Fan selection for large-opening mines: vane-axial or propeller fans – which to choose?

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ABSTRACT: The National Institute for Occupational Safety and Health (NIOSH) has investigated the unique ventilation requirements of large-opening mines to help identify and evaluate the effectiveness of various fan types to improve the ventilation and air quality in the underground workplace. Large-opening mines, with their low airflow resistance factors, can be ventilated with free-standing auxiliary fans because airflow patterns in these mines are primarily controlled by airflow momentum. The flow characteristics of both vane-axial and propeller fans were investigated and tested at four large-opening mines to assess the effects of fan location on recirculation and entrainment. Each fan type has its own airflow, entrainment and penetrating airflow characteristics, and operating costs that are advantageous for specific applications. Either fan type can be used for most auxiliary applications. However, this research has shown that the optimum placement and use criteria for propeller fans differ from those promulgated by the U.S. Bureau of Mines (USBM) for vane-axial fans Brechtel et al. (1985).

1 INTRODUCTION

Moving adequate fresh air volumes in large-opening, room-and-pillar mines presents several challenges due to the large open-space volume of the mine and the extremely low airflow resistance 0.0005 $N{\cdot}s^2/m^8$ (4.5×10^{-13} $in{\cdot}min^2/ft^6$). The low mine resistance is caused by the large 12 m × 8 m (40 ft × 27 ft) entries. A well developed underground stone mine can have a void volume of several million cubic meters (100 million cubic feet) and require many hours to effect a complete air change. Unlike most underground coal mines and many metal mines, the resistance to flow in these large-opening mines is very low. Recognizing this fact, NIOSH demonstrated the use of low-pressure propeller fans for whole mine ventilation (Grau et al. 2004, Krog et al. 2004). Several large-opening mines have subsequently installed propeller fans for main mine ventilation instead of relying on changing natural ventilation. Mine operators are responsible to meet any federal guidelines (Title 30 U.S. Code of Federal Regulations Part 57) regarding placement and installation of fans.

NIOSH has since focused on the application of propeller fans to regional and face ventilation applications in large-opening mines. Previous research on ventilating large-opening oil shale mines conducted by the U.S. Bureau of Mines (USBM) in the 1970s and 1980s tested free-standing vane-axial fans as regional and face fans, Brechtel et al. (1985) and Dunn et al. (1983). The researchers examined vane-axial fan placement for efficient face ventilation; however, similar investigations using propeller fans for auxiliary face and regional ventilation were required and are discussed in this paper.

2 FAN AIRFLOW ENTRAINMENT CHARACTERISTICS

NIOSH researchers conducted studies of auxiliary, free-standing vane-axial and propeller fans, showing that each type has different airflow distribution patterns around the fan. An electronic vane anemometer mounted on an adjustable pole was used to measure average airflow readings on a grid pattern. A propeller fan tends to draw air from behind, and entrains the airflow only up to 30 m (100 ft) or to the first crosscut, as the resultant medium-speed airflow expands rapidly. Conversely, a vane-axial fan, with its lower air quantity and higher fan exit speed, draws minimal air from behind the fan. However, the vane-axial fan entrains the airflow for a distance of up to three crosscuts ahead of the fan because the high-speed airflow takes over 90 m (300 ft) to fully expand. Therefore, propeller and vane-axial fans have different placement criteria when used as auxiliary fans.

2.1 *Vane-Axial Fan*

Figure 1 shows the vane-axial fan used in the study. The free-standing vane-axial fan had a diameter of 0.91 m (36 in). It was powered by a 19 kW (25 hp) motor, and mounted with a reducer at the outlet with a discharge diameter of 0.58 m (23 in). The airflow characteristics generated by the vane-axial fan are shown in Figure 2. The patterns indicate that the high exit velocity of the fan's reducer [39 m/s (7600 ft/min)] causes air turbulence and entrainment for a distance of over 90 m (300 ft) in front of the fan. The venturi effect of the reducer was observed up to 3 meters (10 ft) in front of the fan, where little air interaction was observed surrounding the fan's high-speed airflow.

Figure 1. 0.91 m (36 in) vane-axial fan with 0.58 m (23 in) reducer.

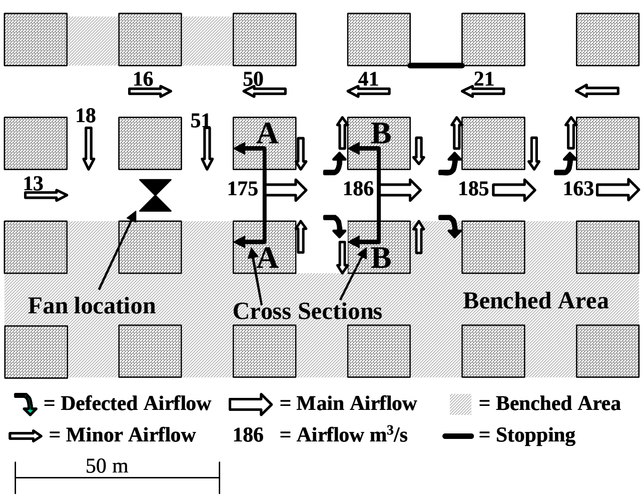

Figure 2. Airflow characteristics for a 0.91 m (36 in) vane-axial fan with reducer, note recirculation patterns generated around the second to forth intersections.

The airflow through the fan was 10.4 m^3/s (22,000 cfm). However, due to entrainment effects, the total airflow 83 m (272 ft) downstream of the fan was over 17 times greater, at 183 m^3/s (388,000 cfm). The airflow patterns in the cross-cuts at the 2nd to 4th intersections in front of the fan were bi-directional (Fig. 2). High velocity air moving down the main entry would catch the corners of the pillars and be directed perpendicularly down the cross-cuts. An eddy formed behind the pillars of the cross-cuts, pulling air into the main ventilation drift. The net result was little change in the total airflow moving down the main entry for the first three intersections, downstream from the fan (Fig. 2). However, because of the high-speed of the expanding airflow, there was recirculation with the surrounding air.

Figure 3 shows the cross-sectional velocity profile 28 meters (92 ft) in front of the vane-axial fan's outlet. The airflow is concentrated at the lower half of the 12.5 m × 8.4 m (41.1 ft × 27.4 ft) opening in the center of the drift as the high-speed air starts to expand. The peak air velocity was 6.56 m/s (1290 ft/min), and the air velocity approaches zero in the upper third of the cross section. Airflow in the top corners was below recordable levels.

Figure 4 shows a similar air profile as in Figure 3 recorded 27 m (88 ft) further down the drift. The air stream is still predominantly flowing along the ground, and very little airflow was recorded in the upper half of the drift. The peak velocity was 3.68 m/s (725 ft/min).

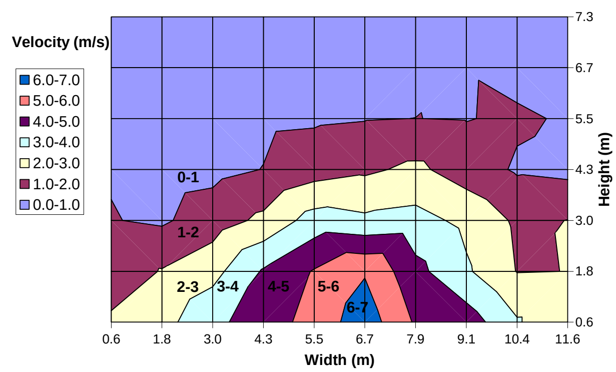

Figure 3. Vertical cross-section A of airflow 28 m (92 ft) in front of 0.91 m (36 in) vane-axial fan, flow out of page.

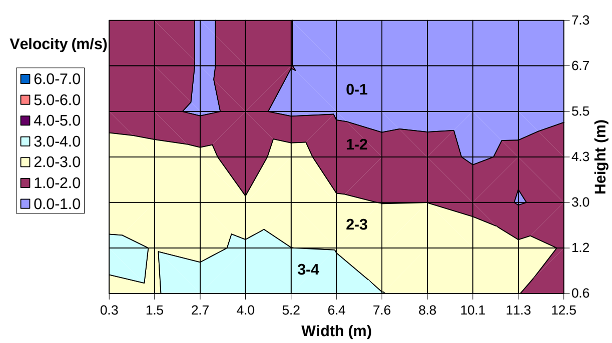

Figure 4. Vertical cross-section B of airflow 55 m (180 ft) in front of 0.91 m (36 in) vane-axial fan, flow out of page.

Figure 4 shows that entrainment will still occur further down the drift. The airflow interaction with the corners of the pillars varies with the height off the floor because of the different velocities along the ribs. Airflow interactions in the crosscuts at the intersections were bi-directional with airflow leaving the main drift along the lower half and airflow entering the main drift in the upper half of the crosscuts. This was due to the difference in airflow velocities in the main drift (Fig 3-4 ribs).

2.2 *Propeller Fan*

Figure 5 shows the 2.44 m (8 ft) diameter propeller fan, powered by a 22.3 kW (30 hp) motor, used in the study. Both the vane-axial and propeller fans were operating at close to 17.2 kW (23 hp) during the field investigations. The propeller fan moves a larger quantity [58.5 m^3/s (124,000 cfm)] of slower moving air that interacts differently with the surrounding air than the airflow from the vane-axial fan. The air leaving the propeller fan outlet is moving at 13 m/s (2500 ft/min), and expands rapidly to cover the entire cross-section of the drift. Figure 6 shows the airflow patterns generated by the propeller fan. Note that, compared to the vane-axial fan, a higher airflow quantity, 253 m^3/s (536,000 cfm) was achieved initially with the propeller fan. The airflow quantity progressively diminishes after each intersection. Also, the airflow does not leave the propeller fan in a straight uniform direction, but spreads out over the entire cross section of the drift.


Figure 5. 2.4 m (8 ft) propeller fan used in study.

Figure 7 shows the cross-sectional velocity profile 25 meters (82 ft) in front of the propeller fan's outlet. The airflow is quickly being dispersed across the entire drift. The peak air velocity was 4.40 m/s (866 ft/min), and the minimum air velocity was 1.12 m/s (221 ft/min). All grid sections of the drift had positive measurable airflow down the drift, with no airflow roll back being observed.

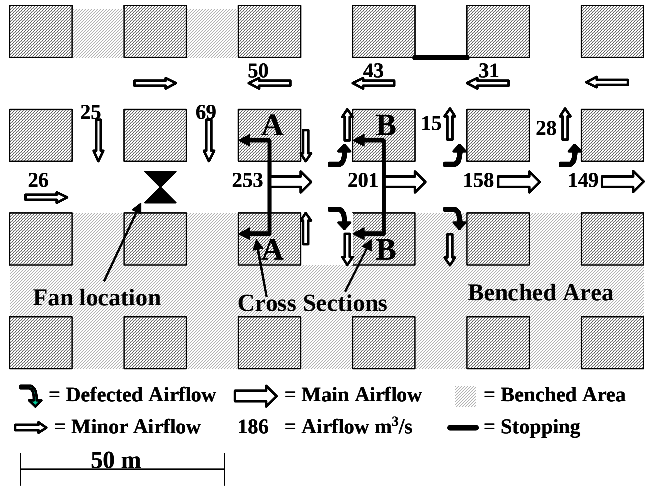

Figure 6. Airflow characteristics for a 2.44 m (8 ft) propeller fan, note recirculation patterns generated at the second intersection.

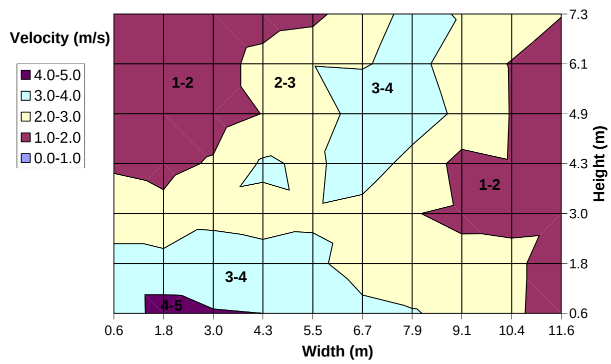

Figure 7. Vertical cross-section A of airflow 25 m (82 ft) in front of 2.44 m (8 ft) propeller fan, flow out of page.

Figure 8 shows the airflow 52 m (171 ft) in front of the propeller fan. The air stream completely enveloped the drift, with a peak air velocity of 2.84 m/s (559 ft/min) and minimum air velocity of 1.26 m/s (249 ft/min). The velocity profile is much closer to uniform (i.e. being more evenly distributed across the drift) than was observed with the vane-axial fan shown in Figure 4. Recirculation is only observed in the second intersection, and it is less than with the vane-axial fan. It appears that some of the airflow is leaving the main drift after the first intersection.

The airflow quantities moving down the main drift for both fans is shown in Figure 9. The vane-axial fan with its high exit velocity maintains a level of entrainment as far as 79.5 m (261 ft) in front of the fan, whereas the propeller fan only maintains entrainment for about 52 m (170 ft). Both fans have similar exponential (natural decay) reductions in airflow quantities beyond the effects of entrainment. The propeller fan acts like a large single source of airflow that quickly settles into a long natural decay trend after the first intersection, with an exponential curve of best fit (R^2 = 0.997). The vane-axial fan does not experience the natural decay trend until after 79.5 m (261 ft) because of ongoing entrainment. The vane-axial fan does not act as a single source of airflow, but covers a larger area of entrainment. The propeller fan pulls air from behind the fan and only up to the first crosscut. The vane-axial fan pulls air from behind the fan and the first three crosscuts.

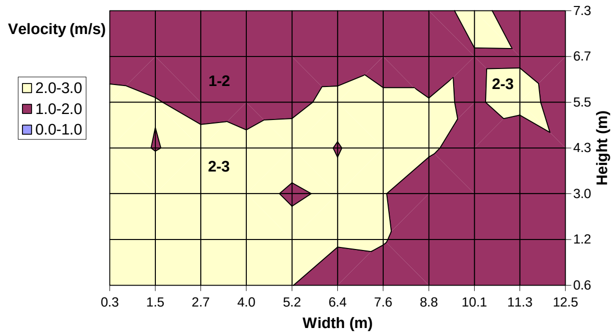

Figure 8. Vertical cross-section B of airflow 52 m (171 ft) in front of 2.44 m (8 ft) propeller fan, flow out of page.

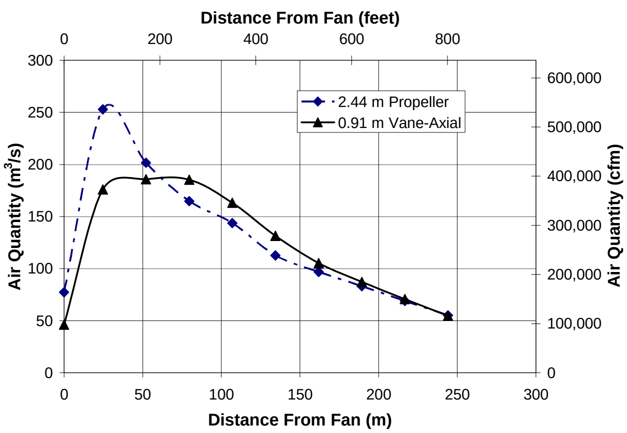

Figure 9. Airflow characteristics for free-standing vane-axial and propeller fans.

Statistical data for the velocity profiles of the cross-sections in front of the fans (Figs. 3-4 and 6-7) are given in Table 1. The level of possible entrainment is a function of the non-uniformity in the velocity profiles across the drift. A uniform distribution of velocities across the drift will not induce entrainment, but non-uniform velocity distributions can. As can be seen in Table 1, the vane-axial fan standard deviation is high, when compared to the mean velocity for both cross-sectional locations, indicating that entrainment will occur further down the drift and work against the natural decay of airflow quantities. Data from the propeller fan have a much lower standard deviation, indicating that additional airflow cannot be entrained beyond the first crosscut, as shown in Figure 9.

Table 1 Mean velocity and standard deviation of cross-sectional airflow in front of the fans.

	Vane-Axial		Propeller	
Distance to fan (m)	28	55	25	52
Mean Velocity (m/s)	1.80	1.86	2.46	1.97
Standard Deviation (m/s)	1.60	0.94	0.81	0.40
Distance to fan (ft)	92	180	81	169
Mean Velocity (ft/min)	354	366	485	388
Standard Deviation (ft/min)	315	185	158	80

2.3 *Use of large propellers fans for regional-area ventilation*

The use of propeller fans for ventilating a large regional area was investigated. One mine operator has successfully used a 3.66 m (12 ft) free-standing propeller fan for this purpose (Fig. 10). The induced airflow for the 3.66 m (12 ft) fan in this application had a similar pattern to that of the previously discussed 2.44 m (8 ft) propeller fan application, i.e. all of the air was pulled from behind the fan or from the first intersection in front of the fan. Flow rates measured in front of the fan 216 m (710 ft) down the main drift were over 250 m^3/s (530,000 cfm) (Fig. 11). After the first intersection, the airflow traveling down the main drift exhibits the same natural decay as the 2.44 m (8 ft) propeller fan.

Figure 10. 3.65 m (12 ft) propeller fan used for regional airflow studies.

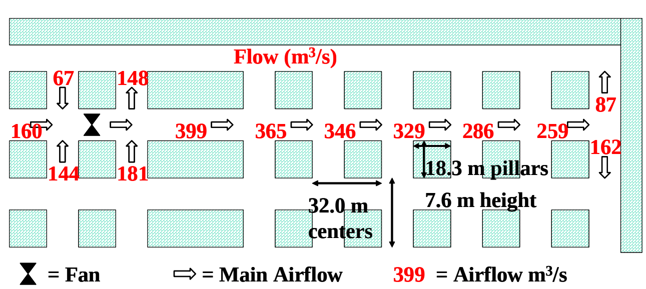

Figure 11. Regional airflow distribution for a 3.66 m (12 ft) propeller fan.

2.4 *Propeller fans used on single entry drifts*

NIOSH tested a trailer mounted, diesel powered 1.37 m (54 in) propeller fan to be used for regional and face ventilation (Fig. 12). The diesel power propeller fan performed well in inducing airflow at the last open crosscut, but performed poorly when ventilating a single-entry heading. Figure 13 demonstrates the effect that an incorrect placement of an inappropriate fan can have on ventilation efficiency. The low exit velocity of 10.0 m/s (1970 ft/min) from the propeller fan has a poor penetrating distance, which could not sufficiently remove the airborne contaminants at the mucking location located 55 m (180 ft) in front of the fan. Very little airflow mixing was observed at the intersection used for loading, and a build up of diesel contaminants soon caused a shut down of production. Based on previous USBM studies a better result would have been achieved with a vane-axial fan equipped with a reducer to create a high-speed jet airflow capable of penetrating completely into the single entry drift, as shown in Figure 3. This would have resulted in more air mixing and dilution at the loading site. Propeller fans, because of their low speed and quickly expanding airflow patterns, are poor choices for ventilating single entry drifts.

Figure 12. 1.37 m (54 in) diesel powered propeller fan used for face and regional mine ventilation.

A good application using a propeller fan to ventilate an underground crusher site was demonstrated by Chekan (2006). The low-speed, wide airflow pattern generated by the propeller fan completely engulfed the entry and pushed the dust towards the return airway drift, without disturbing the dust lying on the ground.

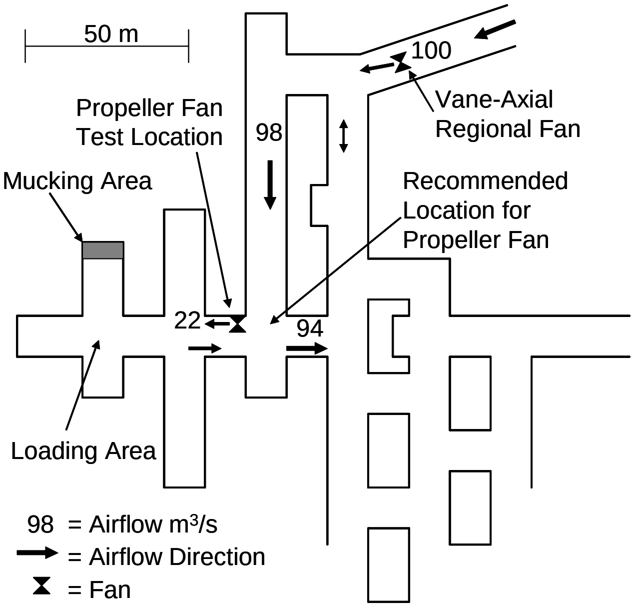

Figure 13. Test of a diesel powered propeller fan in a dead end drift, airflows in m^3/s.

2.5 *Fan placement recommendations*

Vane-axial fans should be positioned in such a way that they can entrain a maximum amount of fresh air. In some cases it is best to have the fan blowing across a fresh air stream because these fans entrain little airflow from behind the fan yet have entrainment for 90 m (300 ft) after the fan before airflow is lost from the main drift (Fig 4). Propeller fans should be located with in the fresh air stream because propeller fans entrain airflow from behind the fan and from the first crosscut after which airflow is lost from the main drift (Fig 6). The following recommendations are also important:

– Propeller fans should be situated in the fresh air stream.
– Vane-axial fans should be placed one entry behind the fresh air stream.
– Propeller fans work best in regional ventilation applications.
– Vane-axial fans work best (better penetration, greater mobility) in face and dead end ventilation applications while propeller fans are not well suited for these applications.

3 REPLACEMENT OF VANE-AXIAL MAIN MINE FANS WITH PROPELLER FANS

As main mine fans for large-opening mines (fans mounted in a bulkhead), propeller fans are the preferred choice (based on lower noise levels, capital and operating costs), so long as the pressure requirements are low [less than 185 Pa (0.75 in w.g.)]. Generally, the pressure requirements are low for large-opening drift mines with several portals. Figure 14 shows typical pressure versus flow curves for a high-resistance coal mine and a low-resistance, large-opening mine. Fan curves are shown for a high-pressure vane-axial fan and a low-pressure propeller fan. Points A and B represent the operating points for the high-pressure vane-axial fan with a high-resistance coal mine and the low resistance of a large-opening mine, respectively. Point C is the operating point for the propeller fan and the large-opening mine.

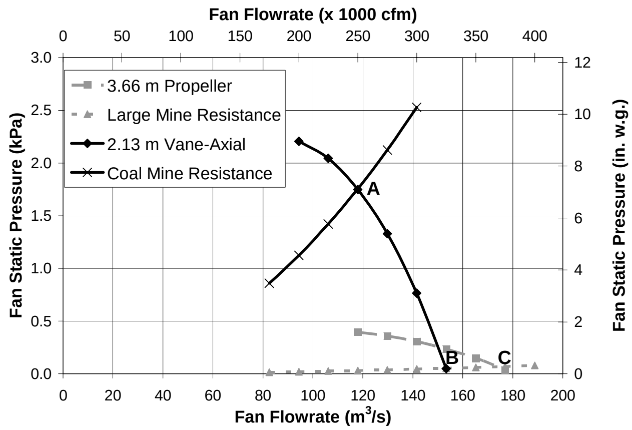

Figure 14. Pressure and quantity curves for vane-axial and propeller fans in a large opening mine.

3.1 *Case study*

A mature large-opening mine made a direct replacement of a 2.44 m (8 ft) vane-axial fan with a 3.66 m (12 ft) propeller fan for main mine ventilation. The original bulkhead mounted vane-axial fan shown in Figure 15 was operating at 119 kW (160 hp) and exhausting 127 m^3/s (270,000 cfm) of ventilation airflow. The replacement 3.66 m (12 ft) propeller fan is operating at 25 kW (34 hp) and exhausting 132 m^3/s (280,000 cfm) of ventilation airflow. Figure 16 shows a 3.66 m (12 ft) propeller fan installation. Table 2 compares the operating conditions for the two fans along with their operating costs. The replacement of the vane-axial fan with the propeller fan saves the mine about $155 per day in operating costs at $0.07/kWh, which results in a payback period of less than three months for the propeller fan purchase. The mine operates approximately 300 days a year, so the expected annual cost saving is over $47,000, an obvious economic advantage for the use of propeller fans as main mine fans in this case. The total ventilation airflow of the mine could be increased by the installation of two 3.66 m (12 ft) propeller fans operating together to exhaust 368 m^3/s (780,000 cfm) and operating at the same power cost as the original vane-axial fan, 119 kW (160 hp). This would represent an increase of approximately 190% more airflow in the mine for the same operating costs as the original vane-axial fan (Table 2).

Figure 15. 2.44 m (8 ft) vane-axial main mine fan mounted in a sheet metal bulkhead.

Table 2. Engineering comparison and cost analysis of replacing a vane-axial main mine fan with a propeller fan.

	Vane-Axial Fan	Propeller Fan	2 Propeller Fans
Diameter (m)	2.44	3.66	3.66
Diameter (ft)	8	12	12
Capital cost		$ 14,000	$ 28,000
Airflow (m^3/s)	127	132	368
Airflow (cfm)	270,000	280,000	780,000
Brake kW	119	25	119
Brake horsepower	160	34	160
Cost per kWh	$ 0.07	$ 0.07	$ 0.07
Cost per day	$ 200	$ 43	$ 200
Cost savings per day		$ 157	$ -
Airflow increase (%)		4%	189%
Payback (days)		89	
Annual cost savings*		$ 47,222	

* Assumed 300 day of operation per year

3.2 *Parallel fans*

The addition of a second parallel fan to a bulkhead of a large-opening mine will create a significant improvement over the original fan due to the little interference between the parallel fans. Placing two high-pressure fans in parallel normally causes the two fans to work against each other, reducing the individual fan's airflow quantity. However, with the low resistance of the large-opening mines, the parallel fans only have to overcome a small static pressure. The result is an almost free-flow discharge by fans operating in parallel, and the actual minor reduction in airflow quantity is within measurement errors. Further testing will be conducted to investigate the possibility of operating three or four fans in parallel. Figure 16 shows a propeller fan mounted in a steel bulkhead with room for a second fan to be installed in the future.

Figure 16. 3.66 m (12 ft) propeller fan mounded in a steel bulkhead.

4 VENTILATING A NEW MINE

NIOSH collaborated with the operators of a new, dual-portal large-opening mine to determine suitable ventilation systems during the first few years of operation. Free-standing fans were recommended to ventilate the mine initially because at the early stage of mine development, bulkheads would not be able to stand up to nearby blast pressures. The same vane-axial and propeller fans (Figs. 1 and 5) used previously to determine underground airflow patterns were used for this study. The research approach consisted of varying the location and directions of the fans, and then evaluating the resultant airflows into and out of the dual portals (Fig. 17).

Figure 17. Site one, 2.44 m (8 ft) propeller fan blowing into a dual-entry large-opening mine.

4.1 *Fans blowing into the mine*

The 2.44 m (8 ft) propeller fan (Fig. 17) was tested at three locations (Table 3) while blowing into the mine as shown in Figure 18. The experiment was repeated again using the vane-axial fan (Fig. 19) at the same three locations. Table 3 summarizes the site locations relative to the portal and the recorded airflow.

Table 3. Fans blowing into mine.

	Distance	Location	Propeller	Vane-Axial
	m		m^3/s	m^3/s
Site 1	19.2	Outside	153	80
Site 2	31.7	Outside	147	98
Site 3	25.9	Inside	134	93
	ft		cfm	cfm
Site 1	63	Outside	325,000	169,000
Site 2	104	Outside	311,000	207,000
Site 3	85	Inside	283,000	198,000

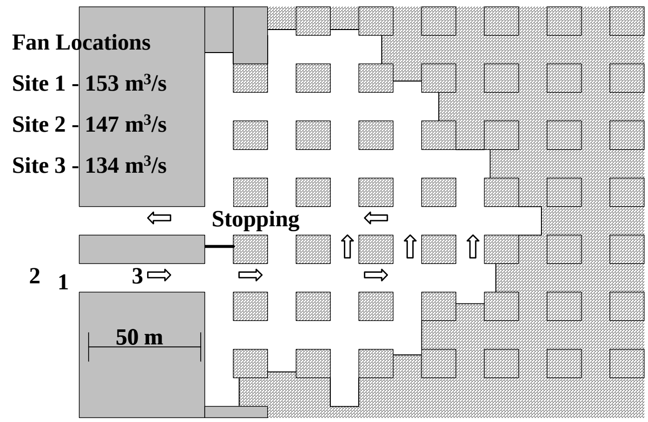

Figure 18. 2.44 m (8 ft) propeller fan blowing into the mine.

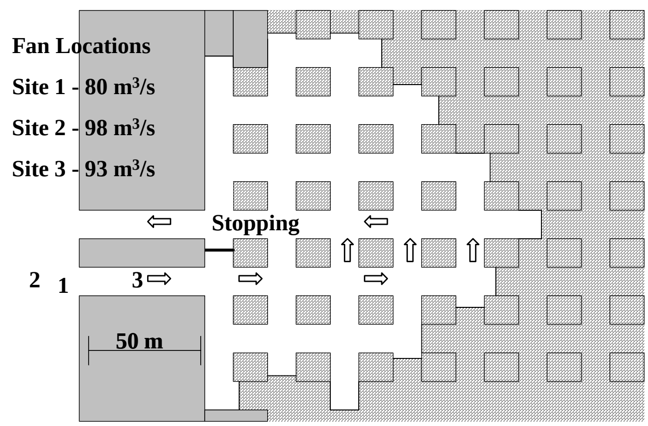

Figure 19. 0.91 m (3 ft) vane-axial fan blowing into the mine.

4.2 *Fans blowing out of the mine*

Tests were also performed with the fans exhausting from the mine, but resulted in less airflow the closer the fans were positioned to the portal entrance because of mixing and entrainment of the air. Site 3 was used again, as well as an additional location (Site 4), located 14.0 m (46 ft) inside the portal. The results for the propeller fan are shown in Figure 20 and Table 4. With the propeller fan blowing out of the mine, a maximum flow rate of 83 m^3/s (176,000 cfm) was achieved, which is much less than that measured with the same fan blowing into the mine at any of the test sites (Fig. 18).

The vane-axial fan was also tested at Sites 3 and 4 inside the mine, but the airflows were below the vane anemometer's detection limits of 19 m^3/s (40,000 cfm) at both locations. The poor performance of the vane-axial fan when used to exhaust from the mine was expected because the confined high-speed jet air stream would be outside the mine before it could expand and entrain any appreciable mine airflow.

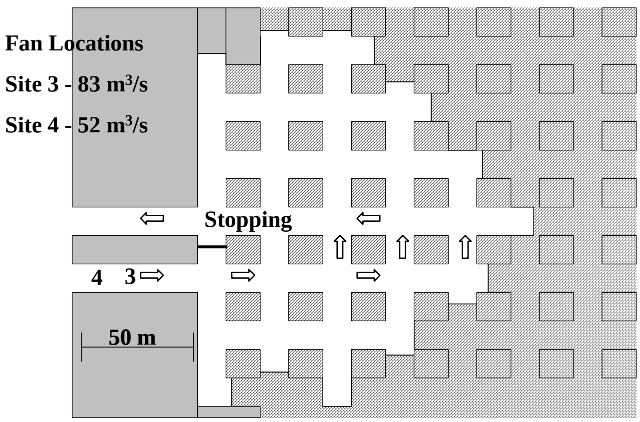

Figure 20. 2.44 m (8 ft) propeller fan blowing out of the mine.

Table 4. Fans exhausting out of mine.

	Distance m	Location	Propeller m^3/s	Vane-Axial m^3/s
Site 3	25.9	Inside	83	<19
Site 4	14.0	Inside	52	<19
	ft		cfm	cfm
Site 3	85	Inside	176,000	<40,000
Site 4	46	Inside	110,000	<40,000

5 SUMMARY

NIOSH investigated the use of propeller fans in underground large-opening mines as an alternative to vane-axial fans. Free-standing propeller fans only pull airflow from behind the fan and from a distance of 30 m (100 ft) in front of the fan (first intersection). The propeller fan acts as a large single source to push the air in one direction, followed quickly by the natural decay of the airflow.

Compared to a propeller fan, a free-standing, vane-axial fan mounted with a reducer pulls less airflow from behind the fan and from the first 30 m (100 ft), but it has a large area of entrainment and mixing for 90 m (300 ft) in front of the fan before the natural decay of the airflow occurs. Both free-standing vane-axial and propeller fans have the ability to effectively ventilate a region or to flush the working areas of a mine. However, propeller fans will have lower operating costs for the same total airflow. Propeller fans should be located in the fresh air stream, whereas vane-axial fans should be located so that they blow through the fresh air stream.

Propeller fans clearly have a large advantage when mounted in a bulkhead for applications in the low mine resistances common to large-opening multiple-portal drift mines. Improvements in airflow quantities, operating costs, and ventilation efficiency can be achieved with the replacement of high-pressure, vane-axial fans with low-pressure propeller fans, as shown in Table 2. For a new large-opening mine, the use of a propeller fan located just outby a portal and blowing into the mine generates a large and effective airflow for the mine. A vane-axial fan mounted with a reducer is far superior to a propeller fan for ventilation of a single development heading. For single-entry ventilation previous USBM work by Brechtel et al. (1985) and Dunn et al (1983) on free standing vane-axial fans is still valid, and is the preferred method.

6 DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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