Life of Mine Ventilation Planning at Diavik

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Abstract

A framework for ventilation planning, with particular focus on planning to the end of mine life, was developed for use at the Diavik Diamond Mine. Diavik has been an underground operation since 2012 and has a mine life of only 13 years. With only eight years remaining the mine will go through some fundamental milestones before closure. These milestones include the closing of two orebodies, leaving a single orebody for the final three years of mine life. A significant change to the ventilation system will be required to support the transition to the final configuration. 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 narrow down relatively quickly the ideas generated to two options for detailed assessment and economic analysis. For Diavik, the framework was successfully utilized by the mine engineers to select a cost effective ventilation plan based on twinning an exhaust raise and re-equipping an old drift to the pit as an exhaust path with a new fan chamber.

Introduction

The Diavik Diamond Mine has been an underground-only operation since 2012 and has a remaining mine life of eight years. In the first year of underground-only operations the production rate ramped up from 60 kt of ore per month to over 160 kt per month, and in the subsequent years this rate was pushed continuously as the operation went through various improvement initiatives. These increases are shown in Table 1; they demonstrate how early plans created before commercial production became detached from reality after a few years. By the end of 2016 Diavik was 1.2 Mt (+14.8%) ahead of the 2012 Mine Plan.

Table 1. Plan vs Actual Ore Production at the Diavik Underground Mine 2012-16 (Harry Winston, 2012) (Yip and Pollock, 2017)

Diavik UG	2012	2013	2014	2015	2016
Actual Underground Production	0.94 Mt	1.96 Mt	2.28 Mt	1.98 Mt	2.21 Mt
2012 Budget Plan	0.96 Mt	1.8 Mt	1.8 Mt	1.8 Mt	1.8 Mt

During its remaining operational life, the mine will pass through several fundamental milestones. For ventilation, these milestones are the opening of C-block for sublevel stoping in the A154N orebody in 2018, the depletion of the A154S orebody in 2019, and the depletion of the A418 orebody while opening D-block in A154N in 2021, identified in Figures 1 and 2. This plan will leave a single orebody in operation for the final three years of mine life (Yip and Pollock, 2017). A significant change to the ventilation system was required to support these transitions to the final configuration. A framework for ventilation planning has been developed and was utilized 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 "FAR" Fans, identified in Figure 1, move approximately 710 m^3/s (1.5 Mcfm) with five Alphair 10150-AMF-5500 Full Blade 2.6m (101.5") diameter fans operated in parallel, each powered by a 336 kW (450hp) motor. These fans push air into the underground through three fresh-air-raises. Diesel heaters in front of the fans maintain a temperature underground that is above freezing. Fresh air is delivered to a mid-point in the mine known as the “Haulage Drift” which connects the southern A418 orebody with the northern A154 South and A154 North orebodies, also shown in Figure 1. Booster fan installations direct air to the bottom of the main ramps at either end of the mine, and other installations push or pull fresh air across the production levels (Robinson and Gherghel, 2013). There are no doors or other regulating controls in the main ramps; airflow is directed around the mine with the aforementioned booster fans.

The mining method for the A418 and A154 South orebodies is sub-level retreat (SLR), which is similar to sub-level caving except without caving of the hanging wall. In A154 North orebody blast hole stoping (BHS), also known as sublevel or longhole stoping, is the mining method with a primary-secondary sequence and backfill (Yip and Pollock, 2017).

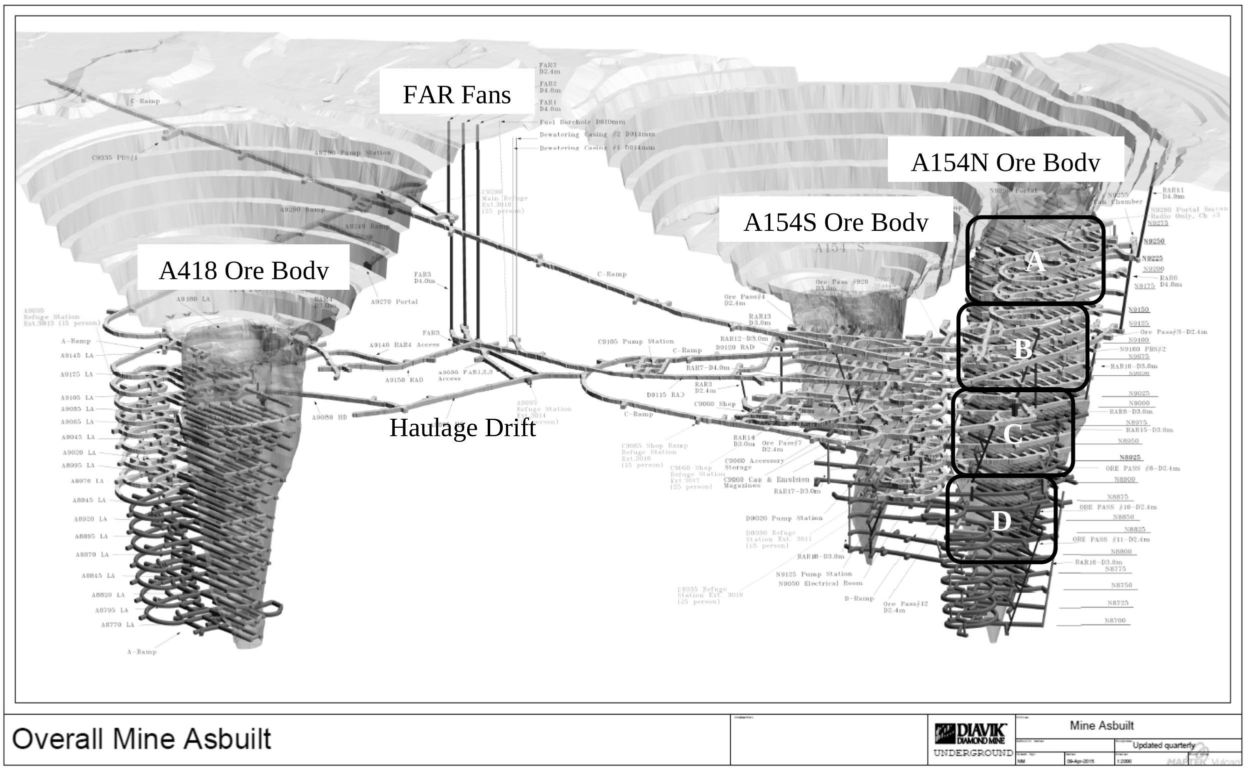

Figure 1. Isometric view of the Diavik Underground Mine

Framework for Ventilation Planning

A framework for ventilation planning was built for use by Diavik but this framework could be used also by other operating mines to guide long range ventilation planning. The framework was designed to help then mine engineers select a ventilation plan after the mine plan had already been completed, rather than in tandem as would be expected for a feasibility study, and uses evaluation methods such as the “value-ease principle” to advance rapidly from numerous ideas to a detailed options analysis. The framework can be summarized as follows.

<u>Prepare Inputs</u>

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

Prepare Inputs for Framework

The goal of the case study was to build a ventilation plan for Diavik's 2016 Q1 Mine plan. Annual ore and waste tonnage targets for the Diavik Diamond Mine are shown below in Table 2.

Table 2. Long range mine plan tonnes, Q1 2016 Diavik Life of Mine Plan
superseded by NI-43 101 Technical Report dated 27 March 2017 (Yip and Pollock, 2017)

2016 Q1 Forecast Mine Plan													
TONNE PRODUCTION STATISTICS													
UNDERGROUND			2016 TOTAL	2017 TOTAL	2018 TOTAL	2019 TOTAL	2020 TOTAL	2021 TOTAL	2022 TOTAL	2023 TOTAL	2024 TOTAL	2025 TOTAL
PIPE	*MATERIAL*	*UNIT*	352	352	352	352	352	352	352	352	352	352
A154N	**ORE TONNES**	*(tonnes)*	683,000	743,000	873,000	863,000	948,000	778,000	821,000	820,000	836,000	325,000
A154S	**ORE TONNES**	*(tonnes)*	546,000	488,000	355,000	286,000	0	0	0	0	0	0
A418	**ORE TONNES**	*(tonnes)*	895,000	873,000	873,000	871,000	851,000	693,000	0	0	0	0
UG	**TOTAL ORE MINED**	*(tonnes)*	**2,123,000**	**2,105,000**	**2,101,000**	**2,020,000**	**1,799,000**	**1,472,000**	**821,000**	**820,000**	**836,000**	**325,000**
UG	**TOTAL CARATS**	*(count)*	**6,866,000**	**6,799,000**	**6,480,000**	**5,879,000**	**4,635,000**	**3,383,000**	**1,964,000**	**1,946,000**	**1,812,000**	**767,000**
UG	**MINED GRADE**	*(cpt)*	3.23	3.23	3.08	2.91	2.58	2.30	2.39	2.37	2.17	2.36
UG	**TOTAL WASTE**	*(tonnes)*	313,000	299,000	188,000	174,000	73,000	97,000	24,000	22,000	8,000	7,000
UG	**TOTAL BACKFILL**	*(tonnes)*	533,000	601,000	621,000	635,000	664,000	724,000	867,000	743,000	577,000	218,000

The first step of the framework is to take the detailed plan, which is the large collection of individual activities occurring over the mine life, and simplify it down to the major work that would define airflow requirements in each primary airflow block for each period. For the case study, the outlook was almost 10 years, therefore it was decided that quarterly periods were appropriate for the first five years, and annual periods thereafter. Figure 2 is a graphical simplification of the mine plan.

For the case study we considered the primary airflow blocks to be levels in SLR production, in the A154N orebody it was assumed that a BHS stoping block would be a primary airflow zone. This block comprises five levels and can roughly be said to have one level in ore production (mucking), one in backfilling, one drilling, one developing ore and one idle level. This greatly simplifies the ventilation requirement of the block and is an appropriate level of detail for a 10-year plan. The results of this exercise are shown on the next page in Table 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. Waste headings are mined under auxiliary ventilation; in the A418 the exhaust from this work travels up ramp and to surface via the portals. In the A154 N/S the exhaust travels up ramp and is reused on production levels. The booster fans that supply fresh air to the bottom of the mine, and these development auxiliary fans, are already sized for the pressure requirement when the ramps reach their final elevation.

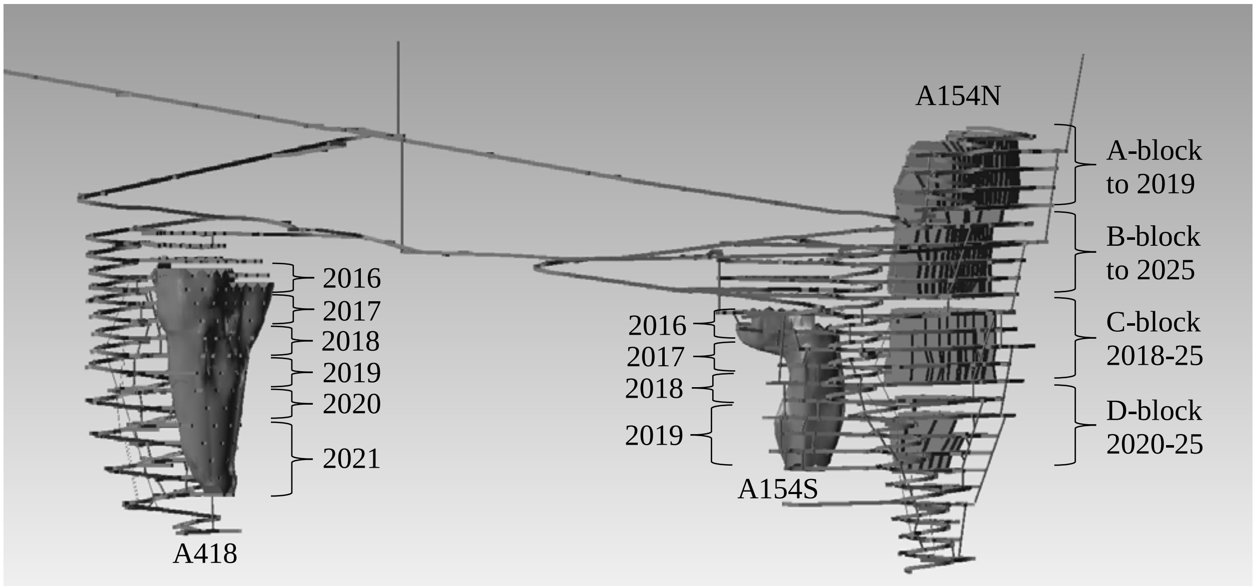

Figure 2. Section view of 2016 Q1 mine plan in 2022
superseded by NI-43 101 Technical Report dated 27 March 2017 (Yip and Thompson, 2017)

Table 3. Simplified mine plan of quarterly activity by level 2016-2021

2016 Q1 Forecast Mine Plan		2016		2017				2018				2019				2020				2021			
		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				
	N8775	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	N8750	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	N8725	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	N8700	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	N8675	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

The next step of the framework was to determine the design acceptability criteria. For the Diavik Diamond Mine these criteria were a collection of standards and practices in use to meet various territorial and corporate policies. The requirements included that 0.06 m^3/s of airflow for each kW of diesel power is supplied, or as determined by CANMET testing, that auxiliary fan recirculation is minimized, that personnel not be exposed to levels in excess of threshold limit value (TLV) for various contaminants, and that exhaust airflow should be captured in an exhaust raise without reuse where practical. Other requirements such as minimum airflow velocities and specific volumes for workshops were also set.

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

The next step of the framework was to prepare a ventilation model and calibrate it to the actual mine. A pressure-quantity survey was undertaken to determine branch specific resistance characteristics and average branch data for projecting forward in the model. The variance of the model to the field measurements was compared to confirm the model was valid and would accurately predict future airflows.

Model Current Plan and Review

At this stage, the framework requires that the ventilation model be extrapolated forward and continue with a search for airflows below the design acceptability criteria. In the Diavik study this was determined by the booster fans' ability to move sufficient airflow across the production blocks. In this step, the ventilation model showed that all A418 and A154S levels in all time periods would be ventilated adequately.

The search for airflows below the design acceptability criteria found in D-Ramp a trend of low airflows in the middle of the ramp. It recognized that the airflow delivered to D-Ramp (75 m^3/s or 160 kcfm) was less than the airflow pulled off of the ramp by A154S production fans at RAR #14 (94 m^3/s or 200 kcfm). Thus, the section of 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 ramp meets air from above coming down ramp). This situation is not an acceptable as it is in the midst of a production zone.

Finally, several levels of unsatisfactory airflows were encountered in A154N production areas, starting with C-block in 2018 as it enters production, getting worse in 2020 as D-block begins production, and continuing to the end of mine life. Using the tools of the ventilation model it was determined that ventilation raise RAR #10 would experience excessive airflow velocity after 2018, and an old vent drift running from the FAR raises to the northernmost RAR formerly used for exhaust stands out as unused.

It is worth noting that at this stage the mine plan works very neatly in some ways; as A-block ends C-block begins, and as A154S ends 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 plan constrained by total fresh airflow, such as this case study.

Options Evaluation

The framework moves rapidly from identifying shortcomings to idea generation and value-ease ranking. The study observed that more airflow needed to be directed to lower D-Ramp for A154S production in the medium term and A154N production in the long term. This adjustment was a relatively simple ventilation exercise as the volume of air moved by the booster fans need be increased only to the volume of air moving past the installation. The project considered (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, and (E) reversing RAR #14. A value-ease ranking, shown in Figure 3, of various ideas found two which were ranked to be equally easy to implement, and with equally high impact. Value-ease ranking, also known as a PICK chart, is used to rank ideas based on relative impact and ease of implementation so that low-impact difficult projects are dropped early and high-impact relatively easy projects are prioritized. The fan selection exercise for both options was completed, construction timetables compared and a project scope decided upon. In this case the deciding factor was the length of ramp shut-down required for construction.

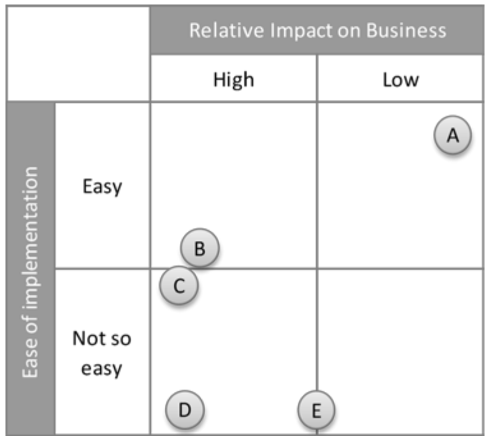

Figure 3. Value-Ease analysis of ideas to increase fresh air delivery to lower D-Ramp

The second shortcoming was the growing requirement of airflow across the A154N orebody as more mining blocks open for production. The following five points were generated as rough methods for achieving the desired results; the locations are identified in Figure 4.

- Twinning raisebores to decrease airflow speed & resistance and get more performance out of current installation. Considered RAR #6, #6+10, #6+10+15;
- Replacing N9250 Fan Chamber with four parallel 84" diameter fans, considered fans operating at 900rpm and 1200rpm, with and without twinning of RAR #6 & 10;
- Repurposing RAR#14 to exhaust from A154N also;
- Exhausting across RAD into the Pit via RAR#13 to create a parallel exhaust path, with and without twinning RAR#10, with and without connecting RAR #14 to A154N exhaust, with and without reversing RAR#14 to provide fresh air after A154S mining is complete;
- Reversing FAR #3 to re-establish RAR #1 on surface.

These five points turned into 15 models with all the variations, which the framework quickly judged in the ventilation model on a pass/fail ability to meet required exhaust volumes. Two options were found to be capable equally of meeting the demand:

Option #1. Excavate a new fan chamber to replace N9250 Fan Chamber, equip with four very large diameter fans, and twin RAR #6 & #10 (two raisebores leading to N9250 Fan Chamber)

Option #2. Create a parallel exhaust route through unused "RAD" drift with a new fan chamber at D9120, twin RAR #10

Next, a thorough evaluation of the two best options was made as per the framework. These two ventilation models were developed fully and checked for mine wide acceptance to the design airflow criteria through the life of mine. Preliminary fan selections had been made using Ventsim and preliminary construction costs were gathered. The results of a financial comparison are summarized in Table 4.

Option #1 was significantly more expensive as a new fan chamber would have to be developed as the old N9250 Fan Chamber was integral to production and could not be shut down during the project; but Option #2 kept the old fan chamber in use and these fans were known to operate at a lower efficiency due to their small diameter.

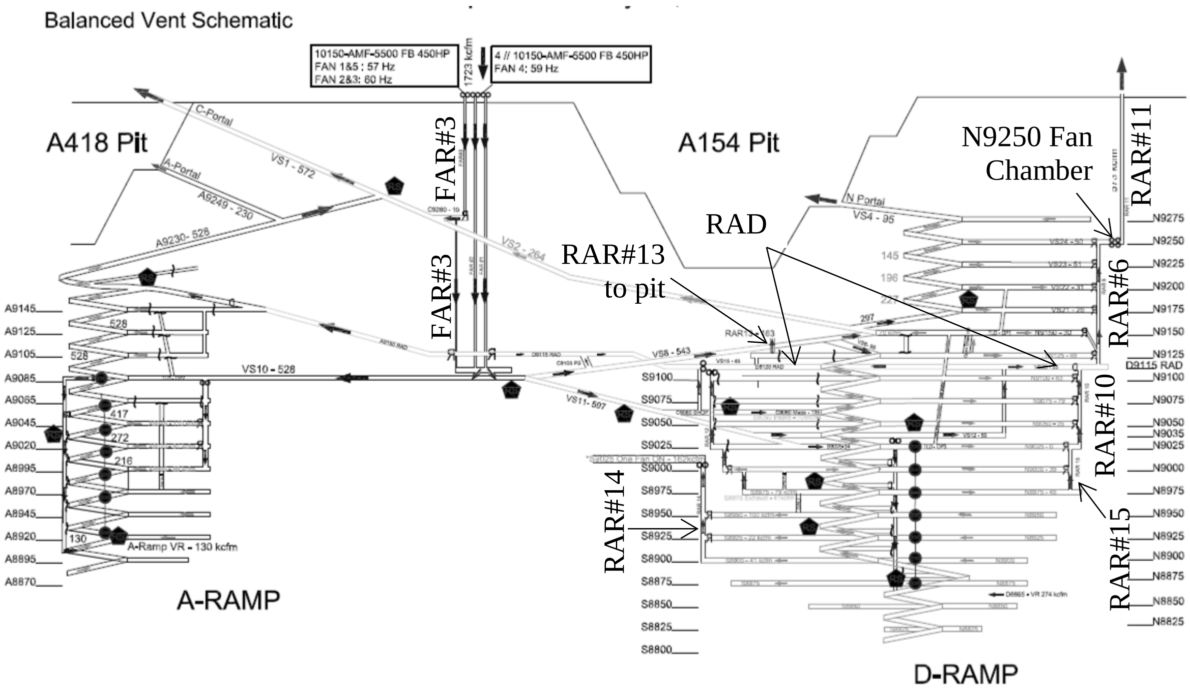

Figure 4. Diavik ventilation Schematic with infrastructure tested for expanded capacity identified

Table 4. First pass life of mine capital and operating costs to facilitate options assessment

Option 1: Replace the N9250 Fan Chamber

	2017	2018	2019	2020	2021	2022	2023	2024	2025
Capital Cost	$ 4,000,000								
Operating Cost		$ 1,819,452	$ 1,819,452	$ 1,819,452	$ 1,819,452	$ 1,819,452	$ 1,819,452	$ 1,819,452	$ 1,819,452
TOTAL	**$ 4,000,000**	**$ 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: Construct RAD Fan Chamber

	2017	2018	2019	2020	2021	2022	2023	2024	2025
Capital Cost	$ 1,500,000								
Operating Cost		$ 2,688,444	$ 2,688,444	$ 2,688,444	$ 2,688,444	$ 2,688,444	$ 2,688,444	$ 2,688,444	$ 2,688,444
TOTAL	**$ 1,500,000**	**$ 2,688,444**	**$ 2,688,444**	**$ 2,688,444**	**$ 2,688,444**	**$ 2,688,444**	**$ 2,688,444**	**$ 2,688,444**	**$ 2,688,444**

While Option #1 had a lower annual operating cost, a comparative economic analysis was undertaken (Table 5) to determine if the significantly greater capital requirements of Option #1 were justified by the slightly lower life-of-mine operating cost. As Diavik has an adjusted EBITDA margin of 48% (Dominion Diamond, 2016), which is a measure of operating profitability as a percentage of total revenue, any project ought to improve this rate of return. It was found that the rate of return of the incremental capital cost increase from $1.5M to $4.0M was below the cut-off for investment, at only 31% with nearly a 3 year payback; therefore Option #2 was selected. A layout of the proposed exhaust path for Option #2 is given in Figure 5.

Table 5. Comparative economic analysis between Options #1 and #2

Added Cost of Option #1 over #2

	2017	2018	2019	2020	2021	2022	2023	2024	2025
Delta Cash Flows (Op2-Op1)	$ (2,500,000)	$ 868,992	$ 868,992	$ 868,992	$ 868,992	$ 868,992	$ 868,992	$ 868,992	$ 868,992
Cumulative Delta	$ (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 NPV @ 8%	$2,309,059								
Comparative IRR	31%								
Comparative Payback	2.88								

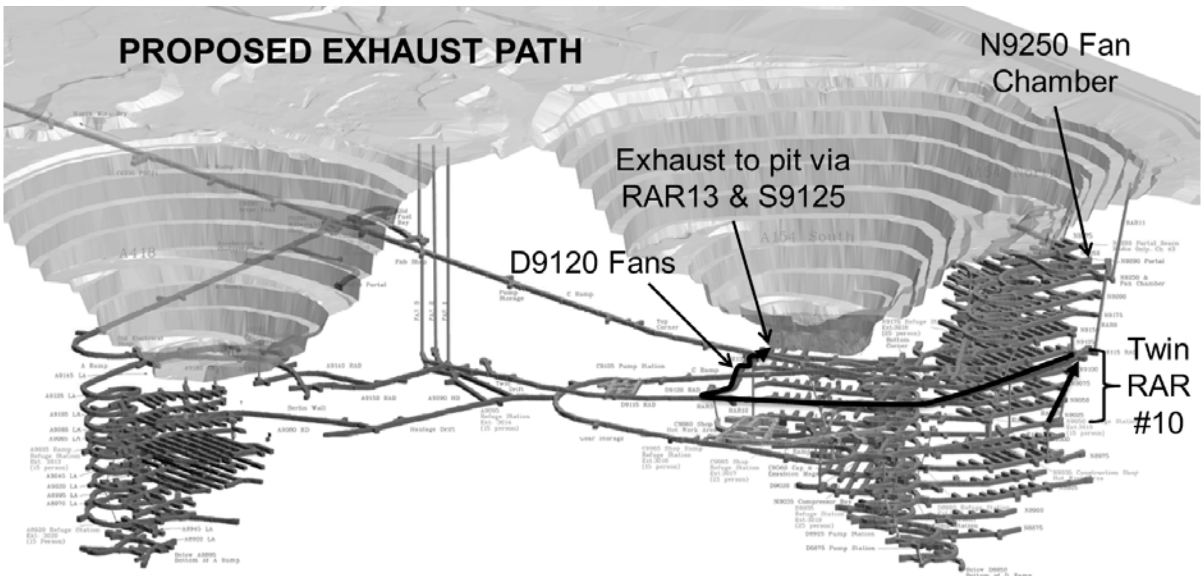

Figure 5. Isometric view of Diavik Underground with proposed exhaust path highlighted through the RAD and RAR #10 Twin

Conclusion

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 narrow down relatively quickly the ideas generated to two options for detailed assessment and economic analysis. For Diavik, the framework helped the mine engineers to select a cost effective ventilation plan based on twinning an exhaust raise and re-equipping an old drift to the pit as an exhaust path with a new fan chamber.

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