Sullivan Mine Fatalities Incident: Numerical Modeling of Gas Transport and Reversal in Gas Flow Directions

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ABSTRACT
The Sullivan Mine No. 1 Shaft Waste Rock Dump is located on a natural slope and covered by till. The outflow of oxygen-deficient gas through a leachate drainage pipe in an enclosure at the base of the dump resulted in four fatalities in May 2006. A numerical model was developed to understand controls on gas flow, which was found to be related to the relative buoyancy of the dump gas phase compared to atmospheric air. Changes in atmospheric air density are caused by atmospheric temperature variations, whereas the dump gas phase density is fixed by the steady internal dump temperature. When atmospheric temperature is lower than the internal dump temperature, atmospheric air density is higher than dump gas density, inducing upward dump gas flow and air entry in the pipe. Instead, downward dump gas flow occurs and exits the pipe when high atmospheric temperature leads to an air density lower than dump gas density. A similar gas flow behavior would still occur without the pipe or without the till cover, indicating that the observed gas flow conditions could be present in other waste rock dumps.

Additional Key Words: waste rock, buoyancy, atmospheric temperature, barometric pressure, dump cover, personnel security.

INTRODUCTION
The Sullivan Mine, now closed and reclaimed, is located adjacent to Kimberley, British Columbia (B.C.), Canada. The No. 1 Shaft Waste Rock Dump was built from the 1940’s to 2001, principally by the deposition of waste rock from the No. 1 Shaft. Waste rock was deposited along a natural slope on bedrock to attain a total height of approximately 55 m. The dump was subsequently resloped and covered with a 1 m till layer.

A fatal accident occurred in May 2006 at the No. 1 Shaft Waste Dump of the Sullivan Mine, B.C. This accident was thought to be related to the downward flow of oxygen-deficient air originating from within the waste dump. That air was presumed to have entered a water sampling enclosure located at the base of the waste dump through the waste dump’s drainage pipe. This paper reports on a numerical model study which had

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the objective of testing the plausibility of various physical mechanisms that were hypothesized to be controlling gas flow in the dump. Companion papers provide a description of the site and the characterization and monitoring program (Dawson et al. 2009; Philip et al. 2009).

NUMERICAL MODELING OF GAS FLOW IN WASTE ROCK DUMPS

General waste rock dump modeling approach
The numerical simulator TOUGH AMD was used to develop a model representing the No. 1 Shaft Waste Rock Dump. TOUGH AMD represents multiphase transfer processes and reactions within acid-generating rock piles containing pyrite (Lefebvre et al. 2001a, 2001b). The numerical simulator TOUGH AMD considers heat and three components: water and air subdivided in two components (oxygen and the other air gases). Oxygen is consumed by pyrite oxidation, which has first-order kinetics relative to oxygen. A reaction core model represents the pyrite oxidation kinetics in mine rock.

Waste rock dumps which generate acid mine drainage (AMD) are partially water saturated media within which oxygen consumption occurs due to sulfide oxidation (primarily pyrite), which leads to heat production (Lefebvre et al. 2001a). Numerical simulation of AMD in waste rock dumps thus involves the simultaneous estimation of four unknowns to determine the state of the system (gas pressure, water saturation, mass fraction of oxygen and temperature). The simulator must also calculate the equation of state defining the equilibrium concentration of components (water, air and oxygen) in the two fluid phases (gas and liquid) as a function of temperature.

Simplifying assumptions for the No. 1 Shaft Dump modeling
Compared to the general case of AMD in waste rock, conditions prevailing in the No. 1 Shaft Dump at the Sullivan Mine allow the modeled system to be simplified as follows:

- **Thermal conditions.** Isothermal (fixed temperature) conditions can be used with different temperatures assigned to the dump and atmosphere, but without considering heat transfer, thus avoiding the need to solve for temperature. This simplification is possible because the average temperature in the dump is uniform and relatively constant throughout the year (Lahmira and Lefebvre 2008);

- **Gas composition.** Fixed gas composition, equivalent to atmospheric air, assigned to gas phases in the dump and atmosphere, thus avoiding the need to solve for gas composition. Fixed gas composition can be imposed because the dump gas phase has a mean molar mass similar to atmospheric air, as the oxygen depletion, which would lower the molar mass, is compensated by the presence of CO₂ that brings its molar mass close to atmospheric air (Lahmira and Lefebvre, 2008);

- **Water flow.** Fixed water saturations, at different values for waste rock and till cover, imposed as residual water. This implies that no liquid water flow is represented, thus avoiding the solution of highly non-linear liquid flow under unsaturated conditions. This simplification is possible due to the assumed relatively stable water saturations in the dump throughout the year.
NUMERICAL MODEL DEVELOPMENT AND VALIDATION

Numerical modeling program
For the numerical simulation of gas flow in the No. 1 Shaft Waste Rock Dump, different emphasis was placed on the representation of gas flow processes. Gas flow related to gas composition changes was neglected a priori because dump gas molar mass is equivalent to that of atmospheric air. Special emphasis was placed on representation of the effect of atmospheric temperature on dump gas flow, because pipe gas velocity monitored at the site was observed to be strongly correlated to atmospheric temperature. Simulations were carried out with a fixed temperature assigned to waste rock but at different values of atmospheric temperature in contact with the dump surface. Complementary simulations were carried out to investigate 1) the effect of high and low barometric pressures, 2) what would happen without a pipe, and 3) the impact of not having a till cover on the dump.

Numerical model conditions
A section that runs through the dump was used as a basis for the 2D vertical numerical grid of the No. 1 Shaft Waste Dump. This section was selected because it is representative of the central part of the dump and is surrounded by monitoring boreholes and the weather station. Gas flow should predominantly be from the wide slope to the top surface because the dump has a wide central part, and could thus be approximated as two-dimensional. A 2D vertical section numerical model having a similar width as the dump should thus be representative of the bulk gas flow in the dump. Figure 1 shows the section and the main features of the numerical grid and the distribution of materials. The grid has a total of 889 elements, of which 53 are non active and serve to impose atmospheric conditions at the dump surface, and 1 element is non active to impose atmospheric conditions at the pipe located within toe drain fill material at the outside base of the dump. The area of the non active element representing the pipe in contact with an active drain element was assigned a value of 0.126 m², which represents the actual flow area of the pipe to allow representative simulated gas fluxes through the pipe.

Figure 1 also shows the distribution of materials and boundary conditions assigned to the numerical grid. At the surface of the dump, two single layers of 1 m thick elements are used to respectively represent non-active (fixed) boundary conditions and the underlying till cover. The pipe used to convey leachate and through which gas flows is within that drain material and it is a non-active element to which atmospheric conditions are assigned. The inside limit and base of the dump are supposed impermeable and thus specified as no flux boundaries. Surface non-active elements are assigned atmospheric temperature and pressure conditions. Atmospheric temperature is assigned to non-active boundary elements. Atmospheric pressure has to be applied with a value decreasing with elevation in accordance to the atmospheric air density in order to represent a stagnant hydrostatic gas column. Even though non-active surface elements are assigned an atmospheric temperature different from the internal dump temperature, no heat transfer is considered. However, imposing atmospheric temperatures to non-active surface elements provides inflowing air densities and viscosities representative of the atmosphere. Lahmira and Lefebvre (2008) provide more details on the numerical modeling work.
Monitoring data from the weather station show that temperature varies by about 30 °C, from -8 to 23 °C, and barometric pressure ranges from 85 000 to 88 000 Pa, with a mean of about 86 700 Pa (raw uncorrected pressures at the elevation of the station on the dump). Monitoring data also show no gas flow through the pipe, so no gas exchange between the dump and atmosphere, when atmospheric temperature is around 10 to 12 °C. This “equilibrium” temperature thus represents the effective mean global gas temperature in the dump, considering that the dump gas phase has a molar mass equivalent to atmospheric air. The magnitude of gas exchanges between the dump and atmosphere should depend on the departure of atmospheric temperature from the equilibrium temperature. In order to simulate these gas exchanges, the numerical model thus has to represent the full range of 30 °C temperature variations. However, the equation of state in TOUGH AMD cannot represent temperatures under 0 °C. Despite this limitation, since it is the departure in temperature relative to the equilibrium that controls gas exchanges, the model uses an equilibrium temperature of 25 °C, which allows the model to represent temperature swings without reaching negative values.

Table 1 summarizes atmospheric temperatures and corresponding atmospheric pressures imposed as boundary conditions. This paper highlights results obtained for the two “extreme” temperature cases at 5 and 36 °C representing the normal range of variation for atmospheric temperature at the site. Table 1 shows pressure values imposed at the top of the dump and at the pipe located near its base. Table 2 summarizes the material properties derived from available data on the No. 1 Shaft Waste Rock Dump (details provided by Lahmira and Lefebvre, 2008). Till properties were assigned on the basis of available laboratory and field measurements. Using available grain size distributions, waste rock properties were estimated by comparison of its grains size distribution to analog waste rock whose properties were measured in the laboratory. Representative soil moistures of the till for wet and dry conditions were based on measured soil moisture profiles on the No. 1 Shaft Dump. A representative waste rock soil moisture was obtained by assuming capillary equilibrium with the till cover.
Table 1. Temperature and pressure conditions with corresponding pneumatic potential

<table>
<thead>
<tr>
<th>Imposed Conditions</th>
<th>Minimum atmospheric temperature (°C)</th>
<th>“Mean” dump temperature (°C)</th>
<th>Maximum atmospheric temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real value</td>
<td>-8</td>
<td>12</td>
<td>23</td>
</tr>
<tr>
<td>Model value</td>
<td>5</td>
<td>25</td>
<td>36</td>
</tr>
<tr>
<td>Pressure at dump top(^a) (Pa)</td>
<td>85 862</td>
<td>86 821</td>
<td>87 300</td>
</tr>
<tr>
<td>Pressure at pipe(^b) (Pa)</td>
<td>86 498</td>
<td>87 415</td>
<td>87 869</td>
</tr>
<tr>
<td>Mean dump gas density (kg/m(^3))</td>
<td>0.991</td>
<td>1.002</td>
<td>1.008</td>
</tr>
<tr>
<td>Mean atmospheric air density (kg/m(^3))</td>
<td>1.062</td>
<td>1.002</td>
<td>0.972</td>
</tr>
<tr>
<td>Pneumatic potential(^c) at dump top (Pa)</td>
<td>85 862</td>
<td>86 821</td>
<td>87 300</td>
</tr>
<tr>
<td>Pneumatic potential at pipe (Pa)</td>
<td>85 905</td>
<td>86 821</td>
<td>87 256</td>
</tr>
<tr>
<td>Potential difference (Top – Pipe) (Pa)</td>
<td>-43</td>
<td>0</td>
<td>34</td>
</tr>
<tr>
<td>Dump gas general flow direction</td>
<td>Upward</td>
<td>No flow</td>
<td>Downward</td>
</tr>
</tbody>
</table>

a: the top of the dump is at an elevation of 1348 m.
b: the pipe at the bottom of the dump is at an elevation of about 1287 m.
c: pneumatic potentials are calculated within the dump for conditions corresponding to the dump gas mean density at the internal dump temperature (25 °C) and gas pressure.

Table 2. Material properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Dry Till</th>
<th>Wet Till</th>
<th>Waste Rock</th>
<th>Drain &amp; Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total porosity (dim.)</td>
<td>0.295</td>
<td>0.295</td>
<td>0.33</td>
<td>0.45</td>
</tr>
<tr>
<td>Residual water saturation (dim.)</td>
<td>0.80</td>
<td>0.950</td>
<td>0.35</td>
<td>0.45</td>
</tr>
<tr>
<td>Hydraulic conductivity (m/s)</td>
<td>5.00E-06</td>
<td>5.00E-06</td>
<td>1.00E-04</td>
<td>1.00E-03</td>
</tr>
<tr>
<td>Estimated effective air permeability (m(^2))</td>
<td>1.46E-13</td>
<td>9.41E-15</td>
<td>9.34E-12</td>
<td>1.02E-10</td>
</tr>
<tr>
<td><strong>Used effective air permeability (m(^2))</strong></td>
<td><strong>5.10E-12</strong></td>
<td><strong>5.10E-12</strong></td>
<td><strong>5.02E-09</strong></td>
<td><strong>5.02E-05</strong></td>
</tr>
<tr>
<td>Van Genuchten α parameter (Pa(^{–1}))</td>
<td>0.000008</td>
<td>0.000008</td>
<td>0.00086</td>
<td></td>
</tr>
<tr>
<td>Van Genuchten m parameter (dim.)</td>
<td>0.55</td>
<td>0.55</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Van Genuchten n parameter (dim.)</td>
<td>2.22</td>
<td>2.22</td>
<td>1.43</td>
<td></td>
</tr>
</tbody>
</table>

Model calibration and validation
Material properties were modified from their initial estimate to calibrate and validate the model. The following criteria were used to determine if the model was representative and appropriately calibrated: 1) the direction (in or out) and magnitude of pipe gas flow as a
function of atmospheric temperature; 2) the gas pressure gradients generated between the dump and atmosphere as compared to those measured at observation wells; 3) the gas flow patterns as compared to inferred patterns based on gas pressure gradients and gas composition measured in observation wells; and 4) the time for the system to reach steady state, as monitoring data show that pipe gas velocities and directions quickly follow changes in atmospheric temperature with a short lag time.

Figure 2 compares measured pipe gas velocities as a function of atmospheric temperature to numerical simulation results. Pipe gas velocities provide the best indication of the importance and direction of gas flow in the dump. Positive pipe gas velocities correspond to gas flow in the pipe, whereas negative values represent gas flow out of the pipe. At the equilibrium temperature of 10-12 °C, there is no gas flow through the pipe, whereas pipe gas velocity is positive at temperatures lower than the equilibrium and negative at temperatures above the equilibrium. Simulations were carried out for a dry till cover at 5 ºC interval above and below the equilibrium temperature. Simulation results (blue squares) are shown at temperatures of the actual system corresponding to simulation temperatures (Table 1). Observations shown (yellow lozenges) are selected daily values measured at Noon. The red line is the linear regression of observations. The dashed blue line linearly links simulation results. Simulated pipe gas velocities very closely reproduce observations, showing that the model is properly calibrated. The model was also validated by comparison to other monitoring observations that are coherent with simulation results (Lahmira and Lefebvre 2008).

![Figure 2](image.png)

Figure 2. Comparison of simulated and measured gas velocities in the pipe.
SIMULATED GAS FLOW BEHAVIOR

Gas flow in the dump at low and high temperature
For simulations at atmospheric temperatures of 5 ºC and 36 ºC, Figure 3 shows calculated pneumatic potentials corresponding to simulated conditions with a color scale (values in Pa). Each figure shows conditions for three simulated cases: the base case with dry till cover and pipe, the case with dry till cover and no pipe, and the case without till cover but with a pipe. The simulated high and low barometric pressure cases are not illustrated as these results are very similar to the base case, but with shifted absolute values of pneumatic potential. Figure 3 also shows streamlines indicating gas flow paths within the dump. Arrows along these streamlines indicate the gas flow direction, whereas black squares are time markers whose spacing indicates 5 day flow duration.

![Figure 3. Pneumatic potential (Pa) and stream traces at 5 ºC (left column) and 36 ºC (right column) for the dry till cover with the pipe (top), without a pipe (middle) and with a pipe but without a till cover (bottom).](image-url)
The top graphs of Figure 3 represent simulated conditions for the base case, at 5 and 36 °C. Although dump gas flows in opposite directions at these different atmospheric temperatures, gas flow patterns have common features. First, most of the gas exchanges between the dump and atmosphere occur through the pipe (and toe drain) and the top surface of the dump. This is indicated by the fact that a vast majority of streamlines extends from the pipe to the top surface of dump. The area of the pipe and toe drain within the dump has a potential similar to the one of the dump surface boundary at atmospheric conditions. However, there is a large potential difference between the uppermost part of the dump and the boundary at the top dump surface (shown by the contrast in color representing potential magnitude). This indicates that a significant loss in potential occurs as gas flows across the till cover at the dump top surface. There is limited exchange through the till cover along dump slope as indicated by few streamlines originating from the slope. On that slope, gas is exchanged in different directions through the till in the upper and lower parts of the dump slope.

Gas velocities are low in the interior and top portion of the dump, become higher in the center of the slope and are the fastest in the lower thin portion of the dump, as indicated by the spacing of streamline time markers on Figure 3 (farther apart markers indicate faster gas flow). There is about the same total gas flow rate from the top dump surface to the pipe located at the base of the dump because minimal flow occurs through the till cover. Gas velocity is thus related to the available gas flow cross section through the dump, which is much larger in the thick upper part of the dump than in the lower thin portion near the base of the dump. Gas velocities are higher for the case at low atmospheric temperature (5 °C) than at high temperature (36 °C) due to the higher difference in pneumatic potential between the dump top surface and the pipe at 5 °C compared to 36 °C (Table 1). These differences in gas velocity between these two cases influence the total gas transit time through the dump. The transit time actually depends on the position within the dump. For the case at 5 °C, if atmospheric temperature remained constant, it would take more than a month for gas to transit through the lower part of the dump, whereas the transit time would be less than 20 days through the upper portion of the dump closer to the slope. In the case of the gas transiting across the dump slope, its transit time would be less than 10 to 15 days. Gas flow is slower for the 36 °C case; hence, the total transit time would take more than 2 months in the lower part of the dump and in the order of 40 days in the upper portion of the dump close to the slope.

Role of the toe drain/pipe and till cover (cases without a pipe or till cover)
The middle graphs of Figure 3 show potentials and streamlines for the simulation case without a pipe, respectively, at 5 and 36 °C atmospheric temperatures. Compared to the base case, the absence of a pipe results in the same general flow direction and quite similar gas flow patterns through the dump. Without a pipe, the main difference compared to the base case is that gas has to flow through the till cover in the lower part of the dump. There is an important potential loss as gas flows through the till (shown by the contrast in color related to potential magnitude). Gas velocity is decreased compared to the base case in the lower part of dump due to more restricted gas exchanges between the dump and atmosphere in the absence of the pipe. Results for simulations without a pipe should only be compared to the base case as they are not meant to represent what would
actually occur without a pipe, but rather what is the role of the pipe under the conditions presently prevailing in the dump.

The lower graphs of Figure 3 show potentials and streamlines for the simulation case without a till cover but with a pipe, respectively at atmospheric temperatures of 5 and 36 °C. Compared to the base case, the absence of till cover leads to much faster gas flow in the dump. As there is no till cover, in this case there is no potential loss across the dump surface. This leads to increased gas entry in the dump through the slope as well as the pipe. However, gas entry through the pipe is relatively less important, compared to gas entry through the slope. This is indicated by the fact that fewer streamlines are transiting through the pipe than what occurred for the base case. Gas velocities are higher through the dump than in the base case, except through the lower part of the dump. Again, results for simulations without a cover should only be compared to the base case as they are not meant to represent what would actually occur without a cover, but rather what is the role of the cover under the present conditions of the dump.

CONCLUSIONS
The numerical model developed to represent gas flow in the Sullivan Mine No. 1 Shaft Waste Rock Dump reproduces pipe gas velocities as a function of temperature and is in general agreement with monitoring observations. In order to calibrate the model, the effective air permeability of the till cover and waste rock had to be significantly increased from the initial estimates based on available data. It is presumed that the increased permeability required by the model reflects the combined effects of coarse preferential flow paths in waste rock and localized variability in the cover. Representative results obtained from simulations support the simplifying assumptions made to develop the model, mainly that 1) the presence of CO$_2$ in the dump gas could make its molar mass equivalent to atmospheric air, 2) the mean dump temperature remains relatively constant, and 3) water flow in the dump does not significantly alter gas flow.

The physical process at the origin of gas flow in the dump is thermal convection due to dump gas buoyancy. The dump gas buoyancy depends on its density difference relative to atmospheric air. The difference between dump gas and atmospheric air densities only depends on their respective temperatures: the dump gas temperature remains quite constant whereas atmospheric temperature is variable and thus controls gas flow direction and magnitude. The dump is supposed to maintain a relatively steady temperature of about 10-12 °C. When atmospheric temperature is similar to the mean dump temperature, there will be no tendency for dump gas to flow. However, when atmospheric temperature is lower than 10-12 °C, its density is higher than dump gas, which will tend to rise up through the atmosphere (positive buoyancy) and air will enter the pipe. Conversely, when atmospheric temperature is higher than 10-12 °C, its density is lower than dump gas, which will tend to sink down through the atmosphere (negative buoyancy) and dump gas will exit the pipe. Under these conditions, the dump gas will tend to be less dense than the surrounding atmosphere in winter and denser during summer. Such a mechanism implies that gas flow is controlled by external forces, namely atmospheric temperature, rather than by the properties of its cover or waste rock, as long as these materials are permeable enough to allow buoyancy-driven gas flow to occur.
Gas flow in the dump is not significantly affected by barometric pressure changes as it does not significantly affect the relative density of dump gas and atmospheric air. The pipe and high permeability toe drain fill material facilitate gas flow and exchanges with the atmosphere. In simulations, the system was found to rapidly reach steady state gas flow conditions, in about 15 minutes, even following major perturbations in atmospheric temperature and pressure. Gas flow through the pipe and till cover can rapidly provide the relatively small gas volume required to compensate the effects of simulated atmospheric temperature and pressure changes. The natural system does not undergo such drastic changes and the system is dynamically reaching a new equilibrium related to variations in atmospheric conditions. Most of the gas flowing through the dump enters or exits through the pipe. However, there would still be similar gas flow patterns without the presence of the pipe. Similarly, although the till cover restricts gas exchanges between the dump and the atmosphere, a low permeability cover is not required to obtain the observed gas flow behavior. Actually, there would be even more gas flow without a cover and gas would similarly flow through the pipe. A perfectly sealed dump cover would not lead to the observed gas flow behavior. However, constructing and maintaining a full-scale cover system that controls gas transport to the extent required, while a promising technology, remains a challenge in the mining industry. On the basis of the processes found to control gas flow at the study site, a companion paper identifies general conditions that could lead to a similar gas flow behavior at other sites (Hockley et al. 2009).

REFERENCES


