Ventilation optimization at the La Camorra mine

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ABSTRACT: This paper describes a case study for the ventilation planning at Hecla's La Camorra mine located near El Callao, Bolivar, Venezuela. The La Camorra mine is a high grade narrow vein gold mine originally developed in 1994 by Monarch Resources Ltd. In 1999 La Camorra was acquired by Hecla Mining Co. and production was increased to approximately 450 tpd. The mine uses sub-level longhole and cut-and-fill stoping to extract high-grade gold ore from narrow quartz veins (0.2 – 3.0 meters in width). The ventilation system at the La Camorra mine was in need of improvement based upon required production needs. During January 2001 a survey of the ventilation system was undertaken in order to develop a computer model of the mine. The model was used to optimize the ventilation system, and identify ways to provide more air to the lower workings. Through the use of the ventilation model the airflow intaking the mine was increased by approximately 70% without the need for any major additional infrastructure. This paper describes the ventilation survey, model development, and optimization scenarios that were developed to improve the mine ventilation system

1 INTRODUCTION

As a mine develops, the original design criteria, mining method, and production rate often change, resulting in an outdated or undersized ventilation system. This occurrence arose with the La Camorra mine. The mine was developed deeper than originally planned, and the use of diesel equipment is more prevalent. It was determined that the airflow in the working areas of the La Camorra mine were inadequate for the amount of diesel equipment operating in the mine. High CO and NO_X gasses were noted in the lower areas due to the diesel equipment. In order to optimize the ventilation system and determine a course of action to increase the airflow in the mine, a ventilation model needed to be developed.

In January 2001, Mine Ventilation Services, Inc. (MVS), under contract with Minera Hecla Venezolana C.A., performed a ventilation survey of the La Camorra mine in order to properly develop a correlated network model. During the survey the field data necessary to determine the resistance to airflow of the main airways in the La Camorra mine was acquired.

2 VENTILATION SURVEY AND BASIC COMPUTER MODEL

The ventilation survey of the La Camorra mine involved the determination of the airflow and differential pressure distribution as well as the quantification of the main fan operating point and natural ventilation effects. Airflow quantities were determined 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 manometer connected into a length of tubing.

The gauge and tube traverse method was used to measure the frictional pressure drop along mine airways where the airflow quantity was substantial enough to give meaningful data. Tube lengths of up to 300m 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.

2.1 *Airflow measurements*

Airflows were measured in all main airways. At least two velocity readings were taken at each airflow station and evaluated for consistency. Readings deviating more than 5 % 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). Given that airflow measurements were taken over a 4-day period, some imbalances in the measured airflow distribution were inevitable. Table 1 shows the measured airflow quantities at the portals of the mine. The airflows balance to within 0.3 m^3/s, which is an error of approximately 0.5 % of the total intake airflow.

Table 1. Measured Intake and Exhaust Airflows for the La Camorra mine.

Location	Airflow (m^3/s)
Intake Airways	
Main Ramp Portal	32.2
Winze (measured on +50 level)	25.4
Total Intake	57.6
Exhaust Airways	
Main Fans (sum of all leakage and airway measurements)	57.9
Total Exhaust	57.9
Difference	0.3

2.2 *Frictional pressure loss measurements*

Frictional pressure drop measurements were taken in all main airways using the gauge and tube technique. Where possible, frictional pressure drop traverses were performed around closed loops and the data checked for adherence to Kirchhoff's Second Law (the algebraic sum of the frictional pressure drops around any closed circuit must equate to zero, having accounted for fans and Natural Ventilation Pressure [NVP]). A modified Solomat Zephyr II digital manometer was used to measure all frictional pressure losses. All accessible locations where airflow quantities were significant enough to produce measurable frictional pressure drops were traversed.

2.3 *Fan measurements*

A measurement of fan pressure was obtained for the surface fans, as shown in Table 2. The main fans are modeled in the network as a single "equivalent" fan.

Table 2. Fan Measurements for the La Camorra mine (Airflow and Pressure).

Configuration	Airflow (m^3/s)	P_T Measured* (kPa)
#1 Spendrup Fan	36.8	0.971
#2 Spendrup Fan	21.3	0.971

*Measured and recorded at an average density of 1.14 kg/m^3

For a given pressure the operating airflow through each fan is added together to establish an equivalent curve. It was determined from maintenance records that the #1 fan was operating at the maximum blade setting (6), and by analyzing the fan curves the #2 fan was found to be operating at a setting close to 2½. The main fans were both Spendrup Model 112-70-1760 mounted parallel in a horizontal fan housing.

2.4 *Natural ventilation pressure*

Psychrometric data was obtained between the intake and exhaust airways to calculate the NVP for the mine. The polytropic flow processes were approximated by straight lines and the area representing each natural ventilating energy (NVE) calculated. The mean density between the intake and return air was used to calculate the natural ventilation pressure.

$$\mathrm{NVP} = \rho_{mean} \int \mathrm{Vdp} \qquad (1)$$

Where:

$\int \mathrm{Vdp}$ = area enclosed in PV diagram between intake and returns, this area is the Natural Ventilation Energy (NVE) (Joules)

ρ_{mean} = mean density of air in intake and return airways (kg/m^3)

The computed natural ventilation pressure is shown in Figure 1.

Figure 1. Computed natural ventilation pressures.

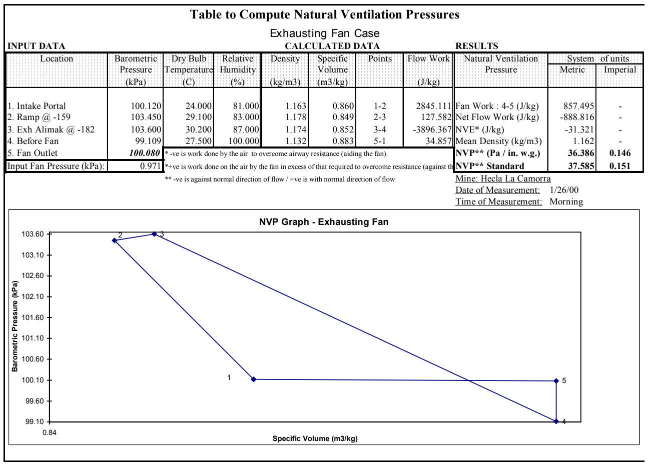

Table to Compute Natural Ventilation Pressures

Exhausting Fan Case

INPUT DATA **CALCULATED DATA** **RESULTS**

Location	Barometric Pressure (kPa)	Dry Bulb Temperature (C)	Relative Humidity (%)	Density (kg/m3)	Specific Volume (m3/kg)	Points	Flow Work (J/kg)	Natural Ventilation Pressure	System of units Metric	System of units Imperial
1. Intake Portal	100.120	24.000	81.000	1.163	0.860	1-2	2845.111	Fan Work : 4-5 (J/kg)	857.495	-
2. Ramp @ -159	103.450	29.100	83.000	1.178	0.849	2-3	127.582	Net Flow Work (J/kg)	-888.816	-
3. Exh Alimak @ -182	103.600	30.200	87.000	1.174	0.852	3-4	-3896.367	NVE* (J/kg)	-31.321	-
4. Before Fan	99.109	27.500	100.000	1.132	0.883	5-1	34.857	Mean Density (kg/m3)	1.162	-
5. Fan Outlet	***100.080***							**NVP** (Pa / in. w.g.)**	**36.386**	**0.146**
Input Fan Pressure (kPa):	0.971							**NVP** Standard**	**37.585**	**0.151**

* -ve is work done by the air to overcome airway resistance (aiding the fan).

*+ve is work done on the air by the fan in excess of that required to overcome resistance (against th

** -ve is against normal direction of flow / +ve is with normal direction of flow

Mine: Hecla La Camorra

Date of Measurement: 1/26/00

Time of Measurement: Morning

One loop was calculated for the determination of the NVP. The loop cycled from the intake portal (ramp) through to the ramp at –159 level to the base of the exhaust alimak at the –182 level and back to the main exhaust fans. The natural ventilation pressure was modeled by placing a fixed pressure fan in the major return airways at the pressure indicated on Figure 1. The positive NVP may be considered as a fixed pressure fan acting with the main fans. To explain why the NVP is positive it is necessary to consider the net flow work of the air. The net flow work, which is the total work required for the air to overcome airway resistance in the circuit is -888.816 J/kg. The fan flow work which is the total work done by the fan is 857.495 J/kg. The discrepancy between these two figures is -31.321 J/kg and is a negative value showing that the fan is doing less work than that required to overcome the system resistance. The additional work, described as the natural ventilation energy (NVE) may be expressed in the form of a pressure (NVP) acting in the normal direction of airflow through the circuit.

2.5 *Basic ventilation model*

The ventilation simulation software used to establish the network model of the La Camorra mine was the VnetPC 2000 program. The VnetPC program is designed to assist mine engineers in the planning of ventilation layouts by simulating the ventilation network. Using data obtained from a ventilation survey 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. The program has been developed based upon the assumption of incompressible flow and follows Kirchhoff's Laws, as well as utilizing an accelerated form of the Hardy Cross iterative technique to converge to a solution.

Branch resistances, determined from measured survey data along with empirical methods, measured fan pressures, and calculated natural ventilation pressures were input to the VnetPC 2000 program. A skeleton schematic representing the La Camorra mine was constructed from mine plans and sections, which is shown in Figure 2. Branches representing inaccessible areas were simulated as fixed quantity branches, or were determined by closing out the pressure around them (Kirchhoff's Second Law) .

The overall network correlation error was approximately 3.6%. This value was computed by dividing the sum of the absolute differences between measured and predicted flow for each branch by the total measured flow, as given by Equation 2:

$$\text{Correlation} = \frac{\sum |\text{MeasuredFlow} - \text{PredictedFlow}|}{\text{TotalMeasuredFlow}} \times 100\% \qquad (2)$$

Given that the survey data was compiled over several days the correlation was considered acceptable. A correlation error of under 5% indicates that the model is sufficiently accurate to provide a basis from which optimization studies and future planning can be conducted.

2.6 *Airway resistance calculation*

Resistances used in the ventilation model were calculated using the results of the MVS/ Minera Hecla Venezolana C.A survey. Empirical computation of resistance for inaccessible or low flow areas were conducted using frictional pressure drops calculated by difference (from Kirchhoff's laws) and measured airflows. NVP's were computed using the psychrometric data obtained during the survey.

For airways in which frictional pressure drop and airflow quantities were measured, the Square Law was utilized to calculate resistance to airflow, as given below:

$$R = \frac{p}{Q^2} \qquad (3)$$

Where: R = resistance (Ns^2/m^8)
p = frictional pressure drop (Pa)
Q = airflow (m^3/s)

Where frictional pressure differential data was not available, branch resistances were computed using Atkinson's equation:

$$R = \frac{k(L+L_e)P_{er}}{A^3} \qquad (4)$$

Where: k = friction factor (kg/ m^3)
L = length of airway (m)
L_e = equivalent length of shock loss (m)
P_{er} = flow perimeter (m)
A = cross-sectional area (m^2)

A resistance to airflow was computed for each branch in the ventilation network schematic. The schematic developed for the La Camorra mine approximates a cross-section view of the mine and is shown on Figure 2

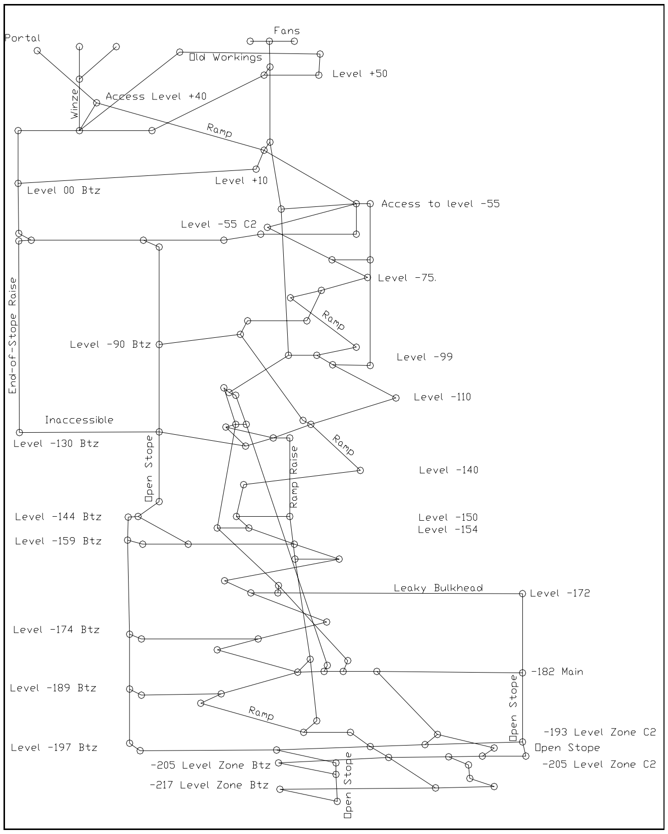

Figure 2. Ventilation schematic of La Camorra mine.

2.7 *Ventilation design parameters*

The friction factor for general airways was calculated at several locations in the mine. Using equation 4 and substituting P/Q^2 for R, the k factor can be determined. To ensure accurate measurements, airways were selected by type and whether meaningful differential pressure drops could be measured. Table 3 shows the results of these calculations.

Table 3. Friction-Factor calculations for main airways.

Airway Type	Friction Factor* (kg/m^3)
Small Betzy Drift ($A = 6.3\ m^2$)	0.0117
Straight Drift ($A = 9.1\ m^2$ to $15.6\ m^2$)	0.0076

*At average measured air density ($1.14\ kg/m^3$ for survey)

3 VENTILATION SYSTEM OPTIMIZATIONS

It was determined that a minimum of $70.8\ m^3/s$ of fresh air is required for the ventilation of the lower levels of the mine. At the time of the survey the lower levels were ventilated with approximately $40.5\ m^3/s$. Several potential alternatives were investigated to increase the airflow to this higher level.

- Installation of a booster fan on level –182.
- Construction of a parallel exhaust raise from level –99 to surface.
- Splitting the Betzy into an exhaust system (-99 to surface) and intake system (-110 and below).
- Reversing the airflow through the Alimak such that the Betzy and Alimak are intakes with the ramp acting as the exhaust.

These four scenarios were investigated for the current mine layout using the correlated "basic" ventilation model. A further constraint was added to the process by limiting the fan selection to only those fans currently at the minesite; Spendrup112-70-1760, Davidson AD98B, and Joy 72-33-1170.

3.1 *Installation of a booster fan in the exhaust system*

The key to increasing the airflow in the La Camorra mine was to overcome the high frictional pressure drops in the exhaust alimak raise system. During the ventilation survey it was noted that approximately 80% of the pressure developed by the main fans was used to move air through the alimak raise system. If additional air was to be passed through the exhaust system, a substantially higher pressure would be required.

The current main fans did not have the capacity to move additional air at the subsequently higher pressure. Hence, one alternative was to consider a booster fan located in the exhaust system in the mine. The –182 level was chosen as a good location for the booster fan installation. The transition drift on this level has a large enough cross-sectional area to allow for a fan installation, and for easier access than an alternative location in the –110/-99 exhaust decline. The two possible locations of the booster fan installations are shown on Figure 3.

Several models were developed that included the installation of a booster fan on the –182 level. Table 4 lists the required fan operating points for varying levels of airflow below level –189. Because of power and space concerns in the underground, the fan installation was split between a larger fan (Davidson) located on surface and a set of smaller fans (Spendrup) located underground. In order to achieve the necessary level of airflow it would be necessary to operate multiple fans in parallel in the underground location. After examining the characteristic operating curve for the Spendrup fans it was determined that the $75.5\ m^3/s$ could be achieved with two fans operating in parallel if both fans are set to their maximum blade setting. However, for a higher airflow a third parallel fan would be required.

With three fans operating in parallel the resulting airflow could be achieved at a higher pressure, thus lowering the pressure on the main surface fan. In addition, the Spendrup fans operate substantially more efficiently at higher pressures.

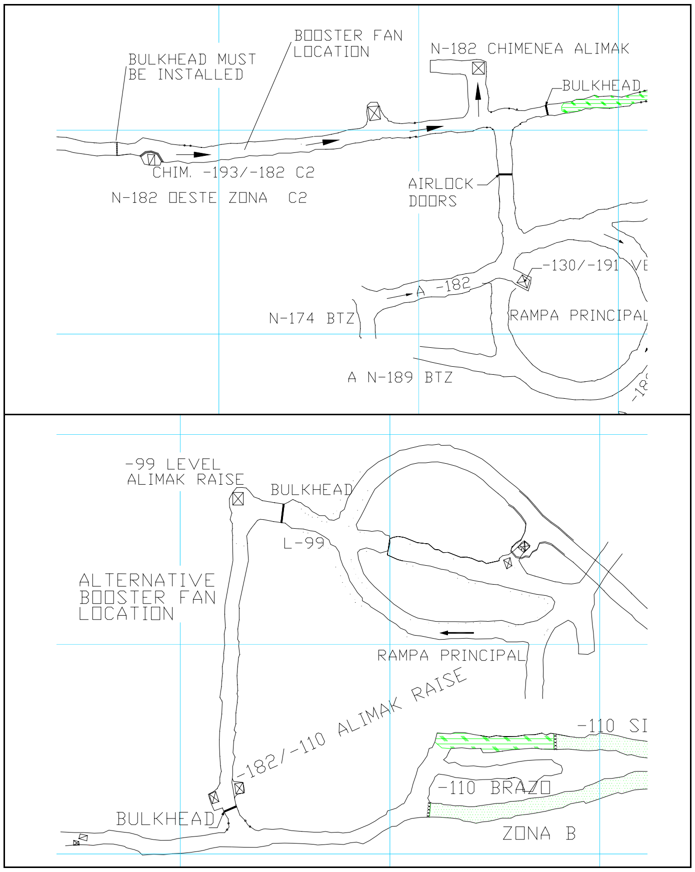

Figure 3. Possible locations of booster fan installations.

The operating point of 87.3 m^3/s could be achieved with three fans at a blade setting of approximately 4½. With three fans operating in parallel the resulting airflow could be achieved at a higher pressure, thus lowering the pressure on the main surface fan. In addition, the Spendrup fans operate substantially more efficiently at higher pressures. The operating point of 87.3 m^3/s could be achieved with three fans at a blade setting of approximately 4½. The operating duty of 99.1 m^3/s could be achieved if the three fans were set to their maximum blade setting. The Davidson fan had the capacity to operate at 80.2 and 85.0 m^3/s, but it would not be able to achieve the 1.69 kPa for the 99.1 m^3/s option. With the existing fans at the mine site the maximum airflow that could be achieved with just the addition of a booster fan(s) would be 82.6 m^3/s below the –189 level.

Table 4. Required fan operating points for booster fan operation.

Airflow Below –189 level (m^3/s)	Airflow From Ramp (m^3/s)	Airflow From Betzy (m^3/s)	Surface Fan Duty		Booster Fan Duty	
			(m^3/s)	(kPa)	(m^3/s)	(kPa)
70.8	47.2	23.6	80.2	1.49	75.5	0.55
82.6	56.6	26.0	85.0	1.05	87.3	1.44
94.4*	64.2	30.2	99.1	1.69	99.1	1.64

*not feasible, surface fan exceeds maximum operating duty

3.2 *Construction of a parallel exhaust raise from level –99 to surface*

A model was developed that incorporated a new exhaust raise developed from level –99 to surface in order to provide a parallel exhaust airway. This new raise was offset from the existing exhaust raise by approximately 30 m. and connected with the existing exhaust raise at each level where the current raise intersected the ramp. The new raise was developed with a 3 × 3 meter cross-section (similar to existing raise). It was assumed that it would be constructed in a manner similar to the existing raise but without the escape ladderway. The existing raise was kept unchanged. An additional fan (Davidson) was placed on top of the new raise. Table 5 shows the required fan duties for differing levels of airflow in the mine below the –189 level.

Table 5. Required fan operating points for parallel exhaust raise scenario.

Airflow Below –189 level (m^3/s)	Airflow From Ramp (m^3/s)	Airflow From Betzy (m^3/s)	Spendrup Fans (existing)		New Fan (Davidson or Joy)	
			(m^3/s)	(kPa)	(m^3/s)	(kPa)
70.8	47.2	23.6	33.0	1.07	56.6	1.25
82.6	56.2	26.9	33.0	1.37	68.4	1.67
94.4	63.7	30.7	47.2	1.82	68.4	2.07

The Spendrup fans would be fully capable of achieving any of the required operating points. The characteristic curves for the Spendrup fans indicated that they could operate at very high pressures, but as their operating pressures increase the fan airflow falls rapidly. In order to operate at 47.2 m^3/s and 1.82 kPa, two fans will be required in parallel at a setting of #4, which approaches their original design operating point. The Davidson fan could be used for the first operating point of 56.6 m^3/s @ 1.25 kPa, however its peak operating duty is approximately 1.50 Pa. The Joy fan could operate at a slightly higher pressure than the Davidson fan. The Joy fan could operate at the 68.4 m^3/s @ 1.67 kPa duty, however it cannot achieve the higher 2.07 kPa It appeared that 82.6 m^3/s was the greatest amount of airflow that could be brought to the lower sections of the mine with the fans currently at La Camorra.

The fan operating pressures could be lowered slightly by clearing out the old exhaust alimak between –99 and –182. This portion of the alimak was in very poor condition. At many of the level connections, mesh was installed across the raise with a lot of sloughage and debris obstructing the mesh.

3.3 *Splitting the Betzy into an exhaust system (-130 to surface) and intake system (-144 and below)*

The Betzy raise/stope system was used as an intake from surface down to the -197 level. From the -144 level down, the Betzy system consisted of an ore pass/ventilation raise and several open stopes. Above the -130 level the Betzy system consisted of fairly large staggered raises. The Betzy raise system could be easily isolated from the ramp above the -130 level. Figure 4 shows an alternative where the Betzy raise is split into an exhaust above the -130.

A model was developed with the Betzy acting in a similar fashion to the parallel raise system in the second scenario. To control the airflow the open stopes and raises between the -130/-144 levels would have to be filled or capped (the only major modification required).

The resulting fan operating duties required to achieve 70.8 m^3/s below the -189 level were as follows: Joy Fan (Betzy) – 37.8 m^3/s @ 1.37 kPa, and Spendrup fans operating in parallel – 51.9 m^3/s @ 1.69 kPa. The Joy fan would be operating near its pressure limit. At 37.8 m^3/s the Joy fan can only generate approximately 1.49 kPa without entering into a stall condition: at the required 1.37 kPa it would be marginal. If any of the airways deteriorated over time adding additional pressure losses, the fan would stall.

In order to consider this scenario several issues would need to be addressed. The velocity of the air through the majority of the ramp would not pose much of a problem. The average velocity of the air through the portion of the ramp acting as the sole intake to the mine would be approximately 5.6 m/s. Although this is fairly high it is still within acceptable limits. However, there was a section of ramp between –5 level and –40 level that was fairly tight. It would be necessary to open a by-pass raise through this area of ramp so that it would be less constricted when the haul trucks traversed through it.

3.4 *Reversing the airflow through the alimak*

The airflow through the alimak could potentially be reversed and used as an intake in parallel with the Betzy raise system. This could be accomplished using the Joy fan currently on the Betzy Winze, and the existing Spendrup fans mounted such that they provided a forcing ventilation system. The problem of high velocities through the –5 / –40 section of ramp would be the same as in the previous scenario. The peak velocity of the air in the section of ramp leading toward the portal where no parallel raise is available would be approximately 6.9 m/s which is very high considering it is a main haul route. A velocity of this magnitude could cause a substantial amount of dust to become entrained in the air. However since this air is exhausting the mine it would not affect any of the working levels. For those sections of ramp with a parallel raise the velocity of the air would be under 5.3 m/s. Operators of haul trucks and auxiliary equipment would be exposed to dusty exhaust air and respirators or airstream helmets would recommended for those operators. By reversing the airflow, fresh air is provided directly to the working faces without contamination by equipment operating in the ramp.

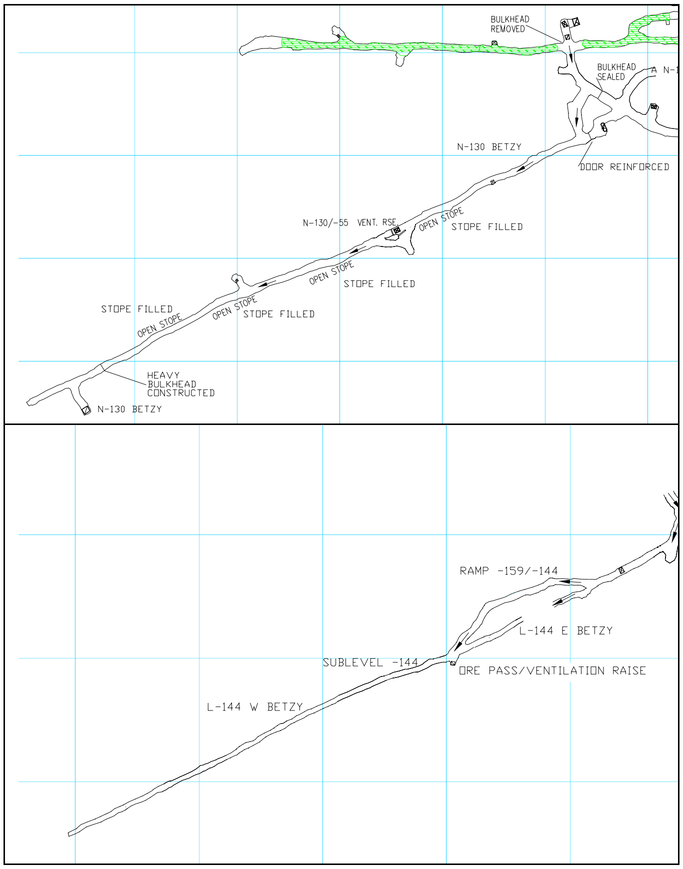

Figure 4. Levels -130 and -144/159 modifications for splitting the Betzy raise system.

The fan operating points to achieve 70.8 m^3/s below the –189 level would be: the Joy fan at 42.5 m^3/s @ 1.35 kPa, and for two Spendrup fans operating in parallel at 61.4 m^3/s (combined) @ 2.07 kPa. The Spendrup fans would be operating close to their peak efficiency for this scenario. The Joy fan would be operating close to its maximum pressure. There would be quite a bit of leakage from the Betzy zone into the ramp through the active levels between –159 and -197. If this leakage were limited then the Joy fan operating point could be lowered.

This alternative has the benefit of supplying fresh air directly to the mining levels with no contamination, and existing fans and locations can be utilized. However, the potential problems with this scenario included: the Joy fan being high on its operating curve, high velocities in the ramp, and the potential for a significant amount of dust to be entrained air through the ramp.

4 RESULTS OF THE VENTILATION SYSTEM MODIFICATION

The ventilation system modification opted for by the mine was to split the Betzy raise system into an exhaust above the –130 level, and keep it as an intake below the –144 level. This modification could be made with the least amount of changes to the mine infrastructure, and utilized the existing fans in their current locations.

The airflow in the mine was increased by 70% from 59.0 m^3/s, to 99.1 m^3/s through the incorporation of some fairly basic infrastructure modifications. The fan duties recorded by the mine after the ventilation change were as follows; Joy Fan (Betzy) – 39.6 m^3/s @ 1.49 kPa, and Spendrup fans operating in parallel – 59.8 m^3/s @ 1.89 kPa. These results were very close to the values initially predicted by the ventilation model in section 3.3. This shows that the ventilation model was accurately developed. Figure 5 shows the airflow before and after the ventilation change.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the effort made by the La Camorra mine personnel during the ventilation survey, and in providing data following the ventilation change.

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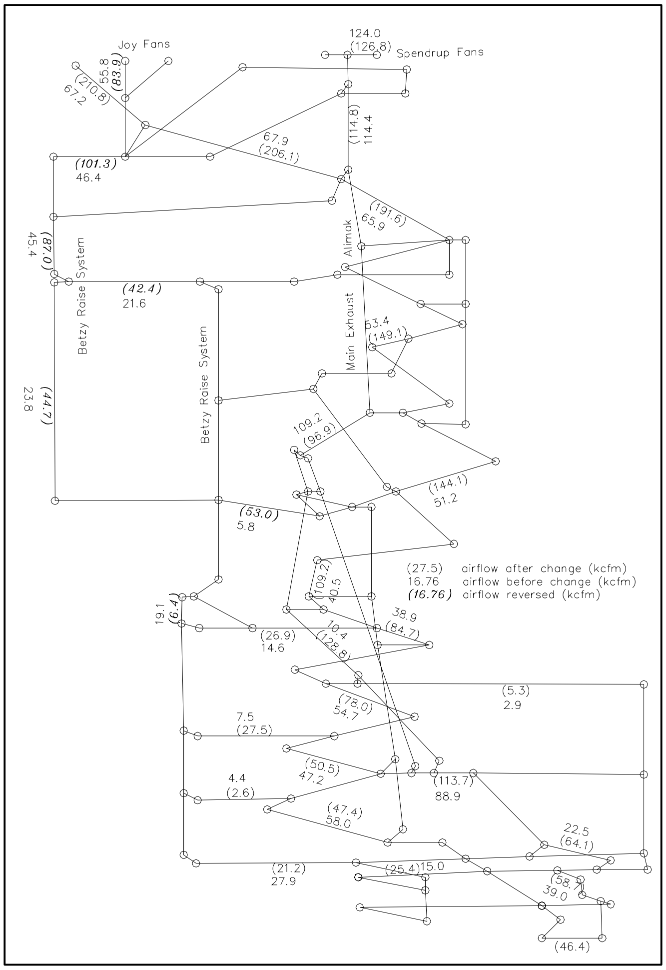

Figure 5. Measured airflows before and after the ventilation change.