An Evaluation of the Effects of Diesel Particulate Filter Systems on Air Quality and Personal Exposure of Miners at Stillwater Mine
Case Study: Production Zone

Report
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INTRODUCTION

The Metal/Nonmetal Diesel Partnership, a coalition whose membership includes, the National Institute for Occupational Safety and Health (NIOSH), the National Mining Association (NMA), MARG Diesel Coalition, the National Stone, Sand and Gravel Association (NSSGA), the United Steel Workers of America (USWA), and the Mine Safety and Health Administration (MSHA), was formed to examine, enhance, and facilitate implementation of emissions control technology that will reduce the exposure of underground miners to diesel particulate matter (DPM) and toxic gases. The first step toward fulfilling this objective was to identify controls that might be technically and economically feasible to use to curtail diesel particulate matter emissions from existing and new diesel powered vehicles in underground metal and nonmetal mines. The study of diesel particulate filters (DPFs) at the Stillwater Mine was organized under the auspices of the Metal/Nonmetal Diesel Partnership to continue the effort of identifying practical DPM control technologies.

Surveys revealed that some miners in U.S. underground mines were exposed to the highest concentrations of DPM of all occupations [McDonald et al. 1997, 68 Fed. Reg. 48668 2003]. The reasons behind such elevated DPM concentrations in certain underground mines include the confined space, the limited supply of fresh air, a large number of older engines, and the limited use of advanced emission control technology. In January 2001, MSHA promulgated rule [Fed. Reg.5706 (2001)], which set standards for total carbon (TC) concentrations in the mine air, thereby regulating the exposure of underground metal and nonmetal miners to DPM [30 CFR 57.5060]. The underground metal/nonmetal mining community has been looking for viable solutions to reduce the DPM concentration in mines to below the interim standard of 400 $\mu g/m^3$ of total carbon (TC) or the recently negotiated equivalent of 308 $\mu g/m^3$ of elemental carbon (EC) [68 Fed. Reg. 48668 2003]. Improvements in ventilation, use of cleaner diesel engines, emissions-based diesel engine maintenance, and the implementation of various diesel emission control technologies, including DPF systems and reformulated fuels, are believed to be the methods with the greatest potential to achieve these reductions.

Both laboratory evaluations [Mayer et al. 1999, Larsen et al. 1999] and long-term and short-term underground mine tests [Watts et al. 1995, McGinn 2001, Bugarski and Schnakenberg 2001, Bugarski and Schnakenberg 2002, Bugarski et al. 2002] showed that DPF systems have the greatest potential of all methods available to underground mining industry for radical reduction of exposure of miners to DPM. Watts et al. [1995] reported significant reductions in DPM concentrations in two underground mines where vehicles equipped with DPF systems were operated. Similar reductions were found in two other studies conducted at Noranda's Bathurst Mining and Smelting Mine [McGinn, 2001, Bugarski and Schnakenberg 2001] and International Nickel Company's Stobie Mine [Bugarski and Schnakenberg 2002] as well as in the isolated zone study conducted recently at Stillwater Mine [Bugarski et al.2003]. It should be noted that the efficiencies for the DPF systems achieved in the mining studies did not always agree with the efficiencies reported in the laboratory studies. These studies also demonstrated that considerable effort is needed to select and optimize DPF systems for individual underground mining applications.

The Stillwater Mine study was designed and executed in two phases. In Phase I of the study, the potential of DPF systems and biodiesel blends to reduce DPM emissions from selected production vehicles was examined through tests conducted in an isolated zone and tailpipe emissions measurements. The isolated zone tests showed that the two used and one new DPF system reduced ambient EC concentrations by 88, 96 and 99%, respectively [Bugarski et al. 2003]. The same systems reduced ambient total particulate matter (TPM) concentrations by 74, 75 and 89%, respectively. The difference between the observed changes in ambient EC and TPM concentrations confirm that the laboratory determination of DPF efficiencies, based on reductions in total DPM mass (fairly equivalent to TPM), substantially underestimates the ability of DPF systems to reduce EC emissions, the metric used by MSHA for compliance. These tests also showed a 26% and 48% reduction in ambient EC concentration when No. 2 diesel fuel was substituted with 20% (B20) and 50% (B50) biodiesel blends, respectively. Another finding of interest from the Phase I study and of significant concern was that the tested DPF systems and diesel oxidation catalyst (DOC) increased ambient NO_2 concentrations; increases between 180% and 270% were found for the DPFs and 26% for the DOC. Each DPF system and the DOC were washcoated with platinum-based catalysts. None of the alternative fuels showed a statistically significant effect on NO_2.

The objective of Phase II of this study was to determine the effects of those DPF systems being used on production vehicles at Stillwater Mine on workplace concentrations of EC and regulated gases in an actual mining application where multiple diesel-powered vehicles operated simultaneously during full-shift mining activities. The effects of the DPF systems were examined by comparing ambient concentrations of EC, carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), and nitrogen dioxide (NO_2) in the production area for two different tests conditions: For the baseline condition, all vehicles that operated within the ventilation split were equipped with standard exhaust systems – a DOC and muffler. For the second condition, three of the vehicles, an LHD and two haulage trucks had their DOC-muffler systems replaced with DPF systems. These three vehicles were selected because a preliminary analysis identified them as major sources of DPM. In addition, based upon engine size and duty cycles during production, Stillwater mine, as part of their own research, had retrofitted those or similar vehicles with passively regenerating DPF systems. This report describes the experimental procedure and results for Phase II of the study.

Due to the nature of the study, Phase II did not address other and no less important matters related to implementation of DPM control technologies in underground mines. These matters include selection of DPF regeneration strategies, economic, logistical, and technical feasibility of implementation of various DPF systems on mining vehicles, and the reliability and durability of the systems in mine settings. Addressing those matters would require a different and more comprehensive type of feasibility study yet to be performed.

EXPERIMENTAL PROCEDURE

Test Methodology

The primary objective of this study was to quantify the effects of the selected DPF systems on the ambient concentrations of elemental carbon and selected gases in an actual mine setting for a production cycle. The systems, all passively regenerating DPFs, were being studied by the mine as possibly the only potentially feasible way, from those then available, to reduce DPM emissions. Those vehicles used by the mine and considered by the mine to be suitable for the use of passive DPFs represent a small fraction of the mine's fleet of diesel-powered equipment.

Figure 1 shows the section of the Stillwater Nye mine that was selected as the test zone. This section is located in the west side of the ventilation split on 3500 level (3500W). The elevation of the mine portal is 1525 m (5003 ft) above sea level and the elevation of 3500W is approximately 1067 m (3500 ft) above sea level. 3500W is ventilated with fresh air from the 3200 level. The two raises situated at 1250 m (4100 ft) and 1890 m (6200 ft) to the west of the 3500 split are used to exhaust the contaminated air from 3500W. An orepass is situated off the main drift approximately 215 m (705 ft) west of the split. The average cross-sectional dimensions of the opening in the main drift are approximately 3.6 m (12 ft) high by 3 m (9.8 ft) wide. The drift is in a horizontal plane. At the time of the tests, ore was mined from seven active stopes located between approximately 200 m (656 ft) and 2100 m (6890 ft) west of the 3500 split. In addition, development work was being conducted approximately 2400 m (7874 ft) west of the 3500 split.

Diesel-powered equipment, primarily LHDs and haulage trucks, were extensively used in the process of ore extraction and transport. In a typical operation, ore was transported from the heading to a stope muck bay with a MTI LT 270 LHD or a MTI LT 350 LHD (Mining Technologies International, Sudbury, Ontario). At the stope muck bay, a single loader, either a CAT R1300 LHD (Caterpillar Elphinstone PTY LTD, Burnie, Tasmania, Australia), loaded ore into one of the two haulage trucks, either the MTI DT-1604 or the Tamrock EJC515 (Sandvik Tamrock, Sandviken, Sweden). It typically required two LHD buckets to fully load a haul truck. Once loaded, the haul truck transported the ore or waste rock to the orepass located approximately 200 m (656 ft) west of the 3500 split. The waste rock from the development work was managed with a development LHD, usually a CAT R1300. The same LHD and two haul trucks used to transport ore from the stopes were used to load and haul the rock from the development muck bay to the orepass.

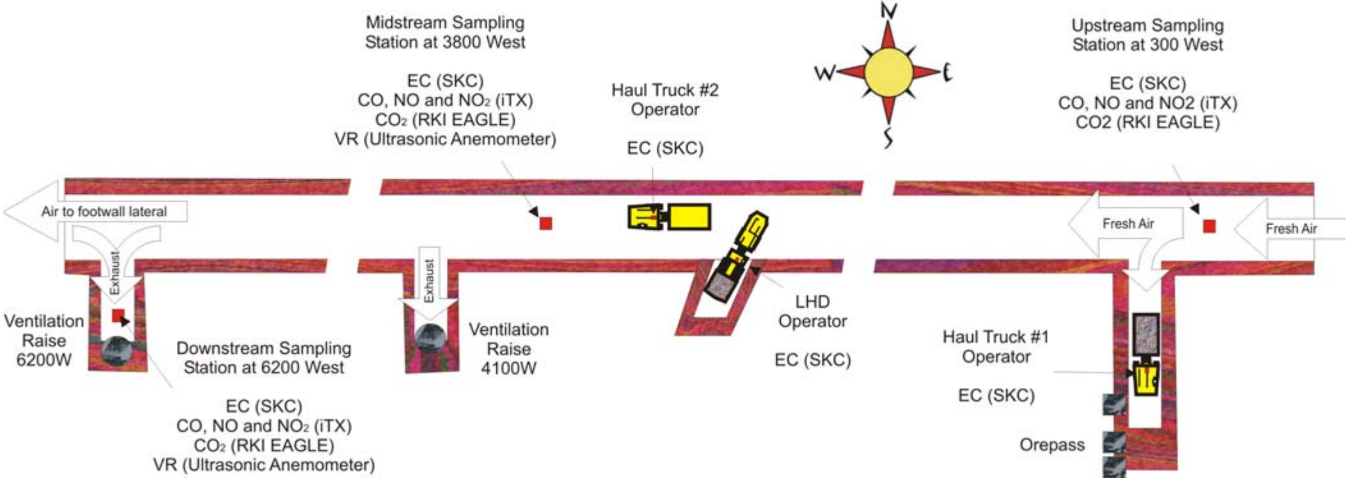

Figure 1. Schematic of the test zone (not to scale)

The vehicles selected as target vehicles for this study were identified as the major contributors to concentrations of DPM and toxic gases in mine air for several reasons including, the size and type of their engines, the type of duty cycle they perform, and the number of operating hours. Due to their size and nature of their duty cycles, those vehicles were also found to be the most suitable for DPF retrofit program of all vehicles available in the mine fleet.

It is important to note that during all four tests, a significant number of other diesel-powered vehicles, besides the aforementioned LHD and two haulage trucks, operated in the test zone on an intermittent basis. Multiple LHDs were used in the stopes and in the development section along with various light-duty vehicles used as personal and supply carriers and by maintenance crews. A road grader was also intermittently used in the test zone. Since the study objective was to evaluate effects of tested DPFs in a typical production setting, this incidental and variable traffic was not limited in any way during the tests. The heavy traffic in the test zone made it impossible to record all the instances during which diesel engines operated therein. However, because of the direct relationship between the amount of fuel consumed and the carbon dioxide concentration, carbon dioxide concentrations were measured at all area sampling locations and used to compensate for day-to-day variability in the usage of diesel-powered equipment.

The study took place from Monday, September 8th through Friday, September 12th, 2003 (Table 1). The initial plan was to conduct a total of six tests, three with the target vehicles equipped with DPF systems and three with the same vehicles equipped with the mine-standard DOCs and mufflers. However, due to the early curtailment of two DPF tests because of high ambient concentrations of nitrogen dioxide encountered by the vehicle operator and technical problems with truck #92133 on Wednesday, September 10th, only four tests were conducted. For three of these tests, the targeted vehicles were equipped with DPF systems while the rest of the vehicles, which operated in the zone on a continuous or intermittent basis, were each equipped with DOCs and mufflers. The fourth test was conducted with all of the vehicles, including the selected LHD and two haulage trucks, equipped with the mine-standard exhaust system consisting of a DOC and muffler.

Table 1. Test matrix

Test# (Date)	Test Type	Vehicle Type	Vehicle #	Aftertreatment System Type	Aftertreatment System Model	Bacharach Smoke Number (0-9)	Operator
1 (September 8)	DPFs	LHD	#92535	DPF	DCL MineX 5223-SA	0	Ed
		Truck 1	#92133	DPF	Engelhard DPX 9308	3.5	Brandon
		Truck 2	#92136	DOC*	Engelhard DOC*	>7	Cliff
2 (September 9)	DPFs	LHD	#92535	DPF	DCL MineX 5223-SA	0	Ed
		Truck 1	#92133	DPF	Engelhard DPX 9308	>3.5	Brandon
		Truck 2	#92139	DPF	Engelhard DPX 9308	>4.5	Jeff
3 (September 11)	DPFs	LHD	#92535	DPF	DCL MineX 5223-SA	0	Ed
		Truck 1	#92133	DPF	Engelhard DPX 9308	3.5	Chad
		Truck 2	#92135	DPF	Engelhard DPX 9308	3	Jeff
4 (September 12)	DOCs	LHD	#92535	DOC	DCL MineX 3206 MD	N/A	Lorry
		Truck 1	#92133	DOC	DCL MineX 3206 MD	N/A	Mike
		Truck 2	#92135	DOC	DCL MineX 3206 MD	N/A	Troy

* The haulage truck #92136 was initially believed to be equipped with Engelhard DPX®, a DPF.

Vehicles and control technologies

Due to technical problems and availability of the vehicles, four haulage trucks were used during this study. Vehicle #92133 was available for all four tests, #92135 for two tests, and #92136 and #92139 were used in one test each. Trucks #92133, #92135, #92136 were MTI Model DT-1604. Each has a box capacity of 8.2 m^3 (10.8 yd^3) with a rated load capacity of 14545 kg (32000 lb). They are powered by Deutz BF6M1013 FC engines. The truck #92139 was a Tamrock EJC515. This truck has a rated load capacity of 15000 kg (33070 lb) and was powered by a Deutz BF6M1013EC engine.

A single LHD, vehicle #92535, a Caterpillar Elphinstone Motel R 1300, was used in all four tests. It has a rated load of 6500 kg (14333 lb) and has a bucket capacity of 2.8 m^3 (3.7 yd^3). This particular vehicle is powered by a Caterpillar CAT 3306 DITA engine rated at 123 KW (165 HP). Unlike the Deutz engines, the Caterpillar engines do not capture emissions from crankcase ventilation/exhaust blow-by. It is important to note that those emissions contribute DPM to the mine air.

An Engelhard DPX® (Engelhard Corporation, Iselin, New Jersey) DPF system was installed on three tested haulage trucks, #92133, #92135, and #92139. Those systems had accumulated 1024, 0, and 171 hours in production prior to the study, respectively. The haulage truck #92136 was initially believed to be equipped with Engelhard DPX®. After the tailpipe emissions measurements and field tests indicated unusually low efficiency of the aftertreatment device installed on the vehicle, mine personnel found that #92136 was actually equipped with DOC. After that discovery truck #92136 was replaced with truck #92139. A DCL MineX Sootfilter® DPF system (DCL International, Concord, Ontario) was installed on LHD #92535 shortly before the study.

Both types of DPF systems tested in this study are passively regenerated systems designed around a Corning cordierite wall-flow monolith filter element washcoated with proprietary platinum-based catalysts. In general, the platinum-based catalysts are applied to DPF element to lower combustion temperature of the soot trapped within the filter and help regeneration of DPF. The platinum-based catalysts were also known to enhance the oxidation of CO and hydrocarbons to CO_2 and the oxidation of NO to NO_2. While from the perspective of controlling exposure of underground miners to toxic gases the two former processes are seen as desirable, the conversion of NO to NO_2 adversely affects air quality.

The other DPF systems evaluated in the Phase I of this study [Bugarski et al. 2003 and Bugarski et al. 2004] including passive systems from CleanAir Systems and ECS, active systems from DCL and system using disposable filter elements from Donaldson were not available for Phase II evaluation.

Smoke samples were collected from the tailpipes downstream of the DPF for each of the target vehicles using the True Spot® Smoke Test Kit (Bacharach, Inc., 621 Hunt Valley Circle, New Kensington, Pennsylvania). The smoke number was determined by comparing the soot spot to a supplied scale in which white is a 0 and black is a 9. Smoke number samples were taken while the vehicle/engine was operated at torque converter stall conditions. These results were used as a quick way to verify the filtration performance of the DPF systems used in each test. A smoke number of 0 for the nearly new DCL DPF system (see Table 1) indicated that this system was efficiently removing DPM and EC from the exhaust of LHD #92535. The relatively high smoke numbers (above 3) observed for the samples collected downstream of the Engelhard DPF systems installed on vehicles #92133 and #92139 indicated that these used systems were providing significantly lower reductions in DPM concentrations than the brand new DCL unit (see Table 1). Those filters did not satisfy previously established criteria[1] on efficiency of DPF systems to be included in the study. In an attempt to find a vehicle with the DPF systems that satisfy the criteria, vehicle #92139, used during second test, was replaced in the third test by an alternate haulage truck #92135 which was equipped with a similar DPF system. The smoke number measured after the test downstream of the DPF on #92135 was about 3, indicating that this DPF system also did not satisfy criteria. The DPF system on vehicle #92133 was replaced before the third test with another similar DPF system, but downstream smoke number measurements showed only slight increase in efficiency. The DPF systems on #92535, #92133, and #92135 were replaced before the fourth test with DCL MineX DOCs and mufflers.

Therefore, when interpreting the test results one should take into consideration the actual condition of the tested DPF systems. However, efficiency of DPF systems encountered in this study might be representative of the in-use DPF systems that have accumulated some time in underground mining operation.

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[1] Uncompromised (used or new) DPFs using a Corning Cordierite element typically exhibit smoke numbers below 1.

Fuel

Stillwater Mine uses No. 1 diesel fuel supplied by local refinery (Cenex, Columbus, Montana) for its entire underground fleet. The basic properties of that fuel are presented in Table 2. This diesel fuel surpasses MSHA requirements (30 CFR 57. 5065, 1995) for diesel fuels used in underground mines and was used by the mine to reduce exposure of underground miners to diesel emissions.

Table 2. Properties of the fuel used in this study

Type of analysis	Method	Units	Cenex No. 1 diesel
1	2	3	4
Cetane Number	ASTM D613	N/A	42.8
Density	ASTM D4052	g/ml	0.8
Sulfur Content	ASTM D5453	ppm	125.0
Flash Point	ASTM D93	°C	57.2

Equipment and instrumentation

Three area sampling stations were established for the 3500W test zone. On the first day of testing, the midstream and downstream stations were established at approximately 900 m (2952 ft) and 1500 m (4921 ft) west of the 3500 split. These sampling locations were later found to be inappropriate, since they were inside the internal ventilation circuits of two active stopes. Therefore, the results of this test were compromised and will not be discussed further in this report. On the remainder of the test days the area sampling stations were established in more appropriate locations (see Table 3 and Figure 1). By convention, sampling stations and other features such as ventilation raises are identified by their distance in feet west of the 3500 split. The upstream sampling station (300W) was situated approximately 90 m (295 ft) from the 3500 split. The midstream sampling station (3900W) was located in the main drift approximately 90 m (295 ft) upstream of the 4100W raise and approximately 1190 m (3904 ft) downstream of the 3500 split. Both of these stations were positioned in the upper third of the drift, above and out of the way of passing vehicles. The downstream sampling station (see Figure 2) was located in the center of the 60 m (197 ft) long stope connecting the main drift with 6200W raise.

Table 3. Sampling stations

Area Sampling Station	Distance Relative to 3500 Split [m (ft)]	Cross Sectional Area [m^2 (ft^2)]
300W	90 (295)	11.87 (127.8)
3900W	1190 (3904)	11.54 (124.2)
6200W	1900 (6234)	12.64 (136.1)

Personal elemental carbon exposure samples were obtained for each of the three operators from the muck haulage team.

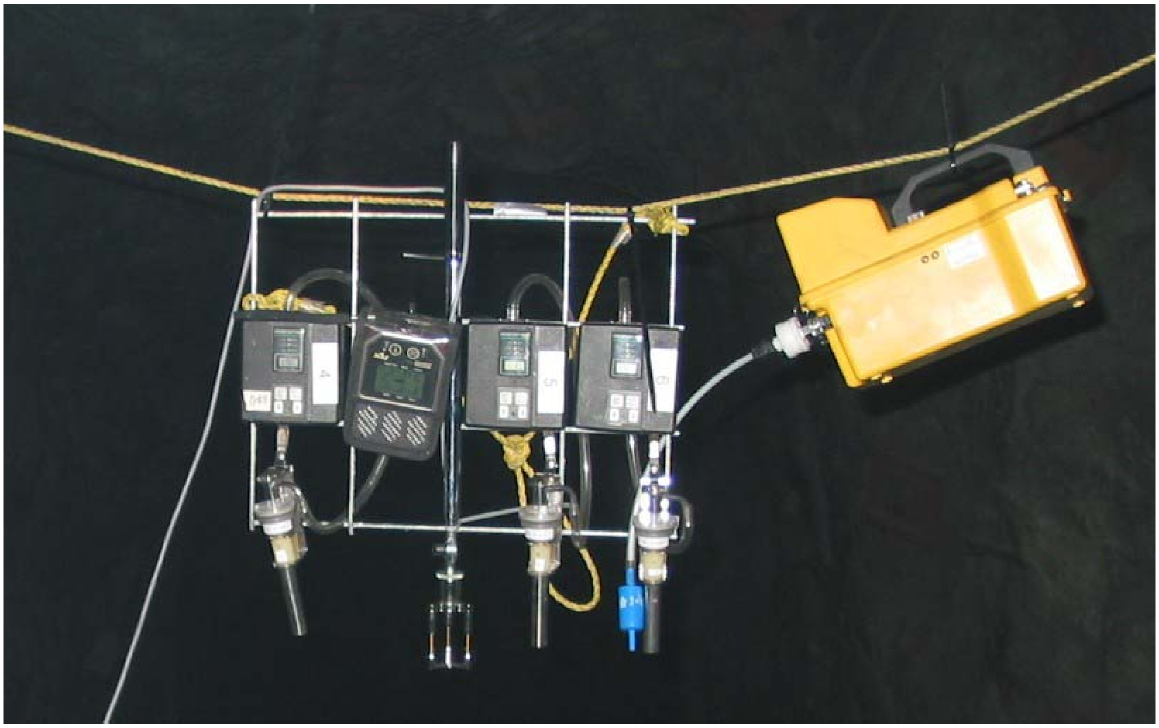

Figure 2. Downstream sampling station consisting of three compliance samplers for EC, an iTX gas monitor, anemometer head, and the RKI (yellow box) sample inlet fastened to a wire grid

Elemental carbon sampling and analysis

Area samples for elemental carbon were collected in triplicate at each sampling station for the duration of each test. In addition, one personal sample was collected from the breathing zone of each of the three operators from the muck haulage teams. The sampling train used for area and personal sampling was similar to the one used by Mine Safety and Health Administration (MSHA) for DPM compliance monitoring [66 Fed. Reg. 5706 and corrections 66 Fed. Reg. 35518 2001]. It consisted of a flow controlled MSA Elf Model pump (Mine Safety Appliances Company, Pittsburgh, Pennsylvania), a 10 mm Dorr-Oliver cyclone, and an SKC DPM cassette (SKC, Inc., Eighty Four, Pennsylvania). The SKC DPM cassette contained a single stage impactor and two stacked 37 mm quartz fiber filters. The pumps were operated at 1.7 l/min and were calibrated at the mine at the beginning of the study. The flow rate for each of the sampling pumps was measured and recorded before and after each sampling event using a Gillibrator II bubble flow meter (Sensidyne, Clearwater, Florida). If the measured flow rates deviated by more than 5 percent from 1.7 l/min the pumps were recalibrated.

The time at which each sampling pump was started and stopped were noted. The duration of sampling period was used in the calculation for determining elemental carbon concentrations from the SKC DPM cassettes. The actual start and stop times for sampling at the area stations for each test were used in determining of the average gaseous concentration and ventilation rate for that test and sampling location from the logged data (see below).

Exposed SKC DPM cassettes were shipped to NIOSH PRL and analyzed by the NIOSH PRL analytical laboratory for elemental carbon content using the NIOSH 5040 Analytical Method [NIOSH 1999, Birch and Cary 1996]. The elemental carbon concentration at a sampling station for a test was the average of the concentrations of the three samples obtained at that station and test. In addition, the coefficient of variation (CV), the standard deviation expressed as a percentage of the average, was calculated for each of the triplicate samples. Each average EC concentration was then normalized with respect to its respective average CO2 concentration for that sample location and test to account for variations in vehicle activity (fuel burned).

Concentrations of CO, CO_2, NO, and NO_2

The ambient concentrations of CO, NO, and NO_2 were measured at all three sampling locations using iTX multi-gas monitors (Industrial Scientific, Oakdale, Pennsylvania) (see Figure 2). One iTX multi-gas monitor was dedicated to each of the three sampling locations for the duration of this study. The ambient concentrations were measured every 10 seconds and stored in the monitor’s memory. The logged data was downloaded to a spreadsheet and averaged over the sampling period of the area samples for elemental carbon. The instruments were calibrated at the site each day, prior to sampling.

The ambient concentrations of CO_2 were measured at all three sampling locations using RKI Eagle CO_2 monitors (RKI Instruments Inc., Hayward, California) (see Figure 2). The ambient concentrations were logged every 10 seconds and stored in the monitor’s memory, downloaded to a spreadsheet, and averaged over the sampling period. These instruments were calibrated at NIOSH PRL and the field results were corrected for the air pressure at the elevation of sampling. The average carbon dioxide concentrations for each sampling location were used to normalize the corresponding elemental carbon concentrations.

Ventilation rates

Air velocities in the test zone were measured continuously at the midstream and downstream sampling station using an Anemosonic UA6 digital ultrasonic anemometer (Airflow Developments Limited, High Wycombe, England). The sensing head of the anemometer was attached to the sampling grid and oriented to the flow (see Figure 2). The output from the anemometer was logged in 10-second averages using a MiniLogger portable data logging system (Logic Beach, La Mesa, California). The data was downloaded to a spreadsheet and was multiplied by the corresponding cross sectional area for the sampling station to obtain an estimate of the ventilation rate at that station. The average ventilation rates during the tests were determined by averaging the data over the sampling period.

The air velocities were also measured on September 9th (test day 2) and tenth by a mine ventilation engineer, at the midstream (3900W) and slightly upstream (6000W) of the downstream (6200W) locations, using a vane anemometer and the full cross sectional traverse method. The ventilation rates were estimated by multiplying the average air speeds by the cross sectional areas determined for the corresponding sampling stations. The air velocities were not measured by traverse on the other test days.

Vehicle emissions

In the afternoon of the third day (09/11/2003) of the study, maintenance personnel from Stillwater Nye mine measured tailpipe emissions of oxygen (O_2), CO, NO, and NO_2 upstream and downstream of the DPF systems and downstream of DOC systems installed on the vehicles #92133, #92135, and #92535. The emissions were measured while the vehicles were parked in maintenance area of the surface shop at Stillwater Nye mine.

An Enerac 400 Micro-Emission Monitoring System (EMS) was used for real-time measurements of emissions generated while the tested vehicles were operated over transient cycle consisting of four steady-state operating conditions performed in the following sequence: low idle (LI), high idle (HI), torque converter stall (TCS), and low idle (LI). Each of the tests cycles was preceded by warm-up session.

The Enerac 400 EMS uses electrochemical sensors to directly measure concentrations of O_2, CO, NO and NO_2. The emissions of CO_2 and NO_x were calculated from the measured values.

ECOM Model KL portable emissions analyzer (ECOM America, Norcross, Georgia) was used to sample DPM using the Bacharach smoke number. The numbers were determined by comparing samples to spots on the gray scale chart (0-9) supplied by ECOM America.

RESULTS AND DISCUSSION

The midstream and downstream sampling locations (2952W and 4921W respectively) used during the test conducted on the first day of the study were found to be inadequate since they were within the ventilation circuits of the two active stopes. Therefore, the results of this test were compromised and they will not be discussed further in this report.

Ventilation rates

The average prevailing ventilation rate, calculated from the velocity measurements obtained using the ultrasonic anemometers at the midstream (3900W) and downstream (6200W) sampling station for each of the test runs, are presented in Table 4.

Table 4. Ventilation rates estimated from ultrasonic anemometer measurements

Test # (Date)	Sampling Location	Average Velocity [m/s]	Average Velocity [ft/min]	Area [m^2]	Area [ft^2]	Average VR [m^3/sec]	Average VR [ft^3/min]
2 (September 9)	3900W	2.53	497.20	11.54	124.20	29.14	61752
	6200W	1.84	362.59	12.64	136.10	23.29	49349
3 (September 11)	3900W	2.47	485.49	11.54	124.20	28.46	60298
	6200W	4.99	981.97	12.64	136.10	63.07	133646
4 (September 12)	3900W	2.22	436.22	11.54	124.20	25.57	54178
	6200W	4.56	898.54	12.64	136.10	57.71	122291

The average prevailing ventilation rates, calculated from the velocity measurements obtained, using a vane anemometer and the full cross sectional traverse method on September 9th and 10th, are presented in Table 5.

Table 5. Ventilation rates estimated from vane anemometer measurements

Test # (Date)	Sampling Location	Average Velocity [m/s]	Average Velocity [ft/min]	Area [m^2]	Area [ft^2]	Average VR [m^3/sec]	Average VR [ft^3/min]
2 (September 9)	3900W	3.05	601.00	11.54	124.20	35.23	74644
	6000W	1.44	283.00	12.64	136.10	18.18	38516
N/A* (September 10)	3900W	3.32	654.00	11.54	124.20	38.33	81227
	6000W	1.64	323.00	12.64	136.10	20.75	43960

*Test was not conducted on this day

It is important to note that the results of the measurements with these two methods obtained during test #2 on September 9th generally agreed. The differences can be attributed to the spatial and temporal fluctuations of the air velocities (see Figure 3 and letter by Jason Todd attached to this document) and different sampling locations. Unfortunately, the vane anemometer ventilation measurements were not available for the last two days of testing. They could have been used to verify the change in the ventilation rates observed for tests three and four. According to mine ventilation engineer (see attached letter from Jason Todd) the air speeds observed with ultrasonic anemometer measurements during these tests are "not possible without disrupting the entire off shaft west ventilation system."

Figure 3, Figure 4, and Figure 5 show the ventilation changes observed. Figure 3 shows the real-time ventilation rate for test #2 on September 10th when the traverse with the vane anemometer was also done. The midstream ultrasonic anemometer speeds are represented by the upper trace. Figure 4 and Figure 5 show greatly elevated air speeds at the downstream sampling location indicating an additional air source between the midstream and downstream sampling stations.

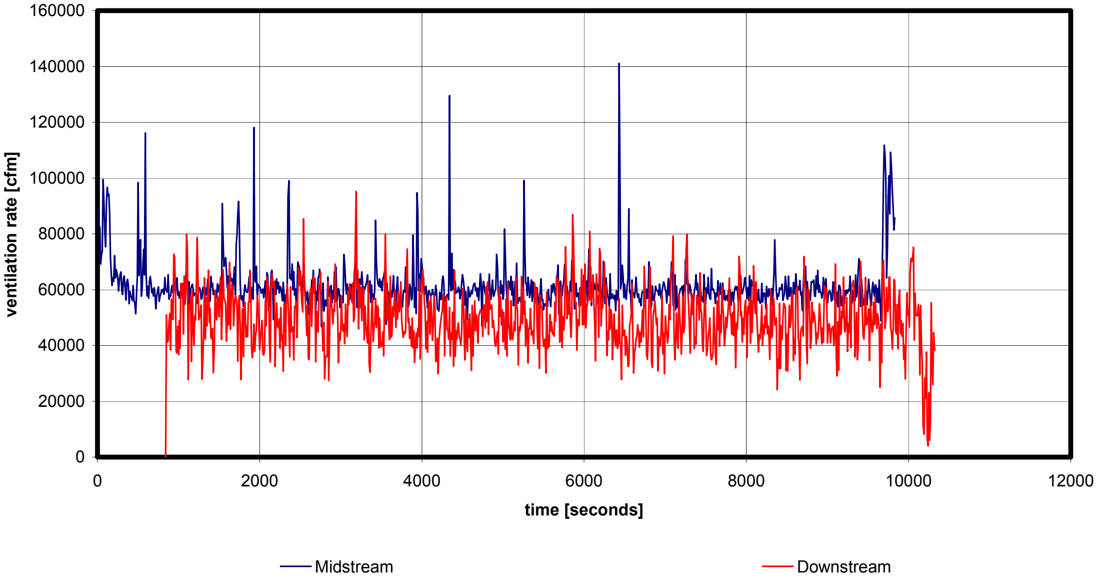

Figure 3. Instantaneous ventilation rates estimated from the ultrasonic anemometer measurements for test #2

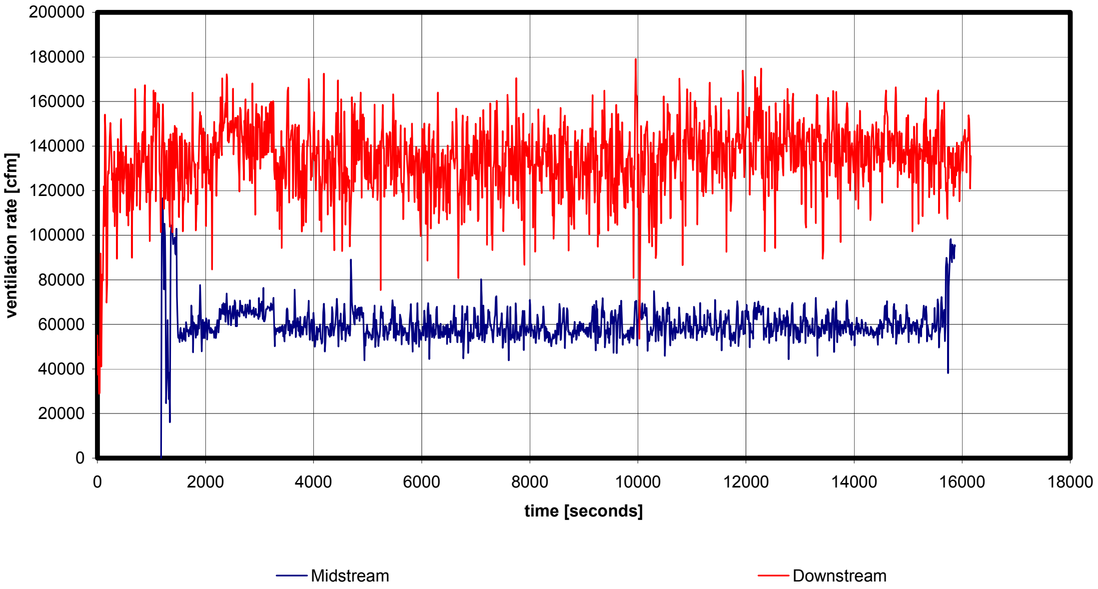

Figure 4. Instantaneous ventilation rates estimated from ultrasonic anemometer measurements for test #3

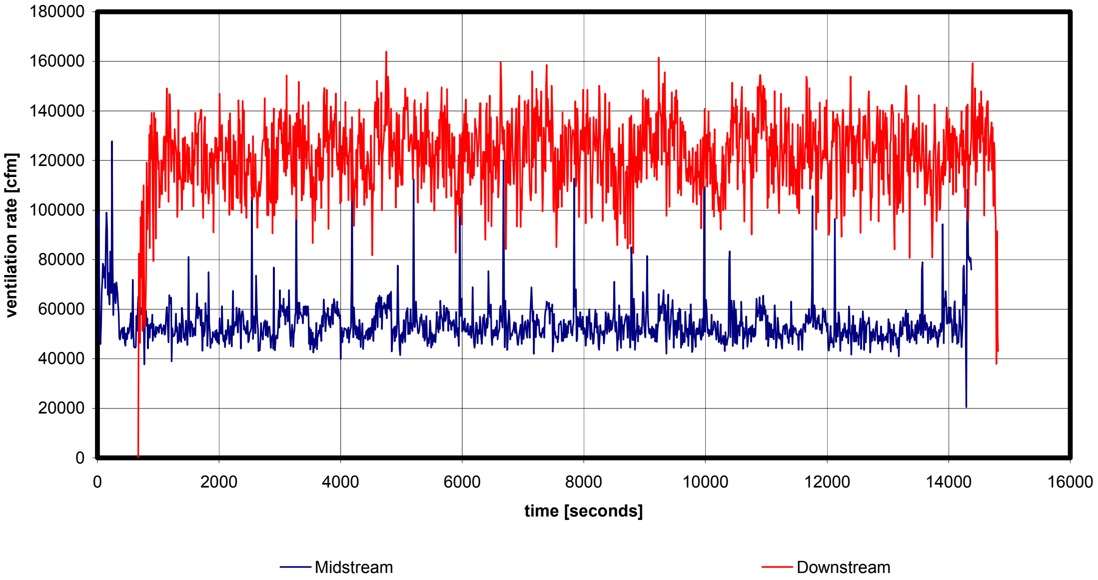

Figure 5. Instantaneous ventilation rates estimated from ultrasonic anemometer measurements for test #4

Concentrations of CO_2

The results of the continuous measurements of CO_2 concentrations are shown in Figure 6 through Figure 8. These concentrations illustrate the differences in production cycles among three test days. The high concentrations of CO_2 observed at the midstream station and the relatively constant concentrations at the downstream station for test #3 reflects the fact that the mucking crew was working exclusively east (upstream) of the midstream station (Figure 7). In contrast, during test #4 significantly higher concentrations of CO_2 were observed at the downstream station than at the midstream station (Figure 8). That, and the large number of peaks at both the midstream and downstream stations, reflect the fact that the mucking crew spent most of the time moving muck from the development section, west of the 6200W, to the orepass (near 300W), passing by both the downstream and midstream sampling stations in the process.

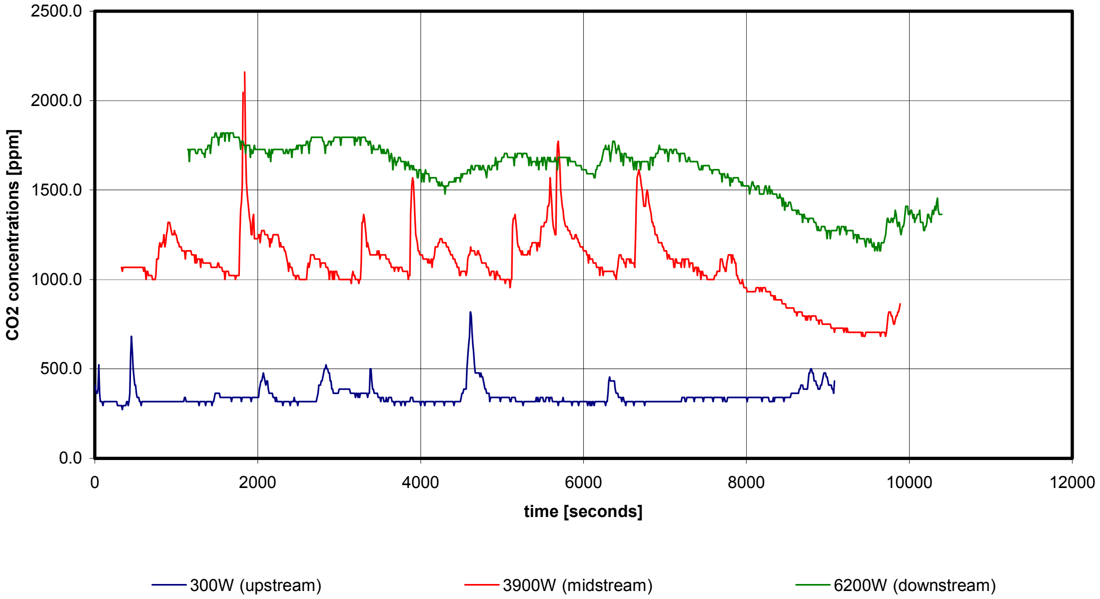

Figure 6. Concentrations of CO_2 observed during test #2

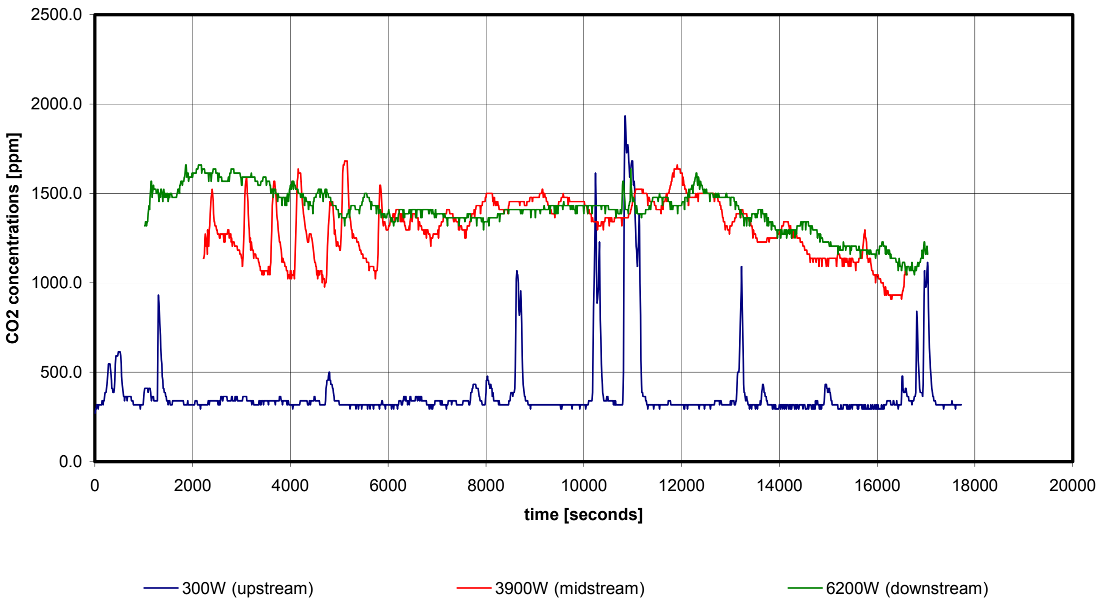

Figure 7. Concentrations of CO_2 observed during test #3

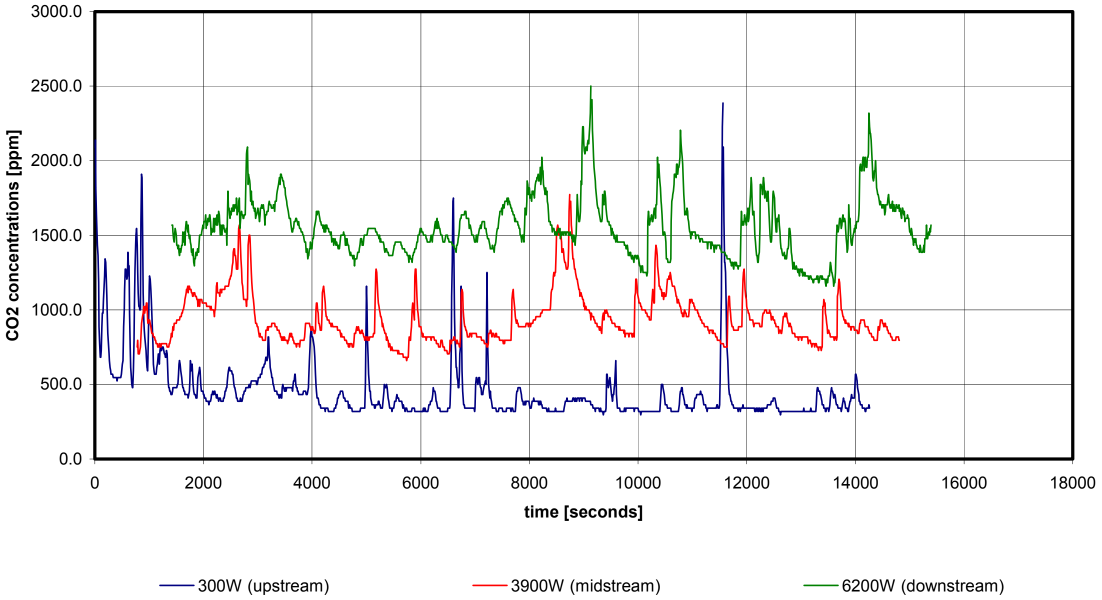

Figure 8. Concentrations of CO_2 observed during test #4

The average and peak concentrations of CO_2 observed during tests #2, #3, and #4 are shown in Table 6. The average values were used to normalize elemental carbon concentrations to the vehicle activity (fuel consumed) upstream of each sampling location. The normalization with respect to the CO_2 concentrations minimizes the effects of the duty cycle and ventilation rates on the results for EC and the other measured pollutants. The normalized data should be exclusively used for comparing the effects of the control technologies.

Table 6. Average and maximum CO_2 concentrations

Test # (Control Systems)	Sampling Location	Average CO_2 Concentration [ppm]	Maximum CO_2 Concentration [ppm]
2 (DPFs)	300W	347	818
	3900W	1073	2160
	6200W	1593	1819
3 (DPFs)	300W	381	1700
	3900W	1312	1480
	6200W	1405	1460
4 (DOCs)	300W	461	2100
	3900W	932	1560
	6200W	1554	2200

Concentrations of elemental carbon (EC)

The EC concentrations measured during this study are summarized in Table 7. The average values were calculated from the triplicate samples collected at each sampling station. The relatively low coefficients of variation indicate a consistency in the sampling and analytical procedures.

The results show relatively low concentrations of the EC at the upstream sampling station (ventilation air supplied from 3200 level) during the tests. The EC concentrations at the midstream and downstream sampling stations were found to be lower during the tests when the three targeted vehicles were equipped with DPF systems than when they were equipped with DOCs plus mufflers (Table 7). However, the ambient concentrations of EC at downstream sampling locations were higher than 308 $\mu g/m^3$ in both cases when three test vehicles were equipped with DPF systems. These results may have been influenced by the fact that two of the DPF systems were not performing up to nominal specifications (smoke number 0 to 1) for such systems, as indicated by a tailpipe smoke number greater than three and by the presence of other diesel equipment operating in the area.

Table 7. Results of elemental carbon analysis performed on the area samples

Test # (Control Systems)	Sampling Location	SKC Sample #	EC [$\mu g/m^3$]	Average EC [$\mu g/m^3$]	Coefficient of Variation (STD/AVG) [%]	Average CO_2 Concentrations [ppm]	Average Normalized EC [(ng/m^3 of EC)/(ppm of CO_2)]
2 (DPFs)	300W	0015957	22	22	6.0%	347	64.1
	300W	0015946	24				
	300W	0015951	21				
	3900W	0015945	226	225	6.7%	1073	210.0
	3900W	0016005	240				
	3900W	0015981	210				
	6200W	0016019	400	387	4.7%	1593	242.8
	6200W	0016028	366				

Test # (Control Systems)	Sampling Location	SKC Sample #	EC [µg/m^3]	Average EC [µg/m^3]	Coefficient of Variation (STD/AVG) [%]	Average CO_2 Concentrations [ppm]	Average Normalized EC [(ng/m^3 of EC)/(ppm of CO_2)]
	6200W	0016022	394				
3 (DPFs)	300W	0015965	33	34	5.2%	381	88.3
	300W	0016017	36				
	300W	0016027	32				
	3900W	0016023	228	218	7.6%	1312	165.8
	3900W	0016008	198				
	3900W	0015971	226				
	6200W	0015995	360	358	0.9%	1405	254.8
	6200W	0016016	354				
	6200W	0016026	360				
4 (DOCs)	300W	0016021	65	69	10.0%	461	149.2
	300W	0016001	77				
	300W	0016015	65				
	3900W	0015857	291	282	2.8%	932	302.7
	3900W	0015853	279				
	3900W	0015858	276				
	6200W	0015865	763	740	5.1%	1554	475.9
	6200W	0015892	759				
	6200W	0015897	696				

The EC concentrations from the personal samples are summarized in Table 8. During the test #4, when all tested vehicles were fitted with DOCs and mufflers, the average EC concentrations to which the operators were exposed, particularly the operator on LHD #92535, exceeded 308 µg/m^3. During tests #2 and #3, when target vehicles were fitted with DPFs, the average EC concentration for each of the three operators were significantly below 308 µg/m^3 and the results in test #2 were well above the final DPM exposure limit of 123 µg/m^3 EC (equivalent to 160 µg/m^3 TC). However as discussed previously, the DPF systems on trucks #92133 and #92136 were performing below specifications. These results indicate that even when the DPF systems are performing below expectations, they can significantly reduce the EC concentrations when compared to conditions when the DPF systems were not used. For test #2, the result of carbon analysis on the personal sample for LHD operator is not available since sampling pump flow fault occurred during the test.

Table 8. Results of elemental carbon analysis performed on the personal samples

Test # (Control Systems)	Vehicle Operator	SKC Sample #	EC (µg/m^3)
2 (DPFs)	#92133	0015987	180
	#92136	0016014	174
	#92535	0016029	flow fault
3 (DPFs)	#92133	0016012	82
	#92136	0015990	86
	#92535	0016031	78
4 (DOCs)	#92133	0015879	397
	#92136	0015866	382
	#92535	0015890	1100

Concentrations of CO, NO, and NO_2

The results of the measurements of CO, NO, and NO_2 concentrations are summarized in Table 9. These data were not collected on midstream sampling station for test #3 due to a failure to initiate the logging session. The average concentrations of CO, NO, and NO_2 were found to be well under the corresponding 1973 ACGIH TLVs® adopted by MSHA (30 CFR §57.5001, 1995). The NO_2 concentrations were found to be elevated in test cases when the vehicles were equipped with either the DPFs or the DOCs (Table 9, Figure 9 and Figure 10).

Table 9. Results of measurements of concentrations of CO, NO, and NO_2

Test # (Control Systems)	Sampling Location	CO [ppm]		NO [ppm]		NO_2 [ppm]	
		Average	Maximum	Average	Maximum	Average	Maximum
2 (DPFs)	300W	0.0	3.0	0.1	5.0	0.0	0.3
	3900W	0.3	4.0	6.3	12.0	0.9	3.5
	6200W	5.2	18.0	11.3	13.0	1.2	1.8
3 (DPFs)	300W	0.0	4.0	0.3	12.0	0.0	1.9
	6200W	3.7	10.0	6.6	9.0	1.1	1.7
4 (DOCs)	300W	0.1	9.0	0.6	13.0	0.0	2.1
	3900W (1)	0.1	6.0	4.2	8.0	0.2	1.4
	3900W (2)	0.1	6.0	4.4	9.0	0.3	1.6
	6200W	3.6	11.0	7.4	12.0	1.1	2.6

Both tests #2 and # 3 were terminated, during the sampling period, due to high concentrations of NO_2 detected by the personal multi-gas monitor carried by the operator of the truck #92135. During test #2, while vehicles #92135 and #92535 were at the development section, the monitor showed NO_2 concentrations higher than 5 ppm, the 1973 ACGIH short term exposure level (STEL) for this gas adopted by MSHA (30 CFR 57.5001 1995). During test #3, when vehicle #92135 was at the orepass, the monitor carried by the operator showed concentrations in excess of 5 ppm. Elevated NO_2 exposures resulted in the removal of personnel from the work area. Exposures above 5 ppm were not reported during test #4; however, the peak concentrations of NO_2 measured at the downstream sampling station (Figure 10) indicate that personal exposures might have been relatively high in this case as well.

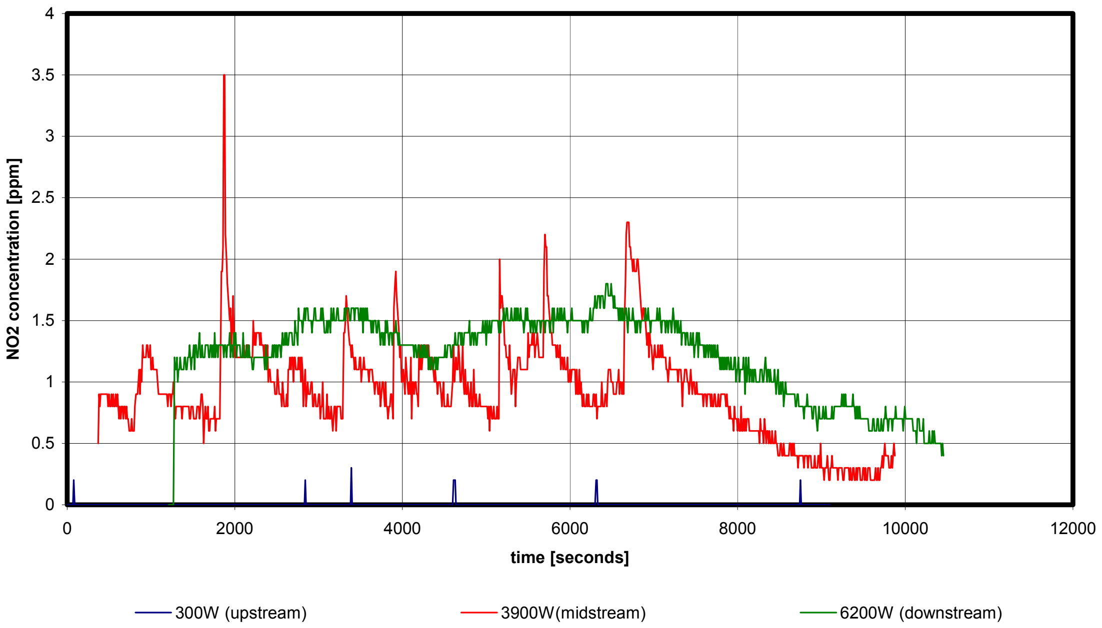

Figure 9. Concentrations of NO_2 observed during test #2

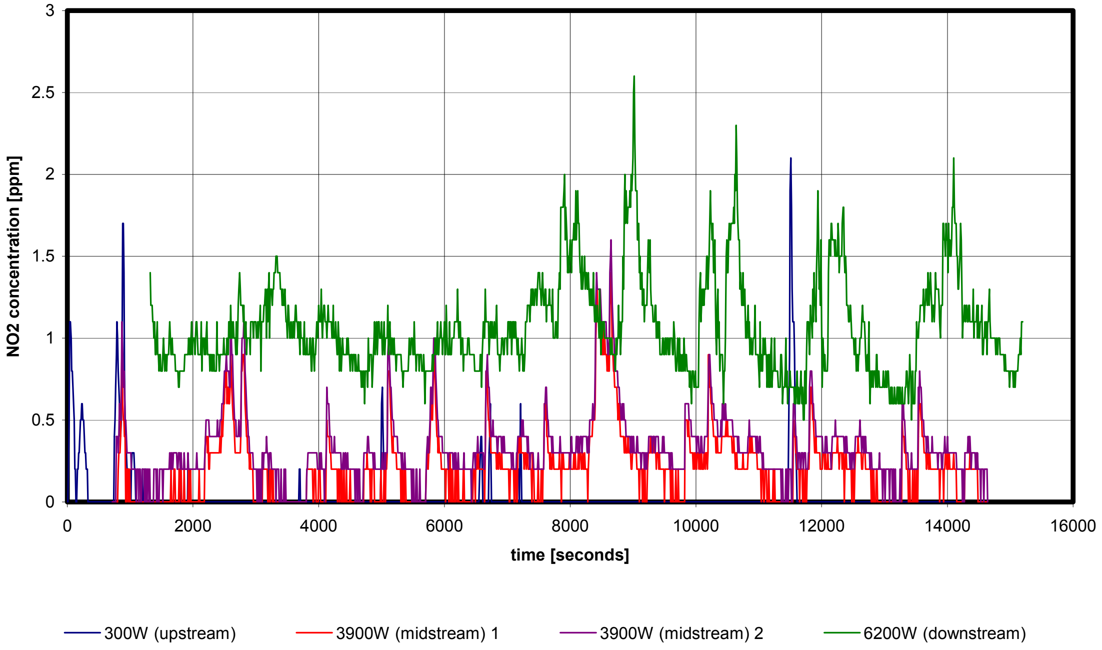

Figure 10. Concentrations of NO_2 observed during test #4

Tailpipe emissions measurements

The emissions of O_2, CO_2, CO, NO, NO_2, and NO_x, measured upstream and downstream of the DPF systems and the DOCs installed on #92133, #92135, and #92535, are shown for three steady-state test conditions in Table 10, Table 11, and Table 12. The values for smoke numbers measured at torque converter stall conditions are shown in the same tables.

Table 10. Gaseous and PM emissions for truck #92133 (Deutz BF6M1013 FC with EMR governor)

Engine Operating Conditions	Sampling Location	O_2 [%]	CO_2 [%]	CO [ppm]	NO [ppm]	NO_2 [ppm]	NO_x [ppm]	Smoke Number (0-9)
Low Idle	upstream of DPF	17.9	2.2	156	327	14	342	N/A
	downstream of DPF	17.8	2.3	9	200	97	298	N/A
	downstream of DOC	18.2	1.9	0	149	83	232	N/A
High Idle	upstream of DPF	14.8	4.4	438	354	67	421	N/A
	downstream of DPF	14.8	4.5	6	235	127	362	N/A
	downstream of DOC	15.9	3.6	20	241	0	241	N/A
Torque Converter Stall	upstream of DPF	9.8	8.2	194	516	0	516	7
	downstream of DPF	9.7	8.3	17	380	53	433	1
	downstream of DOC	12.2	6.4	19	356	0	356	7

Table 11. Gaseous and PM emissions for truck #92135 (Deutz BF6M1013 FC with EMR governor)

Engine Operating Conditions	Sampling Location	O_2 [%]	CO_2 [%]	CO [ppm]	NO [ppm]	NO_2 [ppm]	NO_x [ppm]	Smoke Number (0-9)
Low Idle	upstream of DPF	18.5	1.7	230	197	0	197	N/A
	downstream of DPF	18.1	2.0	0	132	109	241	N/A
	downstream of DOC	18.7	1.5	2	144	0	144	N/A
High Idle	upstream of DPF	15.3	4.1	704	271	0	271	N/A
	downstream of DPF	16.4	3.3	11	197	0	197	N/A
	downstream of DOC	17.6	2.4	29	163	0	163	N/A
Torque Converter Stall	upstream of DPF	9.9	8.1	246	505	0	505	7
	downstream of DPF	12.5	6.2	10	306	0	306	0
	downstream of DOC	14.7	4.5	20	246	0	246	7

Table 12. Gaseous and PM emissions for LHD #92535 (Caterpillar 3306 DITA)

Engine Operating Conditions	Sampling Location	O_2 [%]	CO_2 [%]	CO [ppm]	NO [ppm]	NO_2 [ppm]	NO_x [ppm]	Smoke Number (0-9)
Low Idle	upstream of DPF	18.6	1.6	85	165	28	194	N/A
	downstream of DPF	17.8	2.2	7	252	217	469	N/A
High Idle	upstream of DPF	14.3	4.8	195	245	21	267	N/A
	downstream of DPF	14.1	5	0	239	137	377	N/A
Torque Converter Stall	upstream of DPF	11.7	6.8	63	580	0	580	3
	downstream of DPF	11.4	7	19	598	26	625	0

The results of CO_2 emissions measurements indicate that the engines were loaded relatively consistently during the test involving DPFs. The CO_2 emissions downstream of the DOC systems were consistently somewhat lower than corresponding emissions measured upstream and downstream of the DPFs. This might be explained by lower backpressure imposed by DOC than by DPF systems. Therefore, using emissions measured upstream of DPF systems as engine-out (baseline) emissions for the test involving the DOC systems and comparing them to the emissions measured downstream of the DOC systems is not acceptable practice.

The engine-out CO emissions from truck #92133 (see Table 10) were found to be higher than equivalent emissions from truck # 92135 (see Table 11). The engine-out emissions from both Deutz-powered trucks were quite a bit higher than the equivalent emissions from Caterpillar 3306 DITA engine powering LHD #92535 (see Table 12). It is important to note that electronically controlled Deutz BF6M1013 FC engines powering trucks #92133 and #92135 were originally acquired as mechanically controlled Deutz BF6M1013 ECP engines. Those engines were afterward modified by replacing mechanical governor with EMR governors. The results presented in Table 10, Table 11, and Table 12 show that catalyzed DPFs and DOCs used on #92133, #92135, and #92535 during this study were efficient in curtailing CO emissions.

The results of measurements of NO and NO_2 emissions were relatively inconsistent and less conclusive. That can be particularly concluded for NO_2 measurements performed in exhaust of #92135 (see Table 11) where no NO_2 was detected in exhaust for majority of the tests. Despite this uncertainty, the results of tailpipe emissions measurements support the findings from the tests conducted underground on 3500W. The fact that NO_2 emissions were substantially higher downstream of the DPF systems might explain high ambient concentrations of NO_2 observed during the tests when #92133, #92135, and #92535 were equipped with DPF systems.

The smoke numbers obtained during shop tests were consistently lower than smoke numbers determined during underground spot checks. This discrepancy in the results can be partially attributed to the different methods and instrumentation used for these tests.

ACKNOWLEDGEMENTS

Special thanks to Stillwater Mining Co. for hosting the study.

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STILLWATER MINE

To: Aleksandar Bugarski

From: Jason Todd

Date: October 9, 2003

Subject: 35w Ventilation during Phase 2 DPM study

CC: Rick Anderson, Michael Crum, John Jordan, Chris Zimmer

The ventilation on the 35w FWL consists of air flowing onto the level at 35e900 and splitting east and west. The westward split has historically been in the 75-85 kcfm range. When the air reaches the 4100w return air raise a portion exhausts the level and flows up to the 38w FWL. The remaining air flows westward to the 6200w return air raise. This air flows up the raise to the 38w FWL. Air flows from 35w4100-35w6200 have historically been on the order of 40-55 kcfm. These air flow variances are due to minewide air door settings, muckpass levels, ambient air temperature and other variables. The air flows are not static and change throughout any given time frame. On the 38w FWL at both 4100w and 6200w there are fans (125 hp and 150 hp) which pull air up the raises from the 32w FWL and the 35w FWL.

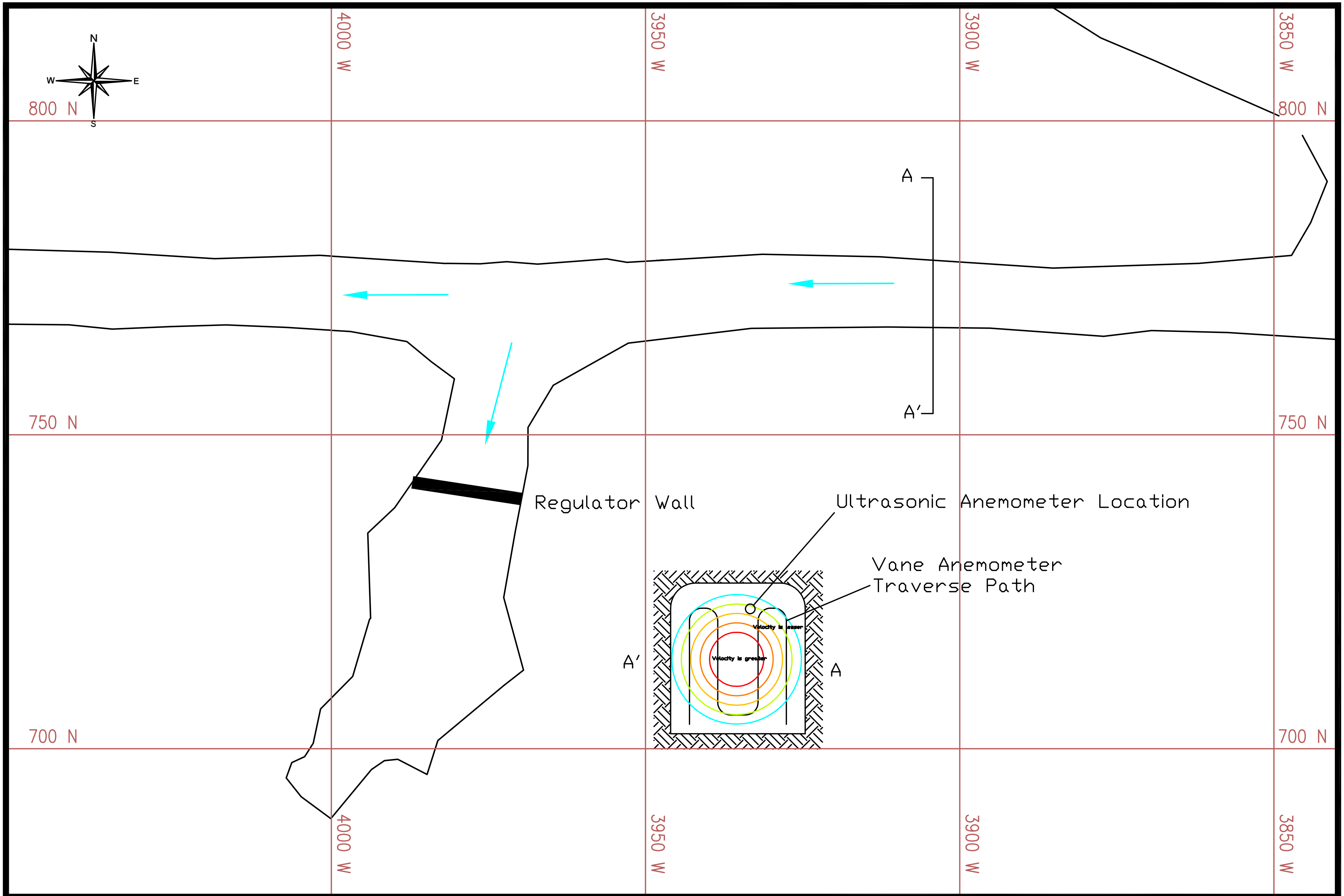
Measurements were taken in this area on September 09-10, 2003. The results are shown below:

Date	Location	Area(ft2)	Corrected Velocity (ft/min)	Quantity (cfm)
9/9/2003	35w3900	124.2	601	74,644
	35w6000	136.1	283	38,516
9/10/2003	35w3900	124.2	654	81,227
	35w6000	136.1	323	43,960

Measured with a Davis Instruments Vane Anemometer using two 60 second traverses.

The measurements taken by NIOSH personnel indicate air was intaking onto the 35w FWL at 4100w. This situation is not possible without disrupting the entire off shaft west ventilation system. There were no reported disruptions to the ventilation systems the week of September 08-12. SMC ventilation personnel have never observed the 4100w raise adding additional air to the 35w FWL.

The results of the ultrasonic anemometer are suspect and do not accurately represent the quantities of air flow in this area of the mine. Quantities measured by SMC are done using a full cross sectional traverse in a relatively straight run of drift. This is done to collect a better representation of the actual airflows in an area (see Fig 1 and Fig 2). The downstream anemometer used by NIOSH was set into a cross cut where the air flow is not as uniform (Fig 2). The ultrasonic anemometer collects data at a single point. This single point is not representative of the airflow for the cross sectional area it represents. A correction factor can be calculated to more accurately approximate the velocity of the air flow to a specific point. These factors for a centerline measurement are usually on the order of 70-90%.



STILLWATER MINING COMPANY
HC – 54 Box 365
Nye, MT 59061

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Figure 1

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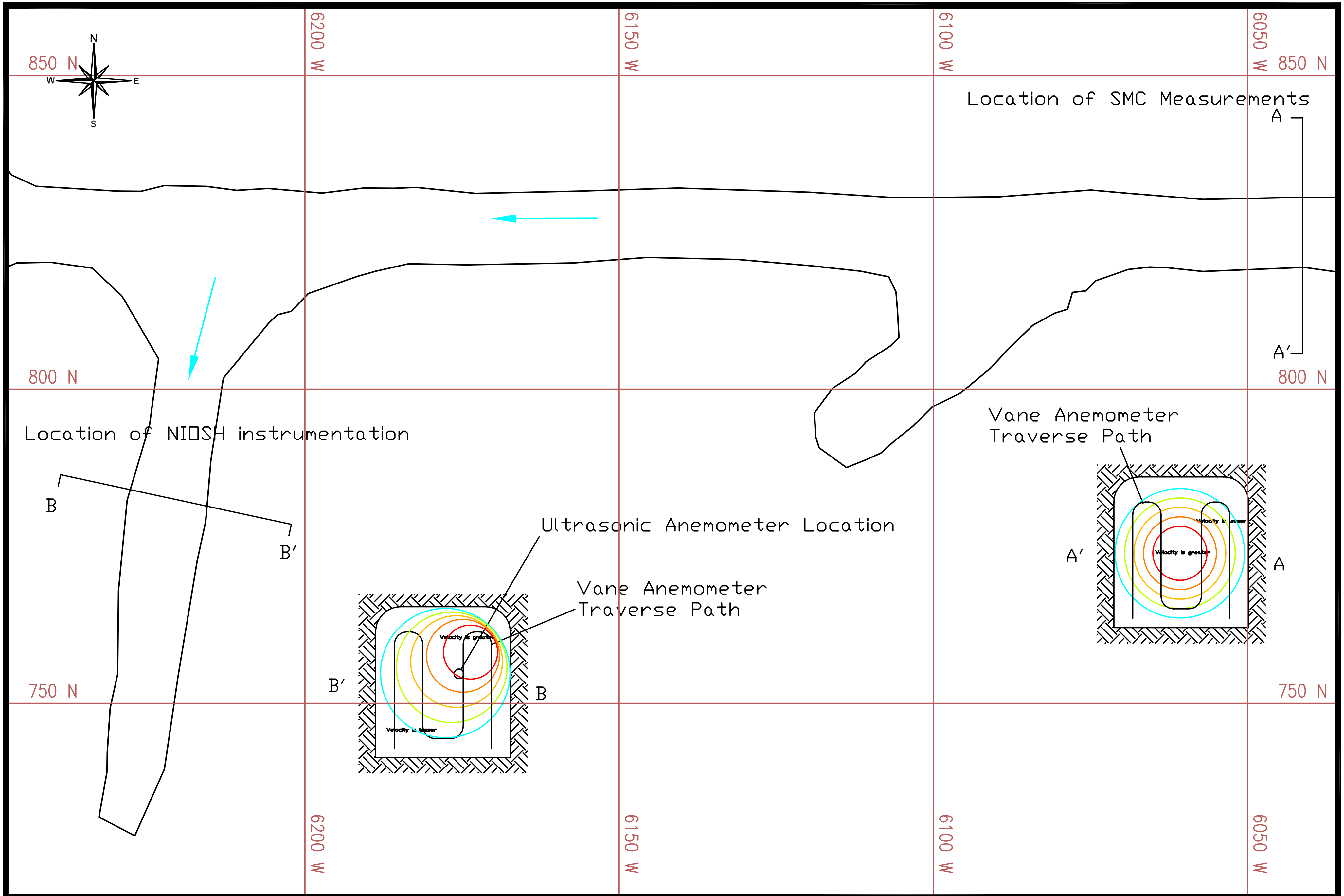

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TITLE: 35W6100 AIR FLOW
Figure 2

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