Sullivan Mine Fatalities Technical Investigation and Subsequent Risk Management Monitoring

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Abstract

In May 2006, four fatalities occurred in an ARD monitoring station at the toe of the No. 1 Shaft waste rock dump at the closed Sullivan Mine near Kimberley, British Columbia, Canada. A Technical Panel was formed following the fatalities to investigate the technical aspects of the incident and disseminate findings to the mining industry. Beginning in August 2006, the dump was heavily instrumented and characterized in stages, documenting how changes in ambient meteorological parameters controlled respiration in a heterogeneous dump. Patterns of early snow melt associated with increased pore gas flux were observed and found linked to reduced cover thickness. In October 2008 the monitoring station and drainage pipe were removed as a preliminary remediation measure, eliminating the main conduit between the atmosphere and the dump interior. Following recommendations from the Technical Panel, cover material was added to the areas with thin cover thickness to produce a more uniform cover in August 2009. This paper will examine post-remediation monitoring to demonstrate changes that have occurred in the two years since the final remediation was implemented.

Additional Key Words: dump respiration, characterization, mine waste, remediation

Introduction

Four fatalities due to oxygen deprivation occurred at the Teck Sullivan Mine May 15-17, 2006 in a monitoring station at the toe of the closed and partially reclaimed No. 1 Shaft Waste Dump (WD1). The Monitoring Station, connected via a 400 mm diameter pipe to a toe drain, had been used for several years to collect seepage samples and measure seepage flow. The station was routinely visited without incident through the seven months following the construction of a reclamation cover on WD1, with the most recent time occurring one week prior to the fatalities. This report summarizes the extensive technical investigations into the causes of the fatalities, provides recommendations to reduce the potential for similar conditions and fatalities at other sites and provides information on the monitoring of subsequent risk management measures. The complete technical report and associated documents will be made available at a date to be announced.

In the fall of 2006, a Technical Panel (Panel) was formed under direction from the British Columbia Ministry of Energy and Mines (B.C. MEM) to guide the scientific investigations into the incident. It consisted of B.C. MEM staff and advisors; Teck staff, technical contractors and advisors; and, independent members from the University of British Columbia (UBC) Dept. of Mining Engineering and from the consulting community. The Panel's mandate was to fully investigate the technical causes underlying the incident and to provide guidance aimed at preventing similar incidents in the future. The Panel operated through early 2010 and convened several times annually to review and direct developments.

Background

Construction of WD1 was initiated in the 1940s and continued periodically until mine closure in 2001 mainly by end-dumping waste rock from the adjacent No. 1 Shaft. The 10.7 ha area dump curves along the slope below the shaft in a southwest to northeast direction and has a height of approximately 55 m. It contains approximately 3.0 Mt of mainly sulphidic waste rock. The estimated dump volume is 1 M m^3 with a void space of approximately 30%.

To reduce impacts of WD1 drainage on the downgradient Lois Creek, a toe ditch was installed in the early 1990s. The ditch intercepted gravel lenses that hosted shallow seepage and was instrumental in the recovery of Lois Creek water quality. To retain the function of the ditch, reclamation plans required the ditch to be converted to a toe drain. Coarse drain rock was placed in the ditch and the dump was reprofiled in 2004. In 2005 a 1 m till cover was placed over the dump (see Figure 1). Such a design was not without precedent at the site, as the near-by North Dump in the Lower Mine Yard had been reclaimed in the mid-1990s using similar methods.

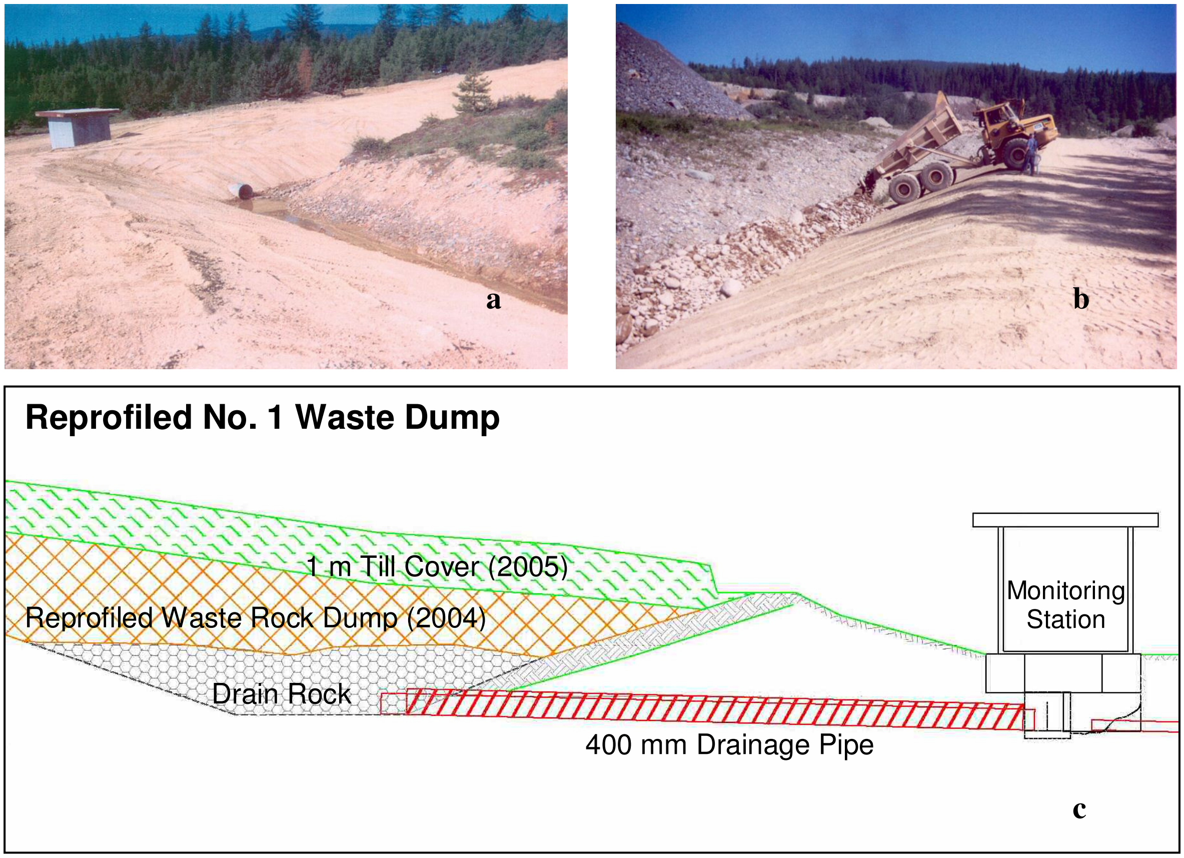

Figure 1. The Monitoring Station and toe ditch confluence prior to reclamation (a). Drain rock being placed in the toe ditch (b). Cross-section showing drain rock, waste rock and till cover in former ditch with 400 mm diameter drainage pipe conveying seepage to Monitoring Station (c).

The tragic fatalities in the WD1 Monitoring Station occurred over the period of May 15-17, 2006. The first individual to perish was an environmental contractor engaged in routine water quality sampling at a large number of locations in the Sullivan Mine area. He entered the Monitoring Station on May 15 to obtain a sample of drainage and record its flow. The second death on May 17 was that of a Teck employee who entered the Monitoring Station during a search for the first individual. The third and fourth fatalities soon followed and were ambulance service personnel who had been summoned to the scene.

Investigations into the incident were initiated on May 17 and included gas sampling and other measurements in the Monitoring Station using confined space procedures with appropriate personal protective equipment. Chromatographic analyses of gas samples indicated concentrations of about 2% oxygen and 7% carbon dioxide in the Monitoring Station sump and in the pipe connected to the waste rock dump toe drain. No toxic gases, such as hydrogen sulphide or carbon monoxide, were found in the gas samples taken. The measurement of low oxygen concentrations at the Monitoring Station prompted the investigators to examine a number of other locations at the mine, including pump stations and ARD stream collection points but no other instances of significantly low oxygen levels were measured.

Aerial infra-red thermal imagery analyses were conducted through aircraft surveys flown during the nights of May 30 and 31, 2006, but no evidence of “hot spots” in the WD1 was found. Stable isotope analyses later conducted on gas samples confirmed that the carbon dioxide in the gas samples was principally of an inorganic origin. Oxygen deficiency and excess carbon dioxide concentrations can have both individual and synergistic effects on human health (Hockley, 2009).

Investigation Methods

The initial installation of instruments as part of the technical investigations occurred in August 2006. Automated instrumentation monitored air velocity in the 400 mm diameter drainage pipe (400 mm pipe). Gas composition, pressure and temperature were measured at three locations in the 400 mm pipe and Monitoring Station. A meteorological station was installed on a mid-slope bench above the Monitoring Station, recording air temperature, relative humidity, wind speed and direction, net radiation, barometric pressure and rainfall. Soil moisture and temperature were monitored continuously in the till cover at two locations on the slope.

In March 2007, six boreholes were drilled (air rotary) and instrumented to allow for measurement of temperature, differential gas pressure and air composition at several depths within each hole using the Solinst continuous multi-channel tubing (CMT) system. To check shallow conditions (up to a depth of approximately 6 m) at other locations across the dump, ten additional “push-in” gas piezometers were placed through the cover and into the dump. Collection of internal temperature and pressure data was automated at the six original boreholes. Gas composition was measured manually from all boreholes and push-ins. The differential gas pressure is the pressure difference between the atmosphere and the dump interior. Henceforth, this will simply be referred to as the pressure in this report.

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

To provide data from a comparable site, the North Dump was instrumented in the fall of 2007. A limited soil moisture and weather station was installed on the slope of the North Dump. Five push-ins were installed along the crest of the North Dump. Internal temperature, differential pressure and gas composition data were collected from the push-ins. Temperature was also collected from the interior of the North Dump, by installing thermistors at various depths down an old groundwater monitoring well.

In May 2008, an additional 11 boreholes were drilled and four additional push-in piezometers were installed in WD1 to expand the investigation of internal conditions. Solinst CMT was again used to complete the boreholes, which were drilled by both air rotary and sonic methods. The objectives of the May 2008 installations were 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.

In October 2008, the Monitoring Station was removed and replaced by a continuous section of drainage pipe with a U-trap. Water levels in the U-trap were intended to prevent the drainage pipe being a conduit for gas flow between the dump interior and the atmosphere. The U-trap water level was monitored with automated readings from a conductivity meter and a water level sensor.

Gas composition surveys of waste dump surfaces in November 2008 showed detectable effects of pore gas. To determine the extent and magnitude of pore gas outflow through the dump cover, 48 plastic containers termed “gas traps” were installed primarily across the WD1. Four classes of gas traps were installed: 1) Control – located on natural ground adjacent to the waste rock pile; 2) Normal – located on the waste rock pile cover; 3) Biased – located on the waste rock pile over a small hole created through the cover; and , 4) Uber-biased – located on the waste rock pile over known pore gas vents. The gas traps were fitted with both a sample port and a second port for flushing the gas trap with fresh air. Following flushing of the gas traps gas composition changes were monitored over time to allow for the determination of pore gas fluxes.

The initial 18 gas traps were installed in January 2009 on or adjacent to WD1 and the North and South Dumps. An additional ten gas traps were added to WD1 in February 2009. To broaden the gas trap coverage on WD1 and focus more on lower slope and toe areas where pore gas outflow would be expected during warmer weather, 20 additional gas traps were installed on WD1 in April 2009.

Results

Air temperature controlled respiration

Results show a clear relationship between air velocity in the 400 mm pipe at the Monitoring Station and atmospheric air temperature. Air movement in and out of the dump is herein termed “respiration”. Air temperature controls respiration by affecting the relative density of the interior pore gases compared with external ambient air. The internal temperature of the dump remains fairly constant throughout the year while the external air temperature is much warmer in the summer and much cooler in the winter. From fall to spring, the internal pore gas is warmer and thus less dense than the surrounding external atmosphere, and rises up through the dump and exits through the cover, pulling cooler ambient air into the toe and lower slope of the dump. Some of this in-flowing air was drawn in through the 400 mm pipe. During the summer the opposite condition exists, causing some pore gas to flow out of the dump through the 400 mm pipe. A comparison of atmospheric air temperature and air velocity reveals a strong relationship (see Figure 2). The air flow through the 400 mm pipe is designated as a positive velocity if the flow is into the pipe and toe drain; negative if out of the pipe and into the Monitoring Station. A “pivot point” of about 10-12°C is evident, and represents the air temperature at which airflow in the 400 mm pipe changes direction.

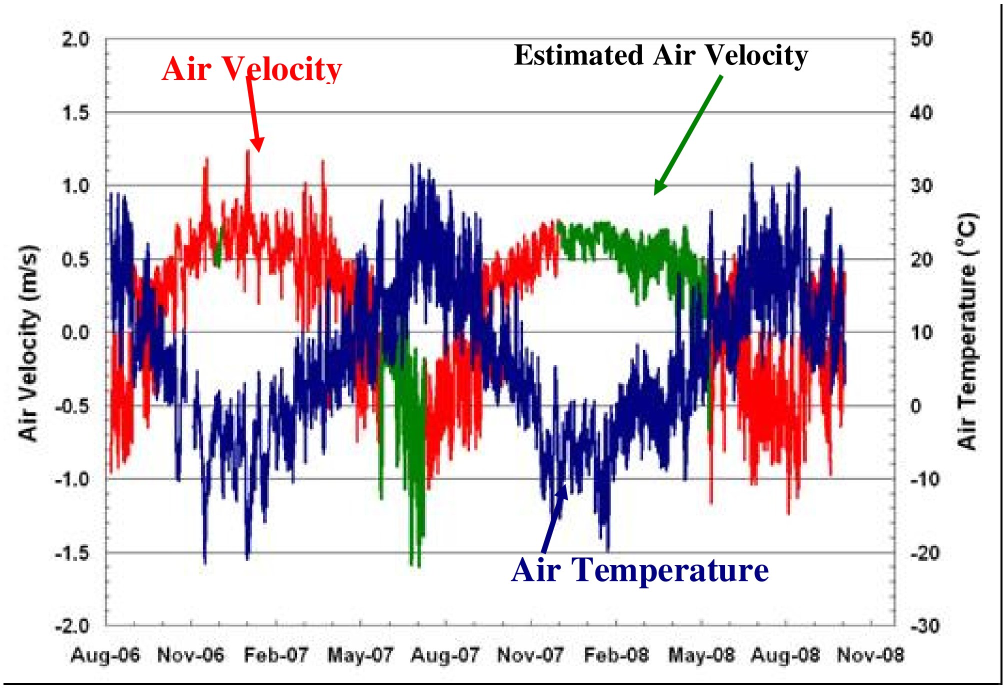

Figure 2 Time series comparison of air temperature and air velocity

Movement of pore gas in response to barometric pressure changes has been noted elsewhere, and while air temperature is the dominant control on WD1 respiration, barometric pressure did control respiration for five hours on March 12, 2007. During this time the till cover became sufficiently saturated by not only snowmelt, but also a significant precipitation event, which reduced the air permeability of the cover and resulted in the 400 mm pipe possibly being the only conduit between the dump interior and atmosphere.

Movement of air into and out of the dump through the 400 mm pipe was very dynamic. Air velocity values and automated gas composition readings correspond well and indicate how quickly conditions in the Monitoring Station became hazardous (see Figure 3).

The internal temperature, pressure and gas composition data confirm the conceptual respiration model. The pressure gradients, gas composition and temperature demonstrated a system with inflow at the toe being prevalent from fall to spring and the opposite during the remainder of the year. Air flow through the dump is not limited to a single preferential pathway, but occurs heterogeneously throughout the dump.

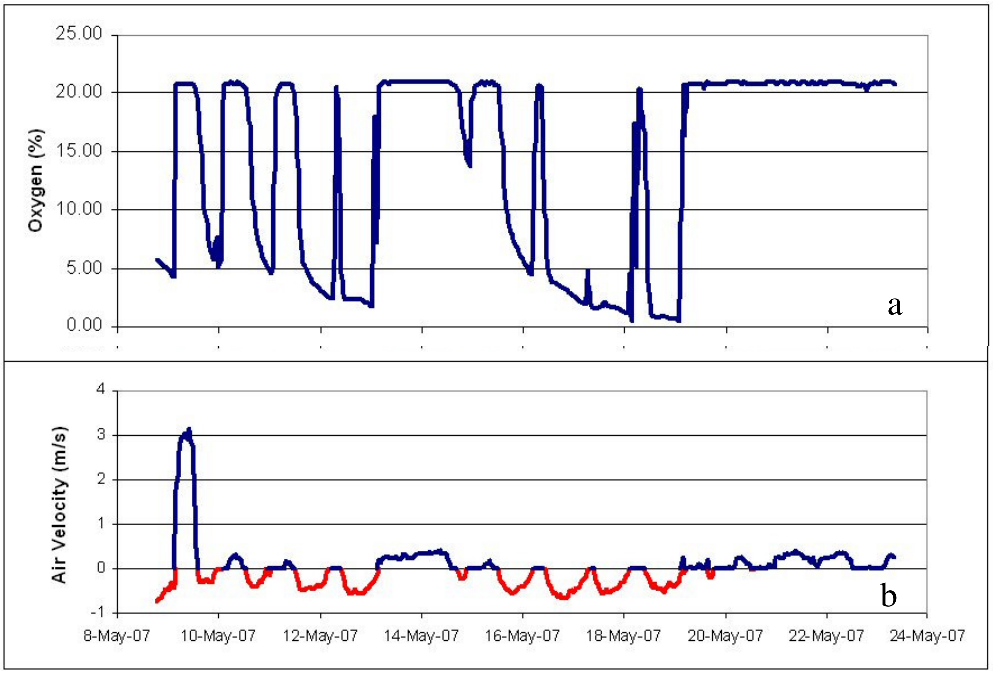

Figure 3. Changes in Monitoring Station oxygen concentration (a) in response to 400 mm pipe air velocity (b). Positive air velocity (blue) represents air flowing into the dump; negative air velocity (red) represents pore gas flowing out of the dump.

Waste rock geochemistry and pore gas chemistry

Analysis of drill cuttings from the 2007 and 2008 drilling programs clearly show that reactive sulphide and carbonate minerals are present in the waste rock. These results support the conclusion that pore gas composition is the result of the air within the dump reacting with sulphide minerals, leading to depletion of oxygen and generation of acid, followed by consumption of acid by carbonates that produce carbon dioxide. These reactions also generate heat that maintains year-round elevated temperatures within the dump.

Pore gas oxygen and carbon dioxide concentrations were measured and generally have an inverse relationship, as expected from the geochemical reactions. Oxygen concentrations measured within the dump ranged from values typical of normal air (about 21%) to near zero. Carbon dioxide concentrations ranged from near zero to about 5% in most locations, but were as high as 21% in one borehole. Analysis has shown that in WD1 the resulting change in gas composition has a very minor effect on pore gas density. Respiration is mainly driven by density differences due to temperature, not changes in pore gas composition.

Internal characterization

Recovery of drill cuttings varied widely when drilling the boreholes in March 2007. For the two deepest holes there were intervals of as much as 3 m with no recovery, which suggested the presence of voids within the dump. To investigate this further, ten geophysical resistivity transects were completed on the dump surface in October 2007. One transect was also completed on the North Dump. The North Dump contained a uniformly conductive waste material; however, WD1 was shown to be very heterogeneous.

The drilling program in May 2008 revealed a waste rock dump comprised of “barren” waste rock, sulphidic waste rock, trash, debris (cables, timbers) and even a pocket of calcine-like oxidized sulphides. The sorting effect arising from end-dumping of waste rock was quite evident, with material becoming coarser with depth. The high resistivity zone highlighted in Figure 5 is believed to correspond to the accumulation of large rocks along the alignment of the original dump toe prior to re-profiling in 2004. The lower resistivity or higher conductivity areas along the current dump toe are finer-grained materials that would have been pushed down during re-profiling.

The most recent monitoring data and additional internal temperature monitoring locations have led to further insights about the processes occurring within the dump, in particular their heterogeneity. More recent boreholes through the thickest portion of the dump have increased the range of known internal temperatures. The original two boreholes located on the top surface of the dump showed similar core temperatures, both steadily increasing from approximately 16-19 ºC between March 2007 and May 2009. The newer boreholes along the dump crest completed in May 2008 show core temperatures of 23, 24 and 27 ºC.

Different airflow regimes in the dump are likely associated with zones of differing temperature. While the zones of 18 and 20 ºC core temperatures may be part of the general flow system shown in Figure 2 the 27 ºC zone along the northern crest appears to be part of a different flow system. When the atmospheric temperature is greater than the pivot point and air is descending through the dump and exiting the 400 mm pipe, pressure gradients and gas composition analysis indicates that the internal pore gas is still rising through the dump along a portion of the northern crest.

Interim remediation measures

In October 2008, the Monitoring Station and 400 mm pipe were removed and a U-trap and new seepage collection line were installed, eliminating a primary conduit between the dump interior and the atmosphere. Pore gas composition has not been significantly affected by the installation of the U-trap; specifically, oxygen levels have not decreased. It is therefore concluded that, while the 400 mm pipe offered an easy and focused conduit to the atmosphere, it has been adequately replaced by diffuse pathways through the unsaturated cover material.

Pore gas surface flux

During the March 2007 drilling, several premature snowmelt areas (PSAs) were observed and mapped across the dump surface, many occurring on the north-facing slope. It was hypothesized that PSAs are indicative of vent areas where warmed internal air would exit the dump. Five discrete vents on the surface of the dump where pore gas concentrations could be measured were discovered as part of manual monitoring during 2008. At the surface, the vents’ exhaust exhibited depleted oxygen as low as 6%, but oxygen values returned to normal atmospheric conditions within 15 cm from the surface. Manual monitoring in November 2008 identified vents exhibiting similar behaviour on the South Dump. These vents occur at cracks in the cover, and at gaps in the cover around fence posts, well casings, and survey stakes.

Of the 48 gas traps monitored, only the three Uber-bias gas traps, located over known surface vents, allowed for calculation of convective pore gas flux through the cover. The remaining gas traps showed either no pore gas effects or such limited effects that timely changes in gas trap composition were not practical to monitor. The gas flowrate into the Uber-bias gas traps was calculated to be up to about 0.5 m^3/hour. Given that the traps covered an area of about 0.25 m^2, the corresponding gas velocities are about 50 m/d. These direct measurements of the convective pore gas flux are believed to be a first for any waste rock pile.

WD1 chevron monitoring

The area at the toe of WD1 where the Monitoring Station was located is known as the chevron area. This area includes the confluence of both sides of the seepage collection drain, which is shaped like a "v" or chevron. The seepage collection pipe was excavated and replaced when the Monitoring Station was removed. It was discovered in 2009 that the material backfilled into the excavation had consolidated and subsided, creating small fractures and holes that allowed pore gas to readily flow from the toe drain to the atmosphere.

A monitoring program was conducted to address concerns that installation of the U-trap (and related loss of the readily available conduit between the WD1 and the atmosphere) would lead to a concentrated venting of pore gas in the chevron area. Automated readings from the push-in P-10 deep port located at the toe drain convergence show that oxygen and carbon dioxide concentration are commonly 0% and 11%, respectively. This dense gas is persistent and diurnal changes in the gas composition in response to the minimum air temperature falling below the pivot point do not occur. The rapid response of pore gas composition seen in Figure 3 no longer exists in the drainage collection system and continuous days of cool weather were needed to slowly affect change in P-10 gas composition.

It was possible to detect largely undiluted pore gas in the chevron area, but only by inserting the gas analyzer sampling tube into a vent hole or crack. Oxygen concentrations measured in chevron vents were as low as 2.7% with carbon dioxide concentrations as great as 11%. In nearly all cases the oxygen concentration was greater than 19.5% when the sample tubing was raised and held in place above the vent, level with the surface. The small fractures and holes were filled by sediment transport caused by summer precipitation events, and pore gas was difficult to detect in the chevron area by late summer 2009.

Premature snowmelt area characterization

As noted above, the PSAs are believed to be areas where warmer pore gas can more readily pass through the cover. A cover characterization program was conducted in 2009 in an attempt to determine if PSAs were the result of till cover material properties and/or conditions. Twenty excavations were made on WD1, half in PSAs and half in areas that did not exhibit premature snowmelt. Till cover samples were collected for analysis and measurements were made during excavation. Results indicate that cover thickness was the only factor that was significantly different in the PSAs. Each of the three Uber-bias gas traps were found to be located in areas where cover thickness was 0.3 to 0.75 m, less than the design cover thickness of 1.0 m.

Remediation

With a detailed understanding of WD1 conditions based on monitoring, the Technical Panel began work in June 2008 to develop recommendations to Teck for WD1 remediation measures that would minimize risks to on-site workers and the off-site public for the long term. With the assistance of Dr. Dirk van Zyl of the University of British Columbia, the Panel identified fifteen possible remediation measures and conducted a multiple accounts analysis (MAA) to screen the options, and a failure modes and effects analysis (FMEA) to identify risks associated with the recommended remediation option.

With the Monitoring Station removed, the U-trap installed in the seepage collection pipeline, and site access controls established, the Panel recommended that the most effective additional remediation measure was the establishment of a more uniform till cover. This would reduce overall surface gas fluxes, and minimize the potential for large focussed gas outflows that could increase risks. This recommendation assumed continued site management, access limitations and application of a risk management plan.

The FMEA identified eleven risks associated with the recommended remediation option of establishing a uniform cover. Three of the eleven failure modes are associated with site management by the owner: a breach of security, and both short and long term loss of experiential knowledge. A risk management monitoring plan was developed to facilitate understand general site conditions and minimize the remaining eight failure mode risks:

1. Erosion of cover. The cover is inspected twice annually and following any storm event greater than 25 mm / 24 hrs.
2. Cracking of cover. The cover is inspected annually for cracking of the cover caused by waste settlement. In addition, any trees greater than a 3 m height are removed to avoid root ball cover disturbance from windfall.
3. Geotechnical stability. The dump will be inspected following any earthquake of M6.0 magnitude or greater.
4. Failure of the U-trap. Redundant sensors confirm that the U-trap is filled with seepage to ensure that the seepage collection line is not a conduit between the dump interior and atmosphere.
5. Instrumentation failure. The U-trap automated monitoring system is remotely downloaded on a weekly basis to ensure that any system failure is identified in a timely manner.
6. Plugging of seepage collection toe drain. While believed to be unlikely, instrumentation that terminates in the toe drain will be converted to piezometers following the third year of risk management monitoring to watch for any development of ponded seepage in the toe drain.
7. Fire impacting the cover. Aside from destroying vegetation, a fire could destroy key monitoring installations. If a fire is threatening the area surrounding the dump, controlled burns may be conducted to prevent damage from a wildfire.
8. Reduction in dump temperature resulting in increased dense pore gas flow. The internal dump core temperature is monitored to understand if a change in the pivot point is likely.

In addition to the failure mode risk management monitoring above, general site monitoring includes meteorology, soil cover temperature and water content, gas trap pore gas flow, *in situ* pore gas composition, and surface gas surveys. The manual component of general site monitoring is conducted on a bimonthly basis in Year 1 of the monitoring plan (2010), a monthly basis in Year 2, and a quarterly basis in Year 3. The frequency and necessity of some monitoring components will be evaluated after Year 3.

Changes after cover repairs

Additional till cover material was placed to obtain the design thickness of 1.0 m in late August 2009 at the three areas with insufficient cover thickness. Multiple gas traps were installed on the additional cover material in September 2009. Gas traps along the dump crest showed at least an order of magnitude reduction in pore gas flux through the cover compared to fluxes at similar temperatures prior to the cover repairs. The order of magnitude reduction in pore gas flux has been maintained. Pore gas effects can no longer be detected at several of the gas traps.

Site monitoring in February and March of 2010 and 2011 showed reduced PSA sizes. Figure 4 shows the greatest extent of recorded PSA for the years 2008 to 2011. Monitoring for pore gas at the surface was conducted in the PSAs, and pore gas was not detected in 2010 or 2011 when using the same equipment and techniques applied in previous years. PSAs were greatly reduced in 2011, but this may potentially be indicative of a very large winter snow pack. PSA monitoring will continue in 2012.

The snow of winter (and lack thereof) provides a readily visible identification of possible pore gas vents. However, a summer flow regime will possibly produce vents along the toe and lower slope area, which are difficult to detect. Such vents were discovered prior to the cover repair in September 2009. To investigate the possibility of summer surface vents, transects were established in 2010 along the lower slope of the east side and inside the Chevron area focusing on areas where pore gas effects were repeatedly measured prior to cover repairs. Six transects vary in length from 95 m to 15 m, with area measurements made every 5 m, or at suspicious locations along the transects (i.e., small holes, or gaps between rocks and till cover material).

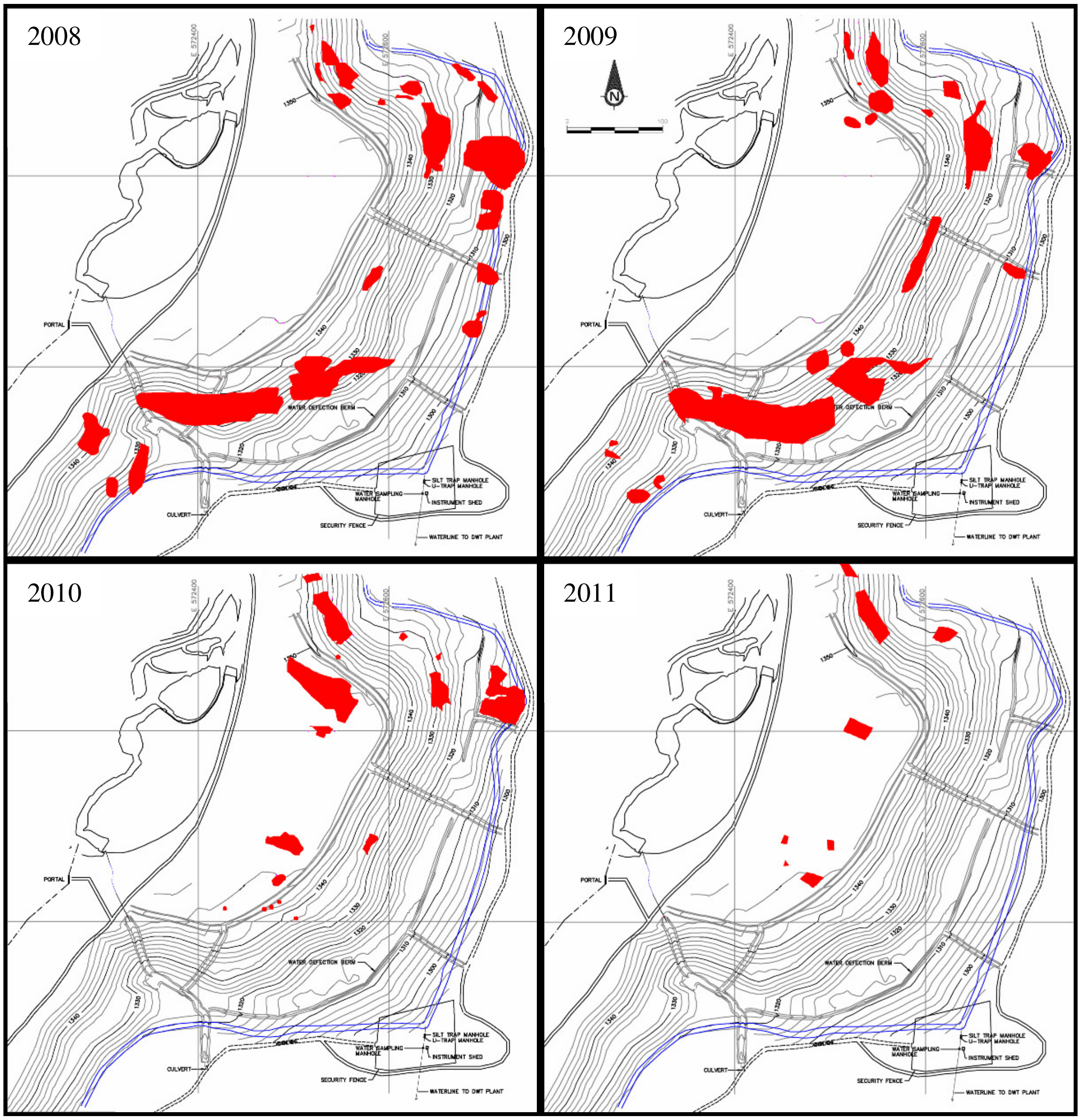

Figure 4. The greatest extent of PSAs in February and March of 2008, 2009, 2010 and 2011.

2010 and 2011 surface gas surveys along the east toe area do show occasional pore gas effects at the ground surface. This is measured with a field gas analyzer drawing a sample from a small depression at an elevation equivalent to the surrounding ground level. Along the eastern lower slope, three readings (two in 2010 and one in 2011) have shown oxygen concentrations of less than 19.5%, ranging from 14.6% to 19.0%.

The two transects in the Chevron area have produced four readings with oxygen concentrations less than 19.5%, ranging from 1.8% to 17.8%. The low reading of 1.8% (from 2011) is not unusual for this area; past experience has shown that this dense gas cannot be detected a few centimetres above the ground surface or tens of centimetres from the origin on the downslope surface, as the gas readily mixes with atmospheric air.

The *in situ* core temperature appears to have stabilized after increasing during the period of the technical investigation. Borehole 1A (BH-1A) is located on the top surface and at one of the thickest portions of WD1. The upper and lower portions of BH-1A are influenced by atmospheric and natural ground temperature, respectively, but the middle of BH-1A maintains a core temperature that was utilized as a reference point for WD1 (see Figure 5). The increase in temperature is believed to be caused by heat retention due to cover placement in 2005. Many borehole or push-in locations along the periphery of the dump continue to show temperature results that are heavily influenced by atmospheric conditions.

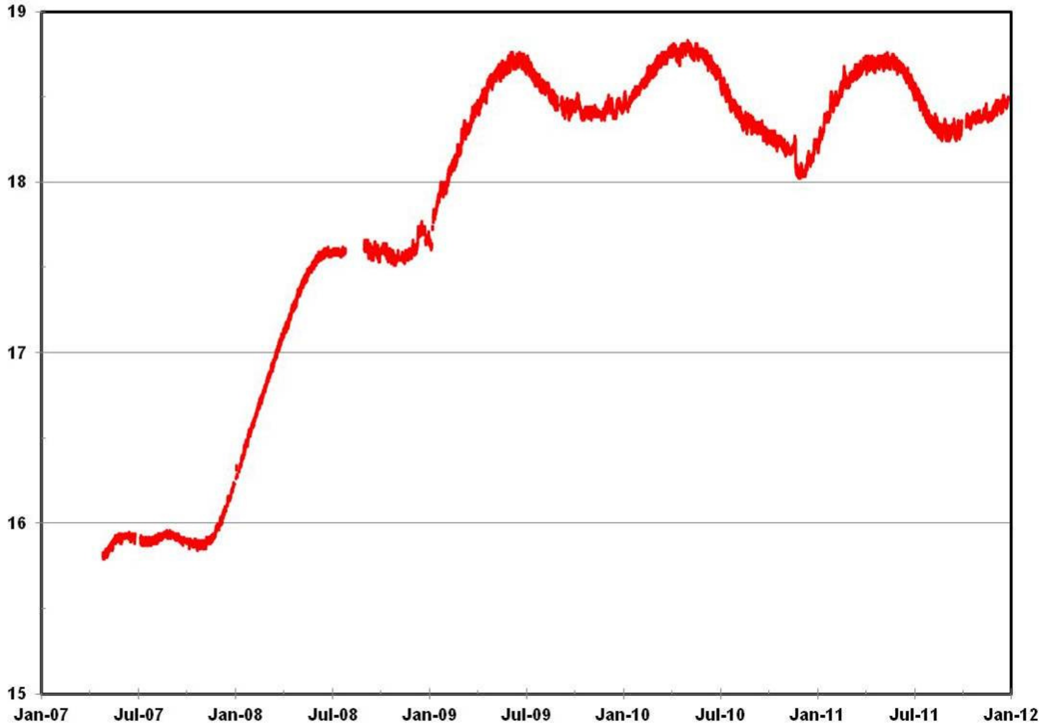

Figure 5. BH-1A core temperature (15 m depth).

In situ pore gas composition is within the same range as found prior to cover repair. Figure 6 shows oxygen concentrations at BH-1A. Since the cover repairs in August 2009, results from individual sampling events show an increased range, but the overall seasonal pattern remains unchanged. The results from the summer of 2009 do not conform to the seasonal respiration airflow pattern, with oxygen concentrations that are expected during the winter. 2009 summer air temperatures were not unusual and cannot explain this deviation. One possible explanation is the cover characterization that was conducted at this time. Test pits were excavated to the waste rock both in and outside of PSAs, and several were on the mid-slope bench below BH-1A. Perhaps this direct contract between the atmosphere and waste rock allowed new pore gas flow paths to develop and influence results.

Figure 6 also shows the oxygen concentration during February 2010 to be less than normal. This is believed to be the result of mild air temperatures, which would have reduced pore gas flow through WD1. The average air temperature for January – March, 2010 was -0.6 °C. The average air temperatures for the same period in 2008, 2009, and 2011 were -3.9 °C, -4.4 °C, and -4.6 °C. This example further highlights the control of airflow respiration by air temperature at the WD1.

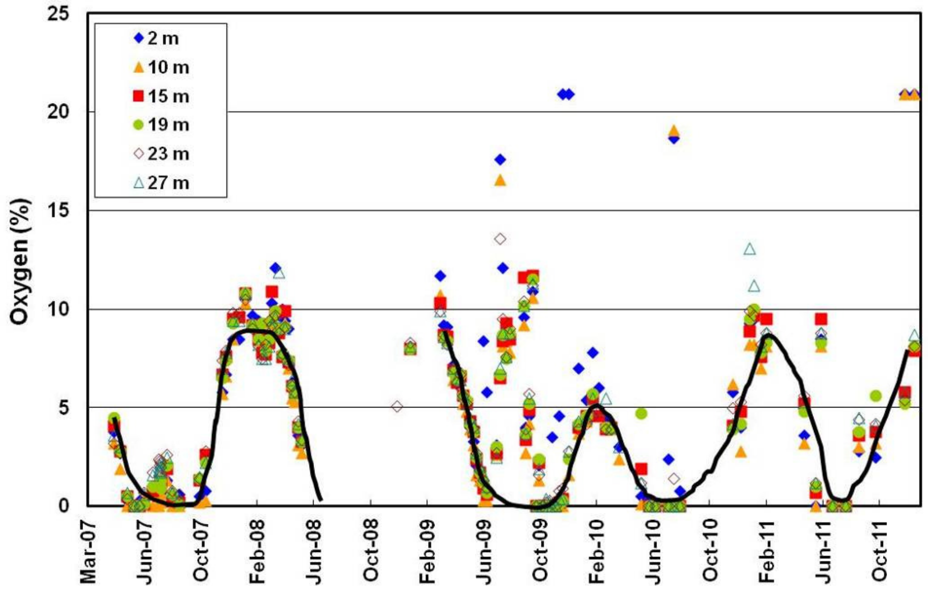

Figure 6. Oxygen concentrations at various depths of BH-1A; the black line highlights the expected seasonal trend.

Conclusions related to No. 1 Shaft Waste Dump

The investigation obtained what is likely the most detailed set of gas and temperature data from any mine dump in the world. This data set allowed for a thorough understanding of the processes that controlled dump respiration, which resulted in four fatalities when waste rock pore gas entered the Monitoring Station.

Each phase of the study provided new insights. It is clear that the difference between atmospheric air temperature and internal dump temperatures controls dump respiration. This was first observed in the relationship between air velocity in the 400 mm pipe and air temperature, and further confirmed with internal pressure and gas composition data (Phillip *et al*, 2009). The toe drain and 400 mm pipe provided an excellent conduit to concentrate pore gas, while the Monitoring Station, although not a sealed structure, provided sufficient confinement of the pore gas.

The physical and chemical nature of the waste dump was characterized through overlapping techniques. Isotopic analysis of pore gas in the Monitoring Station and geochemical analysis of drill cuttings confirmed the link between waste rock geochemistry and pore gas composition. Heterogeneity of the dump was characterized by drilling and encountering voids, analysis of differential pressure and air temperature relationships, and examining the resistivity survey results. The higher than expected air permeabilities needed to calibrate the gas transport model confirmed the effects of heterogeneity within the waste rock, and also raised the possibility of heterogeneity in the cover.

Dump respiration continued after the direct conduit was blocked by a U-trap. Monitoring and subsequent investigation of surface vents confirmed that areas of insufficient cover thickness provided additional pathways for gas flow. Supplementary cover material was placed in the vent areas and initial results indicate that gas fluxes have decreased.

Based on a review of the investigation results as a whole, the Panel found that the following factors contributed to the fatalities incident:

1. The presence of reactive sulphides and carbonates in the waste rock, allowing for depletion of oxygen and generation of carbon dioxide;
2. Convective air flow controlled by the difference between the dump's internal temperature and the external air temperature;
3. The end-dumped construction of the WD1, which most likely resulted in segregation of waste rock by particle size as seen in the increase in coarse material with depth that creates highly permeable zones that facilitate dump respiration and concentrates flow;
4. The covered coarse rock toe drain and 400 mm diameter pipe, which concentrated pore gas flow into the Monitoring Station; and,
5. The Monitoring Station shack covering the sample location, which provided confinement of the pore gas.

After considering the full range of possible remediation measures, the Panel concluded that:

1. The U-trap installation has proven to be an effective control in preventing advective gas flow through the seepage collection piping system;
2. The additional cover material placed on the deficient areas is not expected to stop gas flow, but is expected to ensure a more uniformly dispersed release of any hazardous pore gases;
3. The addition of institutional controls such as fences, gates and signage has been and will be effective in limiting trespass of unauthorized personnel onto the dump; and,
4. The establishment of a permanent risk management plan, including institutional controls, will prevent the addition of any structures onto the dump surface and ensure long term integrity of the dump cover.

Recommendations for other sites

The Panel mandate also included making recommendations to apply the lessons learned from the Sullivan fatalities incident to other sites.

The Sullivan No. 1 Shaft Dump clearly illustrates the effects of temperature on the outflow of potentially hazardous gases from waste rock piles. The internal temperature of WD1 falls between the extremes of local air temperatures, which results in seasonal changes in the direction of gas flow. During the winter, the internal pore gas is buoyant and exits upwards through the dump surfaces, while in the summer the pore gas is denser than the surrounding air and exits at the dump toe.

In more general terms, the production of buoyant or dense pore gas within a waste dump can be caused by temperature or composition differences, and both buoyant and dense gases can potentially be hazardous.

Buoyant dump gases are those that 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. During release to the open atmosphere rapid dispersion occurs. However, it would be inappropriate 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 WD1, and could be hazardous to animals at ground level or even to humans who sit or lie on the ground.

Dense gases are those that are heavier than the ambient air. Waste rock pore gas can become heavier through the addition of carbon dioxide (Hockley *et al*, 2000), or when the dump internal temperature is lower than that of the surrounding atmosphere. Dense gases can be particularly hazardous because they are less likely to disperse in the atmosphere. Under the range of gas densities and outflow rates typical of waste rock piles, dense gas pools are only likely to form at wind speeds less than about 2 m/s (Hockley et al, 2009). However, low wind speeds can be quite common at night or under other very stable atmospheric conditions. For example, the Sullivan data indicate that wind speeds of less than 1 m/s are observed about 20% of the time at WD1.

Confinement of a gas outflow clearly increases the hazards associated with both dense and buoyant gas outflows, even at very low gas flow rates. 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 restricted enough that an occupant would be exposed to essentially undiluted pore gas.

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. The physics of "density-stratified flows" is complex and it is difficult to derive general criteria. Idealized cases and model studies in the literature provide only broad guidance as to when such processes could result in a persistent pool of dense gas. The results indicate that gas outflow rates would need to be high, as could result from flow concentrating effects inside the dump or permeable zones in the cover.

The Technical Panel believes that all individuals responsible for safety on mine sites should be aware of the hazards associated with pore gas in reactive waste dumps, 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:

- Sulphide minerals in waste rock, which can deplete oxygen from air;
- Any combination of sulphide minerals and carbonate minerals, which can lead to production of carbon dioxide;
- Air temperatures that are greater than temperatures within waste dumps, which can lead to temperature driven outflows of dense dump pore gas at the toe;
- 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 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. The Technical Panel also believes that these hazards can exist even where no confining structure is present. It is possible that open areas on a calm day, or low-lying or densely vegetated areas along a dump toe, could confine gas outflows to the extent that poses 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, which under some circumstances should include the use of personal gas monitors for all staff working on or transiting potentially hazardous areas.

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