

# **Sullivan Mine Fatalities Incident: Key Conclusions and Implications for Other Sites<sup>1</sup>**

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## **ABSTRACT**

In May 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 was connected hydraulically, via a pipe and dump toe drain, to the covered acid generating waste rock. A panel was formed following the fatalities to investigate the technical aspects of the incident and disseminate findings to the mining industry. The background to the incident, the subsequent two-year instrumentation and monitoring program, and the numerical modeling of gas transport within the dump have been reported in the accompanying papers. This paper addresses the question of whether hazards of this type are likely to be present elsewhere. Three underlying factors are considered: the geochemical processes that alter the composition of gas within mine wastes, the physical processes that can cause release of the altered gases, and the level of confinement required to create a hazard. Conditions that increase the hazard potential are identified.

Additional Key Words: mine waste, waste rock, gas transport, oxygen depletion, hazards.

## **INTRODUCTION**

In May 2006, four fatalities occurred in a water sampling shed located at the toe of the No. 1 Shaft Waste Dump at the Sullivan Mine, near Kimberley BC, Canada. The investigations reported in the accompanying three papers have led to a good understanding of the physical and chemical processes that created the asphyxiation hazard in the sampling shed (Dawson *et al.* 2009, Phillip *et al.* 2009, Lahmira *et al.* 2009).

A review of asphyxiation incidents at other abandoned mines was summarized by Phillip *et al.* 2008. It concluded that the vast majority were related to coal mining or people entering abandoned shafts or adits, and that the Sullivan fatalities may indicate that the hazards are broader than previously thought. This paper presents a mechanistic analysis of the underlying physical and chemical processes, and attempts to identify the ranges of waste rock properties, atmospheric conditions and site geometries that could lead to development of hazardous conditions.

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<sup>1</sup> Paper was presented at Securing the Future and 8<sup>th</sup> ICARD, June 22-26, 2009, Skellefteå, Sweden.

The investigations to date show that the processes contributing to the fatalities at the No. 1 Shaft Waste Dump include the following:

- Development of hazardous gas within the waste;
- Transport of the hazardous gas to the dump toe;
- Concentration of the gas flow by the combined effects of the soil cover, the toe drain and the sampling pipe; and
- Confinement of the outflowing gas by the sampling shed.

The following sections analyze the fundamental chemical and physical processes underlying each of the above, to assess whether they are likely to create hazardous conditions elsewhere.

## **DEVELOPMENT OF HAZARDOUS GASES**

The oxidation of sulphide minerals in waste rock consumes oxygen and can create dangerously low levels of oxygen in the pore gas. This is clear from the internal monitoring of the Sullivan No. 1 Shaft Dump, and similar monitoring at many other dumps. In fact, one objective of many cover designs is to reduce the oxygen concentration within the waste to levels that restrict the release of metals.

The rates of oxidation measured in waste rock range from  $1 \times 10^{-11}$  to  $1 \times 10^{-7}$  kg of oxygen per cubic metre of rock per second. To give an indication of what those rates mean, Table 1 summarizes the hazards associated with varying levels of oxygen depletion and Figure 1 shows the amount of contact time required to reduce the oxygen concentration to each of the effect levels from Table 1. The figure shows, for example, that a moderately reacting waste rock, with an oxidation rate of  $1 \times 10^{-9}$  kg/m<sup>3</sup>s, can completely deplete oxygen in less than a few hours of contact time. Even a less reactive waste rock, with an oxidation rate of  $1 \times 10^{-10}$  kg/m<sup>3</sup>s, can drop oxygen to the 14% level that would cause “faulty coordination, impaired judgment” in about a day of contact time.

The contact time between the waste rock and its pore gas will depend on how fast the gas moves, and the length of the gas flowpath. In waste rock piles with zones of active gas circulation, gas flowrates of up to 100 m/d have been measured or inferred (Lefebvre et al 2001c). Only rapidly reactive waste rock is capable of creating such low concentrations when flowrates are that high. However, intermittent stagnant periods comparable to the pore gas residence times indicated in Figure 1 can lead to much lower oxygen concentrations in gas that could subsequently be transported to the dump surface. Internal monitoring has shown the presence of stagnant or poorly circulating areas in waste rock piles, where the contact time is effectively infinite and very low oxygen concentration develops (e.g. Hockley et al 2001, Lefebvre et al 2001b).

If carbonate minerals are present, neutralization of the acidity arising from the sulphide oxidation can release carbon dioxide. Table 2 shows the effects of exposure to various carbon dioxide concentrations. Figure 2 shows the contact time between waste rock and gas needed to reach each level of carbon dioxide hazard. As was the case for oxygen levels shown in Figure 1, moderately or rapidly reactive waste rock can create hazardous levels of carbon dioxide with contact times of a day or less. Hockley et al (2001) reported carbon dioxide concentrations of 3-

10% in the actively convecting zone of the Nordhalde waste rock pile near Ronneburg, Germany, and up to 45% in stagnant zones.

Table 1. Effects of acute exposure to oxygen deficient air (McManus, 2009).

Oxygen	Effects
20.9%	O <sub>2</sub> in normal dry air (vol/vol)
>16%	No symptoms
16%	Increased heart and breathing rate, some incoordination, increased breathing volume, impaired attention and thinking
14%	Abnormal fatigue upon exertion, emotional upset, faulty coordination, impaired judgment
12%	Very poor judgment and coordination, impaired respiration that may cause permanent heart damage, nausea and vomiting
<10%	Nausea, vomiting, lethargic movements, perhaps unconsciousness, inability to perform vigorous movement or loss of all movement, unconsciousness followed by death
<6%	Convulsions, shortness of breath, cardiac standstill, spasmodic breathing, death in minutes
<4%	Unconsciousness after one or two breaths

Table 2. Effects of exposure to carbon dioxide (McManus, 2009).

Carbon Dioxide	Effects
0.035%	CO <sub>2</sub> in normal dry air (vol/vol)
0.55%	No noticeable effect after five hours
1.5%	No measurable effect long-term
3%	Slight effect (with normal oxygen content), weakly narcotic, reduced hearing acuity, increased blood pressure and pulse
4%	Respiratory volume doubled
5%	Respiratory volume re-doubled
7.5%	Headache, restlessness, dizziness after 7-15 minutes
7.6%	Increase in heart rate and blood pressure, shortness of breath, throbbing headaches, dizziness, vertigo, poor memory, inability to concentrate, photophobia
>10%	Unconsciousness
11%	Unconsciousness in less than one minute
30%	Unconsciousness in less than 25 seconds

Notes to Tables 1 and 2.

- Concentration values assume dry air at sea level pressures; oxygen deficiency effects will be more significant at higher altitudes.
- Combinations of oxygen deficiency and carbon dioxide excess can have significantly greater effects than shown in the individual tables.

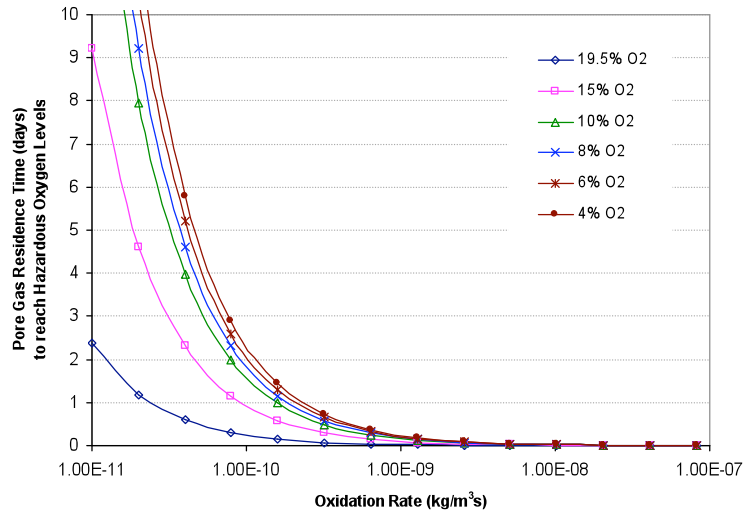


Figure 1. Oxygen content in pore gas of reactive waste rock as a function of oxidation rate and residence time. Assumes dry gas at 20°C and 760 mmHg (101.325 kPa), waste bulk density of 1900 kg/m<sup>3</sup>, and air-filled porosity of 0.15.

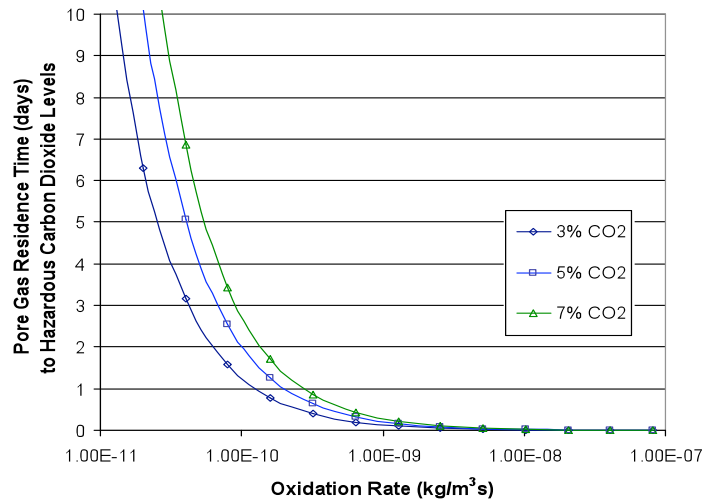


Figure 2. Carbon dioxide levels in pore gas of waste rock as a function of oxidation rate and residence time. Assumes stoichiometric ratio of 1 mole CO<sub>2</sub> production per 3.5 moles of O<sub>2</sub> consumption, as well as other assumptions of Figure 1.

### GAS TRANSPORT WITHIN WASTE ROCK

The reaction of oxygen with sulphide minerals release heat, as does the reaction of carbonate mineral with acidity. In a waste rock pile, the heat released from the chemical reactions causes a warming of the dump interior, and that warming leads to thermal convection of the pore gas. Increasing the temperature of a gas causes it to expand and become less dense or, in simple terms, lighter. Figure 3 shows the effect of temperature on the density of dry gas. The rightmost points on the triangles indicate the density of dry air at various temperatures. The remainder of the triangles are explained below.

When the gas becomes warm enough and light enough, it will start to rise. The result is a thermal convection process that is exactly analogous to the one that has been studied by physicists for decades. In the classic physics experiment, oil is sandwiched between two metal plates and the bottom plate is heated while the upper plate is cooled. Once a critical temperature difference is reached, the oil starts to rise from base, creating a series of circulation cells. The circulation effect occurs in broad flat areas of waste rock, and in fact also in unreactive rock subject to seasonal heating and cooling (e.g. Lebeau & Konrad, 2007).

Near the outside edge of a waste rock dump, the process is slightly different. Figure 4 shows a simple schematic that helps to explain this case. The schematic shows a flowpath through a waste rock dump, and connects it to hypothetical flowpaths in the surrounding atmosphere. When the gas within the dump is warmer than the surrounding air, it expands and becomes less dense. The combination of lighter air within the dump, heavier air outside the dump, and the connections along the slope create an imbalance that leads to an upward flow. Convection begins at lower temperature differences along a slope than it does in the classical physics case of a single flat layer. In other words, thermal convection is more likely along the outside edge of a waste rock pile.

Figure 4 also shows the case where the atmospheric temperature rises above that of the dump interior. The pore gas within the dump is now “heavier” than the surrounding atmosphere, and the result is a downward flow within the dump and an outflow at the dump toe. This situation is only possible along the outside edge of a waste rock dump.

There is another driving force for convection in waste rock piles. The changes in oxygen and carbon dioxide content noted in the preceding section also affect the density of the pore gas, and can lead to the same types of flows arising from temperature changes. Oxygen is one of the heavier components of air, so its depletion tends to make the pore gas within waste rock piles lighter. Carbon dioxide is also heavier than other components of air, so its addition to pore gas tends to make it heavier. The triangle in Figure 3a shows the range of densities caused by oxygen depletion and stoichiometric carbon dioxide addition on a gas held at 20°C and standard pressure. It shows, for example, that complete depletion of oxygen without any carbon dioxide addition causes the density of air to drop by about 2.8%, which is roughly equivalent to the effect of a 7°C increase in temperature. Water vapour has a similar effect. It is lighter than air and its addition to dry pore gases as they pass through moist rock further contributes to the lower density. At 40°C, for example, saturated air is about 2.5% lighter than dry air. The effects of oxygen depletion and water vapour addition may partially explain why upward gas outflows from waste rock seem to be more common than downward outflows. In the case of the Sullivan No. 1 Shaft Dump, carbon dioxide addition partially compensates for the density changes caused by oxygen depletion, and probably contributes to the ease at which gas flows change direction (Phillip *et al.* 2009, Lahmira *et al.* 2009).

The main constraint on thermal or other density driven convection of gases in waste rock is the limited permeability of the matrix. Waste rock permeabilities for gas flows are influenced by both the grain size of the material and the amount of water blocking the pores. Effective permeabilities reported in the literature range from about  $10^{-8} \text{ m}^2$  to about  $10^{-12} \text{ m}^2$ . Assuming that the effective permeability of the waste rock is known, it is possible to use a form of Darcy’s

equation to convert temperature or density differences such as those shown in Figure 3 into estimates of gas flow rates. The model described in the accompanying paper by Lahmira *et al.* (2009) does this conversion rigorously.

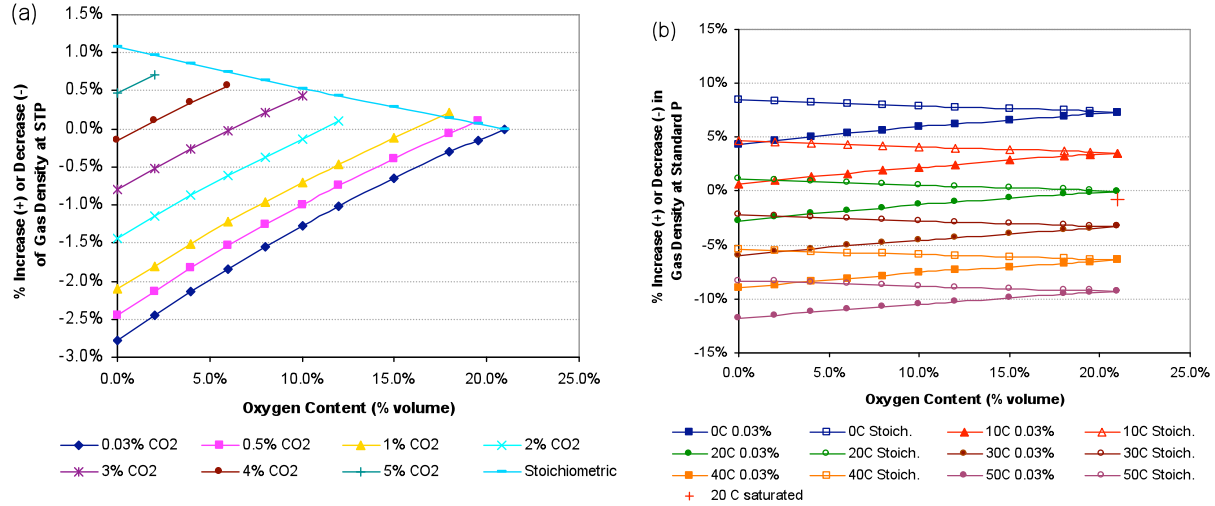


Figure 3. Effects of waste rock on gas density. (a) Effect of oxygen depletion and carbon dioxide addition. Rightmost point is dry air. Lower line shows effect of oxygen removal only. Other lines show effects of increasing carbon dioxide addition. Upper line shows effect of oxygen depletion and stoichiometric carbon dioxide production, at 3.5 moles oxygen per mole carbon dioxide. (*n.b.* In stagnant pore air, it is possible for carbon dioxide to collect and reach concentrations above the stoichiometric line.) (b) Effects of oxygen depletion, carbon dioxide addition, and temperature. The triangle centered at the 0% line is the upper and lower curves from Figure 4a (i.e. 0.03% CO<sub>2</sub> and stoichiometric CO<sub>2</sub>), and represents the range of density changes when the temperature is fixed at 20°C. Other triangles show the range of density changes for different temperatures. All curves are for dry gas. The + symbol indicates the effect of adding water vapour, and represents air at 20°C saturated with water vapour.

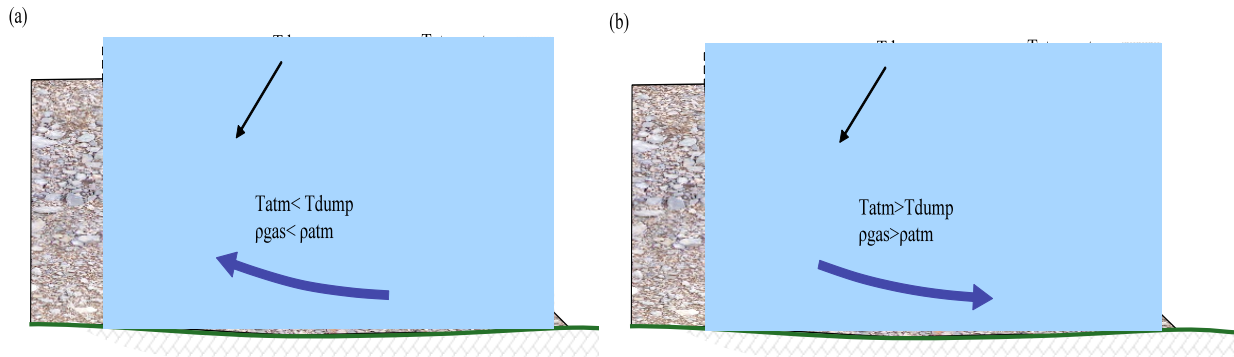


Figure 4. Simple flowpath model for gas flow in waste rock, and relationships among temperature, density and flow direction.

Figure 5 shows results of a simplified model set up in a spreadsheet. The simplified model uses the flowpath analogy shown in Figure 4, but is able to predict the relationship between temperature and gas flowrates reported in other papers. Figure 5a shows the predicted gas flowrates in a waste rock dump with an internal temperature of 65°C, for a range of effective permeabilities and a range of air temperatures. Since the dump is always warmer than the air in this case, the gas flow is always upwards. Figure 5b shows the case where the dump internal temperature is only 15°C, which results in upward gas flows when the atmosphere is cooler than 15°C and downward gas flows when it is warmer. The simple model clearly reproduces the dominant effect of temperature on flow direction that was noted in the data from the Sullivan No. 1 Shaft Dump.

The other noteworthy feature in both Figure 5a and 5b is the extremely strong effect of the waste rock permeability on the gas flowrate. No other factor in the analysis has such a wide range of values and such a direct effect on predicted flowrates. Given the difficulty in estimating permeabilities of coarse grained material, these results indicate why our ability to quantitatively predict gas flowrates from waste rock piles is limited.

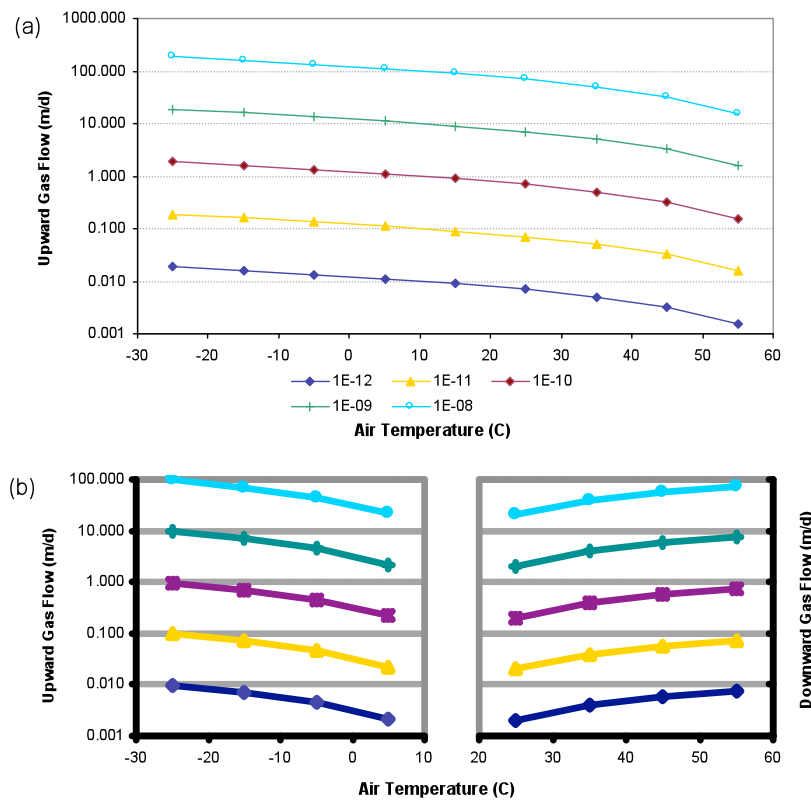


Figure 5. Gas flowrates for combinations of air temperature and waste rock permeability. Legend shows waste rock permeability in  $\text{m}^2$ . (a) Internal dump temperature of 65°C, resulting in upward gas flow for all values of air temperature. (b) Internal dump temperature of 15°C, with gas flows upward when air temperature is below 15°C and downward when air temperature is above 15°C.

The simplified flowpath analogy can also be extended to cases where waste rock dumps are covered, and the cover has a lower effective permeability than the waste. Along the (one-dimensional) flowpath, the effect is to reduce the overall average permeability to the geometric mean of the cover and waste permeabilities. For example, covering a waste that has a permeability of  $10^{-8} \text{ m}^2$  with a cover that has a permeability of  $10^{-11} \text{ m}^2$  reduces the overall average permeability and therefore the gas flowrate by about 20 times. A cover permeability of  $10^{-10} \text{ m}^2$  would only reduce the average permeability and gas flowrate by about three times. These estimates vary depending on assumptions about the length of the flowpath and the thickness of the cover, but the pattern is always the same. Very significant differences in permeability are needed to make significant reductions in gas flowrates. It is worth noting that *a priori* estimation of cover permeability is also difficult. For example, the best-fit model of the Sullivan No. 1 Shaft Dump (Lahmira *et al.* 2009) indicates that the wet till cover has an overall effective gas permeability of  $5 \times 10^{-12} \text{ m}^2$ , which is about two orders of magnitude higher than initially estimated from grain size and moisture content data (Lefebvre *et al.* 2008).

### **CONCENTRATION OF GAS FLOWS**

The other effect noted within the Sullivan No. 1 Shaft Dump was the concentration of gas flows caused by the covered toe drain. Observations reported by Phillip *et al.* (2009) indicate that the coarse rock in the toe drain allows upward gas flow to move preferentially along the base of the dump. It probably plays a similar role when the gas flow is downward, acting to funnel gas towards the sampling pipe.

Flow concentrating effects are straightforward in concept; they can be visualized as highly permeable flowpaths in the simple model of Figure 4. It is much harder to characterize the extent to which such effects actually occur. A concentration of coarse bouldery material is commonly observed along the toe of waste rock deposits. In order to fit an air flow and reaction model to field measurements in a waste rock pile at the Questa Mine in New Mexico, Wels *et al.* (2003) found it necessary to assume an underlying “boulder layer” with permeabilities up thirty times higher than the “bulk of material”. But Lahmira *et al.* (2007) also showed that relatively small heterogeneities in grain size distributions can interact with moisture contents to create preferential flowpaths for gas in waste rock.

The geophysical and drilling investigations at the Sullivan No. 1 Shaft Dump, reported by Phillip *et al.* (2009), appear to be the first detailed investigation of internal dump heterogeneity and its effect on gas flow. The effect of the heterogeneity is evidenced by the fact that Lahmira *et al.* (2009) had to significantly increase the initial estimates of the waste permeability in order to match the observed gas flowrates.

Using the simple flowpath model, it also can be shown that higher permeability zones in a dump cover have two negative effects: they increase overall gas flowrates through a dump and they concentrate gas outflows. The observations of snowmelt patches on the No. 1 Shaft Waste Dump are clear evidence of the latter effect.

### **GAS DISCHARGE AND CONFINEMENT**

The preceding sections show the conditions that create hazardous gases within waste rock pores, and that transport gases to the waste rock surface or toe. Once the gas flows out of the dump, it



enters into a complex set of interactions with the surrounding atmosphere, topography and structures. The nearly infinite number of possible circumstances can be grouped on the basis of whether the gas outflow is confined or unconfined, and whether it behaves as a buoyant, passive, or dense gas.

Confinement of a gas outflow clearly increases the hazard, regardless of the other conditions. Even at very low gas flowrates, confinement can create significant hazards. In one of the cases reviewed by Phillip *et al.* (2008), a Pennsylvania family suffered carbon monoxide poisoning when gases from open pit blasting over 500 feet distant entered their basement, apparently through fractures in the ground. At the high gas flowrates that the previous sections indicate are possible, even partial containment could be enough to create a hazard. As a hypothetical example, a tent pitched on the crest of a waste rock pile with a gas outflow rate of 10 m/day would not completely confine the gas. But the rate of gas exchange through the tent could be significant enough that an occupant would be exposed to essentially undiluted pore gas.

If the outflowing gas is not confined, the level of hazard will depend on how fast it disperses in the surrounding atmosphere. To examine that question, air pollution researchers have found it useful to distinguish among gases that are buoyant, passive, or dense.

Buoyant gases, and the name suggests, are lighter than the ambient air. If the gas flowing out of a waste rock pile is buoyant, either because it is warmer or because of the effects of oxygen depletion or water vapour addition, it will continue to rise. This condition represents the lowest risk, but it would be going too far to assume there is no risk. Combinations of atmospheric stability and long-duration outflows over broad areas could conceivably create hazardous gas concentrations at normal breathing height. Furthermore, the possibility of a “receptor” nearer to the ground level cannot be ruled out. Reduced oxygen concentrations were measured just above the ground level in the snowmelt areas on the Sullivan No. 1 Shaft Waste Dump, and could be hazardous to animals at ground level or even to humans who sit or lie on the ground.

Dense gases, in the air pollution jargon, are those that are heavier than the ambient air. As the above section shows, waste rock pore gas can become heavier through the addition of carbon dioxide, or when the dump internal temperature is lower than that of the surrounding atmosphere. Even when such conditions exist within a waste pile, the mixing that occurs at the ground surface can disperse the gas before it forms a dense pool. Under the range of gas densities and outflow rates typical of waste rock piles, dense gas pools are only likely to form at windspeeds less than about 2 m/s. However, low windspeeds can be quite common at night or under other very stable atmospheric conditions. The Sullivan data indicate that windspeeds of less than 1 m/s are observed about 20% of the time at the No. 1 Shaft Waste Dump.

Perhaps the most hazardous situation would be one where a dense gas outflows from the toe of a dump and travels downhill to a topographic low point. In a 1990 incident in West Virginia, also reported in Phillip *et al.* (2008), an elementary school maintenance worker was incapacitated by elevated levels of carbon dioxide exhausting from an abandoned portal adjacent to the school playground. The physics of “density-stratified flows” is complex and it is difficult to derive general criteria. One idealized case analyzed by Castro *et al.* (1993) provides some insights into when such processes could result in a persistent pool of dense gas. Figure 6 shows the results for

various combinations that might be typical of gas outflows from waste rock into small stream valleys. The results indicate that gas outflow rates would need to be high, for example as a result of flow concentrating effects inside the dump or permeable zones in the cover.

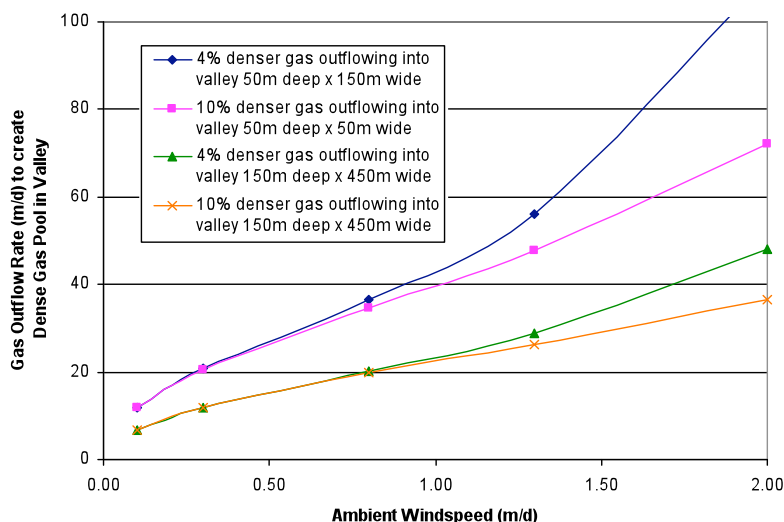


Figure 6. Gas outflow rates predicted to form dense pools, for various density differences and valley dimensions, based on wind tunnel experiments by Castro et al. 1993. Gas is assumed to be emitted from one side of valley.

## CONCLUSIONS

Mechanistic analysis of the physical and chemical processes that contributed to the Sullivan fatalities indicates that there are likely to be other similarly hazardous situations at other waste rock piles. It is clear that the reactions that take place within waste rock piles can produce hazardous gases, and that density differences caused by heating, cooling or changes in composition can cause the hazardous gases to move. Gas flows are likely to be upward in most cases, but downward flow of pore gas is possible, especially in situations where the waste rock temperature is intermediate between extremes of the local air temperature. In general, pore gases within the dump will flow upward and out the top of the dump when temperatures inside the dump exceed air temperatures, and downward when the dump temperatures are lower than air temperatures. Depletion of oxygen and addition of moisture to the pore gas tends to favour upward flow, whereas addition of carbon dioxide tends to favour downward flow. Overall gas flowrates are most strongly influenced by the waste rock permeability, but heterogeneities in the material are capable of creating distinct flow channels. Low permeability covers tend to slow overall gas flows, but again heterogeneity has important influences; permeable zones in the cover act to increase overall flows and, more importantly from a hazard perspective, concentrate outflows. Any form of confinement of the gas outflows will significantly increase the likelihood that hazardous concentrations will develop. However, even in the absence of confinement, hazardous conditions could develop when outflows are strong and/or when the outflowing gas is heavy enough to form dense gas flows or pools.

Consideration of the hazards associated with any particular dump needs to take into account the whole range of physical and chemical processes and their variability. There will be significant uncertainty in any estimates of oxidation rates, waste permeability and cover permeability, as well as inherent uncertainty in the rates at which outflow gases will disperse. In the authors' opinion, it will be difficult to rule out *a priori* the possibility of hazardous conditions developing at any dumps that have a measurable oxidation rate. A precautionary approach is warranted.

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