Development of a Fire Modeling Study for the Chuquicamata Underground Mine

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The addition of fire modeling during the development of a ventilation system design can greatly enhance the safety aspects of the mine. When a fire modeling program is developed in conjunction with the ventilation design, mitigation aspects and infrastructure can be incorporated into the design process. This fire modeling encompasses the identification of intake/exhaust airways, access routes, and the provision of fresh air bases from which development activities will progress. Understanding how the ventilation system will respond to fires in critical or high risk areas is a fundamental element of the ventilation design. The ventilation system for the new Chuquicamata underground block cave mine is in the intermediate stages of development. During November 2015, a fire modeling study established a correlated ventilation model which was used to simulate mine fire scenarios at key locations. The study was used to determine the placement and application of essential mitigation infrastructure and to identify the consequences of a fire including fume spread, heat, and air reversals. This paper will describe the methodology and results of the fire modeling study.

1 Introduction

The Chuquicamata underground mine is located in the northern Atacama Desert. It is part of the Chuquicamata mining complex. The economical ore reserves - accessed from the central open pit mine at the Codelco Chuquicamata mining complex - are being rapidly depleted. To continue mining operations, a decision was made to develop an underground block cave mine below the existing open pit. The workings development necessary to support the new block cave mine requires a significant amount of equipment, personnel, and construction headings. The close proximity of personnel, equipment, and development areas significantly increases the risks and consequences of a fire. In 2015, Codelco and MVS/SRK performed a fire modeling study for the current underground developments at the Chuquicamata Mine. The study started with a full pressure/quantity ventilation survey to develop an accurate correlated ventilation model. The correlated model was used as a basis for the fire simulation models. The fire models are computer simulations used to predict temperatures, airflow reversals, and fume front propagation during a fire. Alternative scenarios were examined to predict the various interactions when the underground mine workings are joined with the intake and access tunnels.

2 Study Methodology

The study consisted of many segments that lead up to the final fire simulations. The fire study was broken down into several components:

- initial ventilation survey,
- development of ventilation model
- correlation of ventilation model
- hazards analysis
- development of fire simulation model
- analysis of individual fire scenarios

In order to create a credible study, fire modeling must be based on an accurate ventilation model. Establishing this model typically requires a ventilation survey in which airflows and frictional pressure losses are measured and quantified. These measurements are used to determine the model branch resistances and airway geometry. The
model is then correlated and an error value is established for the model. A correlation error of less than 10% (between measured and modeled airflows) is typically used as the evaluation criterion for accuracy.

Hazard analysis is conducted to determine the likelihood and consequence of a fire as well as to identify high risk areas. Fires in these areas are then simulated in the fire modeling.

3 Ventilation Survey
The ventilation survey of the Chuquicamata Mine development areas - including the main underground mine (OIM), injection tunnels, service tunnel, and conveyor tunnel development - involved determination of airflow quantities and differential pressure distributions, as well as quantification of fan operating pressures. Airflow quantities were calculated by performing full-section vane anemometer traverses or centerline smoke tube measurements and multiplying by a measured cross-sectional area. Static pressure differentials across bulkheads, doors, and regulators were measured directly using a digital micro-manometer connected into a length of tubing. A traditional gauge and tube traverse method or trailing hose technique was used to measure frictional (total) pressure drops along mine airways where airflow quantities were substantial enough to give meaningful results. Tube lengths of up to 1,000 feet (ft) or approximately 300 meters (m) were used. To assist in the quantification of natural ventilation energies and the fan operating point, dry bulb temperature, relative humidity and barometric pressure were also measured at key locations throughout the mine.

General quality assurance procedures were adhered to throughout the ventilation survey, with at least two velocity readings taken at each airflow station and evaluated for consistency. Readings deviating more than 10% from each other were repeated as necessary. At ventilation airstream splits, measurements were taken to ensure adherence to Kirchhoff's First Law of airflow (the sum of the airflow entering a junction equals the sum of the airflow exiting a junction). In order to define airway resistances accurately, measurements of frictional pressure drop were taken at approximately the same location and time as measurements of airflow. Where possible, frictional pressure drop traverses were performed around closed loops and the data was checked for adherence to Kirchhoff's Second Law (the algebraic sum of the frictional pressure drops around any closed circuit must equate to zero, after having accounted for fans and Natural Ventilation Pressure [NVP]).

4 Ventilation Model Development
The ventilation network simulation software used to establish the network model of the Chuquicamata Mine was the VnetPC Pro program. Using data obtained from ventilation surveys or determined from known airway dimensions and characteristics, existing ventilation networks can be simulated in such a manner that airflow rates, frictional pressure drops and fan operating points approximate those of the actual system.

Branch resistances were determined from measured survey data and empirical methods (for airways that had insufficient airflow for a meaningful pressure measurement). These branch resistance values, measured fan pressures and calculated natural ventilation pressures were input to the VnetPC Pro program.

The overall network correlation error is computed by dividing the sum of the absolute differences between measured and predicted flow for each branch by the total measured flow, as shown below in Eq(1):

$$\text{Correlation} = \frac{\sum |\text{Measured Flow} - \text{Predicted Flow}|}{\text{Total Measured Flow}} \times 100\%$$

A correlation error of less than 10% is desired to ensure the model is sufficiently accurate to provide the basis for future ventilation planning. The ventilation model created for the Chuquicamata Mine had a correlation error of approximately 5.4%. Various factors contribute to this error. Although the overall ventilation quantity of the mine
will remain relatively constant if no major changes are made to the system, some local variances will occur as a result of normal activity. Airflows in local areas are affected by traffic, mucking, and auxiliary ventilation.

5 Hazards and Scenario Identification
At the beginning of the study, a hazard analysis was performed by the mine engineering personnel in order to identify likely fire locations and locations of high consequence. Potential sources of underground mine fires at the Chuquicamata Mine include: mobile diesel mining equipment and services equipment; electrical substations; compressor stations; electric motors on various machines and pumps; oil/lubricant storage areas; diesel fueling/storage bays; sulfide dust (spontaneous and flash combustion) and at dry dust collectors; grinding/welding areas in shops; shop maintenance areas; general housekeeping (e.g. trash, etc.); electrical cable sheathing; powder/explosive magazine; lunch room; offices; tires and wood in warehouse; and compressed gas storage facilities.

A series of eight fires were modeled in the Chuquicamata Mine before the Inyeccion Tunnels and the Tunnels Transporte y Acceso connect to the OIM (main underground). These models include the ductwork necessary to ventilate the mine before the connection of the tunnels is made. The location of the fires and the fire sources are listed in Table 1 and on Figures 2, 3, and 4. These fires are simulated at a lower intensity based on inputs for the MineFire simulation contaminate input parameters. This was accomplished by using a relatively low heat output and fume concentration for the fire source.
Choice of fire locations was based on possible fuel sources and the effect of the fire. Shops and electrical substations are examples of stationary fuel sources that may or may not affect large areas of the mine footprint. This uncertainty is due to fume front propagation. Air moving through that location may not distribute through a greater portion of the mine. Fire locations simulating mobile fuel sources like haul trucks can have a much greater impact because they may be located in areas where air is distributed throughout the mine footprint. This also has implications for mine design in that positioning large stationary fuel sources in or near isolated exhaust circuits will have a mitigating effect.

<table>
<thead>
<tr>
<th>Fire No.</th>
<th>Location</th>
<th>Fire Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rampa 10</td>
<td>Lubrication Shop</td>
</tr>
<tr>
<td>2</td>
<td>Rampa Principal</td>
<td>Explosives Magazine</td>
</tr>
<tr>
<td>3</td>
<td>Rampa 1</td>
<td>Haul Truck</td>
</tr>
<tr>
<td>4</td>
<td>Rampa 4</td>
<td>Haul Truck</td>
</tr>
<tr>
<td>5</td>
<td>Rampa Exploracion</td>
<td>Electrical Substation</td>
</tr>
<tr>
<td>6</td>
<td>Rampa 6</td>
<td>Haul Truck</td>
</tr>
<tr>
<td>7</td>
<td>Tunel Inyeccion 11 Face</td>
<td>Lubrication Truck</td>
</tr>
<tr>
<td>8</td>
<td>Tunel Transporte Face</td>
<td>Lubrication Truck</td>
</tr>
</tbody>
</table>

Table 1: Location of fires in the Chuquicamata Mine before connection of the Inyeccion Tunnels and Tunnels Transporte y Acceso.

![Figure 2: Locations of simulated underground fires in the Codelco Chuquicamata OIM Mine before Connection of Tunnels.](image-url)
6 Development of the Fire Model

The fire simulation software used for this analysis is the MineFire program. This is a Windows application that is to be used in conjunction with the VnetPC network ventilation simulation software package. It is designed to simulate a mine ventilation system’s response to external influences such as fires. The program is based on the former US Bureau of Mines MFIRE code, but modified by MVS/MVS to run in the Windows environment and to increase the number of available branches and fans. This calculation kernel was then adapted into the user-friendly interface of Mine Ventilation Services’ VnetPC ventilation network software package.

MineFire performs ventilation network planning calculations and dynamic transient state modeling of ventilation networks under a various conditions. The program simulates a system’s response to altered ventilation parameters such as: the introduction of fire to the system; varying outside temperatures; changing ventilation control structures; or development of new mine workings. This is accomplished by using data from ventilation surveys in conjunction with information derived from known airway dimensions and characteristics. Heat release rates are calculated based on which types of fuel are burning. The location of the fire (e.g., in a main intake/exhaust airway or area of low flow) is important in determining whether to assume an oxygen-rich or fuel-rich fire; subsequently, it helps the user determine which parameters to use in the fire simulation and which may be left blank. Contaminants may be determined based on the chemistry of the fuel components.

Fire is difficult to predict and the results of a simulation will only be as good as the inputs. For this reason, it is a good practice to simulate several different fire intensities for each location. This allows for the sensitivity of the ventilation system to be examined and for an increased level of confidence to be associated with the study.
6.1 Conductivity
The Conductivity variable is the rock thermal conductivity for the rock mass. The value is used by the program to define the thermal diffusion to or from the air as it travels through the airway. This will affect airflows in the mine. An understanding of which rock type defines a branch is needed for detailed models. A theoretical average or general value for the rock mass may be sufficient. Where the rock type in the model is uniform, large numbers of branches will have the same value. The appropriate units are Btu/hr×ft×°F or W/m×°C. For this model a global value of 3.5 W/m×°C was chosen.

6.2 Diffusivity
Rock diffusivity is obtained through lab testing of core samples or from tables. It defines how quickly heat moves on the boundary between the rock and the air as air moves through a branch. The units are ft²/hr or m²/sec. For this model a global value of 1.6 × 10⁻⁶ m²/sec (0.072 ft²/hr) was chosen.

6.3 Rock Temperature
The Rock Temperature variable uses the average temperature of the rock for a given branch. Samples can be taken in numerous key locations throughout the mine or the geothermal step can be used to determine average rock temperature at a given elevation and may be averaged as necessary for branches with vertical relief. Note that the geothermal step may not provide entirely accurate results for older workings where the rock has aged and the temperature profile has changed. Detailed information regarding rock temperature was unavailable therefore a value of 25.4°C was used as a basic rock temperature. This value is based on average air temperatures measured inside the mine.

6.4 Fan Data
Fan characteristic curves are registered by entering two to ten sets of pressure/airflow data points. Fans must be entered with a curve of at least two points for the MineFire program. Since MineFire assumes compressible flow, the use of inject and reject branches and NVP fans are not recommended except where absolutely necessary to balance the basic, “Initial” network. The effects of auto-compression and ventilating energies are accounted for by MineFire based on the temperature, elevation, and density values.

7 General Results
The fire simulation models are used to reflect the spread of fumes throughout the mine during the ramp-up of a fire and during the steady state fire event. It is also important to examine the temperature distribution to determine whether the electrical equipment can operate at the projected air temperatures or if special motors or electrical equipment will be required. The goal of the simulation is to see how the system will react to the transient conditions developed by the fire event. The introduction of the heat from the fire can have significant impacts on the ventilation system. These heat may result in air reversals, elevated levels of airflow, recirculation, and elevated temperatures. The identification of possible air reversals and recirculation risk is critical because typically safe areas may become uninhabitable by miners attempting to escape a fire scenario or seeking shelter. Figure 5 identifies one area where a fire event in the lubrication bay or haulage drift generates a recirculation loop or airflow reversal event.

7.1 Infrastructure Additions
Based on the development of the fire models and the reaction of the ventilation system to the fires, several recommendations were made to enhance the ventilation system.

In areas with auxiliary ventilation, the auxiliary fans should be shut off, if possible, to prevent fumes being propagated or rapidly moved to the construction areas. This will give the workers time to determine whether to evacuate to the surface, move to a refuge chamber, or find shelter. In most of the models, the fume front reaches the
face shortly after reaching an auxiliary ventilation system. Each of the systems has a “local” control that can be utilized to shut the fans off.

In most fire scenarios modeled, the lunch room and maintenance shop areas experience significant fume concentrations and duration. It is recommended that the lunch room refuge be inspected/tested periodically to ensure functionality. Because the airways around the central refuge station become contaminated for most of the scenarios, personnel working away from the immediate area of the central refuge station should seek shelter in one of the other portable refuge stations. The central refuge station will be important for the workers in the equipment shop, lubrication bay, lunch room, and in the haulage drift.

The installation of six isolation doors was recommended to isolate fume fronts and prevent their recirculation as shown in Figures 6 and 7.

![Figure 5: Fume propagation from a fire in the OIM Lubrication Shop approximately 20 minutes after the fire starts.](image-url)
7.2 Main Ventilation Fans
As a rule, the main fans should be left on during a fire with only a few critical exceptions. The electrical system currently developed for the mine only allows for the entire system to be shut off, shutting off all of the fans at once. Once the ventilation system has been turned off, all control over the system is lost. It is not uncommon for the airflow to reverse through the system and contaminate more areas than if the fans were left on. Several models were examined to demonstrate this phenomenon and were identified in the presentation to mine management. To shut off or reverse a single fan, the precise location of the fire must be known to clear the affected areas. However, determining the exact location of a fire can be difficult during the chaotic time of a fire occurrence. A remote monitoring system can and should be incorporated into the overall design of the ventilation system; but, it should be noted that this type of system has a long lead time and would not be available for the near term ventilation system configuration. It should be incorporated into final design of the mine.

8 References
Chilean Mining Safety Rules, Title III, Underground Mine Exploration, Chapter Eight, “Fire Prevention and Control.”