Kimberly Incident Technical Panel
Update on Technical Findings

June 2007

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1. Background

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

This realization led to recommendations for technical investigations into the chemical and physical processes affecting air in the No. 1 Shaft Waste Dump and monitoring station. These recommendations are in the Chief Inspector's report on the incident as posted on the Ministry of Energy, Mines and Petroleum Resources (MEMPR) website. The initial phase of the investigations, involving the installation of monitoring equipment in the dump cover and in the monitoring station, was implemented in August 2006. That monitoring is continuing and the overall program has been expanded as noted below.

The investigation program is being guided by a Technical Panel that consists of independent experts from UBC, staff from both the MEMPR and Teck Cominco, and their respective technical advisors. The terms of reference for the panel clearly state:

> "It is a technical panel and, in relation to the incident, has the sole purposes of recommending and overseeing scientific investigations concerning the underlying causes and developing preventative measures in the most expeditious manner possible."

The panel has now met three times, in November 2006, March 2007 and June 2007. At each meeting, the panel reviewed the data collected from the site and recommended changes or additions to the investigation program.

A significant outcome of the November 2006 meeting was a recommendation that the initial monitoring equipment be supplemented with additional instruments to examine conditions within the dump itself. A detailed plan for the internal dump instrumentation was presented to the panel and reviewed at the March 2007 meeting. The panel recommended that installation of the new equipment begin prior to the spring 2007 warming, so that conditions as similar as possible to those of May 2006 could be monitored. Teck Cominco and its consultant acted on these recommendations and installed the bulk of the internal dump instrumentation in March and April 2007. As a result, it was possible to collect a comprehensive set of monitoring data from the station and within the dump through the entire spring melt. Those data were presented to the Technical Panel at the June 2007 meeting.

The panel's terms of reference also state:

> "Its tenure will continue until such time that these purposes (as stated above) have been achieved as determined by consensus of the panel".

Experience in waste dump monitoring projects elsewhere has shown that it is prudent to collect at least a full year of data prior to drawing conclusions. Allowing time for thorough review of a full year's data from the instruments placed in August 2006, the panel is expecting to release a final report late in 2007 or early in 2008. If the panel concludes that patterns in the internal dump data also require a full year of monitoring, those dates could be extended into the summer of 2008.

However, the panel recognizes both the level of concern over the May 2006 incident and the need to expedite any findings related to the potential for similar risks elsewhere. Therefore, the panel agreed in its June 2007 meeting to issue this Update on Technical Findings. The remainder of this document briefly describes the investigation program, and then presents the panel's answers to key questions as they stand at this time.

2. Current Status of Investigations

The No.1 Shaft Waste Dump was created from 1950 to 2001, principally by the deposition of waste rock from the No. 1 Shaft. The dump curves along the slope below the shaft in a southwest to northeast orientation. The height from the upper flat portion of the dump to the toe is approximately 180 feet. The May 2006 fatalities occurred in the monitoring station located at the southeast corner of the dump toe. A 16-inch pipe runs between the dump and the monitoring station, and conveys contaminated water from the dump to another pipe that ultimately leads to the site's water treatment system.

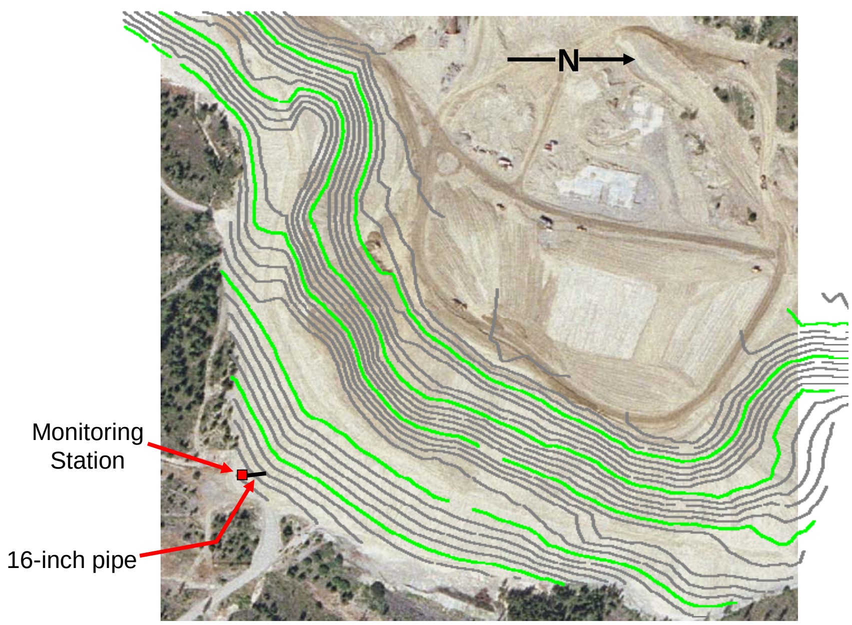

Figure 1. No. 1 Shaft Waste Dump and seepage monitoring station.

The initial installation of monitoring equipment, in August 2006, included instruments to automatically track conditions within the monitoring station. Gas composition, pressure and temperature are measured at three locations: eight feet up the 16-in pipe, at the end of the pipe, and at approximately waist height in the monitoring station. Air flow into and out of the 16-in pipe is measured, as well as the flow of drainage water. All of the monitoring instruments within the station are operated remotely from a heated instrument shed located a short distance downhill.

A weather station was also installed in August 2006, about midway up the dump slope. The weather station measures air temperature, relative humidity, wind speed and direction, net radiation, and rainfall. Two other instrument sets that measure conditions within the soil cover were installed adjacent to the weather station and above it near the top surface of the dump.

The March and April 2007 installations were directed towards monitoring conditions within the dump. Six boreholes were drilled and instruments to measure temperature, gas pressure and air composition were installed at several depths within each hole. To check conditions at other locations, a series of additional monitoring pipes were pushed through the cover and into the dump. Only some of the so-called "push-ins" were completed initially. The remainder were kept in reserve to be installed once the initial data show where additional monitoring would be most helpful.

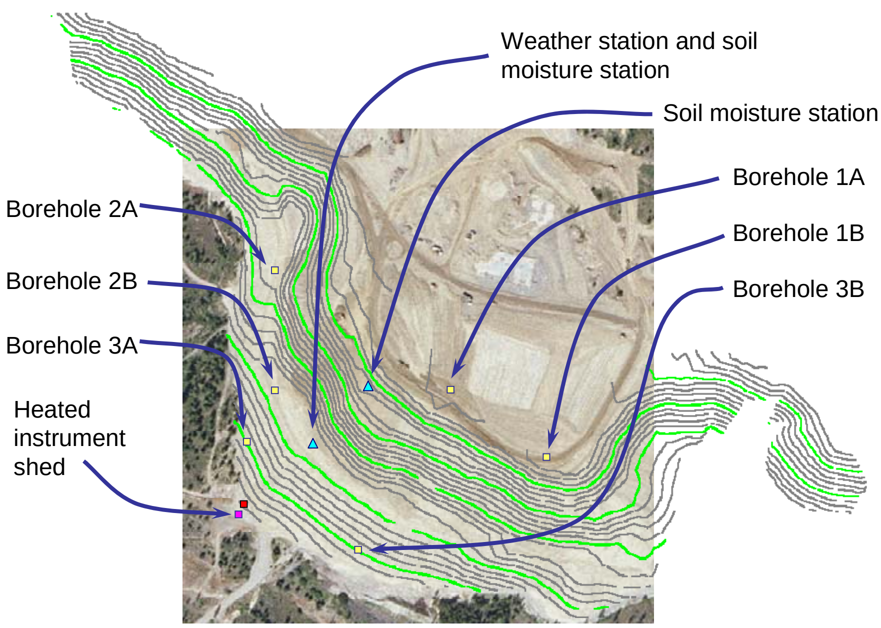

Figure 2. Locations of monitoring instruments and boreholes.

Data from the monitoring station, weather station, and boreholes and push-ins are collected at 15-minute, hourly and daily intervals. Soil station data are collected every six hours. The data are collected in automated recorders, which can be downloaded remotely. However, as with all monitoring systems of this kind, the data need to be carefully checked for errors prior to use. At the time of this update report, monitoring data were available up to early June 2007.

3. Current Understanding of Fundamental Processes

How does oxygen become depleted in waste rock dumps?

Most of the rock in mine waste dumps comes from well below the earth's surface, and can contain components that are unstable in other environments. Specifically, mine waste rock often contains a class of minerals known as sulphides that are reactive when they are brought to surface and exposed to water and air. The result is a chemical reaction between the sulphide minerals and oxygen in the air. That reaction consumes oxygen.

When the rock is in open air, any oxygen that is consumed is quickly replaced. However, when the air flow is restricted, as for example within a large pile of waste rock, oxygen depletion can result. When the waste rock is covered by soil as part of reclamation efforts, the flow of air is further restricted. The oxygen in the air that is trapped inside the dump can then be almost entirely depleted.

The reaction between sulphides and oxygen has another effect. It leads to the release of acidity and metals that can contaminate any water that passes through the dump. For that reason, many soil covers on waste rock dump are designed to restrict the flow of both air and water into the rock.

There is a secondary set of reactions that can also change the composition of air within a waste rock dump. The acidity released by the sulphide oxidation can react with another class of minerals known as carbonates. That reaction results in the production of carbon dioxide gas. Carbonate minerals are less common than sulphide minerals at many mines, so this type of secondary reaction is less common. However, high levels of carbon dioxide gas have been measured in some waste rock dumps at other mines.

How does air move in and out of waste rock dumps?

The movement of air into and out of waste rock dumps at a number of other mines has been studied for about fifteen years. Most of the studies have been directed towards understanding the processes influencing sulphide oxidation and the generation of acidity, metals and other contaminants. However, a good deal has been learned about the basic processes that drive air flow.

In general, air flow in waste rock can be driven by changes in temperature, changes in barometric pressure, or changes in gas composition.

As most of us know from everyday experience, hot air rises and cold air sinks. The reason is simply that heat causes air to expand and become slightly less dense or lighter, while cold makes it contract and become slightly more dense or heavier. Within a waste rock dump, there are many sources of heat. For example, the sulphide oxidation reactions mentioned above can generate significant amounts of heat, and temperatures of up to 65 °C have been measured in some sulphidic waste dumps. When those conditions occur, air within the dump is rapidly heated, and it rises upwards and outwards. Air from the surroundings is then drawn into the base of the dump, and in turn is also heated and rises. The overall result can be a very strong and consistent upward flow of air through the dump.

But it is also possible for dumps with less sulphide minerals to exhibit more moderate temperatures. In some of those cases, the dump can be hotter than the surrounding air in winter, but colder than the surrounding air in summer. Air then rises out of the dump only in winter. In summer, the cooler air within the dump is heavier than the surrounding air, so it sinks and flows out the dump base.

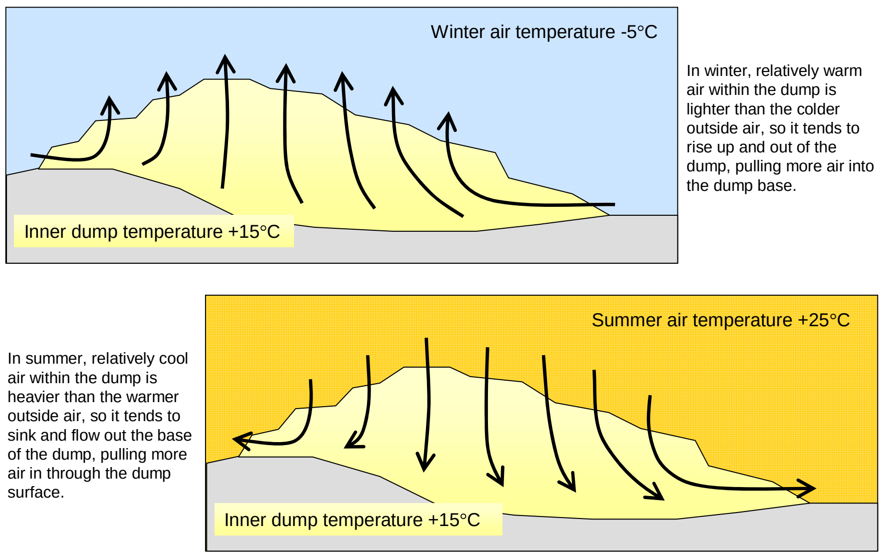

Figure 3. Air movement within waste dump controlled by seasonal temperature.

Most of us cannot notice the slight changes in air pressure that accompany weather shifts, but these “barometric pressure” changes are certainly strong enough to cause air to flow. We know, for instance, that there is often a flow of cold northern air out of the high pressure cells that form over the Canadian north in winter. At the smaller scale of waste rock dumps, barometric pressure changes can also cause air movement. When a zone of high barometric pressure moves into a region, the air within the dump is compressed and tends to flow inward. When a low pressure cell moves in, the air within the dump expands and tends to flow outward.

Generally, only a small amount of air needs to enter or leave a waste rock pile in order to make the pressures inside the pile catch up with changes in barometric pressure. However, studies of some covered waste rock piles have shown a prolonged response to barometric pressure changes. The reason is thought to be that the cover acts as a seal over most of the dump, so that the air can only move out through holes in the cover. If the barometric pressure drops below the pressure in the dump, the air in the dump needs to find its way out of the holes. In such cases, the dump is much like a tire with a slow leak, and the air can continue to leak out for hours or days.

Changes in air composition can also cause air movement in waste rock piles. For example, oxygen is one of the heavier components of air, so when it is depleted by sulphide oxidation reactions, the air becomes less dense or lighter. The lighter gas then tends to move upward and out of the waste dump. That is thought to be one reason why most air flows in waste rock piles are upwards, at least when temperature effects are small. Carbon dioxide, on the other hand, is relatively heavy. Reactions that add carbon dioxide to the air therefore cause it to sink downward. That seems to be one reason why the highest concentrations of carbon dioxide are most often found near the base of waste rock dumps.

What about combinations of the chemical and physical processes?

The chemical reactions that remove oxygen or add carbon dioxide in waste rock piles almost always occur in combination with the physical processes that cause air to move. In fact, the heat and the changes in composition from those reactions tend to enhance the air movement. Scientists refer to this sort of combined effect as a feedback loop, and they know that it makes the combined system difficult to fully characterize. For example, a small amount of heat in one part of a waste rock pile can lead to a slightly increased air flow that leads to more reactions and more heat production, which accelerates the air flow, which then accelerates the reactions, etc.

Fortunately, it is seldom necessary to understand precisely where the air goes within a waste rock pile. For most purposes, it is possible to focus on how much air goes in or out. For example, one of the main areas of environmental research over the last fifteen years has been how to build soil covers that limit the amount of air that can flow into waste dumps. In the Sullivan No. 1 Shaft Dump investigation, we are primarily interested in how the air altered by chemical reactions moved out of the dump and into the monitoring station.

4. Current Understanding of Underlying Causes of May 2006 Incident

Which fundamental chemical processes are active in the No. 1 Shaft Waste Dump?

As part of the installation of instruments within the No. 1 Shaft Waste Dump in March 2007, samples of dump material were taken and sent to a laboratory for mineral and chemical analyses. The analysis clearly showed that both sulphide minerals and carbonate minerals are present in the rock. The sulphide minerals were expected; the lead and the zinc in the Sullivan ore occur as sulphides and there are also abundant iron sulphide minerals. The carbonate minerals were not expected, but there was evidence of carbonate in most of the chemical analyses, and the carbonate mineral calcite was identified in about half of the mineralogical samples. Carbonate minerals were also found in samples of the till material that was used to cover the dump and which form the base of the drainage collection system running beneath the dump toe.

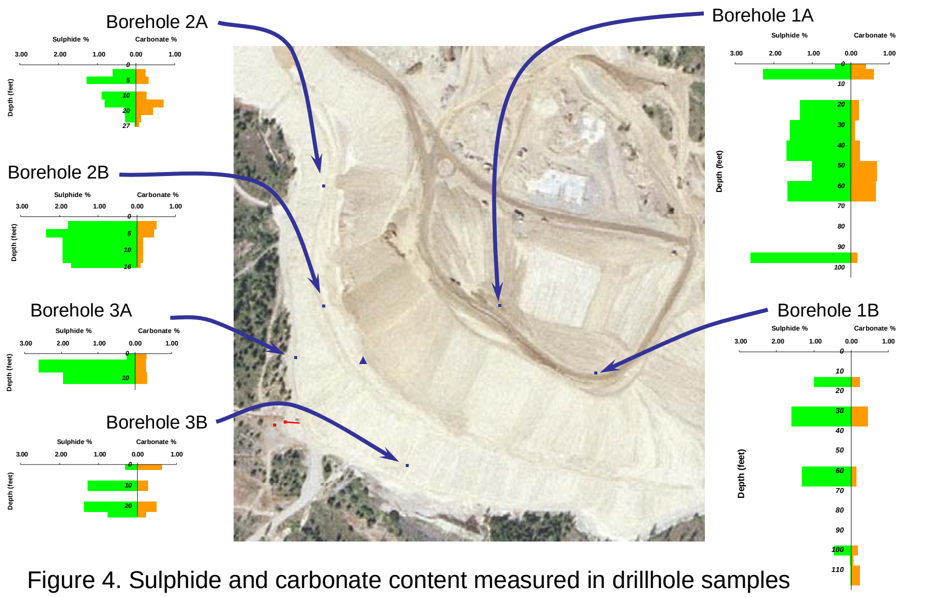

Figure 4. Sulphide and carbonate content measured in drillhole samples (% S and % CO_3 by weight).

The presence of sulphides and carbonates indicates a potential for the rock to both consume oxygen and produce carbon dioxide. Analyses of air samples taken from within the dump confirm that this is occurring. 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 drillhole.

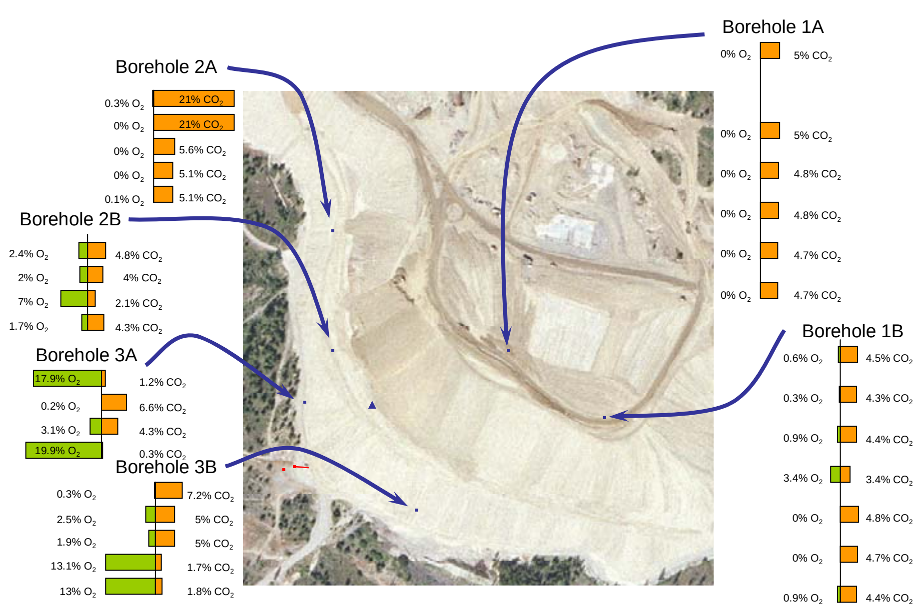

Figure 5. Borehole oxygen and carbon dioxide at depth (June 7, 2007).

These results conclusively demonstrate that air within the dump is reacting with sulphide minerals, leading to the depletion of oxygen. The reactions also produce acidity, which then reacts with carbonate minerals to produce carbon dioxide. The fundamental chemical processes that create bad air within the No. 1 Shaft Waste Dump are understood.

<u>Which fundamental air movement processes are active in the No. 1 Shaft Waste Dump?</u>

The instruments within the No. 1 Shaft Waste Dump show that internal temperatures range from about 5 °C to about 16 °C. The temperatures vary from one location within the dump to another. The higher temperatures are generally found at the greater depths near the middle of the dump, and the lowest temperatures are found near the dump surface and at the base where the dump material meets natural ground. At any one location, however, the temperatures are very nearly constant, i.e. they do not change much over time.

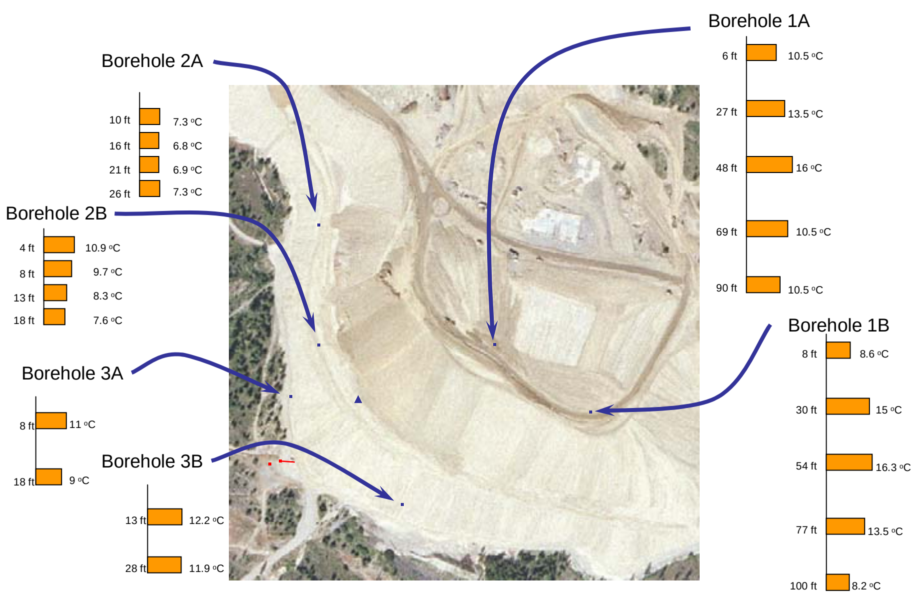

Figure 6. Borehole temperatures at depth (May 31, 2007).

As is well known to Kimberley residents, air temperatures in the area cover a much broader range. During the period in which the internal dump data were collected, outside air temperatures ranged from -7 °C to +26 °C. Comparing that range to the range of internal temperatures shows that there is a clear potential for temperature driven air flow. There are periods when the surrounding air is much cooler than that in the dump, leading to a tendency for the air to rise upward and out of the dump surface. There are other periods when the air within the dump is cooler than the surrounding air, leading to air movement downward and out of the dump toe.

The potential for barometric pressure to drive air flow is less clear from the internal dump data. Measurements of air pressures within the dump show that they consistently follow changes in the atmospheric pressure. The rapid response to barometric pressure changes indicates that the dump is not behaving like a "tire with slow leak", to use the analogy introduced above. Barometric pressure effects therefore appear to be much less likely than temperature effects to drive sustained air flows.

As explained above, oxygen depletion tends to make air lighter and carbon dioxide addition tends to make it heavier. Since both processes are occurring within the No. 1 Shaft Waste Dump, it is possible that changes in gas composition could affect gas flow. The ranges of oxygen and carbon dioxide concentrations measured to date indicate that most of the dump air is, on average, slightly lighter than the surrounding air. However, the differences are unlikely to be sufficient to cause a sustained flow of air throughout the dump as a whole.

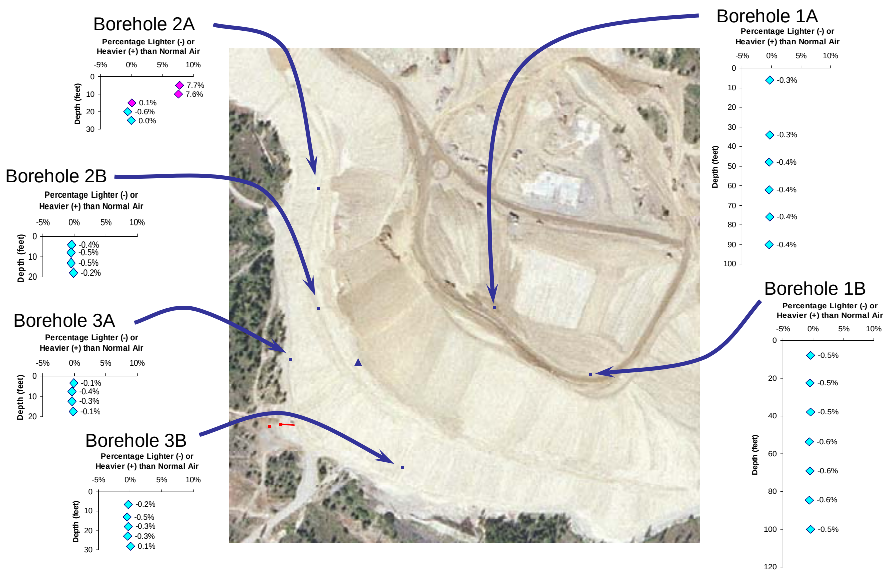

Figure 7. Differences in air density resulting from oxygen depletion and carbon dioxide production.

It can be concluded that the dominant cause of air movement within the No. 1 Shaft Waste Dump is the differences between air temperatures within and outside of the dump. Barometric pressure and gas composition effects may cause localized or short-term air movements, but are much less important than temperature in driving overall air flows.

How did the monitoring station come to be full of oxygen-depleted air in May 2006?

Samples taken in May 2006 from within the monitoring station at the toe of the No. 1 Shaft Waste Dump indicated that the air was depleted of oxygen and contained carbon dioxide. The concentration of oxygen was about 2% and that of carbon dioxide was about 7%. For comparison, normal air typically contains about 21% oxygen and 0.03% carbon dioxide. The concentrations measured in May 2006 are in fact much closer to those currently being observed within the dump itself than they are to the normal air values. It is clear therefore that the air within the station originated from within the dump.

Generally, the construction and reclamation measures at the No. 1 Shaft Waste Dump are in accordance with standard practices at other mines. However, there are physical attributes of the dump that increase the potential for air to flow towards the monitoring station. The first is the dump's location on a slope, which induces gravity flow towards any low point. The second is the drainage collection system under the dump toe. The drain was initially a ditch that wrapped around the entire dump toe, so that all drainage water would flow to a low point just above the monitoring station. When the dump was re-graded to allow construction of the soil cover, the ditch was first filled with coarse rock through which the water could continue to flow. Dump material was then pushed out over the filled ditch. The geometry of the "toe drain", as it is known, probably contributes to the connection between the monitoring station and the inside of the waste dump. Not only water but also air can flow along the drain to the lowest point, from where it can pass through a 16-inch water collection pipe and into the monitoring station. The third potentially important feature is the soil cover itself, which was constructed in late 2005 and designed to be about three feet of till soil over the entire dump and toe drain. When the till is saturated with water, as it very likely was in May 2006, it acts as a barrier to air flow. Air that would normally flow out of the dump surface or along a broad area at the dump toe, would then be forced to funnel along the toe drain and out the 16-inch pipe that leads from the toe drain to the monitoring station.

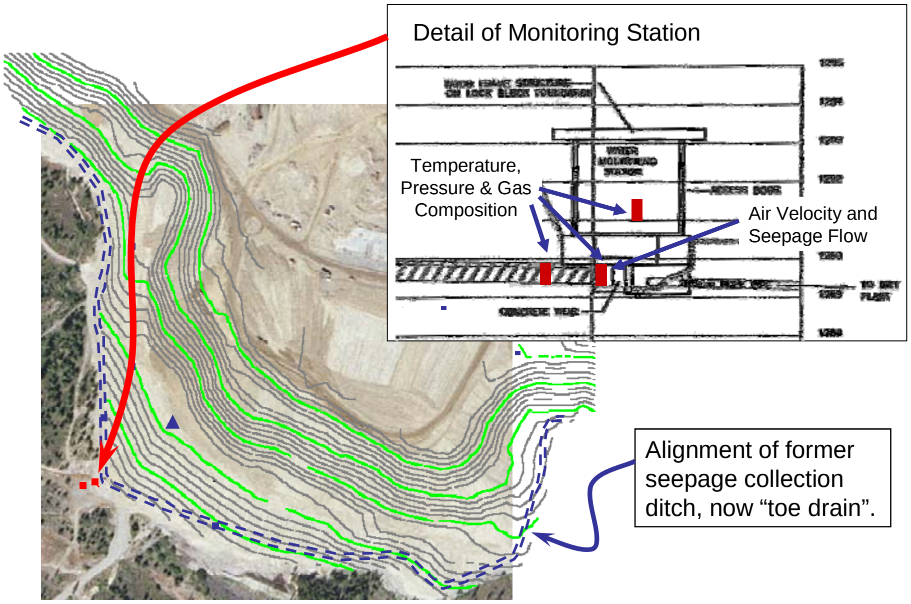

Figure 8. Seepage collection system and monitoring locations.

As part of the initial instrument installation in August 2006, an air flow meter was placed in the 16-inch pipe. The meter's records show that air flow was mostly inward, i.e. from the station into the dump, from October 2006 through April 2007. However, the earliest measurements, from late August and September 2006, showed an outward air flow from the dump into the station, and the most recent measurements, from May 2007, show fluctuations between inward and outward flow.

The pattern of inflows and outflows matches well to the pattern of temperature changes in the surrounding air. Gas outflow periods tend to correspond to periods where the air temperature is above about 10 °C, and gas inflow seems to dominate when air temperatures are below about 10 °C. There is also one brief period in the data where an air outflow occurred at much lower temperatures, apparently in response to a sharp change in barometric pressure. But the dominant effect controlling air flow into and out of the pipe is clearly temperature.

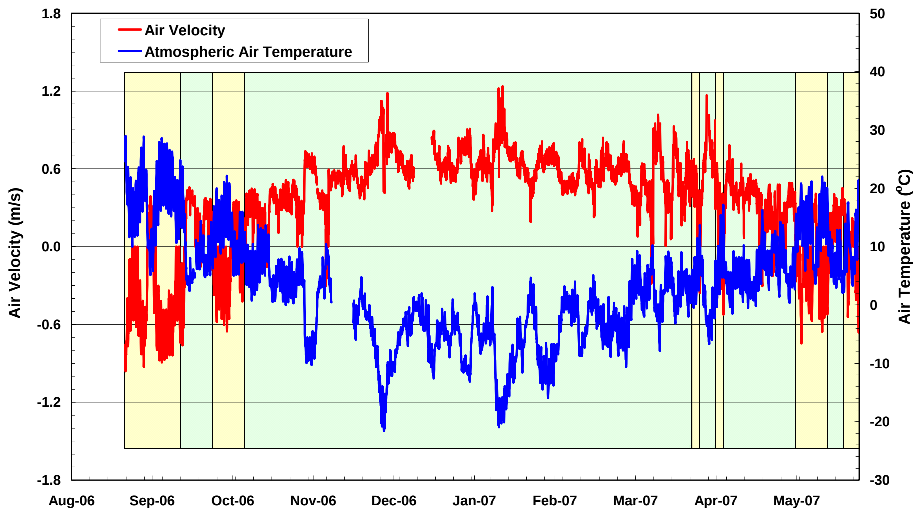

Figure 9. Air flow in the 16" pipe and atmospheric air temperature. A positive velocity indicates air was moving into the pipe; a negative velocity means air was moving out. Periods of inward flow are shaded green; periods of outward flow are shaded yellow.

At the time of the May 2006 incident, there was no air temperature or barometric pressure monitoring at the site. However, the weather station at Cranbrook airport was collecting both measurements. Based on the Cranbrook airport data, the May 13-17, 2006 period included both a sharp increase in air temperature to about 20 °C and a strong decrease in barometric pressure. It has been reported that the monitoring station was safely entered in the preceding week on May 8, 2006. The Cranbrook airport data for that date indicated a sharply rising barometric pressure and a temperature of less than 10 °C.

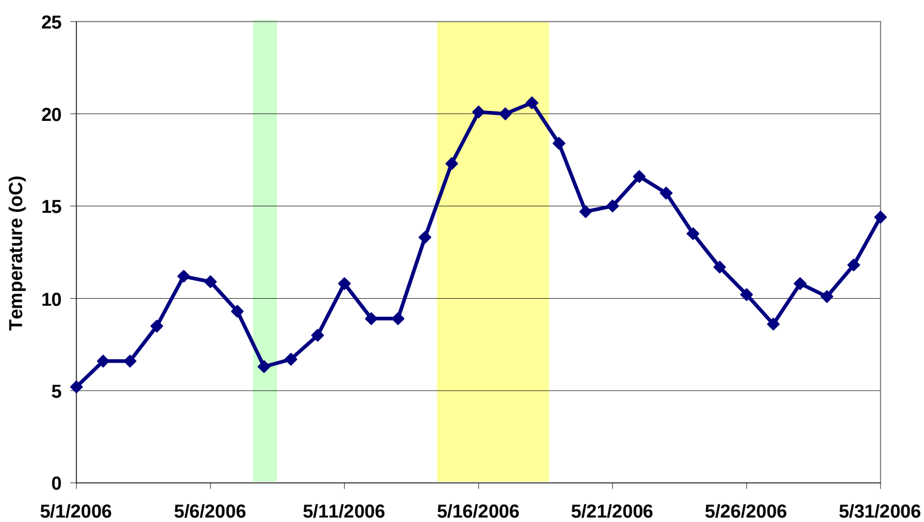

Figure 10. Daily average air temperature at Cranbrook airport in May 2006. Monitoring station was entered safely on May 8, 2006.

We know now, from both the station monitoring data and the internal dump instrumentation, that air temperatures drive air movements in this system. It is reasonable to conclude that the increase in air temperatures during May 13-17, 2006 made the air around the No. 1 Shaft Waste Dump lighter than the cooler air inside the dump, and caused the air inside the dump to flow downward, out of the 16-inch pipe, and into the monitoring station. The possibility that the barometric pressure changes also contributed to the air movement in May, 2006 probably can never be ruled out completely, but the dominant effect of the temperature change is clear.

5. Remaining Uncertainties

<u>What is left to be known about the underlying causes of the May 2006 incident?</u>

The above discussion of underlying causes is focused on identifying the dominant processes affecting the No. 1 Shaft Waste dump as a whole. However, there are a number of less influential processes that affect portions of the dump. For example, the high carbon dioxide concentrations measured in one borehole could lead to different patterns of gas flow in the immediate vicinity.

In fact, several pieces of evidence suggest that there are variations in both chemical and physical processes within the dump. The simplest of these is the observation made by site staff during the winter of 2007 that the snow was clearly thinner on some parts of the dump. The thin patches appear to indicate areas where up-flowing warm air was leaving the dump. The fact that they were localized indicates that air flow within the dump is not homogeneous. Similar inferences can be drawn from detailed consideration of the internal dump pressures, temperatures and gas compositions.

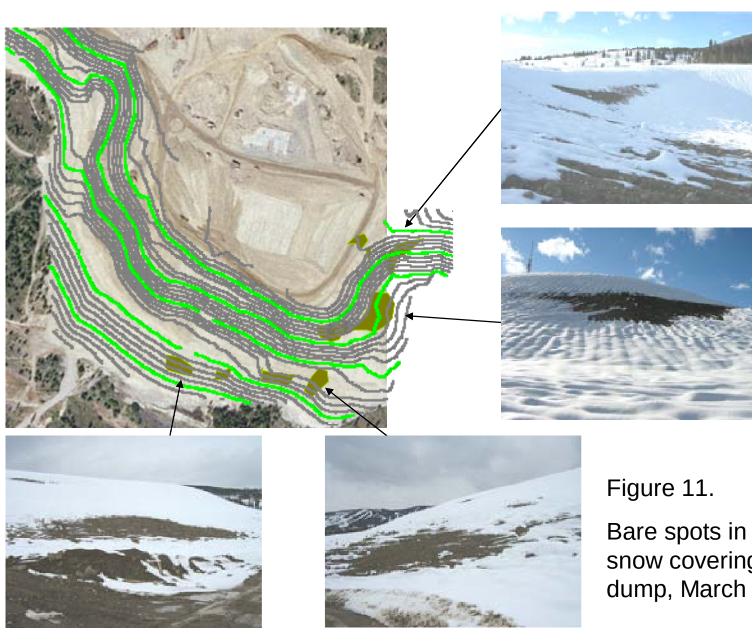

Figure 11.

Bare spots in the snow covering the dump, March 2007.

Similarly, processes that are active only over short periods of time may be more evident in the complete data set. An example is the outward flow of air measured in February, 2007, during a period where the air temperatures were consistently low. As noted above, the cause in that case appears to be a change in barometric pressure. Although such effects are less important overall than the dominant effects of temperature, they would have equally dangerous consequences during the brief periods over which they occur.

Further investigation of these localized and short-term effects is needed. It is the opinion of the Technical Panel that the further investigation will not change the current conclusions about underlying causes of the May 2006 fatalities, but that a diligent review of all possibilities is warranted both to complete the understanding of the No. 1 Shaft Waste Dump and to learn any lessons that can improve safety elsewhere.

Can similar things happen at other sites?

While it is true that the tragic events of May 2006 incident are unprecedented, the Technical Panel believes that similar risks could exist elsewhere. One of the goals of the panel is to ensure that any lessons that can be learned from the May 2006 incident are applied to develop preventive measures that will save lives at other sites.

In that respect, further data collection and review is essential. In general, each waste rock dump represents a unique combination of chemical and physical processes, geometry and setting. Factors that, at the No. 1 Shaft Waste Dump, are only noticeable through detailed review of the monitoring data can be the dominant effects at some of these other sites.

Several specific questions that have occurred to the Technical Panel relate to how combinations of fundamental processes with site specific conditions can enhance risks. For example, is the combination of temperature and sulphide minerals alone enough to create risks, or are the other elements present at the No. 1 Shaft Waste Dump, such as the toe drain, the cover, the 16-inch pipe and the enclosed station, necessary factors? Only a more detailed review of the monitoring data and a careful extrapolation to other sites will answer those questions.

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

- 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 higher than temperatures within waste dumps, which can lead to temperature driven outflows of dump air;

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

Although the above risk factors are stated in terms of waste rock dumps, some of them may also be present in tailings dams, tailings piles, ore stockpiles, and other site components. 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.