Life-of-mine ventilation planning at Diavik

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ABSTRACT A framework for ventilation planning, with a focus on planning to the end-of-mine life, was developed for the Diavik Diamond Mine, Northwest Territories. This framework was successfully used by Diavik's mine engineers to select a cost-effective ventilation plan that met the life-of-mine requirements. The framework achieved this result by reconciling the production plan with the ventilation plan. A set of design acceptability criteria was created and a PICK (possible, implement, challenge, kill) chart was used to quickly narrow down the generated ideas for detailed assessment and economic analysis.

KEYWORDS Diavik, Framework, Life of mine, Mine, Planning, Underground, Ventilation

RÉSUMÉ Un cadre de planification de l'aérage, qui met notamment l'accent sur la planification jusqu'à la fin de vie de la mine, a été développé pour la mine de diamants Diavik. Les ingénieurs miniers de Diavik ont su mettre à profit ce cadre pour sélectionner un plan d'aérage rentable qui répondait aux exigences propres à la durée de vie de la mine. C'est en conciliant le plan de production et le plan d'aérage que cet objectif a pu être atteint. Un ensemble de critères d'acceptabilité de la conception a été créé et un tableau PICK (de l'anglais *possible, implement, challenge, kill*, une méthode donnant la priorité à certaines actions proposées ou à des idées visant à résoudre des problèmes) a été utilisé pour rapidement limiter les idées générées et les soumettre à une évaluation et une analyse économique détaillées.

MOTS CLÉS aérage, cadre, Diavik, durée de vie de la mine, mine, planification, souterrain

INTRODUCTION

The Diavik Diamond Mine, Northwest Territories, has been an underground-only operation since 2012 and has a remaining mine life of 8 years. In the first year of underground-only operations, the production rate increased from 60 kt of ore per month to more than 160 kt of ore per month. In subsequent years, this rate was continuously increased (Table 1) because the operation went through various improvement initiatives. By the end of 2016, Diavik's total production was 0.41 Mt (+22.8%) ahead of the 2012 budget for 2016 production.

During its remaining operational life, the mine will pass through several fundamental milestones. For ventilation, these milestones are the opening of a new deeper mining block in the A154N orebody for sublevel stoping in 2018, the depletion of the A154S orebody in 2019, and the depletion of the A418 orebody while the final mining block in A154N is opened in 2021 (Figures 1 and 2). This plan will leave a single orebody in operation for the final 3 years of mine life (Yip & Pollock, 2017). The ventilation system required significant changes to support these transitions to the final configuration. A framework for ventilation planning has been developed and was used to select a ventilation plan that will meet the requirements of the life-of-mine plan.

VENTILATION AND PRIMARY FAN DESCRIPTION

Diavik's primary surface fresh air raise (FAR) fans, identified in Figure 1, move approximately 710 m^3/s (1.5 Mcfm),

Table 1. Actual and planned ore production at the Diavik underground mine (2012–2016; Harry Winston Diamond Corporation, 2012; Yip & Pollock, 2017)

Year	2012	2013	2014	2015	2016
Actual underground production (Mt)	0.94	1.96	2.28	1.98	2.21
2012 budget plan (Mt)	0.96	1.80	1.80	1.80	1.80

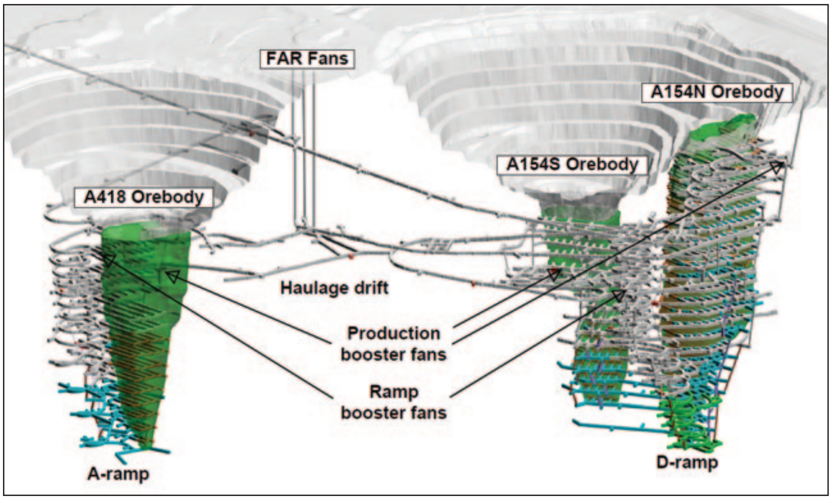

Figure 1. Isometric view of the Diavik underground mine

with five Alphair 10150-AMF-5500 full-blade, 2.6 m (101.5 in.) diameter fans operating in parallel, each powered by a 336 kW (450 hp) motor. These fans push air underground through three fresh air raises. Diesel heaters in front of the fans keep the underground temperature above freezing. Fresh air is delivered to a midpoint in the mine known as the "haulage drift," which connects the A418 orebody with the A154S and A154N orebodies, as shown in Figure 1. Booster fan installations direct air to the bottom of the A and D ramps, and other installations push or pull fresh air across the production levels (Robinson & Gherghel, 2013). There are no doors or other regulating controls in the main ramps; airflow is directed around the mine with the booster fans.

The A418 and A154S orebodies are mined using the sublevel retreat (SLR) method, which is similar to the sublevel caving method except without the caving of the hangingwall. In A154N, the mining method used is orebody blasthole stoping (BHS)—also known as sublevel or longhole stoping—with a primary-secondary sequence and backfill (Yip & Pollock, 2017).

FRAMEWORK FOR VENTILATION PLANNING

A framework for ventilation planning was built for use at the Diavik mine but this framework could also be used by other operating mines to guide long-range ventilation planning. The framework was designed to help mine engineers create a ventilation plan after the mine plan had already been completed, rather than in tandem with the mine plan creation as would be expected for a feasibility study. The ventilation framework uses evaluation methods such as the PICK (possible, implement, challenge, kill) chart (George, 2006) to rapidly advance from many ideas to a detailed options analysis. The framework is summarized in Figure 2.

PREPARE INPUTS FOR FRAMEWORK

The goal of the case study was to build a ventilation plan for Diavik's 2016 Q1 mine plan. The first step of the framework was to take the detailed plan, which is a large collection of individual activities occurring during the mine life,

Prepare Inputs

1. Simplify the Mine Development and Production Plan
2. Determine Design Acceptability Criteria and Estimate Airflow Requirements
3. Prepare Calibrated Ventilation Model of Current Mine

Model Current Ventilation Plan and Review

4. Create Forward Looking Ventilation Models
5. Search for Airflows Below Acceptability Criteria
6. Use Tools of Ventilation Model to Highlight Bottlenecks and Inefficiencies

Idea Generation and Options Evaluation

7. Generate Ideas for Solving Shortcomings
8. Preliminary Evaluation of Options, Value-Ease Ranking
9. Re-simulate with Likely Options
10. Thorough Evaluation and Economic Analysis of Option(s)
    May need to go through several iterations of modelling or even change production plan
11. Selection and Design Optimization of Mine Ventilation Plan

Figure 2. Simplified mine plan of quarterly activity by level, 2016–2021

and simplify it down to the major work that would define the airflow requirements in each primary airflow block for each period. For the case study, the outlook was approximately 10 years, so it was decided that quarterly periods would be appropriate for the first five years and annual periods thereafter.

For the case study, the primary airflow blocks were considered to be levels in the SLR production of A418 and A154S. In the A154N orebody, it was assumed that a BHS block would be the primary airflow zone. This BHS block comprises five levels and typically has one level in ore production (mucking), one level in backfilling, one drilling level, one developing ore level, and one idle level. This greatly simplifies the ventilation requirements of the block and is an appropriate level of detail for a 10-year plan. The results of this exercise are shown in Figure 3; airflows are not yet assigned to these activities.

The case study considered the ventilation of waste development at Diavik to be a straightforward process not requiring investigation. Booster fans deliver fresh air near the ramp faces using a series of drop raises, whereas waste headings are mined under auxiliary ventilation. In the A418 orebody, the exhaust air from waste development and production mining travels up the ramp and to the surface via portals. In the A154 north and south orebodies, the exhaust air from waste development mixes with fresh air, travels up the ramp, and is reused on production levels where the exhaust air is captured in return air raises (RARs).

The second step of the framework was to determine the design acceptability criteria that would set the minimum airflow volume requirements. For the Diavik Diamond Mine, these criteria were a collection of standards and practices in use to meet various territorial and corporate policies. The criteria specified the airflow volume required to dilute and expel exhaust from diesel equipment; that auxiliary fan recirculation is minimized; that personnel not be exposed to levels above the threshold limit value for various contaminants, including CO and NO_2; and that exhaust airflow from production should be captured in an exhaust air raise without reuse where practical. Other requirements such as minimum airflow velocities and specific volumes for workshops were also set based on historical data.

The design acceptability criteria were then converted into airflow requirements and applied to the mine plan shown in Figure 3. The total fresh airflow requirement for the mine was calculated for each period to ensure that the surface fans could meet the supply requirements.

The third step of the framework was to prepare a ventilation model using Ventsim™ (Chasm Consulting, 2015) and calibrate it to the actual mine. A pressure-quantity survey

2016 Q1 Forecast		2016		2017				2018				2019				2020				2021			
	Level	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
A418 Orebody	A9085																						
	A9065																						
	A9045	SLR	SLR	SLR																			
	A9020	Ore dev	Idle	SLR	SLR	SLR	SLR																
	A8995	Ore dev	Ore dev	Ore dev	Ore dev	Idle	SLR	SLR	SLR	SLR													
	A8970			Ore dev	Ore dev	Ore dev	Idle	Idle	Idle	SLR	SLR	SLR											
	A8945				Idle	Ore dev	Ore dev	Ore dev	Idle	Idle	Idle	Idle	SLR	SLR	SLR								
	A8920							Ore dev	Ore dev	Ore dev	Ore dev	Idle	Idle	Idle	SLR	SLR	SLR						
	A8895								Idle	Ore dev	Ore dev	Ore dev	Idle	Idle	Idle	Idle	SLR	SLR					
	A8870											Ore dev	Ore dev	Ore dev	Idle	Idle	Idle	SLR	SLR				
	A8845												Ore dev	Ore dev	Ore dev	-	-	-	SLR	SLR			
	A8820														Ore dev	Ore dev	Idle	Idle	Idle	SLR	SLR		
	A8795															Ore dev	Ore dev	Idle	-	Idle	SLR	SLR	
	A8770																Ore dev	Ore dev	Idle	Idle	Idle	SLR	SLR
A154S Orebody	S9000																						
	S8975	SLR	SLR																				
	S8950	TLD	SLR	SLR	SLR																		
	S8925	Ore dev	TLD	TLD	SLR	SLR	SLR																
	S8900		Ore dev	Ore dev	TLD	TLD	SLR	SLR	SLR														
	S8875			Idle	Ore dev	Ore dev	TLD	TLD	SLR	SLR	SLR												
	S8850					Idle	Ore dev	Ore dev	TLD	TLD	SLR	SLR											
	S8825							Idle	Ore dev	Ore dev	TLD	TLD	SLR	SLR									
	S8800									Idle	Ore dev	Idle	TLD	SLR									
A154N Orebody	N9275	Auxiliary ventilation from ramp																					
	N9250	Active BHS block		Active BHS block				Drilling	Drilling	Drilling	Drilling	CRF	BHS	Idle	Leak	Leak	Leak	Leak	Leak	Leak	Leak	Leak	Leak
	N9225							CRF	CRF	CRF	BHS	BHS	Idle	-	-	-	-	-	-	-	-	-	-
	N9200							BHS	BHS	BHS	Idle	-	-	-	-	-	-	-	-	-	-	-	-
	N9175							0	0	0	0	-	-	-	-	-	-	-	-	-	-	-	-
	N9150	Active BHS block		Active BHS block																			
	N9125																						
	N9100																						
	N9075																						
	N9050																						
	N9025	-	-	-	-	-	-	-	-	Leak	Leak	Active BHS block											
	N9000	-	-	-	-	-	-	-	-	Leak	Ore dev												
	N8975	Leak	Leak	Leak	Leak	Leak	Leak	Leak	Leak	Ore dev	Drilling												
	N8950	-	-	-	-	-	-	Idle	Ore dev	CRF	CRF												
	N8925	-	-	-	-	-	-	Ore dev	Ore dev	BHS	BHS												
	N8900	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Leak	Idle	Active BHS block			
	N8875	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Leak	Idle	Ore dev				
	N8850	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Leak	Idle	Ore dev	Idle				
	N8825	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Idle	Ore dev	Idle	Idle				
	N8800	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Ore dev	Idle	Idle	Idle				

Legend
SLR = sublevel retreat stoping
Ore dev = lateral ore development
Idle = inactive level with significant leakage
Leak = closed level with minimum leakage
CRF = backfilling with cemented rockfill
TLD = production ore loading to truck on level
Active BHS block = mix of activities to cycle stopes

Figure 3. Simplified mine plan of quarterly activity by level, 2016–2021

was undertaken to determine branch-specific resistance characteristics and average branch data for forward projections in the model. The variance of the model airflows and field measurements were compared to confirm that the model was valid and would accurately predict future airflows.

MODEL CURRENT PLAN AND REVIEW

In the fourth step of the framework, the ventilation model was extrapolated forward. In step 5, airflows that fell below the design acceptability criteria were identified. In the Diavik study, this was determined by the booster fans' ability to move sufficient airflow across the ventilation zones. In this step, the ventilation model showed that all A418 and A154S levels would be ventilated adequately during all time periods.

The search for airflows that fell below the design acceptability criteria found a trend of low airflows in the middle of the D ramp. The airflow delivered to the D ramp (75 m^3/s or 160 kcfm) was less than the airflow pulled off the ramp by the A154S production fans (exhausting 94 m^3/s or 200 kcfm). Thus, the section of the D ramp below the lowest addition of fresh airflow would see a reversal of flows, leaving one ramp loop almost without air movement where the airflow direction transitions (air from below coming up the ramp meets air from above coming down the ramp). This situation is not acceptable because it occurs in the middle of a production zone.

Finally, several levels with unsatisfactory airflows were encountered in A154N production areas, starting with the C block in 2018 as it enters production, with airflows getting worse in 2020 as the D block begins production (Figure 3), with a consistent shortfall from then until the end of the mine's life. Using the ventilation model tools (step 6) to analyze friction losses, it was determined that one of the ventilation raises exhausting from A154N would experience excessive airflow velocities after 2018, and an old ventilation drift running from the FARs to the A154 exhaust air raise would be unused.

As seen in Figure 3, at this stage the mine plan works very neatly in some ways: as the A block ends the C block begins, and as A154S ends the D block begins. With a fixed airflow supply, the fresh air supply will be moved from one mining block to another, which works well in a mine plan that is constrained by total fresh airflow, such as in this case study.

OPTIONS EVALUATION

The framework moves rapidly from identifying shortcomings (step 5) to idea generation (step 7) and options ranking (step 8) with a PICK chart (George, 2006). A PICK chart is a Six Sigma™ tool used to rank ideas based on relative impact and ease of implementation. The study observed that more airflow needed to be directed to the lower D ramp for A154S production in the medium term and A154N production in the long term. The project considered

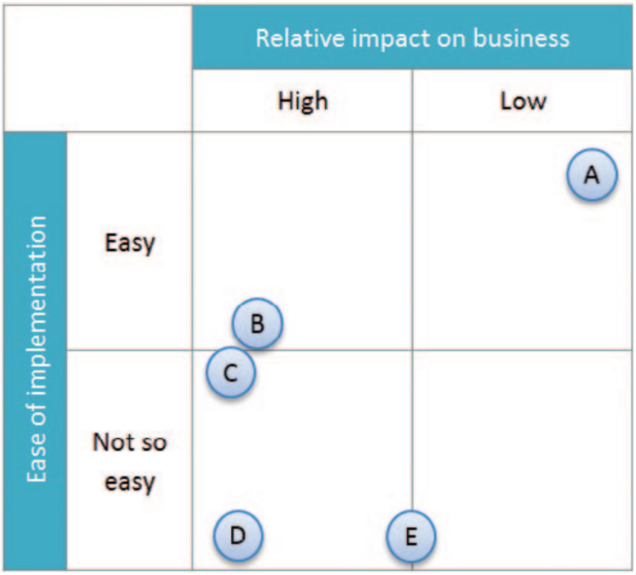

Figure 4. PICK (possible, implement, challenge, kill) chart of ideas to increase fresh air delivery to the lower D ramp. A is increasing fan power, B is adding fans to the bulkhead, C is replacing the bulkhead and installing larger diameter fans, D is building a parallel fan chamber, and E is reversing the A154S production booster fans.

- (A) increasing fan power;
- (B) adding fans to the bulkhead;
- (C) replacing the bulkhead and installing larger diameter fans;
- (D) building a parallel fan chamber; or
- (E) reversing the A154S production booster fans.

The PICK chart compared the ability to deliver the required airflow against the predicted cost and is shown in Figure 4. Both the impact and cost are subjective estimates (where such estimates can be reasonably made). Of the various ideas, two were ranked as being equally easy to implement and having equally high impact. These two options were fully simulated for step 9 in Ventsim and a fan selection exercise was completed. For the thorough evaluation of step 10, more detailed costs and construction timetables were created and compared, and a project scope was decided upon. In step 11 the final selection was made; in this case the deciding factor was the length of ramp shutdown time required for construction.

The second shortcoming identified in step 5 was the need to increase airflow across the A154N orebody as more mining blocks open for production. The following five points were generated for step 7 as rough methods to achieve the desired results using the model analysis in step 6; the locations are identified in Figure 5:

- twinning exhaust raisebores leading to the N9250 fan chamber to decrease system resistance
- replacing the N9250 fan chamber with larger diameter fans
- repurposing the A154S exhaust fan via RAR 14 to exhaust from the A154N orebody as well

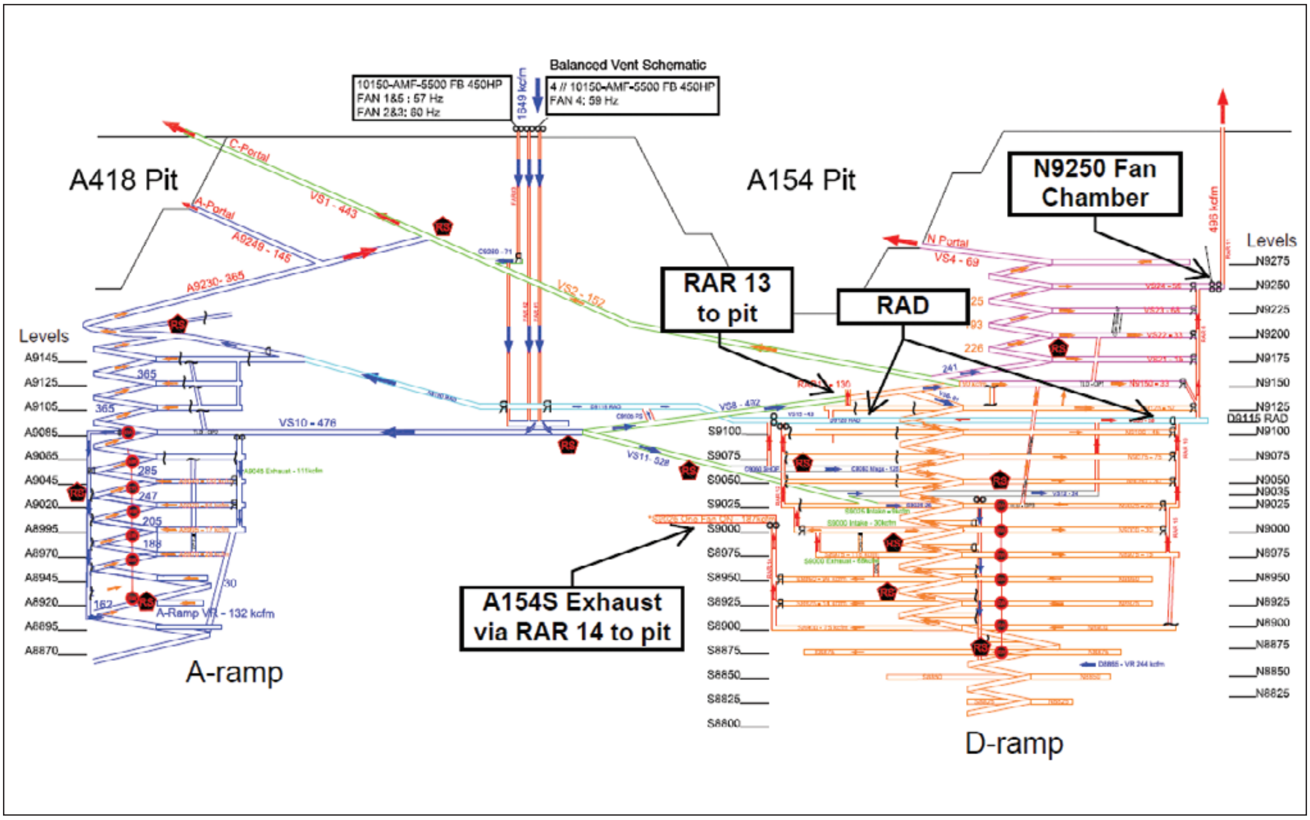

Figure 5. Diavik ventilation schematic identifying infrastructure tested for expanded capacity (FAR, free air raise; RAD, return air drift; RAR, return air raise)

- exhausting across the RAD (return air drift) into the pit via RAR 13 to create a parallel exhaust path from A154N
- reversing one of three FARs to the surface

With all the variations, these five points turned into 15 models. In the next step (step 8: preliminary evaluation of options), the relative impact could not be estimated very well due to the magnitude of the change, so Ventsim was used to model future airflow volumes for each model during each period. Two options met the required exhaust volumes as determined by the design acceptability criteria. With only two options available a PICK chart was not necessary. The potential options were

Option 1: Excavate a new fan chamber to replace the N9250 fan chamber, equip the chamber with four very large diameter fans, and twin RAR 6 and 10 (two raisebores leading to the N9250 fan chamber); or

Option 2: Create a parallel exhaust air route through an unused RAD with a new fan chamber at D9120 and twin RAR 10.

A thorough evaluation of the two best options was made as per the framework. These two ventilation models were fully developed and checked for mine-wide acceptance to the design airflow criteria throughout the life of the mine (step 9: resimulate likely options). Preliminary fan selections had been made using Ventsim and preliminary construction costs were gathered (step 10: thorough evaluation and economic analysis). The results of the financial comparison are summarized in Table 2. Option 1 was significantly more expensive because a new fan chamber would have to be developed; the old N9250 fan chamber was integral to production and could not be shut down during the project. Option 2, however, kept the old fan chamber in use, which had fans that were known to operate at a lower efficiency with significant velocity pressure loss at the fan discharge due to their small diameter.

Although option 1 had a lower annual operating cost, a comparative economic analysis was undertaken to determine if the significantly greater capital requirements of option 1 were justified by the slightly lower life-of-mine operating cost. Because Diavik has an adjusted EBITDA (earnings before interest, taxes, depreciation, and amortization) margin of 48% (Dominion Diamond Corporation, 2016; adjusted EBITBA margin is a measure of operating profitability as a percentage of total revenue), any project should improve this rate of return. The rate of return of the incremental capital cost increase from C$1.5 million to C$4.0 million was below the cutoff for investment, at only 31% with nearly a 3 year payback; therefore, option 2 was selected. A layout of the proposed exhaust air path for option 2 is given in Figure 6.

Table 2. First pass life-of-mine capital and operating costs to facilitate options assessment (RAD: return air drift)

	2017	2018	2019	2020	2021	2022	2023	2024	2025
Option 1: New fan chamber									
Capital cost (C$)	$4,000,000								
Operating cost 670 kW (C$)		$1,819,452	$1,819,452	$1,819,452	$1,819,452	$1,819,452	$1,819,452	$1,819,452	$1,819,452
Option 2: RAD exhaust									
Capital cost (C$)	$1,500,000								
Operating cost 990 kW C($)		$2,688,444	$2,688,444	$2,688,444	$2,688,444	$2,688,444	$2,688,444	$2,688,444	$2,688,444
Comparison: Option 1 vs. Option 2									
Delta cash flows (C$)	$(2,500,000)	$868,992	$868,992	$868,992	$868,992	$868,992	$868,992	$868,992	$868,992
Cumulative delta (C$)	$(2,500,000)	$(1,631,008)	$(762,016)	$106,976	$975,968	$1,844,960	$2,713,952	$3,582,944	$4,451,936
Comparative internal rate of return (IRR)		31%							
Comparative payback period (years)		2.9							

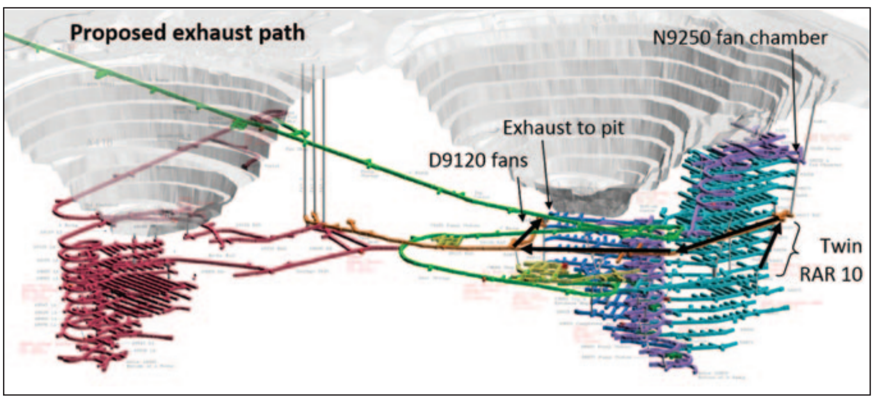

Figure 6. Isometric view of Diavik underground mine with proposed exhaust air path highlighted through the return air drift and return air raise (RAR)

CONCLUSIONS

This paper describes the development of a framework for ventilation planning at the Diavik Diamond Mine. This framework facilitated the selection of a ventilation system capable of meeting the requirements of the life-of-mine plan. The framework achieved this result through the reconciliation of the production plan with the ventilation plan by creating design acceptability criteria and using the value-ease analysis method to quickly narrow down the ideas generated to two options for detailed assessment and economic analysis. For Diavik, the framework helped the mine engineers select a cost-effective ventilation plan that involved twinning an exhaust air raise and re-equipping an old drift to the pit as an exhaust air path with a new fan chamber.

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