition.
6. Look for areas with reversed airflow and determined if there are any adverse effects.
7. Keep a list of locations where airflow needs to be reduced or where modifications to the system are needed.
8. Examine how the changes to the ventilation system affect the escape routes from the mine and look for any potential issues in the event of an emergency.

Document the models and save a file for each scenario for future reference. A pattern should emerge that should allow for multiple models to be completed swiftly. A spreadsheet can be developed to keep track of the important information gathered from the models. This can be a very useful reference should a scenario come to pass. A simplified spreadsheet for collection of the data, similar to the one used for Oyu Tolgoi, is shown in Table 1.

Table 1. Example spreadsheet for collection of model data.

Scenario	Intake Shaft Flows		Exhaust Fans		Airflow Reduction Summary
	Shaft A	Shaft B	Shaft C		
	Airflow (m <sup>3</sup> /s)	Airflow (m <sup>3</sup> /s)	Airflow (m <sup>3</sup> /s)	Pressure (kPa)	
Steady state	-	-	-	-	List changes needed to the ventilation system and any potential issues
Heater Shaft A -15 °C	-	-	-	-	
Heater Shaft A at -12 °C	-	-	-	-	
Loss of 1 Fan Shaft C	-	-	-	-	

During modelling, certain challenges may be presented such as airflow distribution issues or booster fans expected to reach stall conditions. These issues should be noted and form part of the response plan for each respective scenario. While completing the study for Oyu Tolgoi, it was found that the Shaft #3 decline booster fan encounters prohibitively high operating pressures during Shaft #3 airflow reductions. A mitigation strategy identified was to turn off Shaft #3 decline booster fan and to stop the airflow in the decline. Due to the limited airflow in the decline, access would need to be restricted.

An airflow distribution problem was also presented when Shaft #2 is completely closed to flow due to a both heater modules being inoperable. A balance of airflows on the extraction level was difficult to produce. A solution was generated that allowed air to flow from Shaft #3 to Shaft #2 by opening isolation doors in the shaft bottom area. This creates an area of high air velocities that should have limited access. Airways with velocities above 6 m/s can cause excessive dust pickup by the fast-moving air. These high velocity areas also become increasingly uncomfortable environments to work in.

### 3.6 Step 6: Communicate the plan

Any plan must be communicated to key stakeholders, so that it is available to be enacted quickly to minimize any downtime. This also allows others to provide feedback for improvement of consequences of certain actions in the plan. A simple spreadsheet or checklist could be developed for each reduced airflow scenario with the key information obtained during the modelling. This can be used for a Trigger Action Response Plan (TARP). A graphical representation can be developed for each scenario for quick reference. Figure 7 provides an example of a graphical reference created for Oyu Tolgoi. The figure represents a case where a single heater module is offline on Shaft #2 at an inlet temperature of -31 °C

Someone must be appointed to be able to understand the plan and risks to be able to implement on an operational daily basis. This appointee should be able to communicate, monitor and actuate the plan with operations, safety and any other relevant employees. Adjustments to the plan may likely be needed and the coordinator should be responsible for relaying this information. This person should also be responsible for making sure ventilation prints are updated accordingly, if it applies for regular work and emergencies.

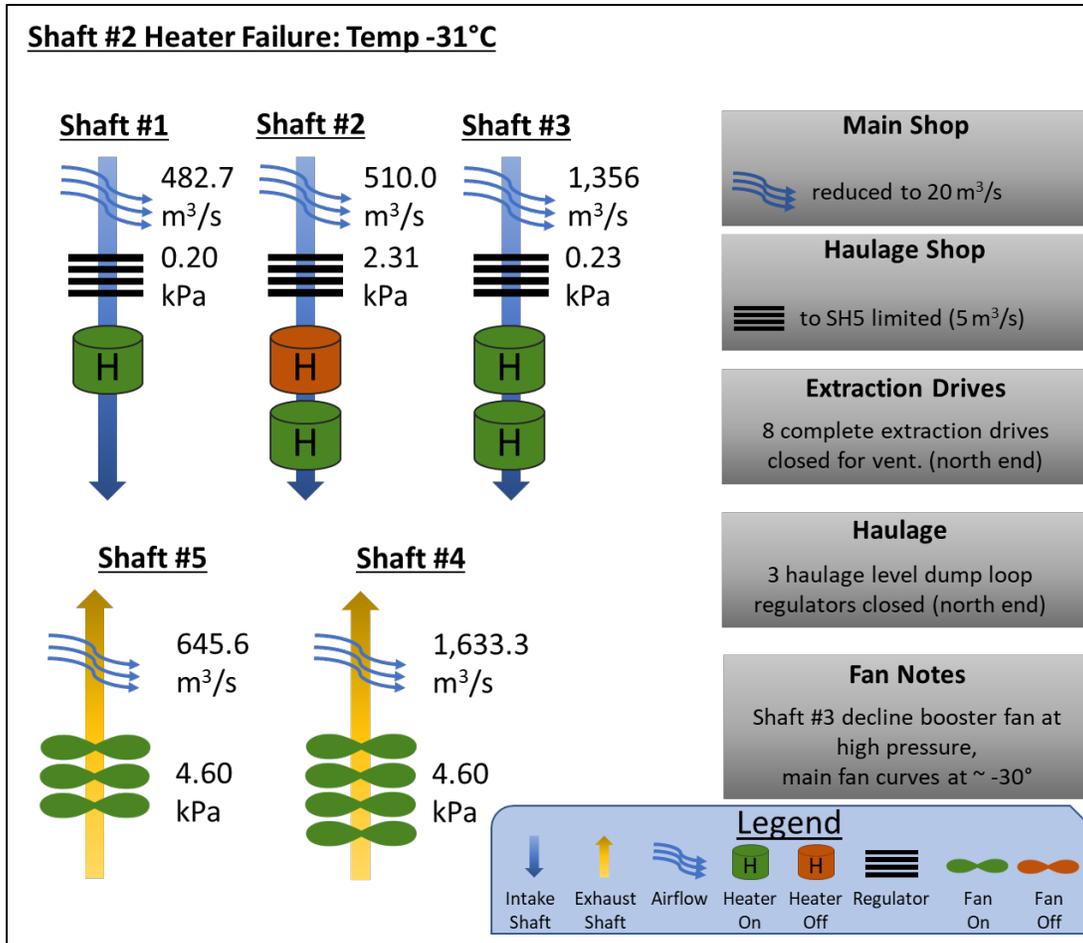


Figure 7. Example graphical representation for the reduced flow plan.

### 3.7 Step 7: Maintain the plan

Any mine is an ever-changing environment, and this holds true for the ventilation system. The ventilation model and plan should be updated and maintained, especially after any major ventilation system changes.

At the time of the study, Oyu Tolgoi is in early development stages. As the mine progresses, the ventilation models can be updated with representative resistances of airways and ventilation controls to develop a correlated model. The updated models can then be checked against the original study and updated as necessary. Additional scenarios and conditions may arise and can be evaluated.

### 3.8 Step 8: Check actuation of the plan

Field tests should be performed on a regular basis to both check the viability of the controls needing adjustment to meet the requirements of the generated plans. Sometimes controls are put in place and not properly maintained or damaged. These issues may be found and corrected during field testing to reduce downtime while implementing the plan. Regulators should be checked for serviceability. In the event of a reduced flow scenario this may detrimentally impact pre-determined plans. If applicable, check that inlet vane controls on centrifugal fans are working correctly. Compare actual fan operating points to manufacturers' curves to determine if there are any variations. Check efficiency of mixing air by purposely turning off heaters/coolers to check assumptions. Any other relevant controls should also be verified.

#### 4. Conclusion

Being prepared with a comprehensive plan is important for maximizing volumetric efficiency for the ventilation system in a reduced airflow environment of a block cave mine. Having an accurate and correlated ventilation model is an important tool that can be used for a wide variety of scenarios. It is important to explore options on recovering airflow through fan settings, or if applicable utilizing the capacities of heater/cooler modules in off peak temperature demand. Using these tools can help generate a plan to modify the ventilation system to maximize production and development areas by meeting required airflow and velocity criteria. Having the plan in place before an expected event can minimize the downtime and maximize airflow distribution for a better volumetric efficiency. As each mine is unique each plan will be unique.

The main ideas presented in this paper are based on a study completed for the Oyu Tolgoi Mine. The results of the study helped to determine the challenges that will be faced during periods of reduced airflow, resulting in time saved when one of these events occurs.

#### References

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- [2] Workplace Safety North. *Auxiliary Mine Ventilation Manual*, Published by Workplace Safety North, North Bay, 2015. Version 1.6. [accessed. 8. April 2018].