Representativeness of Sampling by Shrouded Probes in the Exhaust Shaft of the Waste Isolation Pilot Plant - 11308

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ABSTRACT

40 Code of Federal Regulations (CFR) Part 191, Subpart A, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes*, and 40 CFR Part 61, Subpart H, *National Emission Standards for Hazardous Air Pollutants*, require that DOE implement a monitoring program to demonstrate the safe operation of the WIPP facility. DOE meets this commitment, in part, by sampling the aerosol particles in the return air at the top of the exhaust shaft for the underground facility. This monitoring is performed by shrouded probes that can accurately sample the air stream and its aerosol particles under a wide range of flow conditions and particle sizes. Three probes operate on a continuous basis as part of the defense-in-depth radiation monitoring program. The design and testing of the shrouded probes is summarized and monitoring data from the past three years is analyzed. The ability of the shrouded probe to take representative samples is confirmed.

INTRODUCTION

Regulatory Requirements

Sampling at Station A is consistent with the provisions of 40 CFR Part 61, Subpart H, National Emission Standards for Hazardous Air Pollutants (NESHAP), promulgated under the Clean Air Act for radionuclide emissions from DOE facilities. Although EPA determined that NESHAP monitoring is not needed for disposal activities at the WIPP, DOE committed to implement the requirements of 40 CFR Part 61 Subpart H as they apply to WIPP under a Memorandum of Understanding (MOU) between EPA and DOE ([1], Section 3 of enclosure).

DOE meets this commitment by sampling the return air from the underground facility at Station A at the top of the exhaust shaft, rather than by using multiple sampling stations at the site boundary. The sampling at the top of the exhaust shaft is part of a program to limit public exposure to radiation during the disposal phase of operations, as required by 40 CFR Part 191 Subpart A. Sampling at Station A is preferable to sampling at the site boundary because the random effects of wind and weather may disperse any potential radionuclides released from the WIPP to the point that radionuclide concentrations are undetectable at the site boundary. DOE operates the sampling probes in the exhaust shaft continuously, although continuous sampling is not required by the MOU.

Ventilation of the Underground Facility

The WIPP underground facility is ventilated with unfiltered air that returns to the atmosphere through a vertical exhaust shaft. At the top of the exhaust shaft, the flow passes through a 90 degree elbow and horizontal duct work to the main (“700”) fans. The fans exhaust directly to atmosphere during normal operating conditions.

Mining and maintenance operations at WIPP generate nuisance dust and salt particles that are carried along with the mine air. The repository horizon is in the Salado formation, which is nearly pure halite (NaCl) with trace amounts of evaporite minerals such as anhydrite ($CaSO_4$), gypsum ($CaSO_4{\cdot}2H_2O$), polyhalite ($K_2MgCa_2\,(SO_4)4{\bullet}2H_2O$), magnesite ($MgCO_3$) and clays ([2], Section 2.1 in Appendix SOTERM-2009).

The exhaust air from the underground facility is continually sampled at Station A, which is located approximately 21 feet, or 1½ shaft diameters, below ground level in the exhaust shaft (see Fig. 1). Three shrouded probes are used to continuously sample the exhaust air and aerosol particles at Station A, with one probe identified as the primary probe, a second probe as a backup probe, and the third probe as a redundant spare. The individual probes are located at Skids A1, A2, and A3 on the east, west, and south sides of the exhaust shaft, respectively.

DESIGN AND TESTING OF THE SHROUDED PROBE

Researchers at the Aerosol Technology Laboratory (ATL) of Texas A&M University (TAMU) developed the shrouded probe design. Wind tunnel tests were conducted at ATL on the sampling performance of the shrouded probe over a range of aerosol particle sizes from 1 to 15 μm aerodynamic equivalent diameters (AED) and a range of free stream velocities from 2 to 14 m/s [3]. Scale model testing of the exhaust shaft and elbow confirmed that the location of Station A, 1½ L/D’s upstream of the elbow at the top of the exhaust shaft (see Fig. 1), provides a representative location for point sampling of the exhaust air [4]. Transport line losses between the shrouded probe and the fixed air sampler (FAS) were shown to be minor [5]. The effects of salt loading and flow blockage [6] and the effect of a free stream velocity of 20 m/s [7] were also evaluated. Key results from this testing program are presented here.

Design of the Shrouded Probe

The TAMU shrouded probe is 16 inches (406 mm) long, has an inside diameter of 4 inches (102 mm), and has a 30 mm diameter sampling probe located concentrically within a cylindrical shroud (see Fig. 2 and [3], Shrouded Probe Design). The inlet diameter of the inner probe is 30 mm and is located at a distance of 153 mm from the entrance plane of the shroud. The probe body gradually expands (at a 3.5° angle on the inside surface and a 7.6° angle on the outside surface) to provide a transition to a 51 mm diameter air/aerosol transport line (not shown) at the downstream end of the probe.

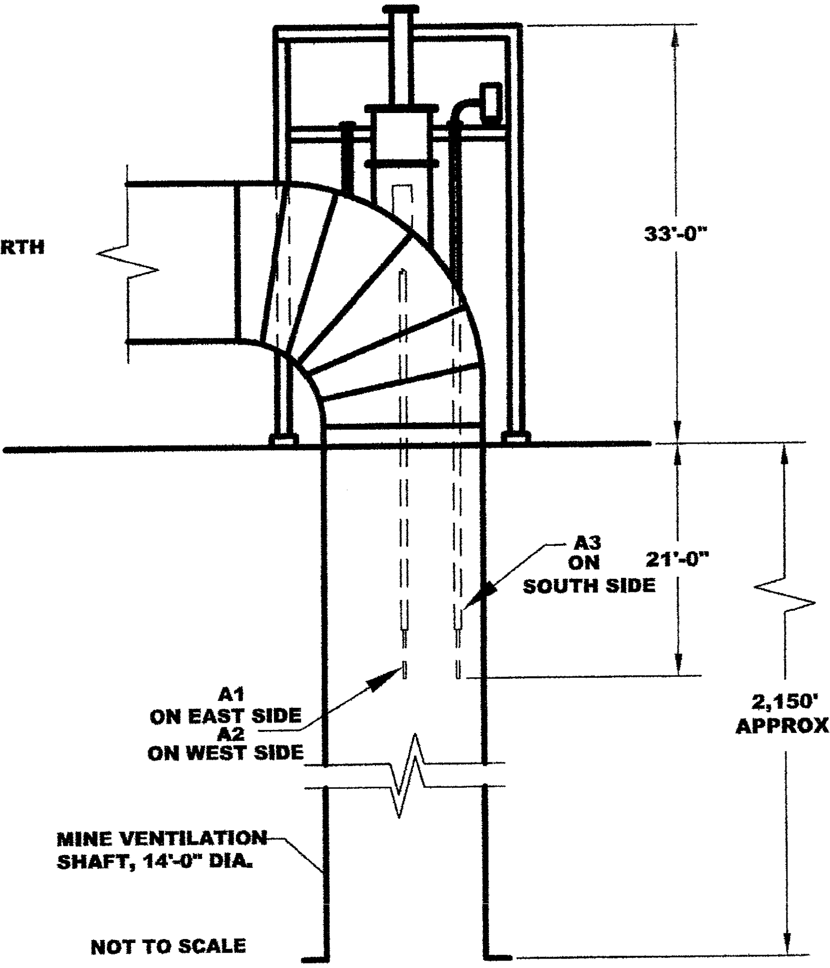
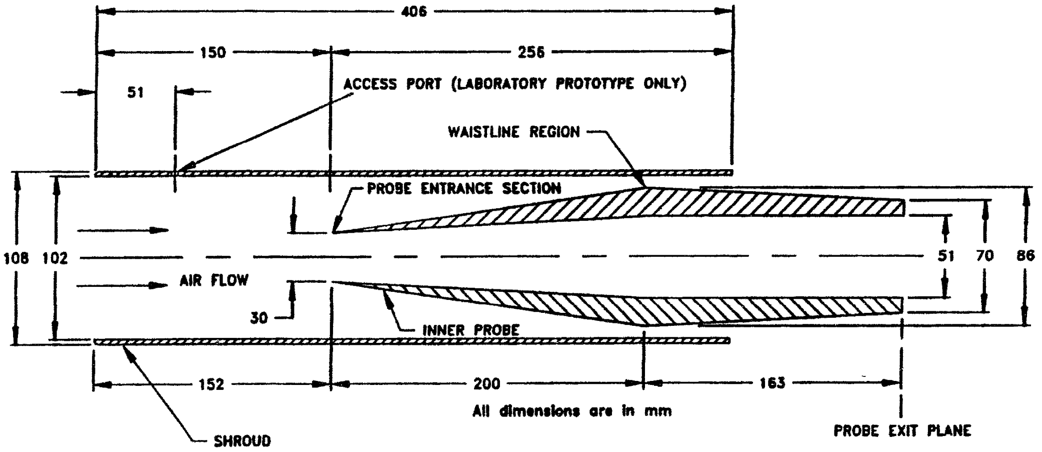


Fig. 1. Location and Layout of Skids A1, A2, and A3 at Station A in the Exhaust Shaft



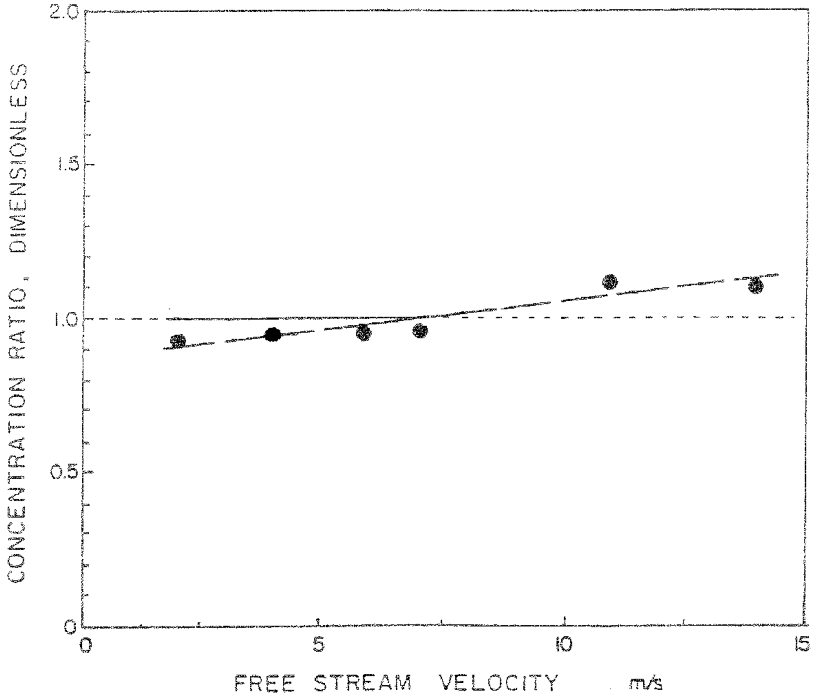
Source: [6], Fig. 1

Fig. 2. The TAMU Design for the WIPP Shrouded Probe

Wind Tunnel Testing

Wind tunnel experiments for the shrouded probe were performed over a range of flow velocities and aerosol sizes ([3], Results). The wind tunnel testing defines the transmission ratio, *T*, which is the ratio of aerosol concentration transmitted through the probe to the aerosol concentration in the free stream. *T* greater than 1 indicates oversampling of aerosol relative to the free stream aerosol concentration.

Fig. 3 presents the results of the wind tunnel testing over a range of free stream velocities with an aerosol particle size of 10 μm aerodynamic diameter and with the standard sampling rate through the probe of 170 liters/min. The values of *T* for the shrouded probe vary from 0.93 to 1.11 over the velocity range of 2 m/s to 14 m/s. In other words, the aerosol concentration transmitted through the sampling probe is accurate to within -7% to +11% under these flow conditions, and significantly better than the informal criterion of -50% recommended by the Environmental Evaluation Group (EEG) for 10 μm aerodynamic diameter aerosol particles [8].



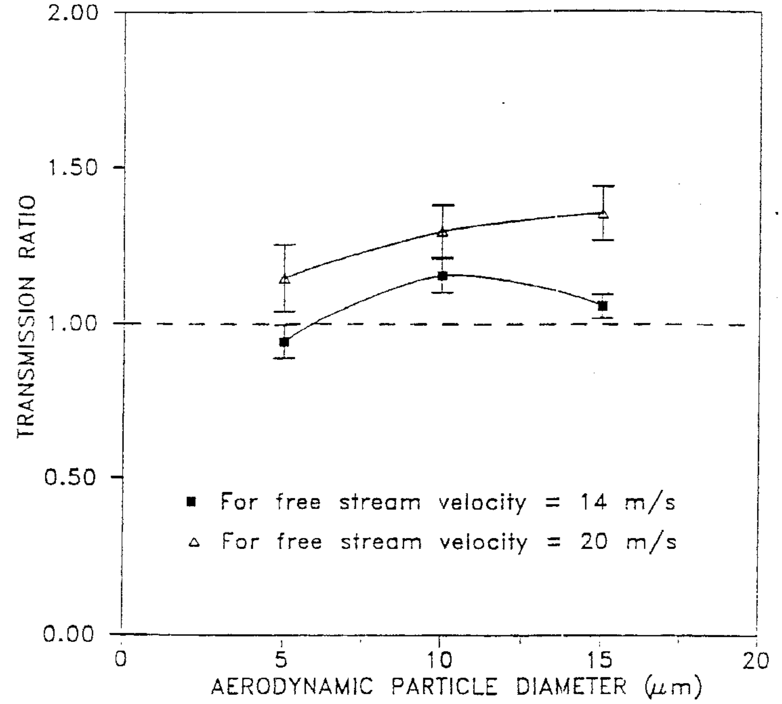
Source: [3], Fig. 4
NOTE: Aerosol particles have a 10 μm aerodynamic diameter.

Fig. 3. Variation of Transmission Ratio, *T*, with Free Stream Velocity

The nominal velocities of the return air in the upper exhaust shaft are 2.0 m/s, 8.6 m/s, and 13.3 m/s to 17.9 m/s for the filtration, alternate, and normal ventilation modes, respectively ([9], Section 2.1). Additional testing (see Fig. 4) has evaluated performance at free stream velocity of 20 m/sec. The wind tunnel testing therefore encompasses the full range of velocities expected in the exhaust shaft under the major ventilation modes.

It is also important that larger-sized aerosol particles be effectively transported through the sampling probe. Aerosol particles with an aerodynamic diameter of 20 μm or greater tend to settle out of the ventilation air during its return transit through the mine, and smaller aerosol particles with aerodynamic diameters of less than 10 to 15 μm remain entrained in the air flow ([9], Section 2.2).

The variation of *T* with the size of the aerosol particles at free stream velocities of 14 m/s and 20 m/s is shown in Fig. 4. *T* is greater than 1.00 for particle sizes from 6 μm to 15 μm aerodynamic diameter. The results in Figs. 3 and 4 indicate a tendency for the shrouded probe design to oversample the aerosol particles in the exhaust shaft over the flow velocities and particle sizes that are relevant to the WIPP.



Source: [7], Fig. 6.

Fig. 4. Variation of transmission ratio with particle diameter for free stream velocities of 14 m/s and 20 m/s.

Scale Model Testing for the Location of Station A

Scale model testing was performed to determine the appropriate location(s) for continuous aerosol samplers in the exhaust shaft ([4], Executive Summary). The basic scale ratios were 1 to 5 for physical size and 1 to 25 for flow rate. A major result from the model testing is the recommendation that Station A should be located 1½ diameters (21 feet) below the elbow at the top of the exhaust shaft (see Fig. 1). Velocity profiles were measured to be within ± 10% of the mean areal velocity or mean areal concentration at this location.

The air flow at the top of the exhaust shaft is also expected to be well-mixed because the flow lengths in the upper and lower portions of the exhaust shaft exceed the approximately 50 L/D’s that are needed to produce a well-mixed flow in a straight pipe [10]. The flow length in the shaft and these test results indicate that there will be a relatively uniform distribution of aerosol particles and flow velocity at Station A, thus justifying the use of single point sampling there.

GROUNDWATER SEEPAGE AND THE POTENTIAL REMOVAL OF SALT PARTICLES

Shallow subsurface water (SSW) was first noticed at the WIPP site in 1995 when it was observed seeping into the exhaust shaft [11]. The water entered through cracks and joints in the concrete shaft liner at depths of 50 to 80 ft (15 to 24 m) below the ground surface [12]. Prior to this time, no water had been observed at this horizon in either boreholes or shafts at the WIPP site. The source of this water was determined to be infiltration from various surface impoundments created as the WIPP facilities area was developed. Remaining surface impoundments are now lined to prevent further infiltration.

At the present time, there are multiple sources of seepage into the shaft. Some fraction of this seepage is entrained in the flowing mine air, breaks up into small droplets, and is accelerated upward, past the skids at Station A. The seepage rate into the exhaust shaft is estimated at 0.5 to 5 gallons per minute (gpm) (0.0315 to 0.315 L/s) and is expected to remain relatively constant because the volume of leakage is orders of magnitude smaller than the total probable reservoir volume [13].

The upper estimate for seepage inflow to the exhaust shaft, 5 gpm (0.315 L/s), is reasonable because, under typical ventilation system operation, little if any fluid consistently reports to the shaft bottom as would be the case for substantial seepage inflow.

Potential for Seepage to Remove Aerosol from the Exhaust Shaft

The removal of nuisance dust from the ventilation air in a mine is discussed by McPherson ([14], Section 20.4.2). McPherson provides a simple model for particle removal efficiency by a water spray system. A key design parameter is the water-to-air ratio, W/Q [L/m^3], where W is the water flow rate [L/s] and Q is the air flow rate [m^3/s]. A typical range of W/Q for efficient removal of nuisance dust from ventilation air in mines is typically 0.3 to 0.6 L/m^3.

A conservative evaluation of W/Q in the exhaust shaft is based on the upper limit for seepage, 5 gpm (0.315 L/s) and the flow rate in alternate mode. A reasonable value of the air flow rate in the alternate ventilation mode is 123 m^3/s ([9], Section 2.1). The W/Q in the exhaust shaft for this mode is then (0.315 L/s)/(123 m^3/s) = 0.00256. This value for W/Q is a factor of 117 below McPherson’s lower practical limit. Stated differently, the seepage flow rate into the exhaust shaft would have to be 117 times greater than 5 gpm

(0.315 L/s) in order to be at the lower limit of McPherson's range for efficient removal of aerosol particles in alternate ventilation mode. The alternate ventilation mode is the minimum flow likely should a hypothetical accident occur.

The conclusion from this analysis is that the observed seepage into the exhaust shaft will not interfere with sampling of the aerosol at Station A.

Measured Flux of Droplets at Station A is Small

An alternate approach to assess the potential for the seepage into the exhaust shaft to remove aerosol particles is to estimate the amount of seepage that reaches Skids A1, A2, and A3. This analysis is based on measurements of the flux of entrained droplets at the skids at Station A [15]. The data for May 1995 (see Table 1) show that the mass flux of entrained droplets in the south and west quadrants is 13% of the total flux, and the mass flux of droplets in the north and east quadrants is 87% of the total flux. Skid A1, which is located in the east quadrant, is in a significantly wetter environment than Skids A2 or A3, which are located in the west and south quadrants, respectively.

Table 1. Mass Fluxes from Droplet Measurements in May 1995

Location	Test Number	Mass Flux (kg/hr-m^2)	Quadrant Mass Flux (kg/hr)	% Total Flux in Quadrant
South (Skid A3)	2	0.16	0.56	10%
	8	0.06	0.21	
	18	0.07	0.26	
West (Skid A2)	5	0.01	0.03	3%
	6	0.04	0.14	
	17	0.04	0.15	
East (Skid A1)	4	0.20	0.73	27%
	7	0.23	0.83	
	16	0.35	1.26	
North	22	0.59	2.10	60%
	23	0.81	2.89	
	24	0.33	1.18	

Source: Table 4.1 in Weaver et al., 1996, with renumbered skid locations.

The mass flux of seepage to an individual skid can be estimated from the data in Table 1. The shroud has a 10 cm (4-inch) inner diameter with a cross sectional area of 81.07 cm^2 or 0.0081 m^2. The shaft has a 4.27 m (14-foot) diameter with a cross sectional area of 14.3 m^2; the area of each quadrant of the shaft is one-quarter of the shaft's cross sectional area, or 3.58 m^2. Assume that the seepage is at the maximum rate, 5 gpm (0.315 L/s), and that all seepage becomes entrained as droplets in the air flow. Based on the data in Table 1, 27% of the entrained seepage, which is 0.5 gpm (0.315 L/s), reaches the east quadrant with Skid A1. The total flux to the quadrant is (0.315 L/s)(0.27) = 0.0852 L/s. The fraction of the seepage to the east quadrant that flows within the cross sectional area of the shroud is estimated as (0.0852 L/s)(0.0081 m^2)/(3.58 m^2) = 1.9×10^{-4} L/s = 0.69 liters per hour = 23 ounces per hour. Even at Skid A1 the maximum flux of seepage to the shroud at Skid A1 is small and very unlikely to remove a significant amount of aerosol particles and dust from the ventilation air.

OBSERVATIONS OF NOZZLE OCCLUSION

The shielded probes at Station A are periodically removed, photographed, cleaned, and reinstalled to ensure that salt occlusion on a probe does not prevent it from taking a representative sample of the aerosol in the return air. Based on the TAMU test data, the shielded probe provides representative sampling if the nozzle occlusion (i.e., the occlusion at the inlet to the inner probe) is less than 66% of its initial area, and if the occlusion at the waistline between the inner probe and outer shroud is less than 33% of its original area ([9], Section 3.2).

The salt occlusion on the nozzle has been measured since May 22, 2007. Digital pictures are taken of each probe after it is removed from the shaft, and a software program counts pixels to determine the percent occluded area of the nozzle. Digitized data for occlusion at the waistline are not currently available. It is difficult to digitize the occlusion at the waistline because salt buildup may be behind the waistline but still appear in the photograph and because the waistline area is split into three parts by the shroud supports.

Salt Accumulation on the Nozzles

Fig. 5 shows the salt buildup on the probes at Skids A1, A2, and A3 from the probe pulls on January 7, 2009 and July 7, 2009. The probes were exposed to the return air and salt aerosol for 8 days and 7 days, respectively. The photographs in this figure are representative of the observed salt buildup over the past 3 years.

Skid A1 has heavier salt buildup than Skids A2 or A3 during the winter months, but lighter salt buildup during the summer months. During the winter months, salt accumulation is greatest on the leading edge of the Skid A1 shroud and near the end of the shroud, where there is a change in flow geometry from the end of the shroud to the smaller diameter transport line. On the other hand, the nozzle occlusion at Skid A1 is often similar to that on Skids A2 or A3, in spite of the much heavier buildup of salt on the shroud for Skid A1.

The heavier salt buildup on Skid A1 during the winter months probably occurs because Skid A1 is closer to the primary source of seepage at the northeast quadrant of the exhaust shaft. This seepage wets the probe at Skid A1 more heavily than at Skids A2 or A3, allowing salt particles to begin sticking and accumulating at the leading edge of the A1 shroud faster than at Skids A2 or A3. Measurements of seepage droplets within the exhaust shaft confirm that there is a higher mass flux of entrained droplets in the quadrant with Skid A1 than in quadrants with Skids A2 or A3 (see Table 1, right-hand column).

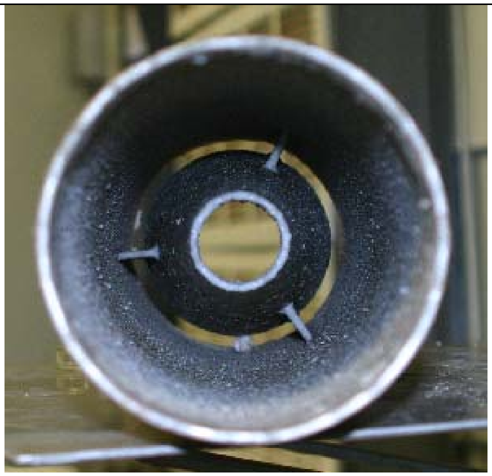
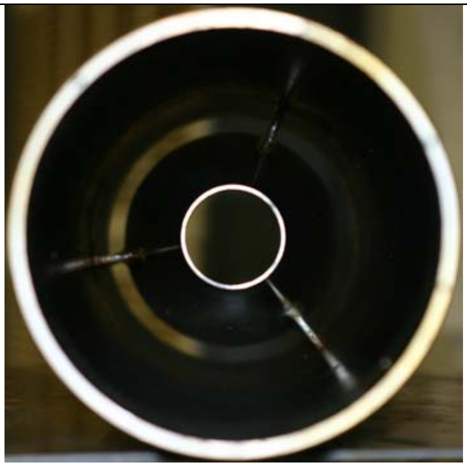
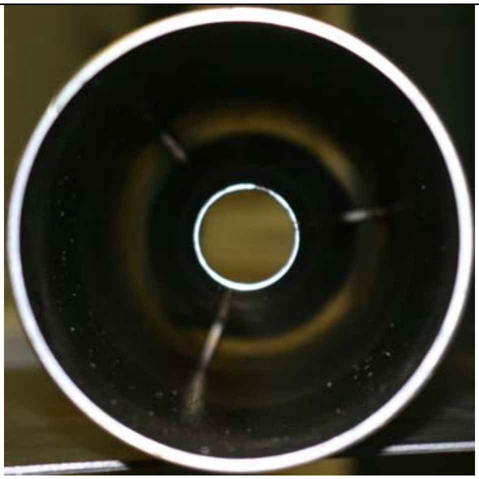
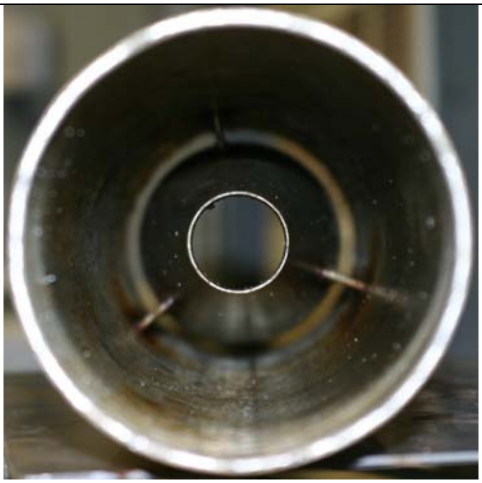
Skid A1	**Skid A2**	**Skid A3**
 Front view as found – focus on nozzle tip	 Front view as found – focus on nozzle tip	 Front view as found – focus on nozzle tip
 Front view as found – focus on nozzle tip	 Front view as found – focus on nozzle tip	 Front view as found – focus on nozzle tip

Fig. 5. Pictures from the Probe Pulls on January 7, 2009 and July 7, 2009, in the top and bottom rows, respectively

During the summer months, the three skids in Fig. 5 show minimal salt buildup. Skid A1 often has zero nozzle occlusion while Skids A2 and A3 maintain a positive but small nozzle occlusion. During the summer, the ambient air is more humid than during winter, particularly during the morning hours from 2 AM to 10 AM. The high water vapor content of the ambient air during these times seems to provide enough liquid moisture to remove aerosol particles from the probes. The presence of liquid moisture on the probes has been confirmed by visual observation during the probe pulls (personal observations by the author and by Ms Jaci Davis) ([9], Section 4.1).

ANALYSIS OF NOZZLE OCCLUSION DATA

A statistical analysis has been performed using the nozzle occlusion data for probes that were installed at Skids A1, A2, and A3 from May 22, 2007 through May 10, 2010. The nozzle occlusion data have been converted to occlusion per day by dividing the measured occlusion by the time interval between the current and previous probe pull. The operating environment varies significantly during this (almost) three-year period due to a wide range of mining activities and a wide range of ambient weather conditions. There are a total of 102, 88, and 77 data points for Skids A1, A2, and A3, respectively.

The nozzle occlusion data for Skids A2 and A3 is of interest because these probes show little seasonal variability and relatively constant occlusion rates. Fig. 6 is a plot of 3 years of data for nozzle occlusion per day for Skid A2. The almost horizontal linear regression fit to the data set indicates little seasonal dependence for nozzle occlusion per day.

Table 2 confirms the similarity of the response at Skids A2 and A3 for the mean, standard deviation, and maximum values of the occlusion data for Skids A2, and A3. The data in Table 2 also show that the standard deviations of the occlusion per day at Skids A2 and A3 are approximately one-half of the mean values, while the standard deviation of the occlusion per day at Skid A1 is greater than its mean value.

Table 2. Comparison of Mean, Standard Deviation, and Maximum Values of Occlusion Per Day for Skids A1, A2, and A3 During the Past Three Years

Skid	Mean Occlusion per Day	Standard Deviation	Maximum Occlusion Per Day
A1	1.67%	2.14%	9.99%
A2	1.37%	0.63%	3.47%
A3	1.52%	0.75%	3.83%

The mean and standard deviation of the percent occlusion per day at Skid A2 for the past two annual periods are very similar to the values for the full data set. Table 3 presents the values for the mean and standard deviation, which confirm that the annual variability of the occlusion data at Skid A2 over the past two years is very similar to that for the full data set.

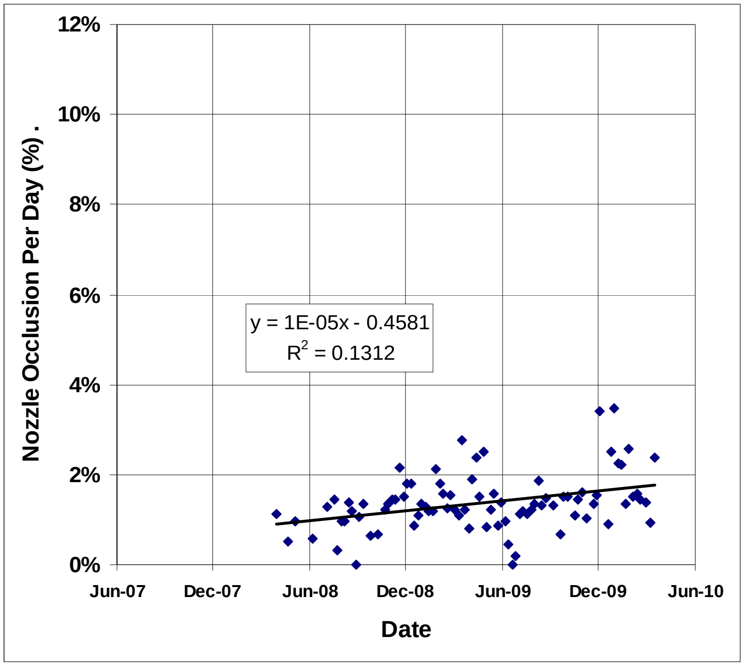


Fig. 6. Nozzle Occlusion per Day for Skid A2

Table 3. Annual Variability of Data for Occlusion Per Day at Skid A2

Period	Duration	Number of Points	Mean Occlusion per Day (%)	Standard Deviation (%)
5/22/2007 – 5/08/2008	12 months	3	0.87%	0.32%
5/08/2008 – 5/12/2009	12 months	42	1.34%	0.55%
5/12/2009 – 5/10/2010	12 months	43	1.43%	0.70%
All Data	36 months	88	1.37%	0.63%

Correlation of Skid A2 and A3 Nozzle Occlusion Data

Fig. 7 is a plot of the pairwise occlusion data for Skids A2 and A3. This plot demonstrates that the occlusion per day data at Skids A2 and A3 have a significant correlation over a wide range of operating environments. This correlation is consistent with the locations of Skids A2 and A3 being equidistant from the northeastern quadrant where seepage enters the shaft under pressure.

Fig. 8 is a plot of the pairwise occlusion data for Skids A1 and A2. There is essentially no correlation between the occlusion at Skid A1 and that at Skid A2. Fig. 8 shows a high density of points with zero or almost zero occlusion for Skid A1 versus Skid A2 which is consistent with Skid A1 being in a wetter environment, closer to the northeastern quadrant where seepage enters under pressure. The additional seepage near Skid A1 (relative to Skids A2 and A3) may prevent the build up of aerosol particles on the probe at Skid A1 during the summer months.

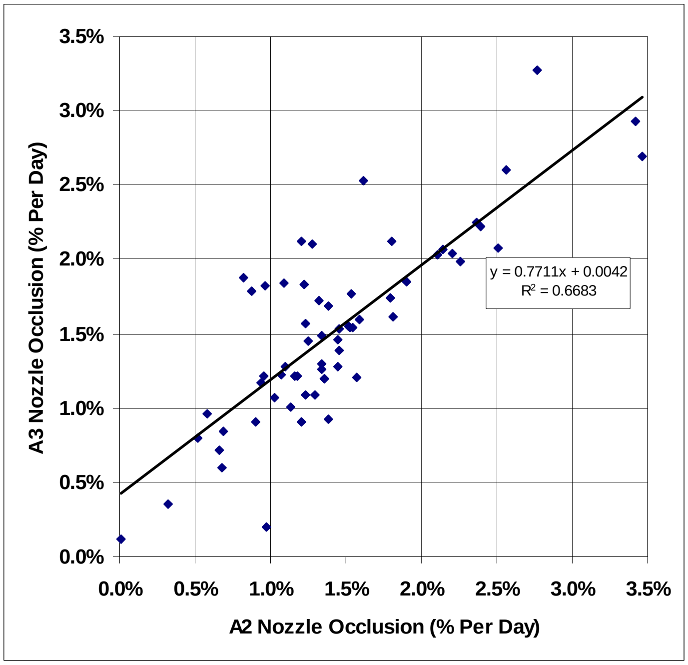


Fig. 7. Pairwise Correlation of Nozzle Occlusion Data for Skids A2 and A3

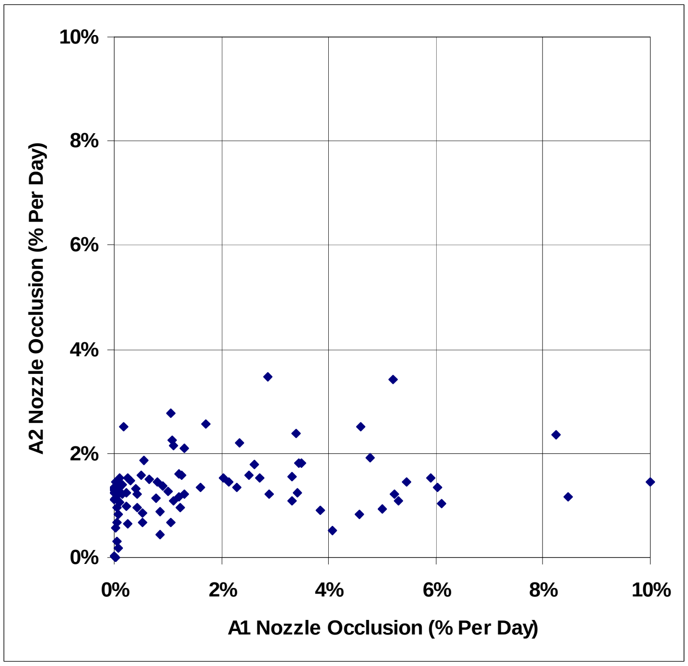


Fig. 8. Pairwise Plot of Occlusion Data for Skids A1 and A2

CONCLUSION ON REPRESENTATIVENESS OF SAMPLING

This paper demonstrates that:

- Seepage into the exhaust shaft cannot remove a significant fraction of the aerosol from the air stream in the exhaust shaft at Station A.
- Maximum flux of entrained droplets to the shrouded probes is quite small and should not interfere with collection of aerosol particles.
- Air flow at the top of the exhaust shaft is well-mixed, with relatively uniform distribution of aerosol particles and of flow velocity throughout the cross section of the exhaust shaft.
- Skids A2 and A3 have very similar nozzle occlusion data for the past three years and for individual years within the three year time period. This result is consistent with the expected uniformity in the distribution of aerosol particles and flow velocity at the top of the exhaust shaft and with the measured mass flux of droplets at the top of the exhaust shaft.

Therefore, it can be concluded that the shrouded probes at Skids A2 and A3 remain fully functional throughout the year, have not failed from nozzle occlusion during a two week period between probe pulls for the past three years, and take representative samples of aerosols at the top of the exhaust shaft

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