SULLIVAN MINE FATALITIES AND THE ROLE OF AIR QUALITY IN MINE-RELATED INCIDENTS

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ABSTRACT

During May 15 – 17, 2006, four fatalities occurred at a partially reclaimed waste rock dump at the closed Teck Cominco Sullivan Mine near Kimberley, British Columbia, Canada. The fatalities occurred at the toe of the dump in a seepage monitoring station that is connected hydraulically, via a pipe and dump toe drain, to the covered acid generating waste rock. Since August 2006, the dump has been heavily instrumented and studied in stages. Results have shown that atmospheric air temperature, not barometric pressure, is the dominant control on air movement between the waste dump and the atmosphere. This air movement, which changes direction seasonally, results in a gas containing elevated carbon dioxide and depressed oxygen exiting the dump. Air quality has been a historic mining issue that is now managed with testing methods and modern ventilation. Advancements aside, air quality remains an issue for current operations and legacy sites. This paper presents recent results of the Sullivan Mine fatalities technical investigations and reviews historic and recent incidents involving poor air quality at mine sites.

INTRODUCTION

During May 15 – 17, 2006, four fatalities occurred at the partially reclaimed No. 1 Shaft Waste Dump at the closed Teck Cominco Sullivan Mine near Kimberley, British Columbia, Canada (see Figure 1). The fatalities occurred at the toe of the dump in a seepage monitoring station that was often used, even as recently as one week prior to the fatalities, without incident.

Samples taken in the days immediately following the fatalities from within the monitoring station indicated that the air was depleted of oxygen and contained elevated levels of carbon dioxide. The concentration of oxygen was about 2% and that of carbon dioxide was about 7%. Isotopic analysis showed that the carbon source was inorganic. Thermal imagery surveys were flown and did not reveal any significant "hot spots" in the dump.

Subsequent to the fatalities of May 15 - 17, 2006, Teck Cominco sought advice from University of British Columbia (UBC) experts and from a technical consulting firm as to the potential underlying causes of the tragedy. Based on inspections of the No. 1 Shaft Waste Dump site, analyses of monitoring station air samples taken shortly after the tragedy and their knowledge of the processes that occur in covered waste dumps, both groups came to realize that movement of oxygen depleted air from the dump into the monitoring station was a likely causal factor.

Fig. 1. Location of Kimberley, British Columbia, Canada

This realization led to recommendations for technical investigations into the chemical and physical processes affecting air in the No. 1 Shaft Waste Dump and monitoring station. The investigation program is being guided by a Technical Panel that consists of independent experts from UBC, staff from both the MEMPR and Teck Cominco, and their respective technical advisors.

It was hypothesized that the 400 mm pipe connecting the drain to the monitoring station was the primary conduit between the atmosphere and dump waste rock, and that changes in atmospheric conditions resulted in *in situ* waste rock pore gases entering the monitoring station. To investigate the respiration behavior of the dump monitoring equipment was installed in two phases. Implemented in August 2006, the initial phase of the investigation involved monitoring the dump cover, site meteorology and the monitoring station. This monitoring is continuing and the overall program was significantly expanded in March 2007 and May 2008 with additional instruments to examine internal dump temperatures, pressures, and gas composition.

BACKGROUND

The No.1 Shaft Waste Dump was created during the 1940's to 2001, principally by the deposition of waste rock from the No. 1 Shaft. The dump curves along the slope below the shaft in a southwest to northeast orientation (see Figure 2). The height from the upper flat portion of the dump to the toe is approximately 55 m. The dump is comprised of approximately 2.6M t of primarily sulfidic waste rock. The estimated dump volume is 1M m^3 with approximately 30% void space.

The upper mine underground workings of the Sullivan Mine were entered through several horizontal drifts to access the ore body. As the workings went deeper underground a steeply inclined shaft (No.1 Shaft) was constructed to bring personnel, equipment and supplies into and out of the mine using a hoist positioned at the surface. A skip connected to the hoist also had the capability of removing waste rock from the mining levels. At surface the waste rock was dumped over the side of the bank downhill

of the hoist to form the No.1 Shaft Waste Rock Dump. Initially the rock was less than 15 cm in size to accommodate the loading of narrow gauge underground rail cars. The waste rock could also have high moisture content if it originated from the lower levels of the mine.

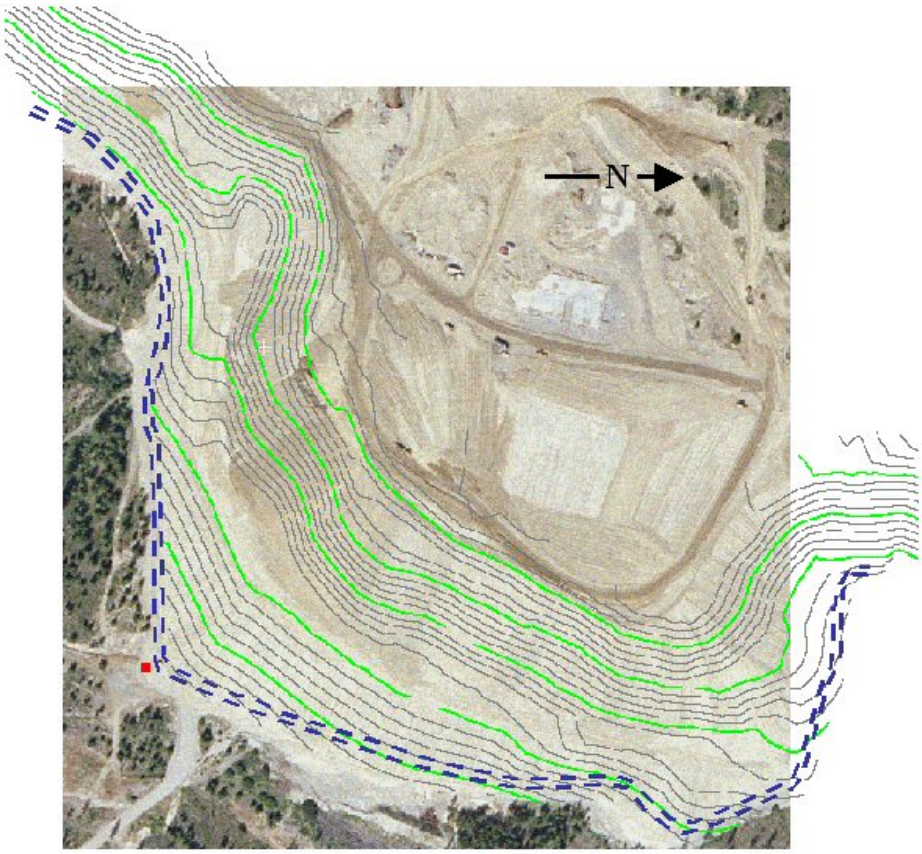

Fig. 2. No. 1 Shaft waste dump. The drain, formerly the ditch, is shown with blue dashed lines along the toe. The monitoring station is the red square at the southeast corner of the dump.

In the 1980s, there was a major conversion of mining methods to mechanized mining using large rubber tired equipment to drill and muck the rock. The waste rock was still removed using the No.1 Shaft hoisting system but the rock was coarser. The oversize rock was placed in designated areas of the dump. The waste rock dump also was used to dispose of other waste materials from the mine such as domestic garbage, industrial wastes such as steel, plastic, wood, etc., spent or residual shotcreted materials, glacial till and other site debris.

Teck Cominco began to examine the water quality downstream of the waste dump and it was found to be affected by the Acid Rock Drainage (ARD) coming from the dump. To eliminate an impact on the receiving waters it was determined the ARD water coming out of the waste rock dump was to be collected and treated at Teck Cominco's Drainage Water Treatment Plant (DWTP). After examining the soils downstream of the dump it was discovered that the dump was placed on a glacial till layer of material overtopped with granular materials. The granular zones were producing springs of contaminated water. In 1995 it was decided to place a drainage ditch around the toe of the dump and collect the water in the ditch and pipe it to the DWTP. This proved to be very effective at intercepting the contaminated water and resulted in substantial improvement in the receiving water quality.

After the toe drainage ditch was put into operation, it was deemed necessary to measure the flow of ARD water from the dump and to sample the water quality. This information was to be used to determine the effectiveness of the reclamation techniques. In 1995 a V notch weir was installed. However, the weir was subject to icing over and it was hard to get a water sample in the winter. In 1997 the weir was surrounded with large concrete blocks and covered by a small building. This became known as No.1 Shaft Waste Rock Dump Monitoring Station (see Figure 3a).

In 2004, the toe ditch was reworked by placing a compacted glacial till impermeable lining in the ditch and on the downstream slope. The ditch was then filled in with coarse rock over topped by finer rock followed by a filter layer of material (see Figure 3b). This was carried out to allow the waste rock to be placed up to and partially over the ditch when the dump was re-profiled for reclamation and geotechnical stability. In 2004 the waste rock in the dump was re-profiled up to and partially covering the toe drainage ditch. In 2005 a 1 m thick layer of glacial till soil cover was placed over the waste rock and the ditch. The surface or uncontaminated water would run off the dump but the contaminated water would be collected. A cross section of the filled ditch, the dump drain and the pipe connection to the monitoring station is shown in Figure 3c.

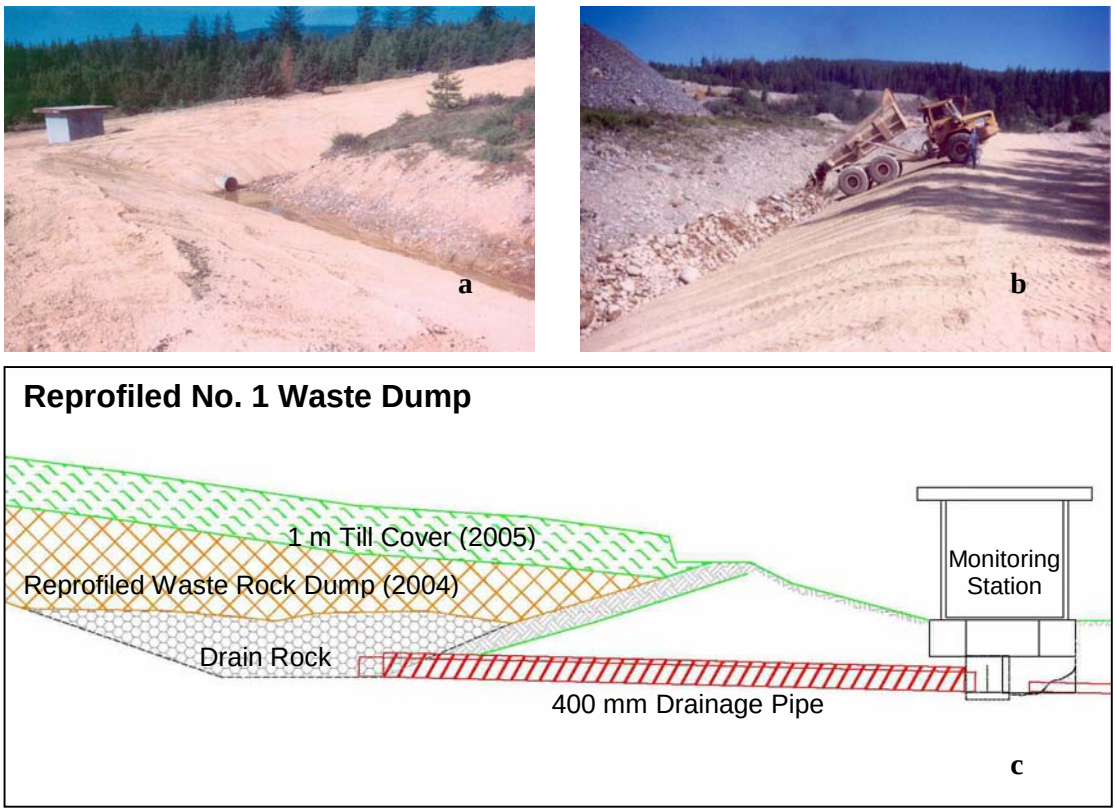

Fig. 3. The monitoring station prior to reclamation (a). Drain rock being placed in the ditch (b). Cross-section showing drain rock, waste rock and till cover in former ditch with 400 mm pipe conveying seepage to monitoring station (c).

MATERIALS AND METHODS

The dump cover was completed in October 2005, under wet conditions. It was left un-vegetated over the winter. In preparation for seeding, the cover was ripped in May 2006, about one week prior to the fatalities.

The initial installation of instruments in the technical investigations occurred in August 2006. Automated instrumentation monitors air velocity in the 400 mm pipe. Gas composition, pressure and temperature are measured at three locations: 2.4 m up the 400 mm pipe, at the end of the pipe, and at approximately waist height in the monitoring station. A weather station is located on a mid-slope bench above the monitoring station, recording air temperature and relative humidity, wind speed and direction, net radiation, barometric pressure and rainfall. Till cover soil moisture and temperature are monitored continuously at two locations on the slope.

In March 2007, six boreholes were drilled and instrumented to allow for the measurement of temperature, differential gas pressure and air composition at several depths within each hole. To check conditions at other locations across the dump, a series of ten additional "push-in" gas piezometers were placed through the cover and into the dump.

A geophysical survey of the site was conducted in October 2007. Resistivity measurements were made along ten transects on the dump to investigate dump heterogeneities and preferential pathways inferred from internal gas composition analysis.

In May 2008, an additional eleven boreholes were drilled and four additional push-in piezometers were installed to expand the investigation of internal conditions. The May 2008 installation was conducted to better understand the causes of dump heterogeneities shown in the geophysical survey, and to further characterize the dump to support a decision on a final remediation plan.

Details on instrumentation and installation methodology have been previously presented [1, 2, 3].

RESULTS AND DISCUSSION

Initial results reported the relationship between air temperature and air velocity [1, 2, 3]. The influence of air temperature on dump respiration has been noted by others [4, 5]. Air temperature controls respiration by affecting the relative density of the interior pore gases. From roughly fall to spring, the internal air is warmer and thus less dense than the surrounding atmosphere and rises up through the dump and exits the cover system, pulling in air behind it. During the summer the opposite condition is true.

Recently collected data have continued to demonstrate the control that atmospheric air temperature has on dump respiration. This control is shown in the relationship between air temperature and the air velocity in the Monitoring Station 400 mm pipe. The air flow through the 400 mm pipe is designated as a positive velocity if the flow is into the pipe and drain; negative, if out of the pipe and into the monitoring station. A comparison of air temperature and air velocity reveals a strong relationship (see Figures 4 and 5) with a pivot point of 10 – 12°C.

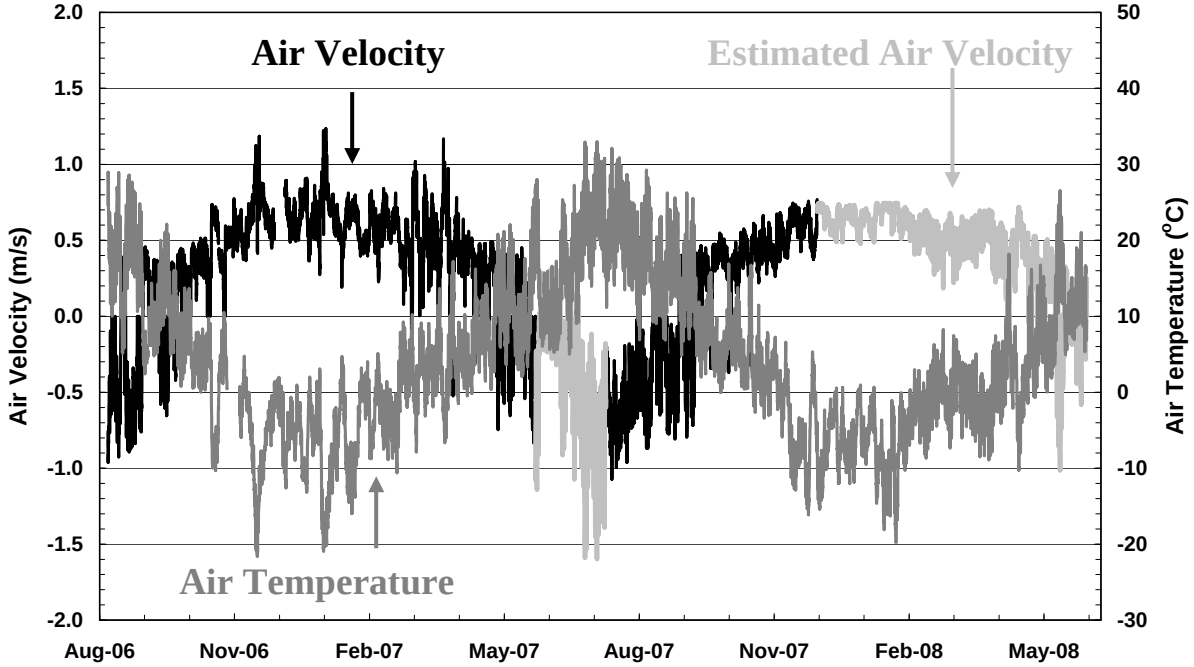

Figure 4. A Comparison of Air Temperature and Air Velocity

During periods of sensor failure, the air velocity is estimated based on the relationship between air temperature and air velocity, shown in Figure 5.

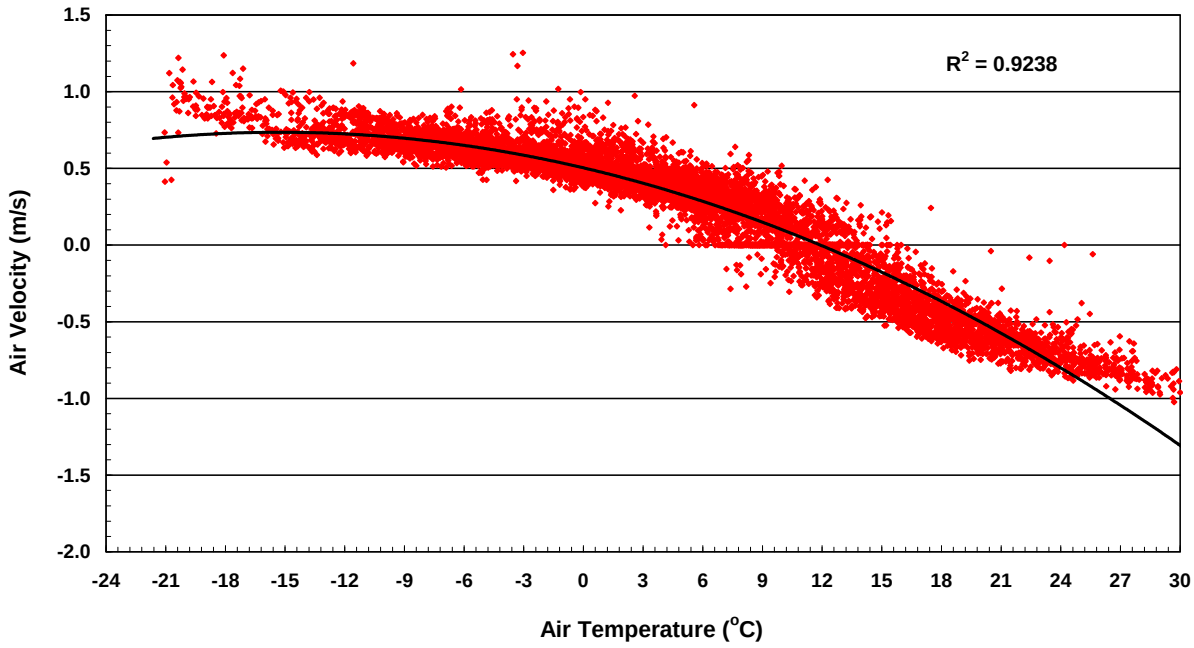

Figure 5. Air velocity versus air temperature.

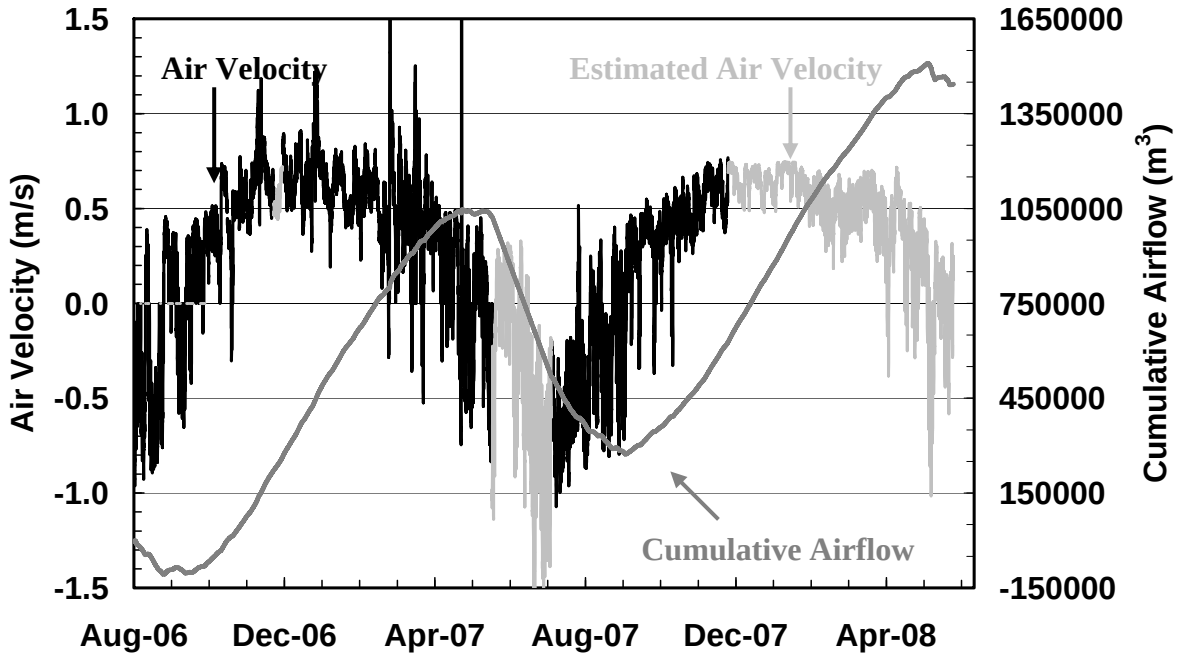

Fig. 6. Air velocity and cumulative air flow.

Knowing the air velocity and the cross-sectional area of the 400 mm pipe that does not contain drainage, the volume of air moving into or out of the dump can be calculated. Figure 6 shows the cumulative airflow volume from August 2006 to June 2008. The change in cumulative airflow during the 2007-2008 winter is less definite than the previous winter because so much of it is based on estimated air velocity; in addition, there were actually brief periods when no airflow when the 400 mm pipe was flooded due to an ice jam downstream in the drainage pipe. Regardless, the calculated cumulative airflow for the 2007-2008 winter is similar to the previous: approximately 1.2M m^3, or four times the estimated dump void space.

The No. 1 Waste Dump airflow pivot point, the temperature at which airflow changes direction, has steadily increased with each periodic evaluation. This could possibly be due to shifts caused by a larger data set. However, the core temperature in BH-1A and BH-1B has increased from approximately 16 to 18 °C in the little more than one year of monitoring, and is it logical to conclude that the pivot point is shifting because the WD1 internal temperature is increasing. Subsets of the air velocity and air temperature data were examined for increases in the pivot point. The subsets were during the three transition periods in the period of record: Fall 2006, Spring 2007 and Fall 2007. Each subset contains the same number of days. For the three periods above, the pivot points were 10.9, 11.1 and 12.4 °C, respectively. While the analysis performed to date treats the air velocity-air temperature relationship as unified, it is important to know that it is dynamic and at some point must be thought of as multiple relationships.

The most recent monitoring data and the additional internal temperature monitoring locations have led to further insights about the processes occurring within the dump, in particular their heterogeneity. New boreholes through the thickest portion of the dump have shown core temperatures of

approximately 20 °C. New boreholes located on the basis of snowmelt patterns have found localized temperatures of 27 °C along the northern crest.

With the different temperatures come different airflow regimes in the dump. While the areas of 18 and 20 °C core temperatures may be part of the general flow system shown in Figures 4 through 6, the 27 °C area along the northern crest appears to have its own flow system. When the pivot point is exceeded and air is falling through the dump and exiting the 400 mm pipe, along the northern crest the internal pore gas is still rising through the dump, an observation supported by pressure gradients and gas composition analysis.

The premature snowmelt area adjacent to the northern crest became the first discovered dump respiration vent area through the till cover. Starting on February 6, 2008, a field gas analyser recorded concentrations of 6% oxygen at the surface. Oxygen measurements commonly return to 20.9% within 15 cm of the surface, demonstrating the rapid mixing that occurs.

REVIEW OF AIR QUALITY INCIDENTS AT MINE SITES

Following the fatalities, gas samples were collected from the monitoring station on May 18 and 20, 2006. Both samples revealed concentrations of approximately 2% oxygen and 7% carbon dioxide; the carbon dioxide was shown to have an inorganic origin. The gas composition can result from standard geochemical reactions common in sulfidic waste dumps with carbonate minerals present. The oxidation of metal sulfides, such as pyrite, consumes oxygen and produces acidity (Equation 1). Carbonate minerals, if present, can then consume acidity, producing carbon dioxide in the process (Equation 2).

$$2Fe_2S + H_2O + 3.5O_2 \rightarrow 4Fe^{2+} + 2H^+ + 2SO_4 \quad (1)$$

$$2H^+ + CaCO_3 \rightarrow H_2O + Ca^{2+} + CO_2 \quad (2)$$

The analysis of drill cuttings clearly showed that both sulfide minerals and carbonate minerals are present in the rock. The sulfide minerals were expected; the lead and the zinc in the Sullivan ore occur as sulfides and there are also abundant iron sulfide minerals. The carbonate minerals were not expected, but there was evidence of carbonate in most of the chemical analyses, and the carbonate mineral calcite was identified in about half of the mineralogical samples; the percent sulfide and carbonate were less than 3% and 1%, respectively. Carbonate minerals were also found in samples of the till material that was used to cover the dump and which form the base of the drainage collection system running beneath the dump toe.

Hazardous gases arise from many other sources in mining. In *Naturalis Historia* (77 AD) Pliny the Elder describes using fire to break rock underground and notes the production of toxic fumes [6]. Setting fires was still in practice in the mid-1500s; *De Re Metallica* discusses this method, notes headaches caused by what was likely carbon dioxide poisoning in stagnant air, and thoroughly reviews ventilation techniques of the day [7]. Terms like blackdamp, chokedamp, stythe, whitedamp, and firedamp have described air with dangerous levels of carbon dioxide, carbon monoxide, and methane, respectively. From canaries to flame tests, methods to assess air quality were used prior to modern equipment. A miner's headlamp was a valuable tool not just for illumination; the lamp would

be extinguished before oxygen levels were acutely dangerous and thus served as a warning of bad air [8, 9, 10].

A review of recent depressed oxygen mining incidents was undertaken by conducting searches of newspaper reports and journal articles. The largest number of incidents found in the review were connected to coal mining.

In Great Britain, the presence of depressed oxygen and elevated carbon dioxide is known as stythe. Recent stythe and methane incidents at the surface, beginning in the 1980s, commonly occur where homes or other inhabited structures overlie historic coal mines [11]. In response to rising water in the now closed mines and low-pressure weather events, stythe and methane emerge into the structures to yield various effects: confusion, blurred vision, headaches, the inability to maintain pilot lights or lit cigarettes, and death. Stythe has claimed lives; the most recent involved workers installing sewer pipes in a trench. In one incident a dog and his master died in a stable without the horses being affected. It is believed the dog, being close to the ground was overcome first, and the master succumbed upon checking on the dog [12, 13].

In response to stythe incidents in Great Britain, local governments began to raise public awareness with information campaigns [14]. Mitigation steps have included monitoring, reviewing mine records and surveying structures in high-risk areas, sealing shafts, and installing ventilated boreholes to intercept stythe before it can enter a building. In the village of Arkwrightone the danger from methane was so widespread that entire village of approximately 200 people was moved [11, 13]

Incidents similar to those in Great Britain have occurred in Appalachian coal mining regions of the United States. After a West Virginia couple was experiencing strange symptoms, investigators found elevated levels of carbon dioxide in their basement and crawl space, which lead to a National Institute of Industrial Safety and Health (NIOSH) 2005 report warning of the risk posed by carbon dioxide to indoor air quality [15, 16]. Recognizing the dangers in coal producing regions, in 2001 the Appalachian Regional Coordinating Center of the Office of Surface Mining issued a report to “facilitate future methane investigations” [17]. In 2001 a Pennsylvania family suffered carbon monoxide poisoning. The source was blasting at a surface coal mine 500 ft away; the carbon monoxide had migrated through fractures to their home [18, 19].

The only asphyxiation incident discovered in literature that involved a metal mine and geochemically-produced gases occurred at an abandoned property in 1996. Two adults were overcome by carbon dioxide in an abandoned silver mine near Virginia City, Nevada after bypassing a fence and walking past a sign warning: “Keep Out – Bad Air” [20]. A review of U.S. Mine Safety and Health Administration annual fatalities reports from 1999-2008 showed only four incidents of asphyxiation. All four incidents occurred at abandoned, makeshift or small-scale mines and were likely the result of equipment exhaust [21].

In nearly all of these cases there’s a component of a sheltered or confined space that restricts air movement and allows dangerous gases to collect or linger. A 1990 incident in McDowell County, West Virginia demonstrates that a confined space is not needed. An elementary school maintenance worker was mowing the grass on the playground when the mower engine cut off. When he bent down

to investigate, the worker fell over. Elevated levels of carbon dioxide were exhausting from an abandoned portal adjacent to the playground [22].

Drawing on lessons from across the mining industry is certainly important, but an incident in Wisconsin shows that the transport of poor air quality is important regardless of the setting. Four persons were killed at a landfill dump in 2007. The landfill had a buried drain system to intercept seepage with manholes to access the drain. Work was being performed to repair a pump in the drain. A worker was in the drain approximately 10-minutes prior to the start of the incident without any sign of adverse conditions. One worker was overcome by hydrogen sulfide and the others in turn tried to rescue those that had fallen. No steps are planned to determine the trigger for air movement at the landfill. Once it was determined the landfill company did not observe that confined space regulations, no further investigation was needed. It is currently unknown if landfill pore gas moved into the drain in response to changes in air temperature or pressure or that other factors may have been involved [23, 24].

The 2005 NIOSH report evaluated the incident of West Virginia couple that suffered carbon dioxide poisoning. The homeowners began to have problems shortly after moving into the newly built house in 2001. A pilot light in the basement kept going out and the utility company performed several inspections. Suspicious at times of a gas leak, the fire department performed several inspections. Testing for carbon monoxide and methane was performed but abnormal levels were never discovered. The first floor became an affected area and serious health problems began in mid-2003. It wasn't until December 2003 when a Hazardous Incident Response Team's sweep for 35 gases showed no detectable levels, that the West Virginia Department of Environmental Protection began to suspect carbon dioxide. The house had been built on a reclaimed coal waste dump, which itself sat above an abandoned underground coal mine. Similar to reviews of the Sullivan Mine incident, the NIOSH report recommends that first responders be trained about the dangers of oxygen-deprived environments [15, 25].

CONCLUSIONS

In response to four fatalities at the Sullivan Mine No. 1 Shaft Waste Dump, an investigation was begun to understand the processes that resulted in low-oxygen, high carbon dioxide gas entering the monitoring station. With a pivot point of approximately 10-12 °C, air temperature is observed to be the dominant respiration control. Conventional geochemical reactions explain the consumption of oxygen and generation of carbon dioxide; however, the resulting gas density change is very small and alone is unlikely to be a major driver in gas flow. Summer and winter air temperature extremes straddle the moderate internal temperature profile, confirming air temperature as the dominant controlling factor for air flow at the No. 1 Shaft Waste Dump.

A review of reports on gas-related fatalities at closed or abandoned mine sites has shown that the vast majority are related to coal mining. The much smaller number of gas-related fatalities at metal mines all appear to involve people entering abandoned shafts or adits. The Sullivan fatalities, at a metal mine waste dump that had been closed using state of the art methods, indicate that the hazards are broader than previously thought.

While data on the Sullivan case continue to be gathered and assessed, the Technical Panel believes that all individuals responsible for safety on mine sites should be aware of the hazards associated with waste dump air, and that the risks should be stated as broadly as possible. Based on the findings to date, the presence of any of the following should be considered to significantly raise the risk level:

- Sulfide minerals in waste rock, which can deplete oxygen from air;
- Any combination of sulfide minerals and carbonate minerals, which can lead to production of carbon dioxide;
- Air temperatures that are higher than temperatures within waste dumps, which can lead to temperature driven outflows of dump air;
- Sharp drops in barometric pressure, which can lead to pressure driven outflows of dump air;
- Any factors that serve to concentrate or confine dump air outflows, including soil covers, toe drains, and water sampling pipes, but also including coarse rock channels formed naturally during dumping, finer rock layers formed by traffic or re-grading, and localized excavations into the dump toe;
- Any factors that serve to limit the mixing of out-flowing gases with the surrounding air, including monitoring stations but also any other walls or berms, heavy vegetation, and local ground depressions, as well as barometric inversions or similar weather conditions that cause pockets of air to accumulate in depressions.

Although the above risk factors are stated in terms of waste rock dumps, some of them may also be present in tailings dams, tailings piles, ore stockpiles, and other site components. At this time the Technical Panel is not limiting possible affected areas to those confined by a structure. It is possible that open areas, such as a low-lying area on a calm day or a sheltered ravine at a dump toe, could harbour impacted gas that pose a risk. The Technical Panel recommends that mine sites conduct risk assessments of site components where these factors may be present and use the findings to develop safe work procedures.

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