Atmospheric Fuzzy Risk Assessment of Confined Spaces at Mine Reclamation Sites

by

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Abstract

In 2006, a tragic accident took place at the Sullivan mine in Kimberley, British Columbia. Four people died as the result of their entry into an oxygen-depleted sampling station located at the toe of a waste dump. The dump had been in active use for over 50 years and the sampling shed for about 5 years without any problem. The accident was reported as being unprecedented in the history of mining. The accident shows that reclamation sites can be an atmospheric danger only recognizable if a risk assessment is carried out on a regular basis for many years after closure. It is important to conduct regular assessments since there are physical, chemical and environmental factors that affect oxygen-depletion in waste dumps that change over time.

In this thesis, an Atmospheric Fuzzy Risk Assessment (AFRA) tool was devised to recognize confined space dangers at sulfide waste dumps undergoing reclamation. The tool is a fuzzy expert system to transfer knowledge on atmospheric hazards. Modeling the complex environment of a waste dump where internal and external factors change temporally and spatially using conventional mathematical tools is a difficult task. Therefore, a technique based on fuzzy logic and weighted inferencing was applied since this method relies on a heuristic approach that allow for case–based reasoning. AFRA can help mining engineers and other safety professionals to recognize this type of danger while developing a confined space inventory at any site.

The second goal of this research has been to create an application for hand-held pocket PCs and/or Smart phones that can be used by first-responders to provide answers about a possible confined space situation to help them decide to enter or not into that space.

Preface

Temperature and pressure data as well as measured/heuristic values of properties of the Number One Shaft Waste Dump at the Sullivan Mine site in Kimberley, B.C. were provided by Teck Resources, the company responsible for the technical investigation of the confined space accident at Sullivan mine. In parallel with the work of the appointed Technical Advisory Panel, my research was conducted in the Centre for Environmental Research in Minerals, Metals, and Materials (CERM3) at the Norman B. Keevil Institute of Mining Engineering at the University of British Columbia. The research was funded by WorkSafeBC and the Workers Compensation Boards of Manitoba and Nova Scotia, independently of Teck Resources and the final outcome was shared with the Technical Advisory Panel for review and comment. The outcome will also be shared with B.C. Ministry of Mines and Energy for practical use by mining engineers and managers.

Some parts of Chapter 2 and 3 were published in the following paper. This includes Parts of Sections 2.1, 2.2.1, 2.3, 2.3.1.1, 2.3.5. Some parts of Sections 3.1, 3.2, 3.3.1, a summary of the accidents in Sections 3.4, a some ideas in Section 5.3.3 and 5.3.4 and a some parts of Appendix E.1.

Mohammadi, L., Meech, J.A, 2008, Implementing Atmospheric Risk Assessment in Mine Reclamation, 23rd International Conference on Solid Waste Technology and Management, Philadelphia, PA, USA, March, pp.12.

I reviewed the literature on confined space accidents and regulations and built the preliminary structure of the Atmospheric Fuzzy Risk Assessment (AFRA) tool and wrote the draft of the first paper. Dr. Meech finalized the papers and gave me ideas about reviewing more focused literature in order to narrow the topic. He also helped to gather confined space fatalities data from the literature and online resources.

The Atmospheric Confined Space Manual introduced in Appendix C was written to help the users of AFRA with recognizing atmospheric confined space hazards. I gathered all relevant information in an attempt to consolidate elements from other manuals (WorkSafeBC, NIOSH, and OSHA). To further enhance the manual, I reviewed different confined space accidents at mines and other industrial sites.

A summary of atmospheric related dangers at mine reclamation sites in Appendix C is reviewed and summarized in the following paper. I wrote the paper and Dr. Meech edited and finalized it. The paper includes some of the ideas and sentences in Sections 1.1, 2.5, 3.3.1, 3.3.2, 3.5, 4.1, 5.2, 5.3.7, 7.2 in this thesis, as well as parts of the Sections C.8.5, C.8.13, C.8.9, C.9., C.10, E.2 in the Appendcies.

Mohammadi, L. , Meech, J.A., 2011. Atmospheric Occupational Health and Safety Issues at Mine Reclamation Sites, Proceedings of the International Conference on Environmental Pollution and Remediation (accepted), Ottawa, Ontario, Canada, 17-19 August 2011.

Parts of the Sections 5.1, 5.2, 5.3, 5.4, 5.7, parts of the conclusion in Chapter 7, parts of the Sections E.1 and E.2 as well as some of the tables in Appendix F were published in a report to WorkSafeBC that was subjected to two anonymous peer reviews by the agency and fed back to me. The report is published online at the WorkSafeBC website. I gathered and interpreted all data and information in the literature related to waste dump environments and applied them to create, verify, and validate the Atmospheric Fuzzy Risk Assessment tool. Dr. Meech revised the tool and provided feedback to make it more user-friendly and understandable. I wrote the report while Dr. Meech reviewed and edited it and suggested ways to improve the report and make it more presentable.

Meech, J.A., Mohammadi, L., January 2011, Confined Space Atmospheric Risk Assessment, Focus on Tomorrow, WorkSafeBC, pp. 81.

Some parts of Chapter 6 have been submitted as a refereed paper:

Mohammadi, L., Meech, J.A., 2011. AFRA – Heuristic Expert System to Assess the Atmospheric Risk of Waste Dumps, Water, Air, and Soil Pollution, (submitted), pp.20.

This paper describes the complete structure of AFRA and was written by myself and revised by Dr. Meech.

I wrote the following paper for Proceedings of the Tailings and Mine Waste 2011 in Vancouver, BC. This paper is also about structure of AFRA and discusses some of the test results.

Mohammadi, L., Meech, J.A., 2011. Atmospheric Fuzzy Risk Assessment of Confined Space Entry at Mine Reclamation Sites, Proceedings Tailings and Mine Waste 2011 Vancouver, BC, November 6 to 9 (submitted), pp 12.

Since the aim of the thesis was to distribute knowledge from the literature to mining industry personnel, I prepared several posters and presented them at several conferences and events:

Mohammadi, L., Meech, J.A., 2008, Risk Assessment of Oxygen-Depletion and Hazardous Gas Emissions at Mine Reclamation Sites, BC Environmental and Occupational Health Research Network (BCEOHRN) AGM and Scientific Exchange, Vancouver, B.C., November.

Mohammadi, L., Meech, J.A., 2009, Atmospheric Fuzzy Risk Assessment of Mine Reclamation Sites, BC Innovation Council Gala Evening, Vancouver, B.C., October.

Mohammadi, L., Meech, J.A., 2009, Atmospheric Fuzzy Risk Assessment at Mine Reclamation Sites, CIM Student Night – Vancouver Branch, November.

I have orally presented my work on two major occasions outside of UBC:

Mohammadi, L., and Meech J.A., 2010. Fuzzy Risk Assessment of Atmospheric Confined Space Dangers at Mine Reclamation Sites. presented at the Canadian Institute of Mining, Metallurgy and Petroleum AGM Conference and Exhibition, Vancouver May 9-12, pp.22.

Mohammadi, L., and Meech, J.A., 2009, Fuzzy Risk Assessment of Confined Spaces at Mine Reclamation Sites. presented to the Chief Inspector of Mines and other mine safety personnel at the Ministry of Energy, Mines and Petroleum Resources, Victoria, May 5, pp.27.

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List of Acronyms

AFRA	Atmospheric Fuzzy Risk Assessment
AFRA CE	Atmospheric Fuzzy Risk Assessment Compact Edition
ARD	Acid Rock Drainage
BCEOHRN	B.C Environmental and Occupational Health Research Network
U.S. BLS	U.S. Bureau of Labour Statistics
CCOHS	Canadian Center for Occupational Health and Safety is a Canadian federal government agency which is responsible to prevent work-related injury and illness.
CDC	Centers for Disease Control
DoB	Degree of Belief
FACE	Fatality Assessment and Control Evaluation - a NIOSH program. It was called Fatal Accident Circumstances and Epidemiology before 1992 (Suruda et al, 1993).
IMIS	Integrated Management Information System in OSHA
IDLH	Immediately Dangerous to Life and Health
LEL	Lower explosive limit of a particular contaminant.
HEL	Higher explosive limit of a particular contaminant.
LFL	If a flammable gas concentration falls below its Lower Flammable Level it will burn. For example, the LFL of hydrogen gas in air is 4%. This range depends on to temperature, pressure and oxygen or chlorine percentage. (http://www.ccohs.ca/oshanswers/chemicals/compressed/compress.html?print).
MVT	Mississippi Valley Type
NIOSH U.S.	National Institute for Occupational Safety and Health. NIOSH is part of the Department of Health and Human Services and acts as a research agency focused on education, and training in occupational safety and health. NIOSH research is to identify health and safety risks and measure them in working places to reduce danger
NTOF	National Traumatic Occupational Fatality surveillance system developed by NIOSH to collate data on traumatic work-related fatalities (Suruda et al, 1993).
OHS	Occupational Health and Safety consultancy in U.K that provides a wide spectrum of policies, guidelines, and activities focused on promoting and

managing health and safety and asbestos-issues in the work place as well as occupational hygiene

OSHA Occupational Safety and Health Administration is a federal agency in the U.S. Department of Labour, which has been active since 1971. According to U.S. DoL, OSHA publishes and enforces safety and health regulations for most businesses and industries in the U.S. to prevent work-related injuries, illnesses, and deaths.

SCBA Self-Contained Breathing Apparatus

TLV-TWA Threshold Limit Values -Time- Weighted Average is a time weighted average concentration of the toxic gas for 40 hours work week (8 hours a day), which will cause no adverse health effect on nearly all workers after being exposed repeatedly during this time (Eltschlager et al., 2001(a)).

TLV Threshold Limit Value is the concentration that should not exceed during all exposures (Eltschlager et al., 2001(b)).

UFL If a flammable gas concentration falls above its Upper Flammable Level it will burn. For example, the UFL of hydrogen gas in air is 75%. This range is dependent to temperature, pressure and oxygen or chlorine percentage. (http://www.ccohs.ca/oshanswers/chemicals/compressed/compress.html?print).

UN Undetermined

WCB Workers Compensation Board of Manitoba

WHMIS Workplace Hazardous Materials Information System

WorkSafeBC Workers Compensation Board in British Columbia

List of Symbols

$\bar{C}_{p,avg}$= Heat capacity of the air or gas = about 1.099 [$J{\cdot}g^{-1}K^{-1}$],

Δf = Free energy of the unit-mass [$J{\cdot}g^{-1}$],

Ψ = Flow exergy of a unit-mass of the gas [$J{\cdot}g^{-1}$],

gz = Potential energy of the unit-mass [$m^2{\cdot}s^{-2}$],

h = Enthalpy of the unit-mass of the gas [$J{\cdot}g^{-1}$],

P = Pressure [Pa],

q_k = Heat transfer to the unit-mass of the gas [$J{\cdot}g^{-1}$],

R = 0.287 [$J{\cdot}g^{-1}K^{-1}$],

s = Entropy of the unit-mass [$J{\cdot}g^{-1}K^{-1}$],

T = Temperature [K],

$\frac{V^2}{2}$ = Kinetic energy of the unit-mass [$m^2{\cdot}s^{-2}$],

v = Unit volume, $v=\frac{RT_1}{P_1}$ [$m^2{\cdot}g^{-1}$],

$\vec{V}$= Velocity [$m{\cdot}s^{-1}$],

w = Work interactions per unit mass of the working gas on the outside [$J{\cdot}g^{-1}$]

x = Exergy of the unit-mass [$J{\cdot}g^{-1}$],

z = Height [m],

Acknowledgements

My special gratitude goes to my supervisor, Dr. John A. Meech, who taught me how to think effectively and question concepts deeply in order to solve complex problems. He helped me gain the confidence necessary to conduct my research independently and showed me how to effectively present my work. He fostered my view of problems broadly and practically while patiently helping and protecting me through the different stages of the research. Without Dr. Meech's novel ideas and initiative coupled with his strong belief for the necessity of this work, this research would have never been started nor completed. I thank him for offering me a new way of living by providing me with the opportunity to study at UBC and changing my life for the better.

I would like to warmly thank the kindness, support, and care of Dr. Leslie Lavkulich during my studies as well as the useful advice of Dr. Marcello Veiga. I offer my enduring gratitude to my adorable parents, Mr. Khosrow Mohammadi and Mrs. Behnaz Akhavan, who have supported me all through the years of my education both emotionally and financially, especially my father who has always inspired me to continue beyond my very best. I owe particular thanks to my husband and soon to be naturopathic doctor, Hamid Reza Tajbakhsh who has patiently supported me during both good and tough times of my Ph.D. studies and managed my stress with all of the naturopathic tools he could use, without whom this work would have been much more difficult to complete. My greatest thanks goes to my friend, Ali AbdulHussein, for his heart warming help in my early years of study. My younger brother, Amirahmad Mohammadi, who I could always rely on for discussing problems of my thesis, also deserves my sincere gratitude. My thanks also go out to my older sister, Katayun Mohammadi, who encouraged me to focus on my studies by always mentioning the value of education when we were younger. I also thank all other faculty and staff at UBC who have helped me through this journey especially in my early years in Canada. Dr. Ali Asghar

Hassanipak at University of Tehran also deserves my gratitude since he encouraged me to not only start my masters' degree but also to apply to the University of British Columbia in pursuit of my PhD.

I would like to thank WorkSafeBC (Workers' Compensation Board of British Columbia), and the Workers' Compensation Board of Nova Scotia for their financial support during this project. I also appreciate the reviews and advice from two anonymous external experts at WorkSafeBC on the final project report. The reviewers' points of view helped the project in terms of making it more understandable and presentable.

My gratitude also extends to the members of the Technical Advisory Panel on the Sullivan Mine Incident formed by Teck Resources (formerly Teck-Cominco) for their input and comments: Walter Kuit and Bruce Dawson from Teck Resources; Ricci Berdusco, (resigned 2008), Phil Pascuzzi (resigned 2008), Al Hoffman, Kim Bellefontaine (since 2008), and Diane Howe (since 2008) from B.C. M.E.M.P.R.; Clem Pelletier from Rescan Environmental (resigned 2008); Dr. Andy Robertson from Robertson GeoConsultants; Dr. Ward Wilson and Dr. John Meech from the University of British Columbia; Mike O'Kane and Mark Phillip from O'Kane Consultants; Daryl Hockley from SRK Consulting.

Finally, I would also like to thank all the researchers who have done investigations on waste dumps since without their papers and insights I would not have been able to build and validate my model and make a contribution to the field of mine waste management and engineering.

Dedication

This thesis is dedicated to the victims who lost their lives at the Kimberly accident between May 15 and 17, 2006.

- Douglas Erickson, 48, a contractor from nearby Ha Ha Creek.
- Robert Newcombe, 49, a Teck-Cominco employee who lived in Cranbrook.
- Kim Weitzel, 44, a paramedic from Kimberley.
- Shawn Currier, 21, a paramedic who lived in Cranbrook.

Chapter 1
Introduction

1.1. Statement of the Problem

In May of 2006, a tragic accident took place at the Sullivan mine in Kimberley, British Columbia. Over a period of about 36 hours, four people died as a result of each of them entering into a sampling station located at the toe of the Number One Shaft Waste Dump (http://thetyee.ca/News/2007/07/09/MineDeaths/; Sullivan Mine Incident Technical Panel, 2010; http://www.bcas.ca/EN/main/news/newsArchive/4274/report-confirms-unprecedented-incident.html). Acid Rock Drainage (ARD) effluent from the waste dump had caused oxygen-depletion to occur within this structure transforming it from a simple "shed" to an extremely dangerous confined space. The direct reason for these fatalities was the concentration of oxygen-depleted gas emissions from the waste dump from a buried pipe into the sump at the bottom of the sampling shed.

Pollution from mine wastes may be emitted into different environments (the hydrosphere, the lithosphere, and the atmosphere). Risk assessment in waste dump reclamation programs is generally done to protect the environment and to develop construction rules to handle issues such as acidic water drainage collection, erosion, slope stability, and liquefaction (Kaczynski, 1986; Amanti et al., 1996; Chaulya et al, 1993; Chaulya et al, 2000; Engels et al., 2007; Kreft-Burman et al., 2007). With the exception of spontaneous combustion, dangerous atmospheric releases from a waste dump have not been regularly assessed or even recognized as a realistic need. It is now apparent that a new risk assessment method should also be applied to identify human occupational-health dangers at reclamation sites especially from atmospheric emissions (Mohammadi and Meech, 2008). It seems prudent that future permitting processes should include such a risk assessment approach. Currently, there is no risk assessment tool available to use with reclamation sites or, for that matter, to apply a standardized procedure to other types of confined spaces with a possible atmospheric hazard. Neither is there a requirement on the part of operators to conduct such an analysis. Recognizing the presence of a hazard and evaluating the development of dangerous conditions at a site are essential first steps in the prevention of such accidents (Mohammadi and Meech, 2011).

Accidents of this kind occur because of a lack of knowledge transfer from experts on a variety of inter-related and inter-connected topics into the actual workplace. One way to accomplish this knowledge transfer is to create a software system to educate and train people about the key issues surrounding confined space hazards at mine reclamation sites. Such a system can be used routinely to perform a risk assessment at a site to discover hazards early and introduce mitigation practices. The consequence in the case of exposure to a confined space with an atmospheric hazard is death of any person who enters the space in an unauthorized or unsafe manner (Mohammadi and Meech, 2011). The degree of danger varies on an hourly, seasonal, and decadal basis, so recognition of the hazard is difficult to establish in situations where such dramatic changes in risk take place. Someone may occupy the space one evening without any problem while the next day the temperature has risen and the space is now deadly.

A major component of this research has been the creation of an Expert System tool to provide knowledge transfer from specialists to industry to workplaces. Regulating mine managers and workers to use this knowledge transfer tool while they design and implement mine closure practices can prevent a "blind" reliance on "past safe performance" of their industry (or the site) – which is one of the major reasons for failing to identify a confined space situation.

Atmospheric risk assessment is perhaps as important a task as is the environmental risk assessment of ARD impact on the aquatic environment and such analyses should be carried out on a regular basis after mine closure. It is emphasized that both environmental and atmospheric risk analysis should be carried out in parallel to find site specific solutions that are best for both aspects. Regular atmospheric risk assessment is important because unknown future activities may be carried out at the site that can change the risk level. Certain provisions and rehabilitation activities at a closed mine may increase atmospheric risk. Over time, changes occur within the dump as sulfide minerals continue to oxidize consuming oxygen from pore gas, generating acid, and producing carbon dioxide from reaction of the acid with carbonate-type minerals. More importantly, temperature changes within the dump due to these reactions lead to periods of danger followed by dormant behaviour and then followed again by danger over decades of time.

1.2. Objectives and Contributions of the Work

1.2.1. Motivations and Objectives

The specific objectives of the research have been to:

1. Investigate the causes of the accident that occurred at the site.
2. Study related accidents and current confined space regulations.
3. Identify potential gasses in waste dump systems (e.g. oxygen-depleted air, carbon dioxide).
4. Identify principal factors that may control possible gas generation (GENERATION).
5. Gather information from experts, technical reports/papers and literature pertaining to the waste dumps to identify environmental, operational, design and structural factors that can cause hazardous gasses to be released from the waste dump (EMISSION).
6. Investigate gas behaviour after emission (dispersion, trapped and/or vented). (CONFINEMENT).
7. Investigate the exposure of people to confined space (HUMAN EXPOSURE)
8. Build an atmospheric fuzzy risk assessment tool.
9. Evaluate and validate the effectiveness of the model.

10. Develop a tool for first-responders to help them avoid harm to themselves while performing a rescue in an enclosed structure with a potential atmospheric hazard.

All these steps in the research have been taken to support a tool that can help prevent future accidents. The methodology is considered applicable to other industrial sites however the focus in this research has been on the specific issues of mine reclamation.

The major objective is to design software to conduct an atmospheric risk assessment to assist in performing the analysis with an emphasis on identifying potential hazards to human health from poor atmospheric conditions. The software focuses mainly on oxygen depletion and the generation of carbon dioxide, but it also includes a "list of possible gasses in confined spaces" that covers toxic or flammable gas (or dust) generation at other places besides mine reclamation sites. The risk is assessed for waste dumps with sulfide contents from 0.5 to 5% and does not account for highly reactive waste dumps that may spontaneously combust.

In this thesis the values of the three elements - gas generation, gas emission and gas confinement - results in the likelihood of a hazard, which in combination with the value of the element of human exposure, will result in a final risk assessment. Since exposure of humans to a confined space with an atmospheric hazard leads to death in seconds or minutes, the likelihood of the consequence of exposure is 100 percent.

A compact version of this risk assessment tool has also been created to operate on a hand-held device to help rescue personnel–firemen, police, paramedics, and others to decide on entering or not a "permit-required" confined space even when signage is not in place.

This thesis presents details of the development of AFRA - Atmospheric Fuzzy Risk Assessment Tool. A heuristic technique based on fuzzy logic was considered a preferred approach since this method mimics a dialog between humans to achieve successful transfer of information. Such systems can be tuned to be cautious or to allow risky behaviour – in this case, of course, the former is clearly preferred. Linguistic terminology is output rather than numerical values which can accelerate the understanding of the model by novice users. A fuzzy logic rule-base allows for case–based reasoning using an If-Then rule structure. Although numerical methods are being developed with respect to the complex interactions between solid material, water, and air within a waste dump, these methods are in the early stages and considerable assumptions must be made to apply the mathematics appropriately. Waste dumps are extremely heterogeneous masses that show different behaviours spatially, temporally, and geographically. The nature of a problem that is difficult to predict renders these mathematical approaches to situations where dumps are heavily instrumented with input data being collected on an hourly basis over months and years. Such methods are both impractical and infeasible in most cases. Fuzzy logic rule-bases on the other hand, use "*approximation arithmetic*" of an unknown but correct model – the mathematics is subsumed within the system itself. The method is a precursor to the concept of "Computing with Words" in which perceptions are as important as measurements (Zadeh, 1965; Zadeh, 2002).

1.3. Thesis Overview

An outline of the structure of this thesis is as follows:

Chapter 2 presents an overview of data on confined space fatalities and regulations around the world. It compares confined space related fatalities in U.S., Canada, and the province of British Columbia. It discusses and compares different confined space regulations and points out their limitations and deficiencies.

Chapter 3 describes the Sullivan Mine accident. It compares the accident with other similar atmospheric related confined space accidents. In Chapter 4 the factors that contributed to the Sullivan mine tragedy are discussed and analysed. This chapter prepares the reader to understand the phases that were considered in developing AFRA.

Chapter 5 is devoted to the development of a detailed and general Atmospheric Fuzzy Risk Assessment (AFRA) tool. In this chapter processes that contribute to oxygen-depleted gas within the dump and its emission to the outside atmosphere will be described in detail.

The verification and validation of AFRA are also described. Details of the development of a compact version of the tool for a Pocket PC are included in Chapter 6.

Appendix C includes an analysis of possible atmospheric gasses that can be hazardous at mine sites. A review is given of hazardous gasses that can be generated from minerals, soils, or any other material or activity at a mine site. An Atmospheric Confined Space Manual for Gasses from Mines and Soils is presented in Appendix C. This manual is an independent document on its own that can be printed and used. The document is designed to help mine engineers and managers understand and recognize the presence of an atmospheric problem at their work place. A new way to describe a confined space hazard is suggested based on the short-comings of existing descriptions.

Each chapter ends with a summary to conclude on the key findings, while the last chapter provides final conclusions and summarizes the contributions, as well as offering recommendations for future work in this field of study.

Chapter 2

Confined Space Definition, Fatalities and Regulations

2.1. Overview

Confined space accidents expose humans to conditions that can cause immediate death. These accidents typically involve asphyxiation due to emission of a hazardous gas into an unventilated enclosed space. The air may contain too little oxygen; or, it may contain poisonous, flammable, combustible or explosive agents; or, contaminants (e.g., fume, dust, or mist) that pose an immediate threat to life or interfere with a person's ability to escape. The gas may be from contaminated soil or other processes, or it may be air that is oxygen-depleted. Confined space accidents may also involve engulfment in bulk materials (soil, grain, snow, etc.) that flow into the space to cover the victims. Rapid influx of water may lead to drowning (Mohammadi and Meech, 2008 – Note many of these hazards are contained within the Confined Space Entry Program - A Reference Manual, 2005 and in OSHA, 2004). The statistics for confined space accidents in the U.S. during the 1980s collected by NIOSH show that of 670 fatalities over 55% were due to atmospheric conditions with about one third caused by engulfment. The remaining deaths were from falls, fires, or drowning (Suruda et al., 1994).

Of all hazards, a confined space atmospheric hazard is the most difficult for an individual to recognize especially when the issue is oxygen-depletion. There is nothing visual to provide warning; there is no odor and no noise. Death is quick and the victim rarely is aware of the danger as bad air enters the lungs to deplete oxygen from the blood resulting in unconsciousness within 10 to 40 seconds. It is a painless death, but in all cases, it can be prevented by following proper safety procedures as outlined in Appendix C.

It is estimated that more than 1.5 million workers actually enter a confined space annually (Confined Space Policy, 2006). The Occupational Safety and Health Administration (OSHA) suggest that 85% of confined space accidents can be prevented if proper safety precautions at job sites are implemented. Of course, each site poses a serious problem for exposed workers and their employers (Confined Space Policy, 2006) and so, management of confined spaces by personnel and managers is an extremely important task. But, in order to follow proper procedures, one must first identify that a confined space hazard exists.

Not all confined structures are hazardous–an ordinary room with the windows and doors shut is a confining space, but with only a few occupants, it is not a problem as air seeps in under doors and through heating ducts. An outhouse is a potentially dangerous confined space through toxic gas emissions (hydrogen sulfide and methane) from the pit below. Most outhouses are designed with good ventilation and so, such facilities are not classified as dangerous and no deaths have yet been reported for this type of structure. But consider an outhouse covered in snow which insulates the structure and blocks vents preventing air from entering. Under these conditions, even an outhouse could become dangerous (Mohammadi and Meech, 2008).

2.2. Review of Confined Space Fatalities

2.2.1. In the United States

Statistics on confined space accidents have been well-documented over the past quarter century in the United States for the period 1980 to 1989 by NIOSH and from 1992 to 2009 by the U.S (Mohammadi and Meech, 2008). Bureau of Labour Statistics (BLS) (Suruda et al., 1994; U.S. BLS, 2010). Figure 2-1 shows the numbers of confined space related fatalities due to inhalation of toxic gasses or oxygen-deficient air or from oxygen-deficiency caused by cave-ins or collapse of materials since 1980 (Suruda et al., 1994; U.S. BLS, 2010). The data in Figure 2-1 show a steadily improving trend as the number of confined space accidents per year has significantly declined (Mohammadi and Meech, 2008).

Table A-1 in Appendix A gives more details on these data which includes the number of fatalities related to each cause. It is difficult to compare confined space related fatalities from different sources. This thesis compares work-related confined space fatalities, but even in this case, some industries may have been excluded from the system used to gather the information and/or some groups may not have been counted in the surveillance. The type of exposure that causes each accident varies from one surveillance system to another. To make the data more understandable, the types of work related fatalities, type of exposure, and source of gathering the data needs to be clarified.

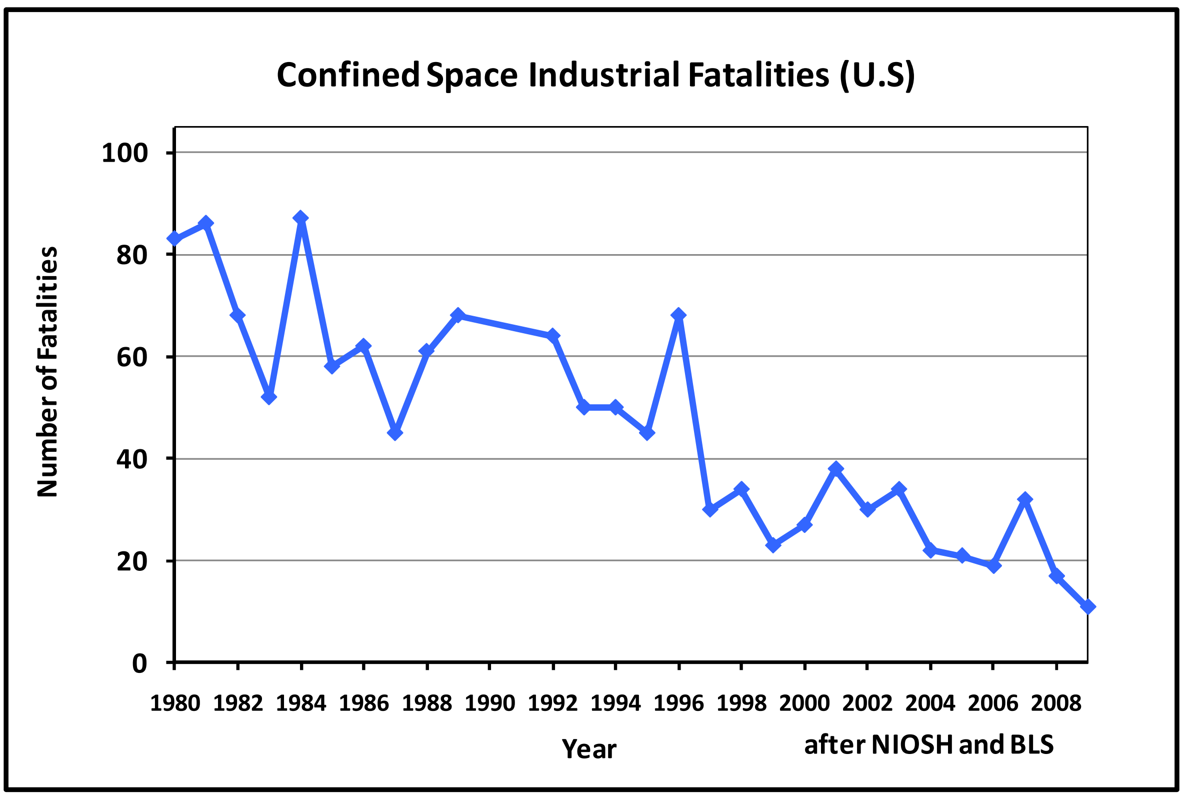

Figure 2-1. Confined-space accident deaths in the U.S. 1980 to 2006 (Mohammadi and Meech, 2008) - (Data before 1989 from NIOSH; Data after 1992 from U.S BLS (U.S. BLS, 2010)). (Data in both NIOSH (by CDC) and BLS are public domain and do not need specific permission)

Figure 2-1 summarizes data on confined space fatalities from 1980 to 1989 (Suruda et al., 1994) based on the National Traumatic Occupational Fatality (NTOF) surveillance system developed by NIOSH to collate data on traumatic work-related fatalities. The NTOF database is a census of traumatic work-related fatalities based on all U.S. death certificates in which the death or injury that caused the death occurred at a work place (Suruda et al, 1993). NTOF contains information from the death certificate that states where and how a death occurred at any workplace. The certificates indicate the cause of death and provide details of the death as well as the opinion of the certifying coroner, medical examiner, or physician. The types of hazards considered by NIOSH were investigated by Suruda et al., (1994) and included asphyxiation, poisoning, and drowning. A fatality was included only if the accident took place in a confined place such as a vat, a pit, a silo, a tank or a bin. If the site of the accident was not indicated in cases of gas poisoning (methane, hydrogen sulfide, etc.), it was still considered as a confined space accident.

Fatalities from engulfment in bulk materials were included but those due to a roof-fall or mine-caving were excluded. Death by explosion, trench cave-in, electrical shock, temperature extremes, barrier failures, radiation or physical hazards such as being hit by moving equipment and machinery or due to a slip or fall were excluded. NIOSH admits that its data on the total number of confined space fatalities is probably lower than the true value, since it is difficult to recognize all deaths in a confined space from the information available in all death certificates (Suruda et al., 1994). There is no integrated source of data or study for atmospheric-related confined space fatalities prior to 1982. However, according to the California Department of Labour Statistics and Research, only 21 of 1,011 (2%) work-related fatalities for 1981-1982 involved confined spaces (Suruda et al., 1994) while NIOSH reported 143 confined-related fatalities during 1976-1977 (average of 72). So it appears that the average yearly fatalities in the U.S. have dropped from 1977 to 1986 by about 20% (Suruda and Agnew, 1989).

Data from 1992 were gathered by the BLS Census of Fatal Occupational Injuries (CFOI). BLS CFOI gathered accurate data of fatal work injuries in all 50 US states and the District of Columbia since 1992. Data from this source were extracted for all types of industrial accident deaths caused by atmospheric reasons for 3 categories of exposure in confined spaces:

1. Depletion of oxygen in enclosed, restricted, or confined spaces;
2. Inhalation in enclosed, restricted, or confined spaces;
3. Depletion of oxygen from cave-in or collapsed materials.

Although confined space related fatalities were not itemized in all categories for all years since 1992, all categories were present from 1992 to 2003 while for 2004 to 2006, the last category is absent and for 2007 to 2009, only the second category is itemized. These data do not include drowning in confined spaces or trench cave-ins as neither of these causes was itemized. So, with the exception of drowning, the BLS data are considered compatible with those of NIOSH. Both sources provide good indications of work-related confined space fatalities in all states (U.S. BLS, 2010).This system uses various sources to identify fatal worker injuries. For each work related fatality - occupation and other worker characteristics, equipment involved, and circumstances of the event - are obtained from source records, such as death certificates, workers' compensation reports, federal and state agency administrative reports and claims, reports to various regulatory agencies, medical examiner reports, or police reports, news and other non-governmental reports. The CFOI data considers the fatalities related to paid-workers that were injured during the conduct of their employment. It also counts volunteer and unpaid family workers who perform the same duties as paid workers. The data include **all** fatal work injuries for workers covered by OSHA or other federal or state agencies. Certain industries such as mining and highway, water, rail, and air transportation, are not covered by OSHA because they are regulated by other Federal agencies, such as the Mine Safety and Health Administration and various agencies within the Department of Transportation. Those accidents outside the scope of regulatory coverage such as self-employed and unpaid family workers are not covered by any Federal or State agencies. (U.S. BLS, 2010; Suruda and Agnew, 1989).

Between 1980 and 1989, according to NTOF, 305 of 1218 (25%) asphyxiation-related fatalities took place in confined spaces (of these 305 fatalities, 31 were by obstruction of the respiratory tract and the other 274 involved mechanical suffocation); confined spaces were also involved in 274 of 1018 (27%) poisoning-related deaths and 91 of 947 (10%) drowning.Table 2-1 categorizes confined space work-related fatalities during these years by cause of accident. Of the 670 fatalities, over 55% were due to atmospheric conditions with about a third of the deaths caused by engulfment. The remainder were from drowning or other causes (Suruda et al., 1994). Clearly, atmospheric hazards are the primary causes of death in confined space accidents (Suruda et al., 1994). There are few studies that categorize atmospheric hazard related fatalities based on type of harmful agent. Suruda and Agnew (1989) have extracted detailed causes of atmospheric-related fatalities for the period between 1984 and 1986 from the OSHA Integrated Management Information System (IMIS).

According to this work, 233 deaths were caused by asphyxiation or poisoning from the total of 4,756 deaths in 47 U.S. states between 1984 and 1986. Of the 233 fatalities presented in Table 2-2, 146 occurred in confined spaces from asphyxiation by oxygen-deficient air or poisoning by gasses or chemicals. It is not apparent how many fatalities which occurred in confined spaces were related to each agent. 27 (11%) of the deaths were related to oxygen-deficiency which most likely occurred in an enclosed area. This number is more than half of the fatalities caused by all other simple asphyxiants in Table 2-2 (Suruda and Agnew, 1989). OSHA data shows fewer fatalities than NIOSH (based on NTOF) during 1984-1986, 146 compared to 207 since the OSHA database is not as complete as that of NIOSH and do not include all confined space fatalities. OSHA reports include all work related fatalities in the United States for which OSHA has jurisdiction (only three states were omitted from this data: California, Washington, and Michigan). The OSHA database excludes mining, transportation, maritime, federal employees, agricultural workers and other sectors regulated by other agencies. For example, the number of total fatalities from 1984-1986 was 4,755 in the OSHA database while NIOSH reports 6,258 work-related deaths during these years. A study in Pennsylvania in 1983-1984 and one in Colorado in 1982-1984 indicate that OSHA only reports about 60% of all occupational traumatic deaths within the industrial sectors for which it has jurisdiction (Suruda and Agnew, 1989). Suruda et al., (1994) have also extracted the cause of atmospheric related fatalities in confined spaces between 1980-1989 from NTOF data – see Table 2-3. Their data show ~17% of the fatalities in this period were related to oxygen-depletion. This is higher than the number of deaths caused by other specified gasses.

During 1984 to 1986, 15 deaths in the U.S. occurred because of using the right respirator wrongly or using the wrong respirator. Of this number, 2 workers died in a confined space due to the use of half-face cartridge respirators in an oxygen-deficient atmosphere instead of a Self-Contained Breathing Apparatus (SCBA). Two workers and one rescuer died when the SCBA ran out of air. One worker died when the air-supplied respirator hose became loose during sandblasting. The 9 other fatalities were related to improper supply of poor air, i.e., contaminated with CO from compressor motor exhaust, nitrogen or argon (Suruda and Agnew, 1989). The proper self contained breathing apparatus or air-supplied respirator should have been used in these cases.

Table 2-1. Confined space fatalities from 1980-89 reported by NTOF (Suruda et al., 1994). (Data are public domain in CDC and does not need specific permission)

Cause of accident	% of Confined Space Fatalities	Number of Fatalities
Atmospheric	56	373
Engulfment in Bulk Material	34	227
Other	10	70
Total	100	670

Table 2-2. Asphyxiation or poisoning deaths from 1984-86 reported by OSHA IMIS in 47 states in U.S. (number in front of each agent is the number of victims) "Adapted by permission from BMJ Publishing Group Limited. [from Asphyxiation and Poisoning at Work in the United States 1984-86, Suruda, A.J., Agnew, J., v 46, 541-546, 2011] ".

Cause of Accident	Agents	No. of Fatalities
Simple asphyxiant	Propane (1), Methane (10), Argon (7), Nitrogen (18), Carbon dioxide (12)	48
Toxic gasses	Ammonia (3), Carbon monoxide (25), Chlorine (3), Hydrogen sulfide (30), Nitrous oxide (4)	65
Oxygen-deficient atmosphere	Substance not reported (lack of oxygen)	27
Mechanical Asphyxiation	-	42
Solvents	Chlorodifuoromethane (1), Coal tar pitch volatiles (1), Dichlorodifluoromethane(2), Diesel fuel (1), Gasoline (3), Isopropanol (1), Methyl chloride (1), Methyl chloroform (4), Methylene chloride (8), Naphtha (3), Perchloroethylene (1), Toluene (2), Trichlorotrifluoroethane (F-113) (4), Trichloroethylene (2), Trichloroethane (1)	35
Undefined or incomplete report		7
Other	Dimethyl sulfate (1), Maleic amhydride (1), Sulphuryl fluoride (1), Cyanide (1), Hydrogen fluoride (4), Phosphorus (yellow) (1)	9
Total		233

Table 2-3. Number of deaths caused by atmospheric hazards in a confined space noted on death certificate identified by NTOF, 1980-1989 ((Data are public domain in CDC and does not need specific permission, Suruda et al., 1994).

Type of atmospheric hazard	% of Atmospheric Fatalities	Number of Fatalities
H_2S	13.7	51
Methane	10.2	38
Inert gasses	8.6	32
Carbon monoxide	6.7	25
Sewer gasses	6.7	25
Oxygen-deficiency	16.6	62
Other gasses	16.6	62
Unknown atmosphere	20.9	78
Total	100.0	373

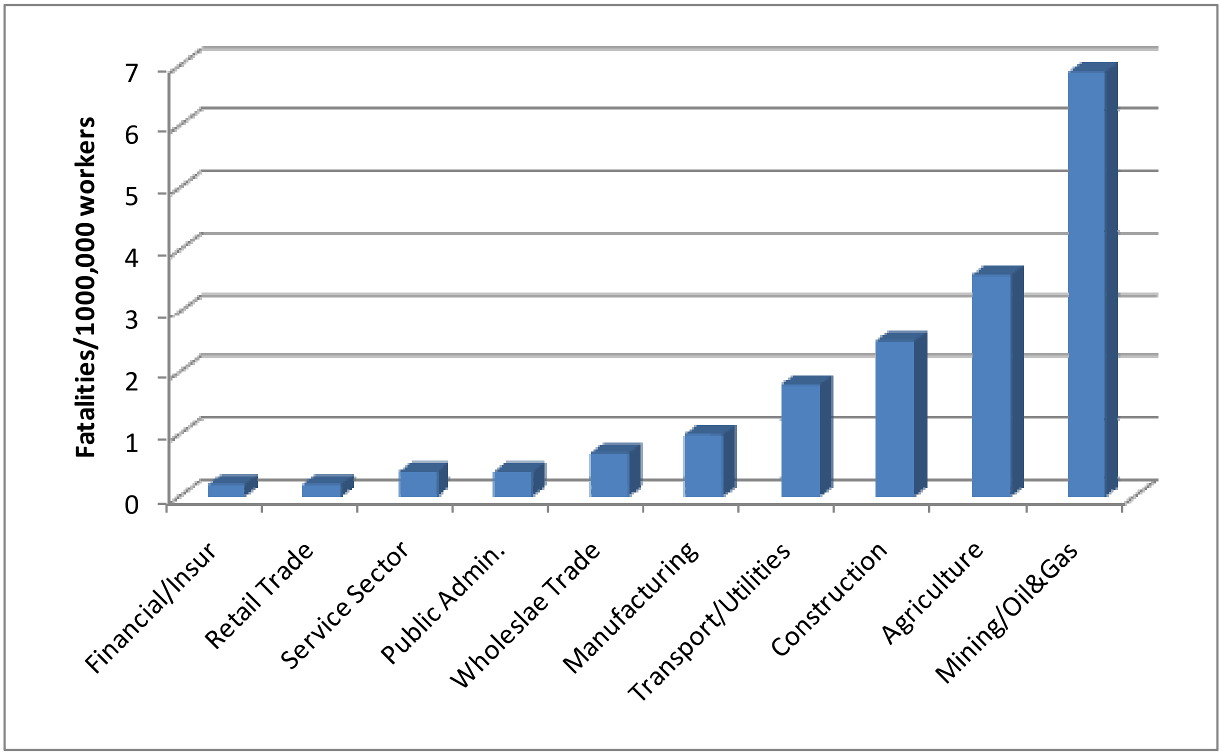

Figure 2-2. Industrial confined-space death rates in the U.S. from 1980 to 1989 (Table is a public domain in CDC and does not need specific permission, Suruda et al., 1994)

Figure 2-2 shows the rate of industrial-related confined-space deaths in the U.S. from 1980 to 1989. Of all industries, mining-oil and gas has a significantly higher rate per 1000 workers than do other sectors (Suruda et al., 1994). No industry is free of these tragic occurrences with events taking place even in the rather commonplace fields of public administration, retail trade, service sector, and real-estate, insurance, and finance (Mohammadi and Meech, 2008) – see Table A-2 for more details. Data on atmospheric-related confined space accidents in mining are less complete than data for other workplaces. Figure 2-3 shows that 40 fatalities occurred in confined spaces in mining since 1992, of which 3 death in 2002 were due to oxygen-depleted air in an enclosed area (U.S. BLS, 2010) – see Table A-3 in Appendix A.

In the BLS data, death by inhalation includes asphyxiation, strangulation, or suffocation involving chemicals or poisonings and toxic effects (except drugs, alcohol, or medicine) which are all categorized as traumatic injuries. For inhalation-related fatalities, the agents and details of the accidents are not given. The fact that these kinds of accidents are continuing to happen in mining causes us to question the current effectiveness of general confined space mining regulations.

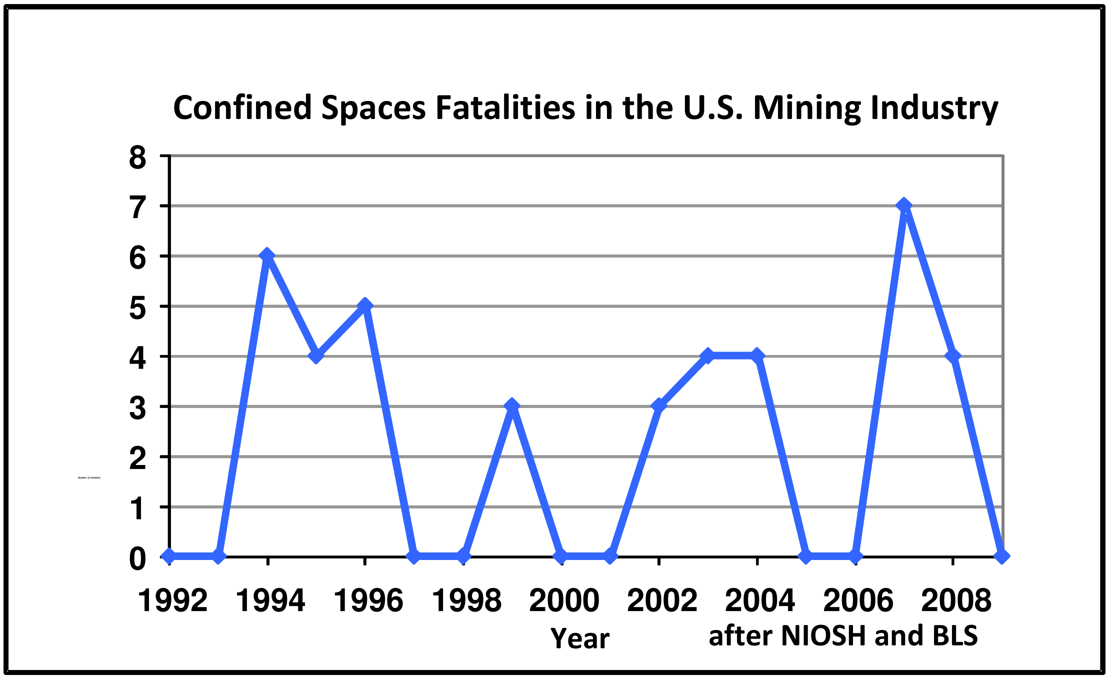

Figure 2-3. Death from inhalation and oxygen-deficiency in confined spaces in the U.S. mining industry (U.S. BLS, 2010). Data in BLS is public domain and do not need specific permission)

According to the Mine Safety and Health Administration (MSHA) in 2003, the major atmospheric-related deaths were 33 cases of black lung and 7 cases of silicosis in surface mining (U.S. Department of Health and Human Services, 2005). The majority of all fatalities occurred amongst sand and gravel operators with the remainder taking place in surface coal mines. Although the reported fatalities are related to chronic atmospheric hazards that occur after many years of exposure to poor atmospheric conditions (dust and gasses), the data by BLS on mining related fatalities (in Figure 2-3) shows the significance of the need for atmospheric risk assessment. According to the NIOSH Surface Mining Fact Sheets, about 85% of mining industry employees work in surface mining making this task more important.

2.2.2. In Canada

Statistics Canada provides data on deaths caused by inhalation of toxic and poisonous gasses. Threats to breathing in this database are classified as accidental or intentional and the type of death is unspecified. Accidental inhalation-related deaths are shown in Table 2-4, however it is not possible to tell which of these deaths were caused by a confined space. Although the report specifies the number of deaths from "being confined in a low-oxygen environment" the data does not seem reliable – for example in 2003 only a single death is reported for this cause despite the fact that British Colombia data show that five persons died in that year because of oxygen-deficiency in a confined space. This indicates little consistency in confined space fatality data for Canada. The Workers Compensation Board of Manitoba (WCB, 2006), indicates that 2% of the total work-related deaths occurred in confined spaces over the period 1995 to 2005. It is important to note that the total number of fatalities by these causes has not dropped in recent years unlike in the United States. See Table A-4 in Appendix A.

Table 2-4. Death from poisoning, inhalation, ingestion and exposure to substances that cause obstruction of respiratory tract in 2000-07 in Canada (Adapted from the Statistics Canada CANSIM database http://cansim2.statcan.gc.ca, CANSIM Table 102-0540, August 3, 2011).

External Cause of Death	2000	2001	2002	2003	2004	2005	2006	2007
Death by being Confined in or Trapped in a Low Oxygen Environment (w81)	5	4	6	1	4	4	5	4
Death from Inhalation or Ingestion of objects obstructing the respiratory tract (w80)	153	160	186	202	163	182	177	223
Threat to breathing due to cave-in, falling earth and other substances (W77)	8	6	6	9	5	6	7	6
Accidental poisoning by and exposure to								
Organic solvents and halogenated hydrocarbons and their vapours (X46)	7	6	5	4	8	5	4	4
Other gasses and vapours (X47)	74	44	56	49	53	32	29	63
Pesticides (X48)	1	1	0	1	0	1	0	0
Unspecified chemicals and noxious substances (X49)	15	16	18	21	19	27	16	24
Total	263	237	277	287	252	257	238	324

2.2.3. In British Columbia

Examining work-related fatalities between 1995 and 2008 in B.C, based on number of claims accepted for fatal benefits by Subsector and the year in which it was accepted, confined space fatalities have been separated out of the data (WorkSafeBC, 2010(a)) - see Table A-5 in Appendix A. Figure 2-4 shows confined-space related fatalities during these years. Despite the high quality of the data, it must be noted that the "four fatalities" of the Sullivan mine are reported under completely different industrial categories – none of which shows that the incident was an accident that occurred simultaneously at a "mine reclamation site". The four fatalities were reported by Sector as (WorkSafeBC, 2010(a)):

- A 44-year old paramedic and a 21-year old paramedic died in a sampling shed because of oxygen-deficient air - the Sector was "Provincial Government".
- A 50 year old project manager died by oxygen-deficiency in a sampling shed - the Sector was "Canadian Pacific Ltd. (Rail and Mining)".
- A 48 year old technical engineer died in a sampling shed by oxygen-deficiency - the Sector was reported as "Technical Services".

This is quite misleading for future investigators in the sense that this does not provide immediate awareness of the potential danger of a confined space at a sulfide waste reclamation site. The problem gives pause for concern about the validity of the separation of data by type of event and industry with respect to "mining industry related", "confined space related" and "mining industry confined space related".

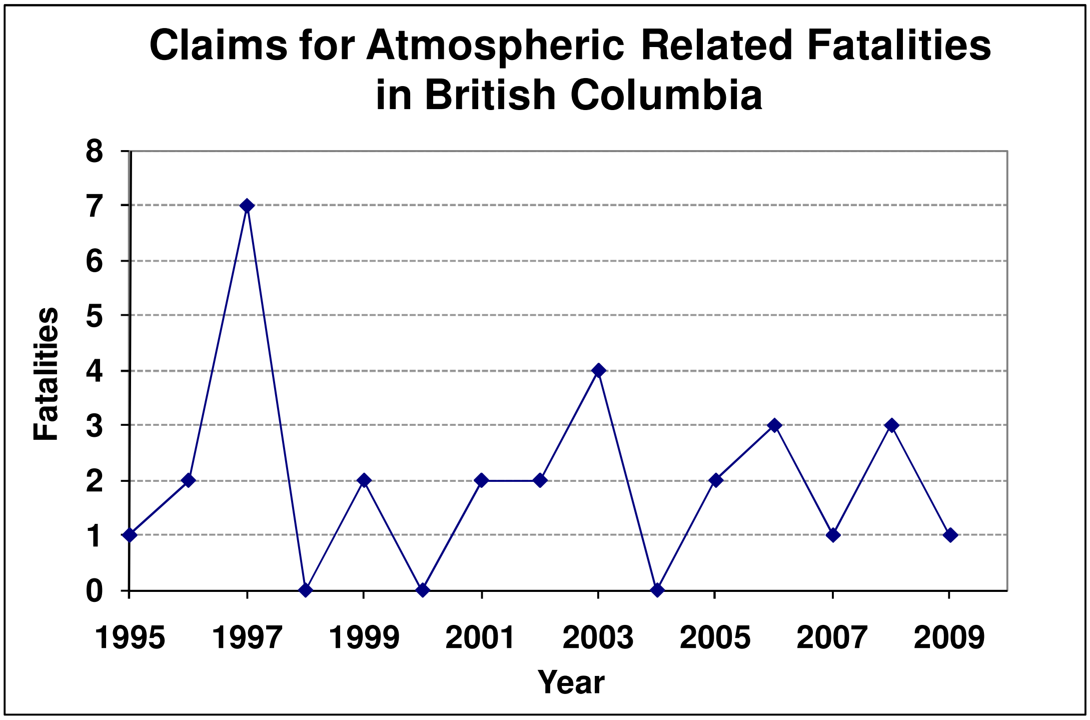

Figure 2-4. Confined space related fatalities in the province of British Columbia (WorkSafeBC, 2010(a)).

Based on claim counts from Standard Occupational Classification (SOC) by accident type and injury year, between 1997 and 2009, there were 55 fatalities in all sectors due to oxygen-deficiency in B.C. (WorkSafeBC, 2010(b)). This number (only for oxygen-deficiency) is much higher than the total number of fatalities related to all atmospheric-related hazards in B.C which is 30 during this period from WorkSafeBC's past annual reports (WorkSafeBC, 2010(a)) - see Figure 2-4. The cause of oxygen-deficiency is unclear in the SOC claim counts and neither does the database specify if the deficiency occurred in a confined space. Of this number, 23% of the deaths were related to other trades (not specified), with agriculture responsible for 10% and forestry, mining and fishing together responsible for 7%. Unfortunately the percentage of accidents related only to mining is unavailable –Table A-6 in Appendix A. Although the information is unclear, this is the only source of data on atmospheric related fatalities in B.C.

In B.C, the total number of fatalities by inhalation in a confined space appears to have remained the same in recent years indicating a need to reassess and analyse current procedures to prevent these types of accidents. The detailed reason for each inhalation-related accident is not stored in the WorkSafeBC database (WorksafeBC, 2010(b)), and further contacts with officials at the Agency did not rectify this deficiency. If such records were available, the causes of the accidents should be known for prevention and comparison.

2.2.4. Multiple Fatalities

As the statistics on fatalities in confined spaces show, these types of accidents continue to occur at high frequency in many apparently innocuous situations throughout North Amercia. Such tragedies invariably involve multiple deaths as rescuers fail to recognize the danger and succumb to the same hazard as the first victim(s), making multiple fatalities a significant characteristic of confined space accidents. Looking at the NTOF data, Suruda et al., (1994), reported that 72 (12%) of confined space related incidents between 1980 and 1989 were multiple fatalities in the U.S. (585 separate confined space incidents with 670 fatalities) in which most victims died from atmospheric hazards (Suruda et al., 1993).

Table 2-5. Multiple fatalities in confined space accidents by NTOF between 1980 and 1989 (data in CDC are public domain and do not need specific permission, Suruda et al., 1994).

Confined Spaces Accidents		
Fatalities	**Number**	**Deaths**
Single	513	513
Double	61	122
Triple	9	27
Quadruple	2	8
Total	585	670

FACE is a project conducted by NIOSH to investigate selected workplace fatalities including confined space related deaths at different sites. The purpose of the study was to understand the effect of different factors on the accident such as management, worker type, and working environment. The information from FACE is more beneficial than that from NTOF since it identifies detailed reasons for the accident such as what was missing (if anything) in the confined space entry procedure, i.e., failure to follow procedures or lack of permit system.

Of these fatalities, 31 were co-workers and 3 were firefighters (Suruda et al., 1993). Death certificate data by NIOSH identified 11 government agency rescuers who died in confined space accidents between 1980 and 1988. Of the 11 multiple-fatality victims, 3 were identified as police, 2 were firefighters, 1 was a paramedic, and 5 were from other government agencies (Suruda et al., 1993). In 6 of the 62 accidents, SCBA were available for use by the rescuers. In 6 cases, the rescuer died because of inappropriate use of SCBA such as using organic vapour cartridges instead of an air-supplied respirator. All rescuers except for one, who died in an explosion, were overcome by a hazardous atmosphere. Of these 97 victims, 8 were killed by oxygen-deficient air (Suruda et al., 1993). According to OSHA, out of 146 confined space fatalities from 1984 to 1986, 17 (12%) were coworkers or emergency personnel. In 16 cases, the rescue was attempted without SCBA, and in one, the SCBA ran out of air. Two out of 17 rescuers were police officers trying to provide help in a sewage treatment plant (Suruda and Agnew, 1989; Suruda et al., 1993).

According to NTOF it is difficult to recognize the actual rescuers since there were incidents in which the initial victim survived and the rescuers died which may have been reported in NTOF as a single victim fatality. There may also be some accidents in which more than one initial worker was inside the confined space and none of the rescuers died (Suruda et al., 1993). As can be seen the quality of data on multiple fatalities in all of the jurisdictions studied is poor and varies considerably from one census system to another. Unfortunately there is no recent data available on multiple fatalities in confined spaces in U.S and Canada.

2.3. Confined Space Definitions and Characteristics

Failures to identify a hazard as well as incompelete risk assessment are major reasons for confined space accidents (Pettit et al., 1987), but many regulations do not help to identify the presence of such a hazard. Terminology used to define a confined space hazard and describe its characteristics vary considerable and needs to be refined. As pointed out previously, statistics on past confined space accidents are inconsistently recorded in different jurisdictions and industries. It is suggested that the following data elements should be gathered: name and age of victim; location of accident; cause of death; time and date of accident; type of confined space; number of associated victims; industry in which the accident occurred; number of victims who lived; number of rescuers who died.

OSHA coined the terms “confined space” and “permit-required confined space” and setup the general requirements to identify and manage confined spaces (Franseen, 1995). While NIOSH, CCOHS, and WorkSafeBC regulations share a common combined form of OSHA’s definitions, differences are apparent. The term "permit-required confined space" refers to a space that meets the definition of a "confined space" AND poses a health or safety hazard. OSHA states that a permit-required confined space has **one or more** of these characteristics:

- Contains or **has the potential** to contain a hazardous atmosphere;
- Contains a material **with the potential** to engulf someone in the space;
- Has an internal configuration that **might cause** an entrant to be trapped or asphyxiated such as inwardly converging walls or a floor that slopes downward and tapers to a smaller cross section;
- Contains **any other recognized** serious safety or health hazard.

A "**non-permit confined space**" does not contain a hazard or hazardous atmosphere. When change occurs in use or configuration, these spaces should be re-evaluated and may be reclassified as "permit-required" (OSHA, 2004). If a workplace is "permit required", a written entry permit must be posted and the employer must inform exposed employees of the problem. A written entry permit is a document showing that a hazard assessment has been done. Unfortunately, the definition of each confined space characteristic differs from agency to agency and the terminology should be clarified to help understand the sensitivity of each characteristic and how spatial or temporal variations can cause a problem. Defining a "confined space" is important in reducing ambiguity and avoiding misinterpretation.

2.3.1. Occupational Safety and Health Administration (OSHA)

The permit system for confined space entry was established in 1989 by OSHA (Suruda et al, 1993). OSHA regulations attempt to protect workers in confined spaces with an emphasis on identifying and monitoring these spaces as well as training workers (Acer and Bayer, 1990). In 1993, OSHA characterizes a confined space based on size, configuration and use as follows (OSHA, 2004, Pettit and Linn, 1987):

> "A place…large enough for an employee to enter fully and perform assigned work, …not designed for continuous occupancy by the employee, and … (with) … limited or restricted means of entry or exit. These…include underground vaults, tanks, storage bins, pits and diked areas, vessels, silos and other similar areas."

"Limited or restricted means" is defined on the OSHA website (ohsaonline, 2007), but not in the written documents. On the website, "any configuration or other characteristic...that interferes with an entrant's ability to escape or to be rescued in an emergency...can cause limited or restricted means for entry or exit, such as ladders or stairs". A basement with stairs containing pipes or other physical instruments that may hinder escape is classified as a confined space.

Examples of confined spaces vary between agencies. OSHA classifies a trench or excavation greater than 1.52 m deep as a confined space due to cave-in hazards (Suruda et al. 1994), but there is no mention of an atmospheric hazard. This type of structure can limit air circulation and may contain an atmospheric hazard from pore gas that migrates through the trench walls. Bad air can be generated by mineral oxidation or decomposition of organic material in the trench.

2.3.1.1 Permit–Required Confined Space Characteristics

Choosing the right respirator and venting with proper air is important in dealing with a dangerous confined space. The designation "permit-required" requires signage and people who enter the space must follow safety practices such as using breathing equipment and O_2-measuring devices. When a person is in the space, another must remain outside to assist. *All* rescue personnel–firemen, police, paramedics, and medical staff–must be trained to *identify* "permit-required" situations even if signage isn't in place. These spaces may have been entered in the past without a problem leading workers to assume no danger exists. They may decide to ignore procedures (see Appendix C).

The term "permit-required" is used in the U.S. to classify a space that must be entered with extreme caution and proper equipment. A confined space must be re-evaluated whenever a change occurs in use, configuration or environment, and if appropriate, reclassified as a "permit-required" space (OSHA, 2004). Unfortunately confined space accidents continue to occur at high frequency and invariably involve multiple deaths as rescuers fail to recognize the danger and succumb to the same hazard as the first victim(s).

OSHA’s definition is prescriptive and does not render as much care in evaluating these spaces as may be necessary. It is suggested that the term “confined space” be substituted for permit-required confined space, and the term “enclosed structure” be used instead of the many differing terms for these types of spaces. The term “confined space” would mean a confined or enclosed structure with a physical, chemical, radiation, inhalation, and/or poisoning hazard in which a permit to enter is always required. An "enclosed structure" on the other hand, does not require a restricted entry permit unless a risk assessment leads to the need to convert it to a "confined space". According to this definition, a room with a closed door and window is an enclosed structure (potentially-safe) while a trench or ditch is an example of a potentially-unsafe enclosed structure (confined space) in which cave-in hazards exist or in which toxic, flammable, explosive, or O_2-deficient gas may migrate through soil and become confined therein.

2.3.2. National Institute for Occupational Safety and Health (NIOSH)

NIOSH defines a confined space as having **one** of these elements (Pettit and Linn, 1987):

1**- Limited entry and exit:** openings limited by size or location; usually small, < 45 cm; difficult to move easily or take-in equipment such as life-saving equipment (respirators); This feature may not be present in all confined spaces - in some open-top spaces such as pits, degreasers, excavations, and ship-holds, the opening may be very large. Access may require ladders, hoists, etc. - escape from such places may be difficult in an emergency.

2- **Unfavorable natural ventilation**: the atmosphere inside may become different than normal due to lack of free air movement. Chemicals may be processed or decomposing, organic substances are present, hazardous gasses can accumulate, or the air may become O_2-deficient (or O_2-rich increasing risk of fire or explosion if a source of ignition is present).

3- **Not designed for continued worker occupancy**: Confined spaces may be designed to store product, enclose materials and processes, or transport products or substances. They are not designed for workers to enter and work. As a result, worker entry into a confined space for inspection, maintenance, repair, cleanup, etc. is often difficult and dangerous.

2.3.3. Definition of a Confined Space by CCOHS and WorkSafeBC

A confined space is an enclosed or partially enclosed structure not designed or intended for human occupancy. It has restricted entrance/exit in terms of location, size or means. Confined spaces can become dangerous due to: design, construction, location, atmosphere, materials in the space, work activities, mechanical processes or presence of a hazard (CCOHS, 2002).

These characteristics are ambiguous. A confined space may not be small and can be located below or above ground. Examples include vats, hoppers, utility vaults, tanks, sewers, pipes, access shafts, truck or rail tank cars, manhole, tunnel, wells, cold storage, silos, ships' holds, sub-cellars, culverts, open ditch, aircraft wings. Ditches and trenches may also be confined spaces when access or egress is limited. Hazards may include (CCOHS, 2002):

> "poor air quality: poisonous gas or lack of oxygen, chemical exposures due to skin contact, ingestion or inhalation of 'bad' air, Fire Hazard: due to flammable liquids and gasses and combustible dusts, Process-related hazards such as residual chemicals, release of contents of a supply line, noise, moving parts of equipment, structural hazards, entanglement, slips, falls, radiation, temperature extremes including atmospheric and surface, shifting or collapse of bulk material, barrier failure resulting in a flood or release of free-flowing solid, uncontrolled energy including electrical shock, visibility problems and biological hazards."

Because of the nature of the hazard and work, air testing should be ongoing:

> "Conditions can change while workers are inside the confined space and sometimes, a hazardous atmosphere is created by the work activities in the confined space".

2.3.4. WorkSafeBC

Part 9 of the **Safety at Work Regulations** in WorkSafeBC deals with confined spaces and is based on OHS regulations. The document contains a brief definition of "confined space":

> "(it) is closed or partially enclosed, is not designed or intended for continuous human occupancy, has limited or restricted means of entry and exit that may complicate provision of first aid, evacuation, rescue and other emergency responses, and is large enough and…configured (so) worker(s) can enter to perform assigned work".

The regulation does not provide a description of each property and no example of a confined space is given (OHS Regulation, 2008). However, all the characteristics of confined spaces based on the OHS definition as well as many examples are present in the document. Confined spaces are not divided between "permit required" or "non-permit required". The **Reference Manual** defines a confined space as a place with **all** of the following characteristics (Confined Space Entry Program - A Reference Manual, 2005, by permission):

1- **Enclosed or partially enclosed** - no need to be small, tight, or fully enclosed; may be large or small and partially enclosed; workers may be able to move freely in the space.
2- **Not designed or intended for continuous human occupancy** - entry for purposes such as inspection, maintenance, repair, or construction; space not normally ventilated; entered on a regular basis such as for sampling.
3- **Limited or restricted means of entry or exit** - difficult to evacuate or provide emergency response services; entry point difficult to walk through; access by ladder or stairway with poor access due to “restrictive slope, narrow width, or extreme length”; physical obstructions may make exit difficult.
4- **Large enough in such a way that a worker can enter to perform the assigned work**; a space that is too small for a worker to enter is not a confined space.

The manual states that a place containing a toxic atmosphere is a confined space, even when entry and exit are unconstrained. A confined space permit can be updated by the supervisor, standby person, or tester. The standby person may alter the permit to update the list of workers inside. The tester may alter the permit to record test results. The entry supervisor who signed the permit may update it if there is a change in the work crew after each shift change, or if another supervisor takes over. In the case of significant change that may affect safe work procedures, only a qualified person can change the work procedures. The entry supervisor changes the permit according to changes made by the qualified person (Confined Space Entry Program - A Reference Manual, 2005, by permission).

2.3.5. B.C. Mines Act

Section 3.4.1 of the Mines Act BC regulations deals with Hazardous Atmosphere and Confined Space Work. The regulation begins as follows:

> "The manager shall ensure…written procedures are developed and implemented for work in confined spaces where irrespirable, toxic or flammable atmospheres might be encountered."

In this regulation, a confined space is defined as:

> "An area, other than an underground mine, that includes **<u>all</u>** of the following:
>
> (a) is enclosed or partially enclosed;
> (b) is not designed or intended for continuous human occupancy;
> (c) has limited or restricted means for entry or exit;
> (d) is large enough and so configured that a worker could enter to perform first aid, institute evacuation, rescue or other emergency response service."

This regulation does not help an individual *recognize* a hazard since there is no definition of each characteristic and no examples are provided. There is no mention of the presence of hazard in the confined space as well. The regulation makes no mention of reclamation work. Section 3.4.2 describes safe work procedures with the necessity for atmospheric testing, ventilation, and use of protective equipment in confined spaces being described in Sections 3.4.3, 3.4.5 and 3.4.6 respectively (Mines Act, 2008). The BC Mines Act, 2008 offers rules on reclamation practices in Section 9.13.1, but nothing on confined spaces. Sec. 10.7.11 refers to waste dumps, but the only risks mentioned for control are slope-stability and erosion, although dangerous gasses such as methane, and dusts such as asbestos, silica, and lead have specific rules. General regulations for waste management and for confined spaces do not help identify a hazard at a reclamation site indicating a need for a consistent approach to identify confined space dangers during reclamation. It would be useful if the definition of a permit-required confined space was added into the Mines Act.

According to the Mines Act BC, a confined space is:

> "a tank, process vessel, underground vault, tunnel, or other enclosure not designed or intended for human occupancy. A person...enters...only if there (is) work to be done".

The Manitoba mining regulations relate to work in confined spaces and provide examples:

> "No worker shall enter and no employer shall cause or permit a worker to enter a tank, pit, sump or other confined space until proper stated confined space procedures are put in place (Operation of Mines Regulation in MB, 1994)".

If these examples were in the BC Mines Act, perhaps identification of the sump at the Sullivan mine as a "permit-required" confined space might have been recognized. The mine plan and reclamation program part of the BC Mines Act deals with acid rock drainage, but does not mention O_2-depletion hazards from air and water coming from a sulfide waste dump. Section 10.1.9 states that a plan to predict, prevent, mitigate and manage ARD should match the Guidelines for Metal Leaching and ARD at mine sites in British Columbia, but this guideline also does not mention atmospheric hazards.

2.4. Shortcomings of Confined Space Regulations

The definition of a confined space, possible characteristics, and examples are incomplete in most mine regulations examined. OSHA's definition of confined spaces talks about size, configuration and use and then evaluates the space as "permit-required" or "non-permit required" based on atmospheric hazard or physical harm potential. NIOSH places emphasis on "limited entry and exit" and refers to the small size and diameter of the entrance. WorkSafeBC defines a confined space as a large or small space that may not be enclosed on all sides.

WorkSafeBC mentions the fact that pits, excavations, and other types of confined spaces near a contaminated site or waste pile containing hazardous material can collect toxic gas depending on the type of waste (Hazards of Confined Spaces, 2004):

> "A confined space may be located next to a source of a hazardous contaminant. The contaminant (can) enter the confined space through porous walls, such as those ...found in sewers or trenches, or through difficult-to-seal openings such as conduits"

Some confined space protocols mention the impact of sudden atmospheric changes that can affect the influx of toxic gasses into an enclosed structure. NIOSH discusses the danger of a manhole located within a swampy area (Michaelsen and Park, 1954; Pettit, 1994) in which a sudden drop in barometric pressure caused methane to diffuse into the manhole through its walls. At other times, this space was entered without problem.

In section 3.4.3 of the B.C. Mines Act as well as section 9.9 of the WorkSafeBC regulations, testing for danger and the conduct of a hazard assessment are discussed. However, no mention is made of changes in pressure and temperature on the conditions in an enclosed structure (BC Mines Act, 2008):

> "Tests of the atmosphere inside the confined space shall be made at intervals during the work progress to ensure that the quality of air does not deteriorate ...test results shall be recorded as required by section 3.4.3."

Mention of the role of atmospheric changes should also be included in this section of the Act. Since the WorkSafeBC Confined Space Manual contains more details to help with recognition, it is suggested that the BC Mines Act should require mining personnel responsible for waste dump reclamation activities to apply this manual in their work.

There is a need for a consistent approach which clearly defines a confined space and contains all information necessary to recognize a potential atmospheric hazard. In this research, a manual called the Atmospheric Confined Space Manual (especially for gasses from mine wastes and soils) has been written to help with such hazard recognition – Appendix C.

2.5. Summary

This chapter has examined and analysed data on confined space accidents and fatalities in North America. While a decline in such events has occurred in the U.S. between 1982 and 1995, there are still significant numbers of confined space accidents occurring each year throughout North America. A consistent method to record such accidents is required to provide accurate and valid data on these situations.

Definitions and descriptions of confined spaces differ significantly among the various North American regulatory agencies. To provide clarity, simplified terminology is proposed to rectify the situation. Any "**enclosed structure**" may become a "**confined space**" containing a hazard. Only these two terms are necessary. All "**confined spaces**" then require a permit and can only be entered using the listed procedures and safety equipment.

It is very important to recognize that a hazard exists (or may exist) within an enclosed structure and then, implement proper procedures, permits, and signage to ensure unsafe exposure is eliminated. Current B.C. Mining regulations do not address atmospheric issues with waste dumps undergoing reclamation. There is insufficient definition and description of confined spaces in the B.C. Mines Act. With reclamation sites, climatic temperature and pressure changes control gas emission into an enclosed area at different times of the day (Mohammadi and Meech, 2011). As such, a confined space can switch from being safe to being unsafe. A confined space may be measured as safe when at other times it is unsafe. The regulations should warn about this transformation (Mohammadi and Meech, 2011).

General confined space regulations may be insufficient for confined spaces in different industries. As a result, confined space regulations should be customized for each industry and perhaps a specific risk assessment tool for each type of workplace should accompany the regulations. Details of previous confined space accidents should be included within existing regulations to help prevent reoccurrence of an accident.

Chapter 3

Sullivan Mine Accident: Similarities and Differences with Other Confined Space Accidents[1]

3.1. Overview

There are many examples of waste management techniques aiming to minimize threats to the environment that have been developed over the years based on experience. Unfortunately, adverse effects of some of these practices create occupational health hazards that are not yet fully-understood or appreciated. With these systems, consideration of a new requirement may be necessary to ensure a safe working environment. Mine waste dumps consist of wastes managed by reclamation policies generally applied after mine closure. The activity is isolated from normal mining operations with the primary goal to make the site as compatible as possible with its surrounding environment (Mohammadi and Meech, 2008). The Sullivan mine accident happened at a reclamation site where the environment was being changed to accommodate innovative designs that had become state-of-the-art in reclaiming waste dumps over the past decade with best practices being applied to minimize threats to the surrounding environment and ecosystems in a safe and economic way. These waste management techniques unfortunately brought a new and initially unrecognized condition to the list of confined space fatalities (Mohammadi and Meech, 2008). Although the accident was a unique occurrence never before reported for sampling practices at any other mine site, the circumstances parallel those of virtually all atmospheric-related confined space accidents (Mohammadi and Meech, 2008 and 2011). These include, but are not limited to:

- The hazard is unrecognized by operators and by the victims;

[1] Many Parts of this Chapter have been published previously. Mohammadi, L., Meech, J.A., 2008, Implementing Atmospheric Risk Assessment in Mine Reclamation, 23rd International Conference on Solid Waste Technology and Management, Philadelphia, PA, USA, pp.12.

- The hazard (in this case oxygen-depletion) has no associated odour or colour;
- Death is very quick (seconds to minutes);
- Multiple deaths take place as rescuers die in a futile attempt to save the first victim(s);
- After the fact, the danger is obvious.

This suggests that the accident might have been predicted (and prevented) if an *a priori* atmospheric risk assessment had been performed (Mohammadi and Meech, 2008). If a long-term atmospheric risk assessment process had been required by the B.C Mines Act as the reclamation and revegetation work ensued, it is possible that contractors and mine employees at the site might have recognized that the sampling station had become what is known as a "permit-required confined space". Then the current standards and regulations that apply to confined spaces in the BC Occupational Health and Safety (OHS) and/or in the BC Mines Act could have been applied to prevent this tragedy.

This chapter describes the accident in detail and compares it with other similar confined space accidents.

3.2. Sullivan Mine Tragedy

The Sullivan Mine was one of the largest lead-zinc mines in the world when it closed in 2001 after 92 years of operation. About 500 people were employed at the mine that year. The No.1 Shaft Waste Dump was created during the 1940s and continued to operate right up to closure – see Figure 3-1. The height from the flat top of the dump to the toe is about 55m. The dump contains about 2.9M tonnes of sulfide rock. The estimated total volume is 1M m^3 with about 30% voids. Other mine waste such as domestic garbage, steel, plastic, wood, residual Shotcrete, glacial till, and other debris was also placed in the dump from time to time.

After closure, a skeleton-crew remained to manage reclamation activities aimed at restoring the site to a form compatible with the local environment. This work began prior to closure and is still on-going today. In 1995, a V-notch weir was installed about 100m from the toe to sample effluent and measure flowrate. In 1997, to overcome winter ice build-up on the weir, concrete blocks were placed around it and a shed erected over it – see Figure 3-2.

In 2004, the open ditch was partially covered as the toe was extended forward about 70m to reduce the dump profile in preparation for revegetation and erosion control. In 2005, 1 m of glacial till was placed over the dump surface and the ditch.

Figure 3-1. No. 1 Shaft Waste Dump at the Sullivan Mine prior to regrading and covering with glacial till (Reports of the Technical Advisory Committee of the Sullivan Mine accident, 2007, by permission Teck Metals Ltd).

Figure 3-2. Seepage collection ditch in September 2005 prior to covering with glacial till (Phillip et al., 2008, by permission).

The accident at the Sullivan Mine occurred when oxygen-depleted air (and water) caused by sulfide oxidation flowed out of the Number One Shaft waste dump through an underground drainage channel and buried pipe that connected directly to a sampling shed - Figure 3-1. Seasonal temperature changes have been found to cause air to flow from the dump into the shed (Phillip et al., 2008). Before the ditch was covered, there was no direct connection between air in the dump and air in the shed. The ditch was open to the air allowing effluent to become re-oxygenated as it flowed along the channel. So, water entering the shed was not oxygen-depleted prior to the ditch being covered – see Figure 3-2.

After covering the ditch as part of regrading activities, a well-sealed, underground drain was created, isolated from the atmosphere, creating an unrecognized hydraulic conduit for air and gasses to flow between the dump and the shed. If an atmospheric risk assessment had been done as the work proceeded, contractors and mine employees might have realized that the shed had become a "permit-required" confined space. Then the confined space regulations in the B.C. Occupational Health and Safety Regulations or the BC Mines Act could have been applied to prevent the accident.

The entire dump was also covered with glacial till. This seal reduces water percolation and, when saturated with water, restricts air infiltration slowing oxidation as the pore air remains depleted of oxygen - see Figure 3-3. Appendix D describes the hazardous gasses that accompany ARD from Sulfide or Coal mine sites. The drainage ditch running along the toe was engineered into a drain and then covered by the toe extension to prevent seepage. The sump collected the effluent and diverted it through a buried pipeline to a water-treatment facility. Monthly sampling was done to monitor flow rate and contaminant levels. The sampling shed at the Number One Shaft waste dump was installed to sample Acid-Rock-Drainage seepage from the waste dump. The sampling shed was in use in the fall of 2005 and winter of 2006 on a regular basis up to one week before the tragedy occurred without any incident or indication of a problem (see Figure 3-2).

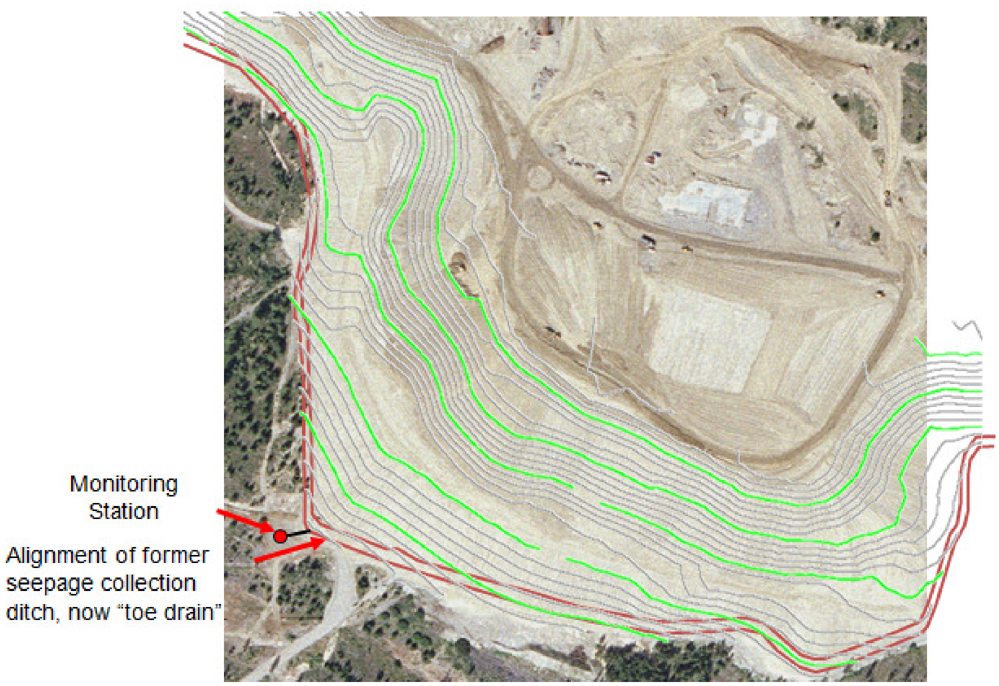

Figure 3-3 Sullivan Mine No. 1 Shaft Waste Dump after sealing with glacial till (Phillip et al., 2008, by permission).

On May 15 and 17, 2006, four people – a consultant, a mine employee, and two ambulance paramedics – died in the sampling shed. They each lost consciousness and fell into the sump because of the lack of oxygen. The accident is described in detail in the following to highlight the errors in judgement made by rescuers that cost them their lives.

The first victim was Doug Erickson, an environmental consultant hired by Teck-Cominco, the owners of the site. He entered the shed in the late afternoon on May 15th to take a water sample when it is assumed he was overcome. He was not reported missing until the morning of May 17th upon which Bob Newcombe, a mine employee, went to see if Erickson was at the sampling shed. He observed Erickson lying in the sump face-down in the flowing water. Newcombe apparently thought that Erickson had drowned as that is how he reported the situation to the 911-operator when he called on his mobile phone requesting emergency help. He then called mine consultant, Dave van Dierden, and asked him to come to the site gate to admit the ambulance. Despite identifying the shed as a "confined area" as he described it to the 911-operator, he entered it to try to help Erickson, but was overcome. van Dierden arrived at about the same time as the paramedics came on the scene. Kim Weitzel, the senior paramedic, who thought she was responding to a possible drowning accident, entered the shed and began to climb down the ladder into the sump. She remarked that there were two bodies, not one, and apparently realized that an atmospheric danger might be present. She began to ask van Dierden if a "gas" problem existed, but her words died away as she fell unconscious and collapsed into the sump. Her colleague, Shawn Currier, ran to the shed when informed by van Dierden that Weitzel had fallen. Before van Dierden could stop him, Currier entered the shed and also collapsed. van Dierden then called 911 to report these new difficulties and stated that H_2S gas might be present. Shortly thereafter, the fire department arrived with appropriate breathing apparatus. They brought out all four people and delivered them to the hospital, but it was too late.

Following a preliminary investigation, The Chief Inspector of Mines for B.C. issued an immediate warning to all mines about possible similar circumstances and ordered other mine effluent sampling sheds to be treated as confined spaces. In October 2006, a report issued by the Chief Inspector identified the accident as being "unprecedented in the history of mining". According to the report "the process that led to the oxygen-depleted atmosphere has not...occurred anywhere else in the world."

3.3. Controlling Factors

3.3.1. Direct Factors

During the summer of 2005, the dump was covered with 1m of glacial till and the slope re-contoured to enhance growth of suitable plant material and reduce erosion. In this way the drainage ditch became covered. A 12 m long, 400 mm diameter pipe directed acidic water from the ditch to the shed – see Figure 3-2. This change in the effluent collection and monitoring system isolated oxygen-depleted effluent and pore gasses from the atmosphere. Covering the ditch meant air in the shed became directly connected to "bad" air in the dump.

In August 2006, the dump was instrumented under the oversight of a Technical Advisory Panel set-up by Teck Corporation and the B.C. Ministry of Energy, Mines, and Petroleum Resources to monitor respiration of the dump. Data collected included air velocity, temperature, pressure, and gas composition in the pipe, at the end of the pipe, and about waist height in the shed. Site meteorology, cover moisture content, internal temperature, gas composition, and pressure at 16 locations were also monitored.

Samples taken immediately following the accident showed oxygen levels at the bottom of the sump of about 2%, while carbon dioxide was about 7% - dangerous limits for these gasses are given in Table C-7 in Appendix C. Based on data from the Cranbrook airport, the May 13-17, 2006 period includes a sharp increase in maximum daily temperature to about 20°C with a strong decrease in barometric pressure. On May 8, 2006 when the shed was entered safely, the Cranbrook airport data indicated a rising barometric pressure and a temperature below 11 ^{o}C. The cumulative airflow volume measure during the 2006-2007 winter was about 1.2 M m^3 – 4 times the estimated void space in the dump.

At different depths around the dump in June 2007, oxygen concentrations of air in the dump ranged from normal (about 21%) to near zero. Carbon dioxide concentrations ranged from near zero to about 5% in most locations, but were measured as high as 21% at one location. The instruments showed that internal temperatures ranged from 5 to 16 ^{o}C indicative of sulfide reactions while outside air temperatures ranged from -7 to +26 ^{o}C. The gas velocity measured at a point 5 cm inside the exit of the effluent pipe has been reported to be well-correlated with the outside temperature measured at a meteorology station located part way up the slope of the dump (Phillip et al., 2008). As can be seen in Figure 3-4, for temperatures below about 11.5 ^{o}C, the direction of flow is into the dump (dump is "inhaling"), and when the temperature rises above about 11.5 ^{o}C, the dump begins to "exhale" resulting in oxygen-depleted air flowing through the pipe along with the effluent water into the bottom of the sump (Phillip et al., 2008). Because of this behavior, this dump can be called "**a breathing waste dump**". The value of 11.5 ^{o}C is close to the average internal temperature at the center of dump. Seasonal variations cause the outside temperature to rise above 11.5 ^{o}C in summer and to drop below this value in winter. Figure 3-5 shows a time series plot of gas velocity and outside temperature from March to December 2007. The dump exhales during the summer while during the winter it inhales. During the spring and fall, both exhaling and inhaling can occur during some days in the month or during the day or night depending on the outside temperature. Temperatures at a level above the center of the dump are high all year long at about 16°C.

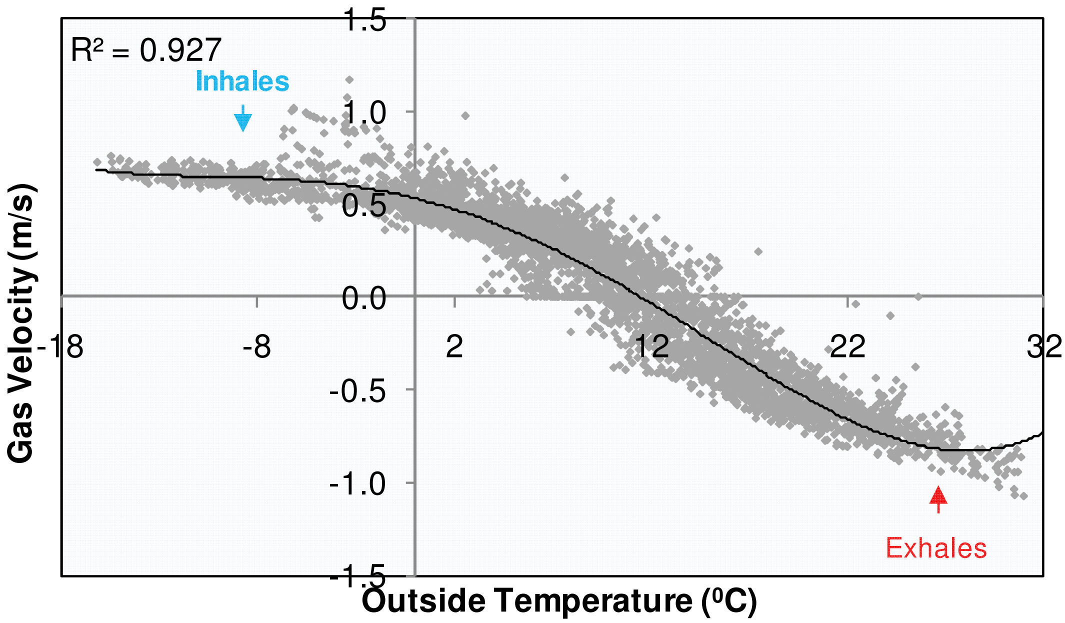

Figure 3-4. Corelation between gas velocity and outside temperature. (Phillip et al., 2008, adapted by permission).
Equation: $y = 2E\text{-}06x^4 - 2E\text{-}05x^3 - 0.0018x^2 - 0.026x + 0.5332$, $R^2=0.927$.

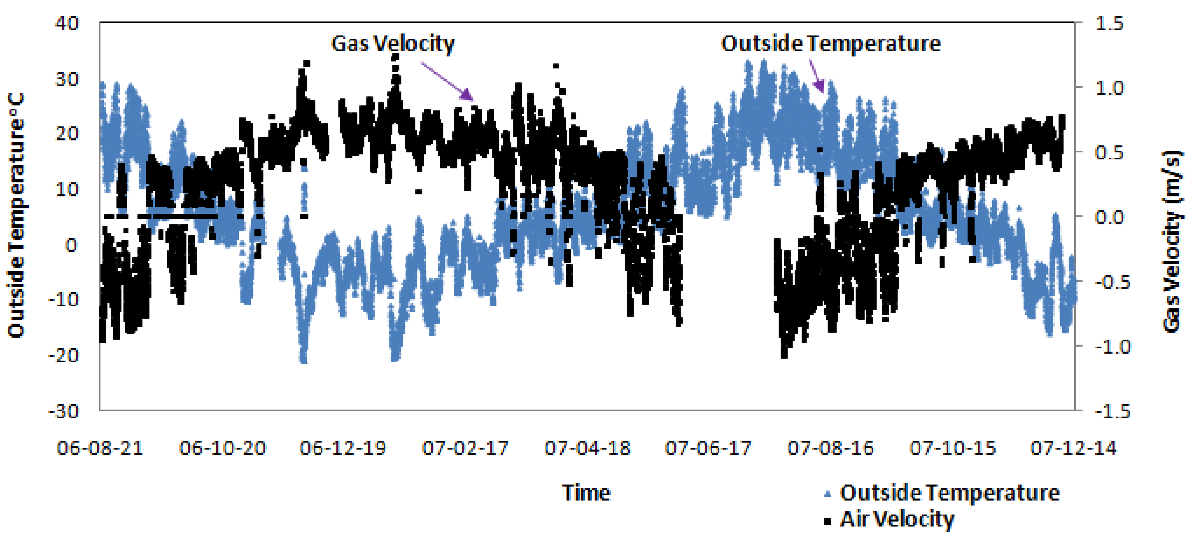

Figure 3-5. Time series of air velocity and atmospheric temperature (Phillip et al., 2008, adapted by permission).

Movement of gas into the shed is not diffusion-controlled. Temperature differences within the dump and outside cause air movement by convection – see Figure 3-6. During the winter, gas within the waste dump is warmer than outside (lighter) and rises from the surface of the dump. This process causes the dump to inhale air from its sides and bottom (i.e., from the shed). Although the atmosphere of the shed is safe at this point, oxygen-depleted water could still cause a dangerous atmosphere – see Section 3.3.2. During the summer, when outside air is warmer (and lighter), the flow reverses itself. This is when the dump exhales leading to a dangerous atmosphere within the shed.

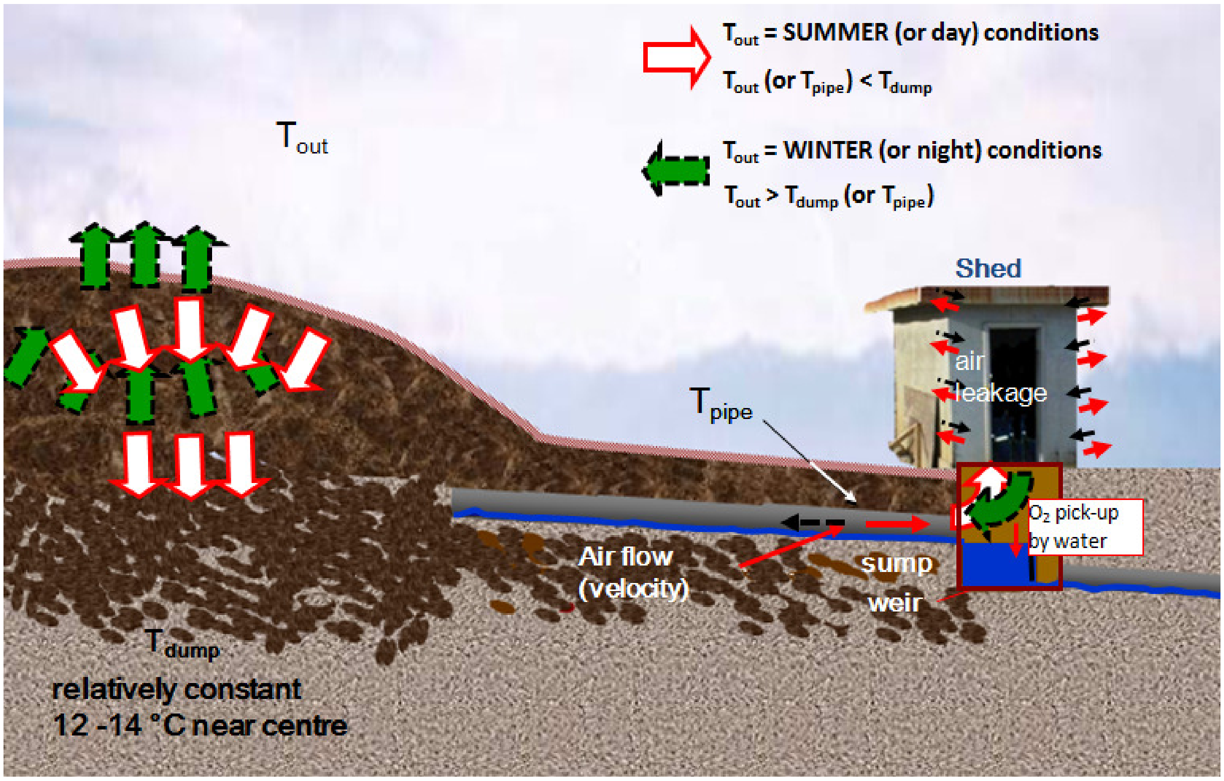

Figure 3-6. Schematic diagram of the sampling shed at the Number One Shaft Waste Dump.

Figure 3-7 shows gas composition measurements at 2.4 m from the pipe discharge to the ARD collection sump. Gas composition changes with flow direction so when the gas velocity is negative for a short period, the oxygen concentration in the sump falls below 21%. Taking into account the flow of oxygen-depleted air from the pipe into the shed (from 11th to 13th of May 2007), the time for the oxygen level in the sump to become depleted can be as short as ten hours for air being displaced by toxic pore gas and about 2 days for oxygen-depleted water flowing at the typical rate observed at the Number One Shaft waste dump assuming no air leakage through the shed walls and doors (see Section 3.3.2).

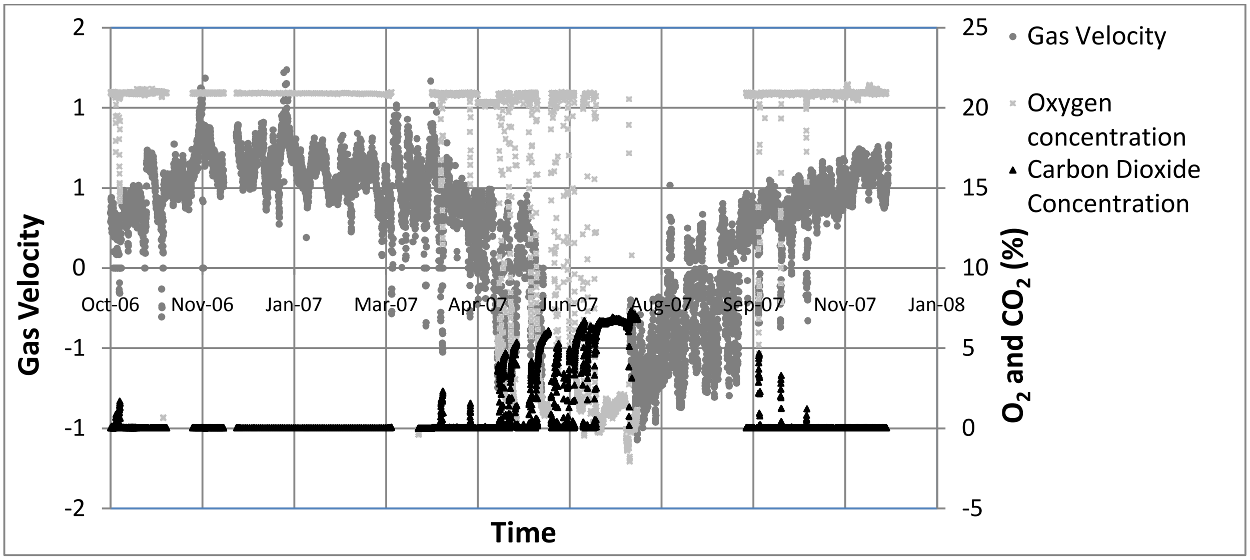

Figure 3-7. Gas velocity, oxygen and carbon dioxide concentrations measured 2.43 m along the ARD pipe from the sump (data collected by the Technical Panel on the Sullivan Mine accident, Teck Metals Ltd).

Sampling sheds like that used at the Sullivan mine exist at many sites around the world and workers are likely using them without knowledge of this danger. Surface anomalies on top of the dump may also concentrate "bad" air creating a danger during colder months. Dangerous gasses can accumulate in a confined space (Mohammadi and Meech, 2011) such as a sampling shed or a topographical feature such as a hollow or erosion channel. Knowledge about similar atmospheric-related confined-space accidents can contribute to developing the risk assessment tool.

3.3.2. Indirect Factors - Role of Oxygen-Depleted Water in Consuming Oxygen

Air flowing out of the dump is not the only potential hazard-causing emission. Water flowing in the pipe is also oxygen-depleted and can remove oxygen from the air confined in the shed above the sump. Prior to 2005, the open ditch brought drainage from the dump to the shed with the water flowing into the bottom of the sump over a weir (Figure 3-8).

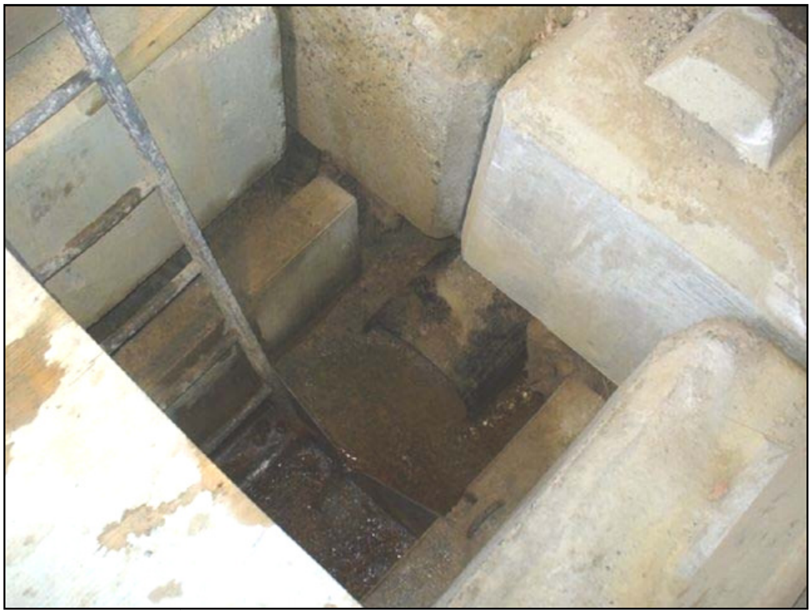

Figure 3-8. The sump at the bottom of the sampling shed. Note the weir to the bottom-right of the ladder (Courtesy of WorkSafeBC).

Because of oxidation of sulfide minerals within the dump, water coming out of the dump is oxygen-depleted. Covering the drainage ditch resulted in the isolation of oxygen-depleted effluent from the atmosphere. What previously was oxygenated surface water now was de-oxygenated groundwater creating an unrecognized and dangerous situation. This oxygen-depleted water can cause air within the sump and shed to become oxygen-depleted according to Henry's Law. Before covering the ditch, this water was exposed to the atmosphere as it flowed between the dump and the shed, and the dissolved oxygen content could return to equilibrium (or close to it) with air at normal oxygen-levels. The chemistry (equilibrium) and physics (kinetics) of these reactions have been described previously for water flowing through backfill material in an underground mine (Bayah et al., 1984).

The equilibrium of oxygen in water as a function of oxygen content in the air and temperature is shown in Figure 3-9. Saturated dissolved oxygen levels in water at four different temperatures and four different oxygen percentages in the atmosphere have been calculated. If dissolved oxygen in the water is below its saturation value, oxygen transfers from the air into the water (Bayah et al, 1984) according to the following equilibrium reactions:

$$C_t^* = K_H P_{gt} \qquad (3\text{-}1)$$

$$K_H = 9.73 \times 10^{-4} \exp(1799/T) \qquad (3\text{-}2)$$

$$P_{gt} = X_{gt} P_a \qquad (3\text{-}3)$$

where:
C_t^* = Saturated Dissolved oxygen at time t (mg/L)
P_{gt} = Partial Pressure of oxygen in the gas phase (KPa)
K_H = Henry's Law Constant (mg/L-KPa)
X_{gt} = oxygen in the air at time t (%)
P_a = Atmospheric Pressure about 102 KPa
T = Atmospheric Temperature ^oC

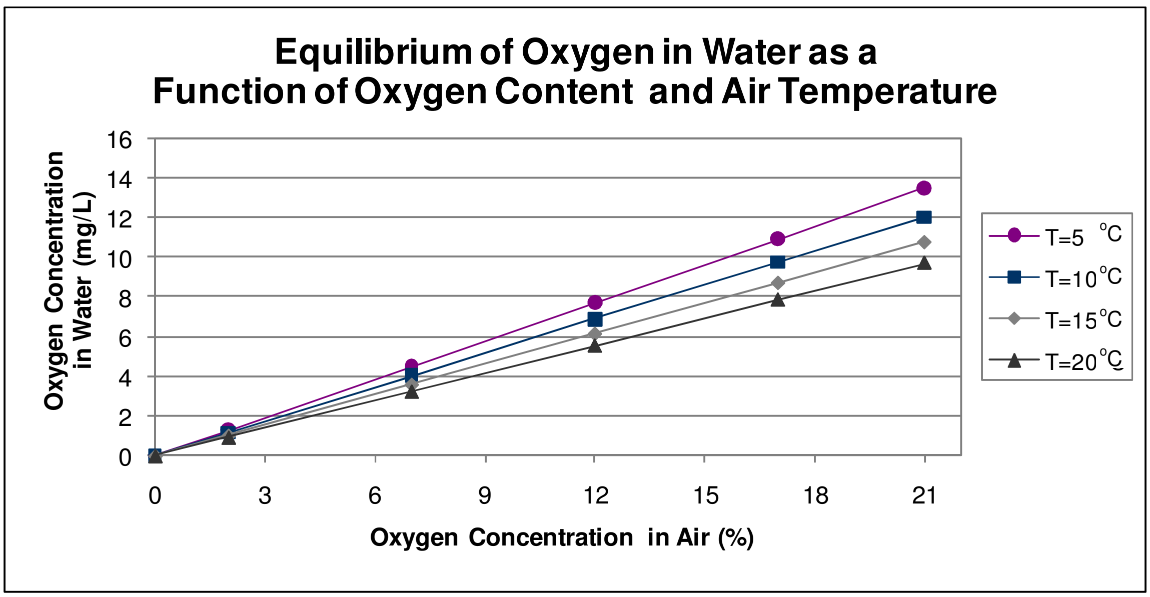

Figure 3-9. Oxygen equilibrium in water as a function of oxygen content in air (Created by Furmals in Bayah et al, 1984).

The actual removal of oxygen by oxygen-depleted water is independent of temperature since the removal rate increases with temperature while the driving force of the saturated dissolved-oxygen level decreases with temperature. These two effects cancel each other out over the temperature range of interest leading to a neutral response of the rate of oxygen removal by water to changes in temperature (Bayah et al., 1984). The extent of oxygen-depletion of air in the sump depends on the effluent flowrate, its level of oxygen, and the leakage rate of air into the shed from outside (Bayah et al., 1984). If no leakage of air into the shed is assumed, and water has only 1 mgL^{-1} oxygen and its flow rate is 33 $Lmin^{-1}$, for the initial oxygen content of sump air of 20.9%, within a period of about 46 hours, oxygen-depleted water will reduce the oxygen content of air in the sump to about 18% (Mohammadi and Meech, 2011), as shown in Figure 3-10. Since the water has not reached the equilibrium value of C^* (about 8 $mg{\cdot}L^{-1}$ for this concentration of oxygen in air), the dissolution reaction continues. Over time, the C_t (dissolved oxygen in water) will drop to about 0 mgL^{-1}. At this point, the value of C_t^* also drops to an amount very close to the value of C_t, and so, the reaction stops. The formulas used to prepare this graph are shown in Equations 3-4 and 3-5 (details in Appendix B.1). Assumptions about conditions and properties of the sump are as follow:

Pressure	=	102 kPa
Temperature	=	20 °C(293 K)
Shed Volume	=	21,600 L
Sump Water Volume	=	1,200 L
Sump Air Volume	=	4,800 L
Sump Interfacial Area	=	2.4 m^2
Sump Depth	=	2.5 m
Water Flow Rate	=	33.3 $L{\cdot}min^{-1}$
Air Leakage	=	0.0 $L{\cdot}min^{-1}$
K_L(293K)	=	32.3 $cm{\cdot}hr^{-1}$

$$\frac{dC}{dt} = K_L \frac{A}{V} (C^*{}_t - C_t) \qquad (3\text{-}4)$$

$$K_L = K_{L(293)} (1.024)^{T-293} \qquad (3\text{-}5)$$

where:

K_L = Mass Transfer Coefficient
A/V = Interfacial Area of Water / Volume of Water (m^{-1})
C_t = Dissolved Oxygen in Water at Time t ($mg{\cdot}L^{-1}$)
C_t^* = Saturated Dissolved Oxygen at Time t ($mg{\cdot}L^{-1}$)

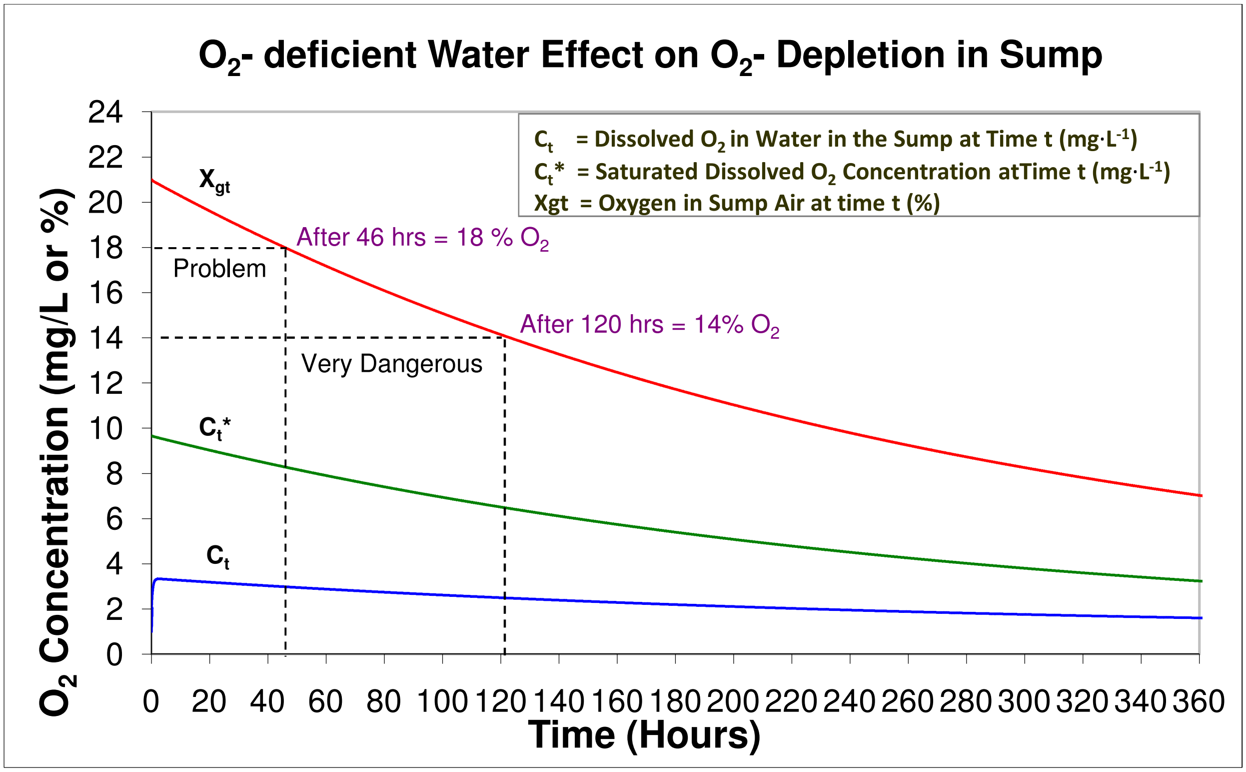

Figure 3-10. Oxygen concentration of sump air in contact with oxygen-depleted water at different times (no air leakage into the shed assumed).

Gas blowing out of the pipe will mix with sump air and decrease the oxygen content further. The concentration of contaminated gas in the space increases relative to the total gas in the sump. For this to happen the total volume must increase or some of the gas in the sump must exit through leakage points. In the case where gas enters the sump through the pipe, as it mixes with the air it will push air out of the sump – see Appendix B.2. When gas is flowing from the pipe, this process will cause oxygen-depletion in the sump, unless fresh air leaks into the structure through gaps around the door and holes in the walls. The combined effect of oxygen-depleted water and air coming from the pipe into the sump for the period between 11-May-07 4:00 to 13-May-07 18 (approximate time of accident in 2006) is shown in Figure 3-11. In this graph, whenever gas flows into the sump, the oxygen content in the sump air was updated to the value of the measured oxygen in the pipe. Otherwise, the oxygen level of the sump in each time interval is a mixture of the oxygen content of the pipe with oxygen content of the sump during the previous time interval of the calculation.

Given the gas velocity and pipe cross sectional area, the gas flow was back-calculated from the measured oxygen level. Gas velocity variations during this period due to changes in outside temperature is shown on an hourly basis in Figure 3-12. Gas velocity is positive from 11 am to 2 am and negative from 2 am to 11 am. Accounting for the flow of oxygen-depleted air from the pipe into the sump, the time for the sump's oxygen level to drop below 18% is less than 10 hours. This shows that the effect of "bad" air blowing into the sump and up into the shed is far more significant than oxygen consumption by the ARD effluent. Nevertheless, oxygen consumption by oxygen-depleted water can be important in other circumstances and should be taken into account especially in situations where the amount of water flow is high relative to the sump volume.

In Figure 3-11, during the first 8 hours, gas is not flowing from the pipe. At this point, oxygen is being removed from the sump air only by oxygen-depleted water and as a result the X_{gt} in the graph shows a slight drop of 0.55% of oxygen. The actual measured oxygen content in the sump at this point remained high at 20.6 % since fresh air can leak in to the shed and sump. This indicates a leakage rate of about 0.19 L/s to compensate for the oxygen-depletion caused by the water. The leakage was enough to maintain the oxygen above 20% and so even a small amount of leakage is enough to compensate for oxygen-depletion by water during the first 8 hours. From the 8 hour to 27 hour time period, the gas velocity becomes negative and gas was blowing out of the pipe in combination with oxygen-depleted water which caused the oxygen level to decline significantly. After this point, for a period of 5 hours, the gas velocity was zero, and fresh air leaking into the sump caused the oxygen to increase back to 20.6%. If air was not leaking into the sump, the oxygen content can not increase by this amount. In the middle of the graph, the oxygen concentration has risen from 2.4 to 10.3%. This increase needs an air leakage flow of 2.7 L/s. In the next hour, the O_2 concentration increased from 10.3 % to 20.0% which corresponds to an air leakage flow of 3.5 L/s. Oxygen removal by water over this two hour period is 0.23%. From hour 28 to hour 29, the gas velocity is zero, yet the oxygen content decreased from 20.5% to 19%. This shows that gas flow from the dump into the pipe has not completely stopped but rather appears to be seeping into the shed at a very low velocity. Air leakage is calculated by the following equation:

$$\text{Volume of Leakage (L/h)} = \left(\frac{X_{gt} - X_{g(t-1)}}{X_{Outside}\Delta t}\right) . V_{\text{sump and shed}} \quad (3\text{-}6)$$

where:

X_{gt} = Oxygen level in the sump air at time t
$X_{g(t-1)}$ = Oxygen level in the sump air at time t-1
$X_{outside}$ = Oxygen content in the air outside the shed
V_{Shed} = Volume of the sump and shed (26400 L)
Δt = time interval between t-1 and t (one hour)

The air in the shed mixes with air in the sump as the oxygen level in the sump air falls. Calculating the oxygen content in the shed after mixing with gas in the sump for each hour, it was concluded that the shed's oxygen level is very close to the sump's oxygen level unless the door is opened. Knowing this, the amount of leakage was calculated for the volume of the sump plus the volume of the shed. In the Sullivan mine accident, workers did not show any symptoms as they opened the door and entered the shed but as each descended the ladder into the sump they collapsed. This took place because when the door is opened, fresh air quickly ventilates the shed making the air in the shed safe to breath. The air in the sump may take a considerably longer time to be ventilated in this way due to the sump configuration. This phenomenon is true for other enclosed structures such as manholes located in an open atmosphere. For such configurations to be ventilated, forced ventilation is needed.

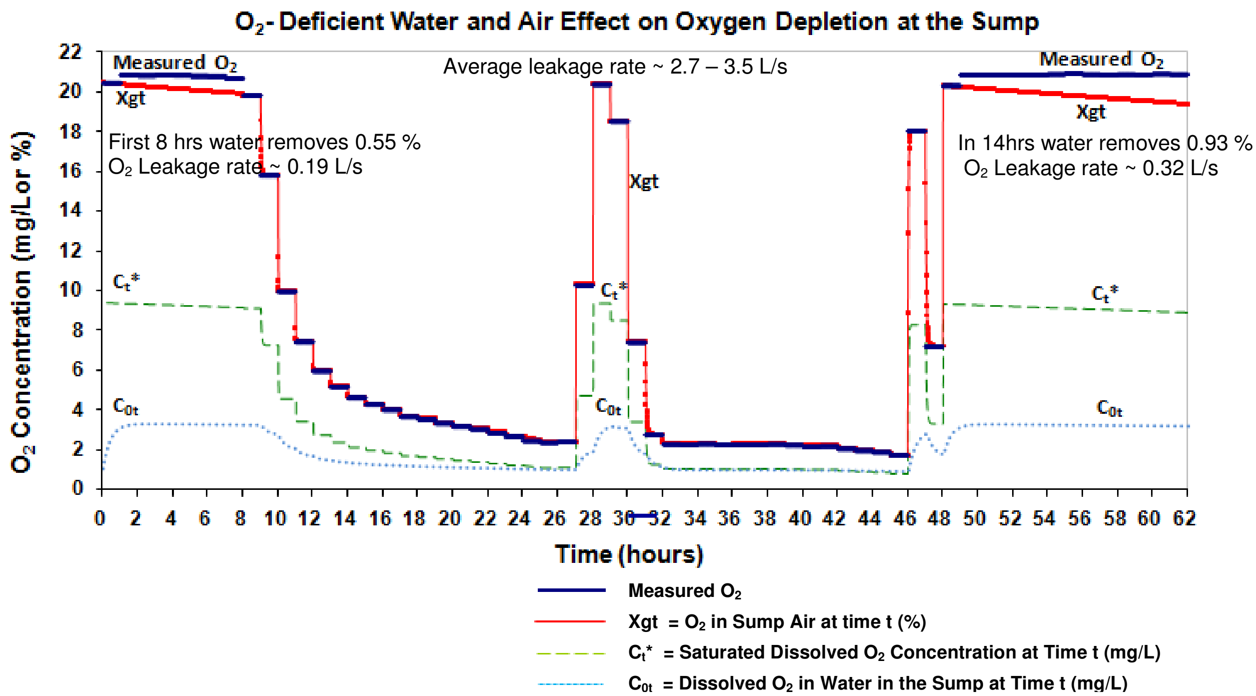

Figure 3-11. Oxygen-depletion of air in the sump by oxygen-deficient water and air (velocity and oxygen content data were provided by technical panel of the Sullivan mine, Teck Metals Ltd).

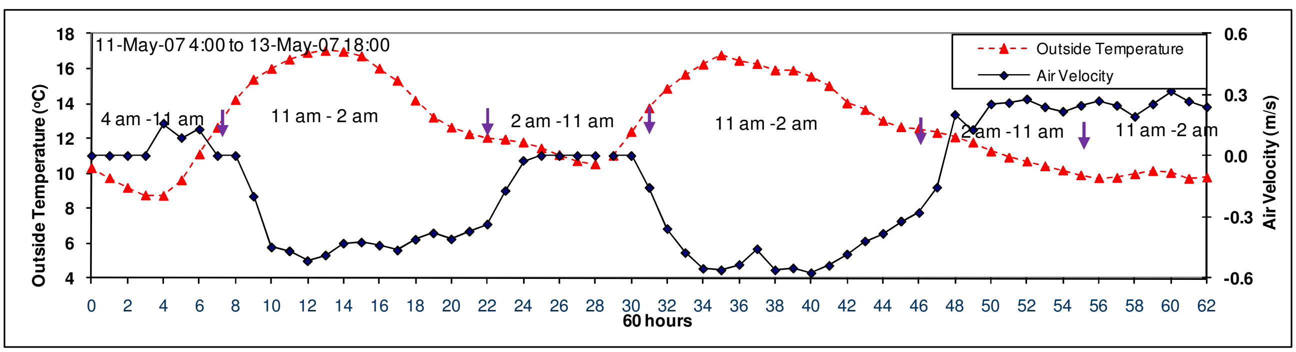

Figure 3-12. Gas velocity and temperature variation approximately one year after accident. (time matched to same period as in Figure 3-11)

Although the mechanism of oxygen removal by water is low in the case of the Sullivan site, it is possible that oxygen-depleted water flow rates and shed volumes at other sites could be much more significant (Bayah et al., 1982). The time to consume oxygen down to 18% by deoxygenated water at different flow rates for the shed volume and sump surface area at the Sullivan mine (A:V = 2 m^{-1}) and considering different leakage rates of fresh air into the shed is shown in Figure 3-13. In this graph, safe and dangerous regions are separated by a line, each line representing a different air leakage volume as represented by the velocity of air flowing in the pipe. Results are presented in Figure 3-14 for a sampling shed with an A:V ratio equal to 4 m^{-1}. With an air velocity in the pipe of 2 m/s, even small water flows can reduce the oxygen level to 18% in about 2 days. Higher water flows will create even more hazardous conditions. Therefore, the potential for oxygen removal from air by flowing water through a confined space is a significant factor in conducting a proper risk assessment.

Safe and unsafe situations at the Sullivan mine based on different air velocities and water flow rates are depicted in Figure 3-15. The range of operating conditions that occurred at the Sullivan mine are represented by the elliptical region in the graph. For water flow rates below 25 L·min^{-1} the sump is safe for all but very low air leakage flows. However, for a water flow rate of 77 L·min^{-1} safe conditions are only achieved if the flow rate of fresh air into the sump is above 0.8 m·s^{-1} (considering a cross section area of water to air in the sump of 0.126 m^2).

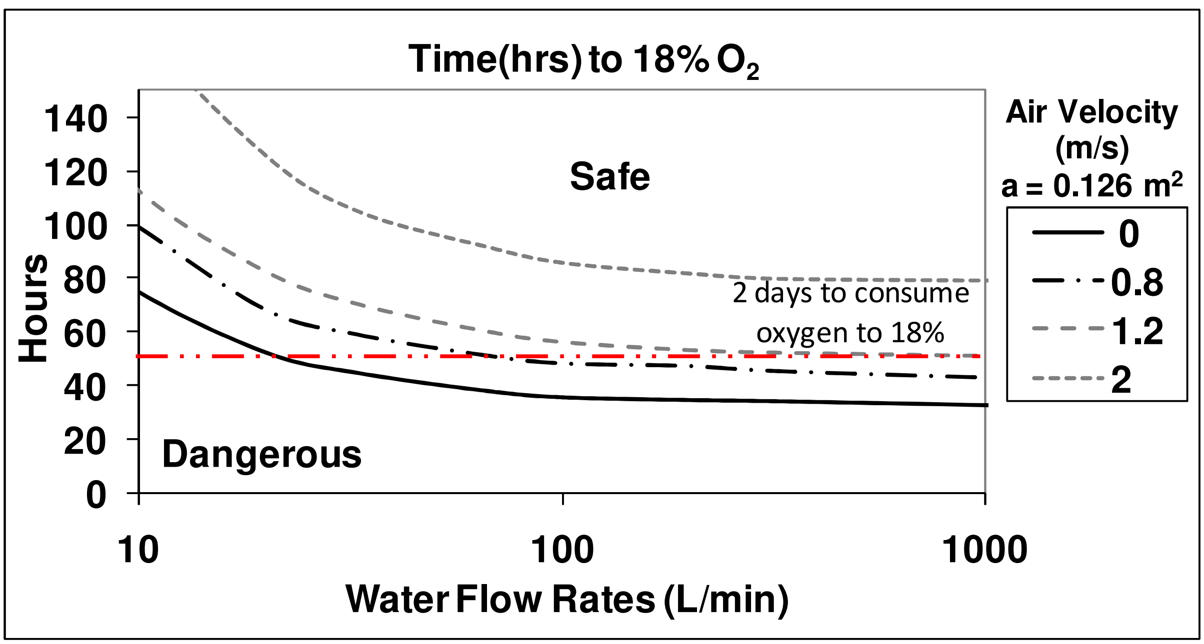

Figure 3-13. Time to consume the oxygen to 18% in the Sullivan mine sampling shed, A:V ratio of 2 m^{-1}.

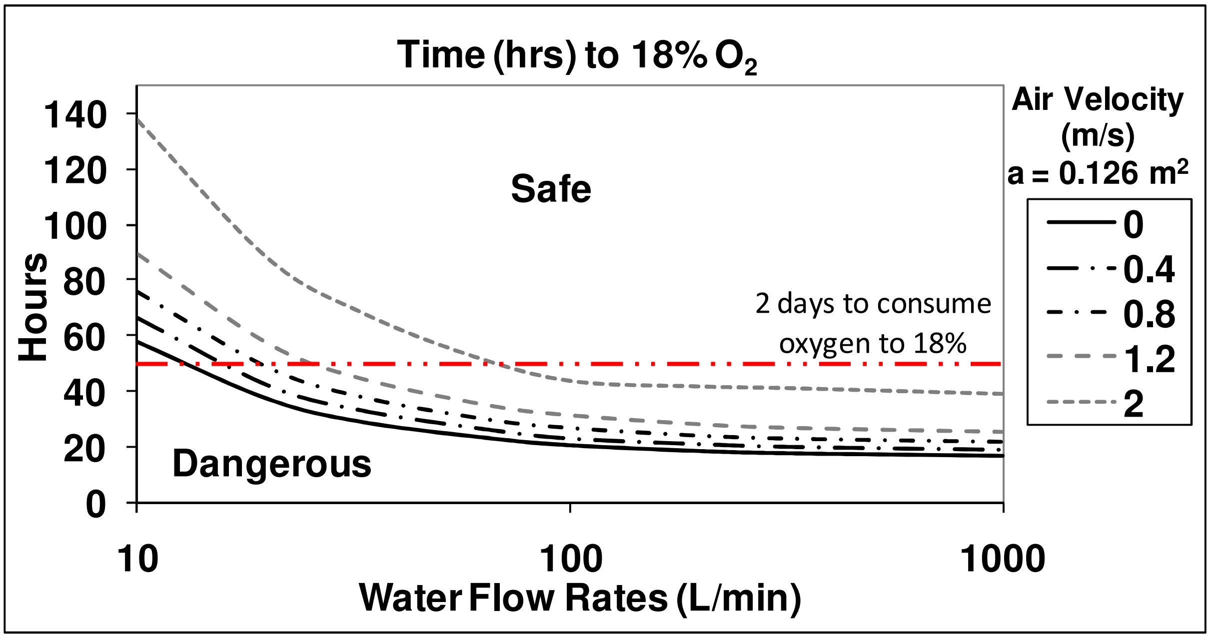

Figure 3-14. Time to consume oxygen to 18% in an arbitrary shed with an A:V ratio of 4 m^{-1}.

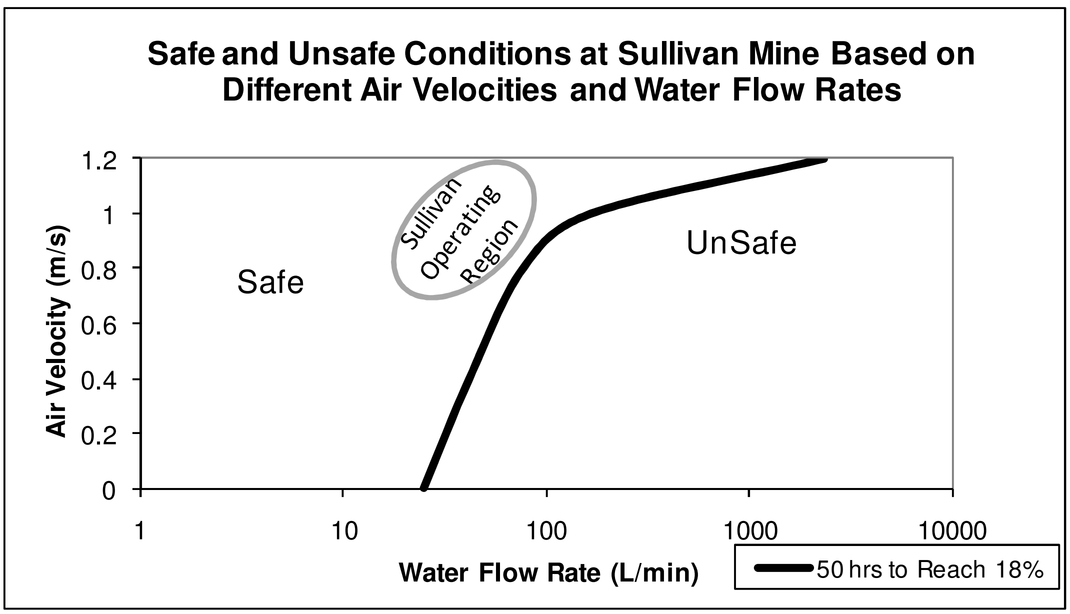

Figure 3-15. Safe and unsafe situations based on different air velocities and water flow rates. for deoxygenated water to reduce the oxygen content in air to 18%.

3.4. Similar Confined Space Accidents around the World

3.4.1. Earth Dam at Carsington, U.K.

In 1982, methane-bearing water seepage in a dam at Carsington, U.K. claimed the lives of four graduate students. Methane-consuming bacteria populated the walls in a well leading to the accumulation of oxygen-depleted and carbon dioxide enriched air. Entry into a drain within the dam resulted in loss of life through "asphyxiation by carbon dioxide". It was reported that sulfide minerals in mud-rock in the dam were being oxidized to produce sulfuric acid that reacted with limestone to produce carbon dioxide at a level sufficient to dilute the air significantly. High organic content in the mud-rock, together with a low flow rate of water through the mud rock caused high dissolved methane concentrations (Gooddy and Darling, 2005).

One graduate student entered the toe drain to check for seepage. He was overcome and collapsed. Three other students were outside and each suffered a similar fate in attempting a rescue. The event had widespread implications in the U.K. regarding an employer's duty to ensure workers are properly trained and competent in all areas of work undertaken. The incident has been described in detail in the following references (Baker, 1986; Pearson and Edwards, 1989; Hooker and Bannon, 1993; McAleenan and McAleenan, 1999). A study conducted on dissolved methane in groundwater in the UK demonstrated that the dissolved methane content was orders of magnitude below the theoretical 1600 µg/L value of its Lower Explosive Limit (LEL) after outgassing in a confined space and higher methane concentrations are required before an explosion will occur. Waters with this much dissolved methane do exist in aquifers with reducing conditions, so in some cases, methane exsolved from groundwater in mud rock can introduce an explosive hazard for a confined space. Mud rock because of its low permeability was not the source of natural groundwater discharge. Therefore, dissolved methane in mud rock water was not considered the problem. Rather the problem arose when mud rock is tunnelled for water transfer between catchments, either for water supply or hydroelectric purposes, or for more general civil engineering reasons. In such cases, mud rock can have an elevated dissolved methane concentration in water because of its high organic level (Gooddy and Darling, 2005).

3.4.2. Breathing Water Well in Alberta

In 1999, two children were killed in a well pit in Alberta. They died from lack of oxygen from oxygen-depleted air blowing from a water-well located in a root-cellar on their farm. The farmer discovered his daughter in the cellar and entered to affect a rescue, but he quickly fell unconscious. His son then attempted a rescue and was also overcome. A neighbor called to the scene was able to extricate the farmer who actually recovered, but the two children could not be revived. This situation has been seen at other locations in Alberta and in the western U.S. and has been dubbed "breathing water-well". In studying the accident, pressure, temperature, air flowrate and oxygen, carbon dioxide and methane levels were measured. The results show significant influence of barometric pressure changes on oxygen levels (Hill, 2002; CGWA Factsheet #5, 2004) from displacement by nitrogen and carbon dioxide. Deoxygenation of air in the well occurs from contact with oxygen-depleted well-water. Moreover, denitrification of commercial nitrate fertilizers in a perched zone above the aquifer generates nitrogen that is picked-up by the ground water. Nitrogen in the water was at a level in equilibrium with gas containing 90% nitrogen. It is also believed that ground water contacts sulfide minerals or organic matter in a semi-saturated, permeable zone. The mineral surfaces and/or organic matter consume dissolved-oxygen and emit carbon dioxide to ground water flowing into the well.

A "breathing water well" is one that has been drilled into a partially-saturated aquitard below a perched or low-conductivity zone in which the well casing stops above the water table. In a "breathing water well", air moves into the well when the barometric pressure rises. Oxygen in this air is consumed within the permeable zone, nitrogen and carbon dioxide are picked-up, and when the barometric pressure drops, the oxygen-depleted air is blown up the well and into the pit or sump at surface. A drop in barometric pressure of about 270 Pa is needed for the oxygen level in air to decline from 20.5% to 19.0%. When the air pressure rises, fresh air is forced back into the well and the cycle continues. The air flow rate is higher in summer than during colder fall and winter periods whenever a pressure change causes exhalation. However, the rate of oxygen removal by oxygen-depleted water was found to be independent of temperature.

3.4.3. Breathing Coal Mines

Water wells are not the only structures in the ground that breathe. Abandoned coal mines do as well. In 1987, a 42 year old woman moved into her new home in Newcastle, U.K. The house had been tightly shut-up for about 2 to 3 days. Shortly after her arrival, she felt dizzy and nauseated and was unable to light a gas fireplace or even a cigarette due to "bad" air that had built up in the house. Gasses from a remediated coal mine beneath her home had leaked into the house. Inspectors could not detect CO or methane, but the air in the house was found to be significantly oxygen-deficient. Escape of oxygen-depleted air from the mine caused the problem in her house and several others over a distance of about 5 km (Hendrick and Sizer, 1992). The heavier carbon dioxide also displaced air (Jeana et al., 2004). Air diffused into an abandoned mine where oxygen was consumed by exposed coal seams. The seams oxidized internally at low temperature in the presence of water and the air became oxygen-depleted. Pyrite is also present in most coal mines in amounts of 1 to 3% which also consumes oxygen and can act as a catalyst in that sulfuric acid generated from pyrite oxidation increases the oxidation rate of specific organic compounds in the coal matrix (Wang et al, 2003). It was also believed that additional oxygen-depleted air derived from the decomposition of timbers in the mine. The sulfuric acid generated by sulfide oxidation can also react with carbonate minerals to produce carbon dioxide directly which can displace air (Hendrick and Sizer, 1992).

A drop in barometric pressure caused the leakage of oxygen-depleted air and carbon dioxide from the mine. The concentration reported for carbon dioxide was 9.4% while the oxygen level was 9.8 % in a shallow venting exploratory shaft sunk adjacent to the house. The oxygen level was as low as 8-9 % in a cupboard and in the kitchen sink. In living areas oxygen levels were measured as low as 16%, although with rapid drop in atmospheric pressure, it declined 13%. The minimum acceptable level for oxygen is 19.5% (Pettit and Linn, 1987; BC Mines Act, 2008). When oxygen goes below 16%, humans begin to feel physiological effects of oxygen-depletion which includes impaired judgment and difficulty in breathing (Pettit and Linn, 1987). If oxygen drops to any level below normal (20.6%), investigations must be conducted.

The most relevant pathway for gas entry was determined to be an underlying defect in the concrete floor through which water pipes entered the home. Geological features (sand layer and faults) above the coal mine allowed bad air to exit from the mine (Hendrick and Sizer, 1992). The sand layer allowed the gas to transfer upwards, while a thin clay layer on top of the sand layer prevented the gas from dispersing into the atmosphere. The concentrated gas found its way to the house through a nearby fault. The National Coal Board sunk a new shaft into the mine to ventilate the mine mechanically. This mitigation was successful as oxygen and carbon dioxide in nearby buildings returned to normal (Hendrick and Sizer, 1992).

The risk of oxygen-depleted air leaking into houses built above coal mines was not recognized prior to this event. Air coming out of a coal mine has never caused any asphyxiation because generally within houses, air does not become confined for significant periods of time that cause the concentration of oxygen to drop. However, if the gas is trapped in places such as cellars and pits, these can become dangerous spaces (Hendrick and Sizer, 1992).

The carbon dioxide concentration in the house was about 9%. If this gas simply mixes with atmospheric air, the situation, although dangerous, may not be fatal for short term exposure. However, in most cases, displacement is accompanied by oxygen consumption, reducing oxygen to a hazardous level. A barometric pressure rise causes air to flow into shafts and adits providing fresh air for further oxidation, i.e., the mine "inhales". A pressure drop causes bad air to flow out through permeable geological features (sand, faults, or man-made structures), i.e., the mine "exhales". If the pressure drop is slow, bad air mixes with outside air creating an uncomfortable oxygen level within a structure. If the pressure drops rapidly, bad air can accumulate in a basement. Air from coal mines blows out at several hundred $L \cdot s^{-1} \cdot km^{-2}$ (Hendrick and Sizer, 1992). There are many cases of oxygen-depleted air blowing into houses built above abandoned coal mines. In North America, deaths by asphyxiation have not yet been reported since bad air is diluted with air entering from outside, but cases of "sick" houses have been observed.

In 2003, there was a case where carbon dioxide infiltrated into the basement of a house built above reclaimed surface land above an abandoned coal mine in West Virginia. The residents of the house complained about shortness of breath, lightheadedness, dizziness, poor concentration, and blurry vision when they went to the basement of their two-story building. Their symptoms went away within minutes after leaving the basement. NIOSH initiated an investigation to determine the cause. Gas monitoring showed elevated carbon dioxide levels about 8.8 % in the basement, while the oxygen level was as low as 13.5 %. There were no signs of carbon monoxide or methane. This agrees with the symptoms of the homeowners. Air and soil gas samples from the mine drainage pipe were analyzed for carbon isotopic composition which showed that carbon dioxide infiltrating into the house was from a carbonate source (Jeana et al., 2004).

To mitigate the adverse effect of the leaked gas, similar ventilation to that generally used for radon mitigation was setup. Other preventive measures included maintaining positive air pressure, sealing the cracks and ventilating by installing fans in the basement. Similar accidents have been reported on houses built on top of abandoned coal mines in many places in West Virginia (Jeana et al., 2004). In some houses, carbon dioxide and oxygen concentrations have reached 25% and 10% respectively in the U.K. and in Pennsylvania. The West Virginia department of environmental protection stated that indoor workers, homeowners, public utility workers, emergency response workers, and remediation workers should use a confined space policy when working in a facility built above an abandoned coal mine. In the case of soil gas leaking into basements and causing symptoms, homeowners should discuss the problem with the Office of Surface Mining to develop active measures. Workers at mine remediation sites should be trained for confined space entry and test the atmosphere regularly for safe entry according to Jeana et al, 2004.

Some additional examples of an atmospheric hazard caused by a change in barometric pressure and outside temperature are as follow:

- According to Hendrick and Sizer, (1992) there was an accident caused by change in atmospheric conditions in Cameroon. In this case, a massive volume of carbon dioxide was released from a nearby lake (crater) which asphyxiated about 1700 residences in a nearby village. The CO_2 came from a magma crater on top of a nearby volcano (http://www.neatorama.com/2007/05/21/the-strangest-disaster-of-the-20th-century/). Carbon dioxide accumulated at the bottom of the lake in the crater and eventually erupted under pressure, releasing to the surrounding vicinity in significant amounts. The gas flowed down into the village with the aid of wind and took many lives.
- There was a case where the pilot light of a gas furnace in a basement of a church in Echart, Maryland extinguished frequently and people in the basement for any length of time began to feel dizzy. The basement of the church was connected to a crawl space covered with soil beneath a chapel which had a 3 m diameter sink hole. The carbon

dioxide gas was coming out of a closed coal mine through the subsidence into the crawl space and then into the basement. (Eltschlager et al., 2001(a)).

3.4.4. Asphyxiation from Oil-Contaminated Soil

In June 1952, a plumber working in a water manhole died in Minneapolis, Minnesota. The manhole had been built to provide water for a building under construction. It was 1.2 m in diameter with a depth of 2.7 m and constructed of concrete bricks and mortar (Michaelsen and Park, 1954). The employee had been working daily in the space for 2-3 days before the accident without any problem. On the morning of June 10th, another worker entered the manhole to turn on the water without incident. Later in the afternoon the plumber went to turn the water off and was overcome by "bad" air. Samples taken 20 days later showed oxygen levels of about 3%. The cause was found to be oil-contamination in the surrounding soil. The soil consumed oxygen three times faster than "black garden soil" producing high levels of carbon dioxide. The oxygen-depleted air diffused into the manhole because of a concentration difference with normal air. It is likely that the acute nature observed was also related to a significant barometric pressure drop (about 202 Pa) accelerating the flow of "bad" air into the space. Similar to a breathing water well, dangerous air can move into the confined space when the pressure drops.

3.4.5. Soil Penetration by CO Gas

In 1997, a municipal sewer project involved installation of new pipes and manholes. Blasting was used to break up rock layers about 2m below surface before excavating pipeline trenches and manhole pits. A construction crew had installed a 3.7m-deep manhole. After the crew left, 120 kg of nitroglycerin in twenty 5.5 m deep boreholes were detonated about 15m away. A worker entered the manhole 45 minutes later and collapsed. Two coworkers tried to rescue him. One was able to retrieve the unconscious worker, but the other rescuer died in the manhole. All workers had elevated blood levels of carboxy-hemoglobin indicating they had inhaled air with high CO levels. It was determined that CO released from the explosion migrated through the soil into the manhole. CO concentrations in the manhole two days after the incident was 1,905 ppm – well above the IDLH (Immediately Dangerous to Life and Health) level of 1,200 ppm. Even after ventilating, high levels continued for 7 days. The incident shows that CO (and other gasses) from subsurface blasting can migrate through porous material to accumulate in a confined space. This was the first reported fatality from this exposure type although nonfatal poisonings have occurred in basements from nearby blasting (Deitchman et al., 1998). Other examples of blasting related accidents are as follows:

1- November 3-8, 1988, Bucks County, Pennsylvania (PA) - 12 blast holes with a depth of 8.8 to 10 m were filled with TNT and ANFO for a blasting project in sewer construction. Six days after the blast, two occupants of a house 30 m away from the site were reportedly poisoned by CO (Santis, 2001).

2- April 1-2, 1993, Perry Hall, Maryland (MD) – Carbon monoxide from a blast to construct a foundation for a house migrated 4.6 - 6 m to a nearby residence. The occupant of the house smelled what they claimed was “Burnt Concrete” in the evening and reported experiencing moderate to severe CO-poisoning symptoms. The following day, emergency responders measured 210 ppm of CO in the basement which did not return to normal levels even after 6 days (Santis, 2001).

3- December, 9, 1994, Havre de Grace, MD - two blasts (consisting of 110 to 220 kg of extra gelatin) were conducted for a new home foundation. Each blast hole was 3.4 m deep and filled with 2.3 to 2.7 kg of explosive per hole. Twenty minutes after the second blast, the CO level was measured in a model house 11 m away, by the contractor at a level of 87 ppm. After the third blast, this level increased dramatically (Martel et al., 2004).

4- March 7 to April 20, 2000, Adrain, PA – 20 overburden blasts in a small surface coal mine were conducted with 2300 kg of ANFO. Blast depths were 7.6 to 9.1 m

> and holes were stemmed to about 4.9 m. After blasting, the ground heaved about 2.3 m. On April 2nd, residents in a house 120 to 150 m away from the blast were diagnosed with CO-poisoning. 650 ppm CO was measured in the basement of their house as well as 400 ppm on the 2nd floor. On April 20th, the CO level was still high at 100 - 200 ppm in the basement (Santis, 2001).

In Appendix C.9, gasses that emit from blasting are discussed. Factors that contribute to their emission and ways to minimize this emission are listed. Knowing about the accidents described in this chapter and reviewing the BC Mines Act, it is known that reclamation sites at surface or underground mines have not received sufficient attention for acute atmospheric hazards. Before the Sullivan mine tragedy, few people understood that mining activities on surface can emit gasses that when confined become an acute hazard. So while confined space accidents are a well-understood hazard in underground mining with modern ventilation practices ensuring that work areas of a mine have high-quality air to support the miners' need for air, similar dangers from surface mining blasts is not widely recognized. Danger comes from seam gas, battery-charging stations, diesel engines, oxygen-depletion from exposed sulfide minerals or from displacement by carbon dioxide in coal mines (black damp), coal seam gasses such as methane at explosive levels (fire damp), CO at elevated levels (white damp), or excess heat at depth (Mohammadi and Meech, 2008). As well, coal with low moisture content produces dust, and coals with higher sulfur content may spontaneously combust (Hargraves, 1983). The sources of atmospheric hazards at surface mine sites may be blasting and other explosions, fires, liberation of gasses from the orebody, sulfide dust explosions, decay of organic materials, use of diesel and gasoline in closed areas, or gas carried by water or transferred through the soil. Many of these hazards are unrecognized in surface mining regulations and practices. As a result, there is no source that discusses these issues directly, except for a few reports that suggest atmospheric problems may exist at a reclaimed site. If the basic chemical processes that control gas generation from soils and minerals are known, then one can begin to understand which conditions lead to the appearance of these gasses. Appendix C (in the form of an Atmospheric Confined Space Manual - especially for gasses from mines and soils) discusses existing or possible atmospheric hazards from all industrial work places (especially mine wastes, minerals, and soils) and highlights pathways for gas emission and diffusion at mine sites to confined areas.

3.5. Summary

The tragedy at the Sullivan mine provides a valuable lesson that personnel in the mining industry must learn in order to account for unforeseen atmospheric risks at surface reclamation sites. The accident was compared with other similar confined space accidents, where temporal changes in temperature and pressure caused "bad" air to flow into a confined structure. How temperature and pressure control gas flow is clear in each accident, but the knowledge was obtained after the fact (Mohammadi and Meech, 2011). When a confined space is connected to an outside environment, atmospheric pressure and temperature changes affect gas flow into and out of the space. Knowledge about these diurnal and seasonal changes is essential in assessing a confined space. As a result, suspicious enclosed structures (especially ones near naturally- or industrially-contaminated areas) should be tested at different times of the day, month, season, and in different years to ensure the space is safe. A unique lesson from the Sullivan Mine tragedy is that the sampling shed was safe before the change in design in which the toe-drain was covered creating a direct connection between air in the shed and air in the dump. Before the glacial till cover was placed on the dump and the toe extended, the oxygen-depleted water seeping from the dump picked-up oxygen as it traveled along the open channel. With the new design, the till-covered dump essentially acted like a giant tea bag and the pipe like a straw. With the cover in place, air flowed into the dump and gas flowed out of the dump to be concentrated in the sump. So, what was a safe place became a dangerous one.

Chapter 4

Analysis of Factors that Contributed to the Sullivan Mine Accident

4.1. Overview

It was shown that seasonal atmospheric temperature fluctuations have been found to significantly affect oxygen-depleted gas emissions in the Sullivan mine accident. Also, several examples of atmospheric-related confined space accidents were discussed in Section 3.4 in which temporal atmospheric pressure changes caused hazardous gas emissions into a confined space (Mohammadi and Meech, 2011). Although diverse with respect to industry type and other characteristics, atmospheric-related confined space accidents have many similarities. These common characteristics can aid in defining and modeling these hazards.

Currently there is no literature that discusses the combined effect of atmospheric temperature and pressure changes on hazardous gas emissions into a confined space, especially one associated with waste dumps. This chapter describes how temperature and pressure differences between the inside of the dump and the outside atmosphere affect gas flow from the dump into an ARD collection pipe. Understanding the problem will be the foundation to develop methods to conduct atmospheric risk assessment of confined spaces at mine waste dumps as well as other confined space sites such as breathing water wells.

4.2. Effect of Atmospheric Conditions on Confined Space Risk

Atmospheric-related dangers have different sources that can be categorized according to the presence of organic materials, minerals and soils or gasses from specific operations and activities. With a confined space connected to an outside environment, atmospheric pressure and temperature variations due to climatic changes affect gas flow in and out of the space.

Examples of such accidents are breathing water wells; breathing coal mines, and manholes located in oil-contaminated soil. These effects are extremely important in establishing and defining risk from atmospheric conditions in the confined space. If temperature and pressure effects change the direction of gas movement, hazardous gas flows through the confined space and to outside, while if they cause air movement into the space from the outside, natural ventilation of the space results. The confined space accident at the Sullivan mine is a typical example of how atmospheric changes affect gas emission. Phillip et al., (2008) performed extensive data measurements of the Number One Shaft waste dump from 2006 to 2008. This work monitored internal and outside pressure and temperature as well as gas velocity in the effluent pipe. Their extensive dataset has allowed the effect of temperature and pressure variations on gas emission to be quantified to assist in later development of an atmospheric-related fuzzy risk assessment of a confined space at a mine reclamation site.

4.2.1. Development of Theory

While temperature alone is able to describe the gas velocity variations, there is a need (and desire) to incorporate the pressure effect. The data have been reexamined in this research to understand the general criteria for determining gas flow direction and magnitude in dumps by considering both pressure and temperature effects. In order to build on this knowledge and attempt to improve the prediction, a First Principles model using the first and second laws of thermodynamics was created. While it is clear that atmospheric temperature affects gas flow in and out of the dump and atmospheric pressure is known to affect gas flow in and out of breathing water wells and underground mines, the real variables of importance are the difference between the atmospheric and internal dump, mine, or well conditions (temperature and pressure). In order to understand this, the approach involves calculating the free-energy changes within the dump that cause gas to flow out or air to flow in.

The development of the theory in this section is based on recent work by Cengel and Boles, (2006). The *first law of thermodynamics,* also known as *the conservation of energy,* states that *energy can neither be created nor destroyed during a process that takes place within a system; it can only change forms.* Therefore, the sum of energy into the system should equal the sum of energy leaving. However, satisfying the first law alone does not show that a particular process takes place, because a process must proceed in a certain direction. While the first law poses no restriction on the direction of a process, the second law can be used to identify its direction. The second law shows that energy has a quality component (with respect to its utility) that indicates the degradation of energy during a process. According to the second law, systems spontaneously move from order to disorder, thereby increasing the disorder of the universe. A process will happen if it satisfies both laws.

The property known as exergy is a valuable tool in determining the amount of useful work that can be gained from a system by bringing it into equilibrium with the environment. In order to satisfy both laws of thermodynamics, a system's exergy must be calculated. The amount of energy available for useful work in an irreversible process is less than the reversible work. The difference between reversible work and useful work is because of irreversibilities present in the process and is called the lost (or destroyed) **exergy** (Cengel and Boles, 2006). The quantity of the energy does not change during the process (first law) but its quality must decrease according to the second law. Irreversibilities such as friction, chemical reactions, heat transfer through finite temperature differences, unrestrained expansion, nonquasi-equilibrium compression or expansion, all of these generate entropy. Entropy describes the tendency for systems to go from a state of higher organization to a state of lower organization on a molecular level. Figure 4-1 depicts two types of systems. In Figure 4-1(a), material flows through a control volume in which changes in the conditions of the material lead to work done on the external environment, while in Figure 4-1(b), work is done on the system to compress material into the control volume without material flow through that volume.

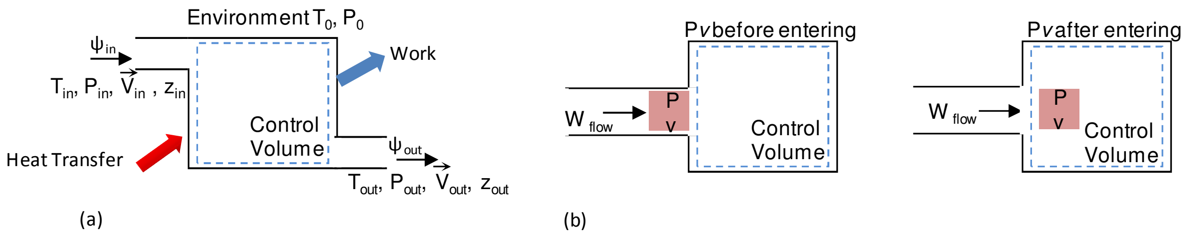

Figure 4-1. (a) single-inlet single-outlet steady flow system – exergy flow (ψ); (b) Flow of energy to move gas in and out of a control volume (Mc Graw Hill Ltd, Cengel and Boles, 2006, adapted by permission).

The exergy change in a gas flowing through a control volume as shown in Figure 4-1 (a) is defined by Equation 4-1:

$$X_{work}-X_{heat}+(X_O-X_I)=\Delta X \tag{4-1}$$

Where X_{work} is the sum of all work interactions per unit mass of the working gas on the outside world other than that needed to push air and gas into and out of the system (flow work). The variable X_{heat} is the heat transferred to the unit-mass of gas. If the exergy of a flowing gas as it is processed from state 1 to state 2 over time does not change, then $\Delta X = 0$. As well, for a system with no work and heat interactions, the exergy balance for a unit-mass of steady gas flow is:

$$(X_O-X_I)=0 \tag{4-2}$$

$$(h_O-h_I)+T_d(s_O-s_I)+\left(\frac{\vec{V}_O^2}{2}\right)-\left(\frac{\vec{V}_I^2}{2}\right)+g(z_O-z_I)=0 \tag{4-3}$$

$$X_{destroyed}=T_d(s_O-s_I) \tag{4-4}$$

where (h_O-h_I) is the change in *enthalpy* as defined by Equation 4-5:

$$h_O-h_I=\overline{C}_p(T_O-T_I)+v_d(P_O-P_I) \tag{4-5}$$

Combining the change in enthalpy and entropy, *free energy* is obtained as in Equation 4-6:

$$(h_O-h_I)+T_d(s_O-s_I)=f_O-f_I \tag{4-6}$$

in which T_d and v_d are properties of the *dead state* where the system is in equilibrium with the *environment* in which it is located, i.e., the system is in equilibrium with temperature and pressure of the environment and has neither kinetic or potential energy. As a result the exergy of a system that is in equilibrium with its environment is zero. By definition, the term *environment* refers to the region beyond the immediate surroundings of the system whose properties are unaffected by the process. As such, a system's exergy depends on environmental properties as well as its own properties.

In an open system (control volumes), a form of energy exists that is called "flow work", $v_0(P_{out}\text{-}P_{in})$. This type of energy does not apply with a closed system. This is the work that pushes gas into or out of a control volume – see Figure 4-1 (b). Flow work maintains gas flow in a pipe or duct and is included as part of *free energy* in Equation 4-5. The specific volume of gas, v_0, is equivalent to the volume change of a unit mass of fluid as it is displaced during flow. In Equation 4-6, the entropy change, for an adiabatic, single stream, steady flow control volume for the unit mass of an ideal gas is:

$$s_O\text{-}s_I=C_p\,\frac{dT}{T}+R\frac{dP}{P}=\int_I^O C_p(T)\frac{dT}{T}+R\,\ln\frac{P_O}{P_I} \tag{4-7}$$

If C_p as a function of temperature remains constant, then the entropy change is:

$$s_O\text{-}s_I=\overline{C}_p\ln\frac{T_O}{T_I}+R\ln\frac{P_O}{P_]} \tag{4-8}$$

So the specific entropy of the gas must increase as it flows through an adiabatic control volume, i.e., $s_{gen}\geq 0$. The difference in entropy for an outflow situation is positive while for an inflow condition, the difference in entropy is negative.

4.2.2. Results of the Theory

When the air inside the waste dump is heated due to the sulfide reactions in the dump, the air inside will expand and rise through the top surface of the dump doing work on the surroundings. The waste dump is considered an open system since the mass crosses the system boundary. As the process in the waste dump is irreversible, the change in exergy must be taken into account. The exergy change (ΔX) of the gas flowing through the dump as it transforms on an hourly basis was calculated from the dump data. This change was found to be essentially zero over the measurement duration. Therefore the dump can be treated as being at steady state over a one hour period. The potential energy is also negligible in comparison to the free energy changes in this case, but may be required for higher dumps. By applying these conditions to Equation 4-3, the result for an adiabatic system (with no outside heat interaction) and no work interaction (i.e., at steady state) gives an exergy balance between the outside and inside of the dump as in Equation 4-9:

$$\overline{C}_p(T_O-T_I)+v(P_O-P_I)+T_O\,(s_O-s_I)=\left(\frac{\vec{V}_I^2}{2}-\frac{\vec{V}_O^2}{2}\right) \tag{4-9}$$

Note that according to Equation 4-6, the left side of the above equation is the delta free energy or Δf (outside-inside). Here the temperature measured in the monitoring station is considered to be the dead state condition. This condition is shown by T_0 and was measured at waist height in the sampling shed. Temperature and pressure measured inside the dump 27.4 m down BoreHole (BH) 1A (T_I, P_I) (see Figure 4-2) and outside on the dump slope (T_O, P_O) were considered to characterize the inlet and outlet conditions of the exergy balance equation respectively. Note that the pressure was specifically recorded above each bore hole, while outside temperature was measured at one place (meteorology station). The pressure above borehole 1A was chosen as the outside pressure since borehole 1A was located at the centre of the dump and so, it was considered representative of the pressure above the dump.

As the dump height is 55 m, the pressure measured at 27.4 m down BH 1A does not represent the pressure at the bottom of the dump, but since this was the lowest level for which a pressure measurement was available, this was considered representative of the internal pressure in the dump. As expected, all values for (P_O - P_I) were negative which shows that the outside pressure was lower than the internal pressure. This value varied seasonally between -1 Pa and -12 Pa in summer and between -12 Pa and -30 Pa in fall and spring.

In Equation 4-9, the gas velocity inside the dump (V_I) and velocity of the gas while it moves out across the entire dump surface (V_O) cannot be measured. From Equation 4-9, it can be seen that free energy due to temperature and pressure differences between the inside and outside of the dump causes the gas to flow into or out of the dump by convective and/or advective flow. Gas going into or out of the pipe is part of this massive convective gas flow. As a result, the velocity of the gas flow measured in the pipe should be correlated with the free energy difference between the inside and outside of the dump and so can be used as a proxy – see Figure 4-3. A clear relationship between Δf and the gar or air velocity is evident.

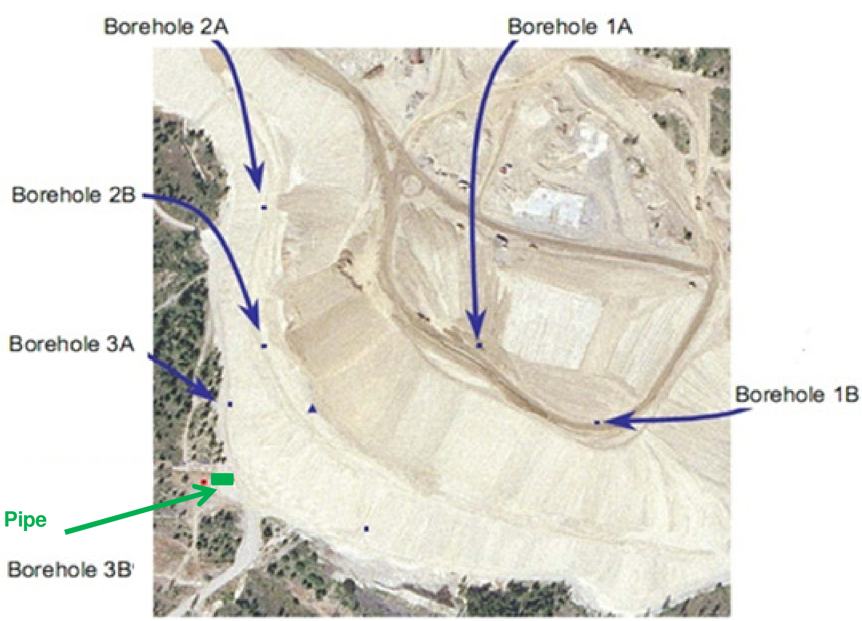

Figure 4-2. Locations of the boreholes at No.1 Shaft waste dump (Phillip et al., 2008, adapted by permission).

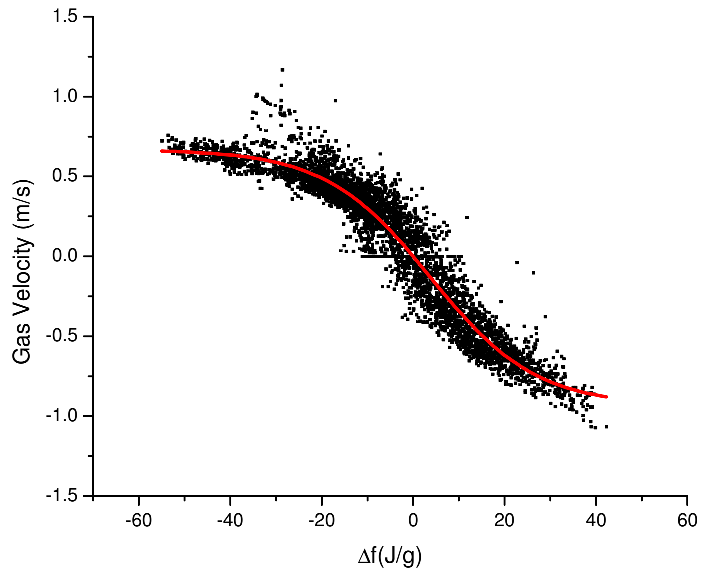

Figure 4-3. Correlation of gas velocity in the pipe with Δf.
Equation: $y = 1E\text{-}07x^4 + 8E\text{-}06x^3 - 0.0002x^2 - 0.0312x - 0.0087$, $R^2 = 0.929$.

As can be seen in Equation 4-9, rather than using measurements of a single temperature and single pressure to predict gas flow, First Principles use differences in these two conditions.

$(T_O\text{-}T_I)$ = Difference in outside temperature and inside temperature of BH 1A

$(P_O\text{-}P_I)$ = Difference in outside pressure and inside pressure of BH 1A

By considering differences in outside and inside conditions, the graph should pass through zero velocity at zero free energy difference. The correlation of determination (R^2) for this relationship is slightly better (0.929 vs. 0.927) than that for outside temperature alone in Figure 3-4.

In order to further improve the correlation shown in Figure 4-3, the data were separated into the four seasons. As can be seen in Figure 4-4, summer, fall, and winter data give a higher overall correlation of determination (0.954) which justifies the claim that the relationship between gas velocity and Δf vary seasonally with different patterns. However, the data for spring show much more scatter and the relationship is linear rather than fitting a polynomial expression suggesting that a transition to a smaller pore volume being involved occurs in the cold months of fall and winter through freezing of ice in the cover and upper surface of the dump as depicted in Figure 4-5. Due to a higher pore volume in spring, greater amounts of air flow into the dump at very negative delta free energy values. The maximum positive gas velocity of 1 m·s^{-1} occurs in spring compared to 0.75 m·s^{-1} in late fall and winter. When colder conditions involve lower pore volume, the gas velocity is restricted to about 0.75 m·s^{-1}. During the summer, gas blows out of the pipe reaching a maximum negative velocity of -1.0 m·s^{-1}, showing that much more of the internal pore volume is involved in the process as would be expected. Figure 4-6 schematically represents how the pore volume of air shrinks during colder periods to affect the pattern of inhaling and exhaling throughout the year.

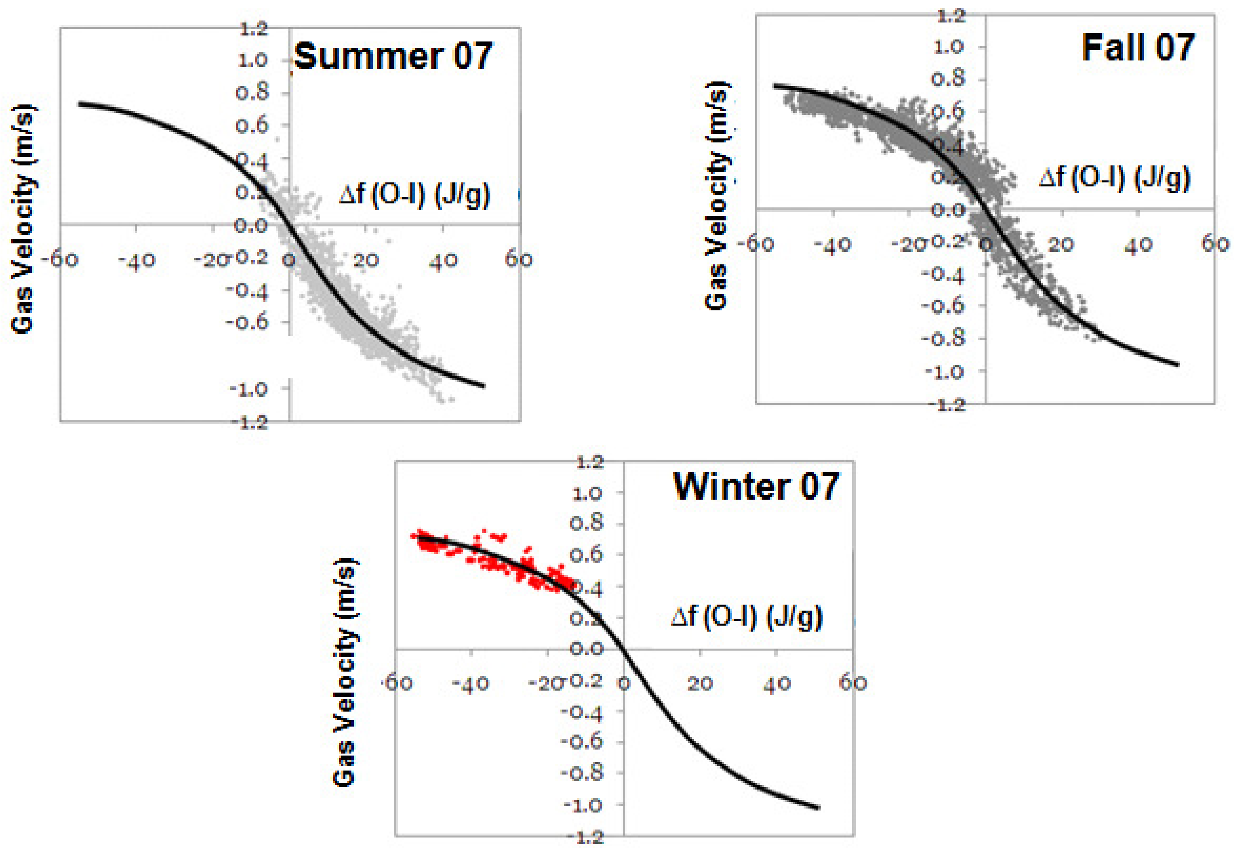

Figure 4-4. Correlation of gas velocity in the pipe with Δf (Summer, Fall and Winter, 2007), the trendline is shown for Summer, Fall, and Winter Equation: $y = 2E\text{-}07x^4 + 9E\text{-}06x^3 - 0.0003x^2 - 0.0314x + 0.0132$, $R^2 = 0.9537$.

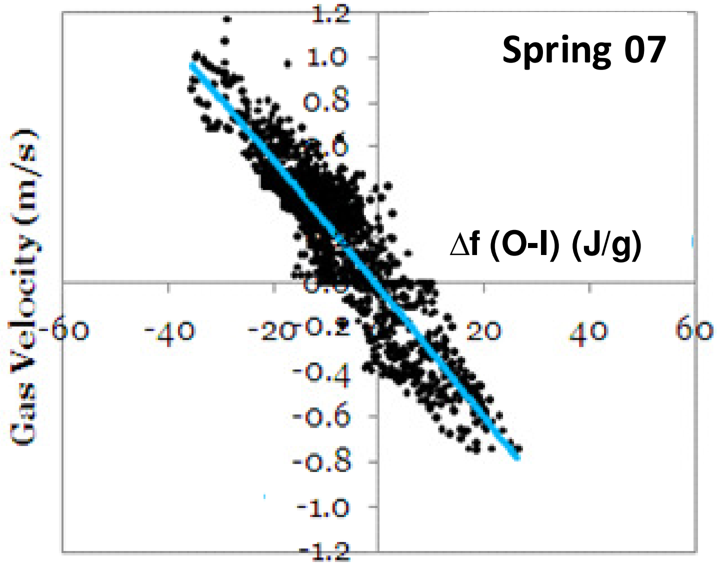

Figure 4-5. **Correlation of gas velocity in the pipe with Δf (Spring 2007).**
Equation: y = -0.0283x - 0.0446, R^2 = 0.837.

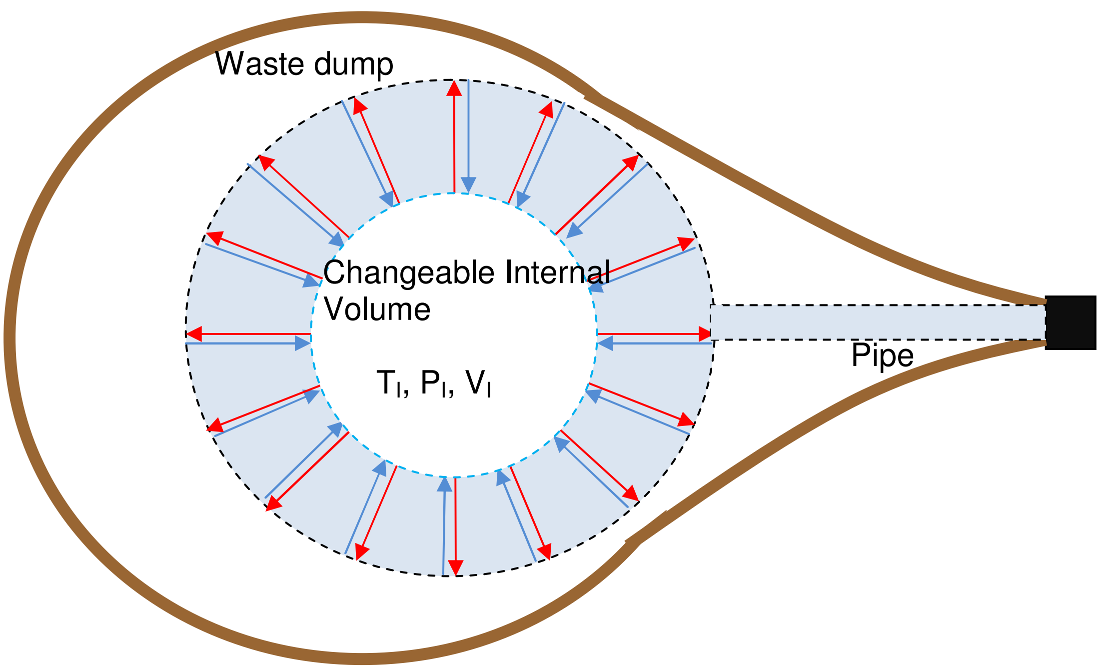

Figure 4-6. Representation of volume change in Number One Shaft waste dump (Chnages occur during the Spring melt)

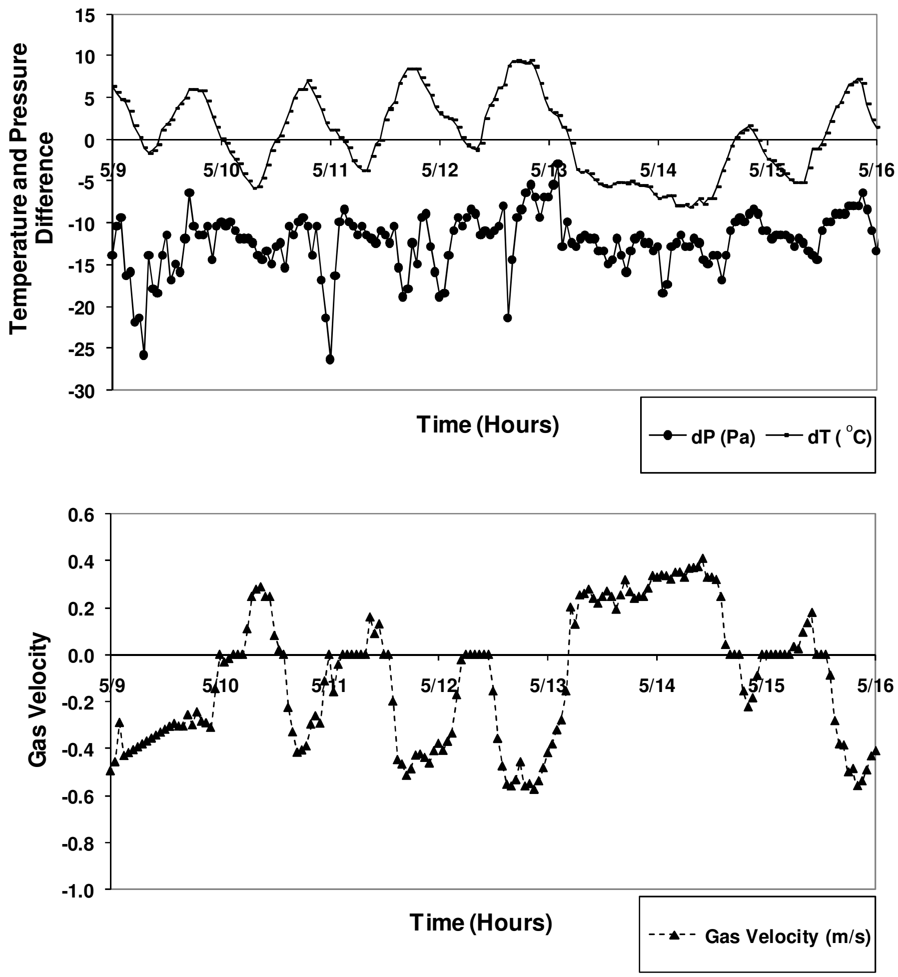

Figure 4-7. Diurnal changes in (P_O- P_I), (T_O- T_I) and gas velocity at the same time period in the year following the accident (May 9th to 16th 2007). Internal data are from 27 m down borehole 1A (data by permission from Technical Panel of the Sullivan Mine Accident, Teck Metals Ltd).

The dump inhales and exhales during the cold and warm times of the year respectively as well as cold and warm periods of each day respectively – see Figure 4-7. In some months or seasons, the inhalation and exhalation patterns may change to days of inhalation without exhaling and vice versa. For example, during the warm months of the year (July and August), the dump mainly exhales with long durations of negative velocity. In colder months (such as late November, December, and February) the dump mainly inhales with a positive velocity.

In the "*cooling or heating*" seasons (Spring and Autumn), daily variations in gas flow become very important due to fluctuations occurring in outside temperature and barometric pressure that straddle the internal dump temperature. In any specific climate, the balance between pressure and temperature outside and inside the dump throughout the year determines the direction of gas flow.

4.2.2.1 Effect of Pressure and Temperature Difference on Gas Flow

The relationship between (T_O- T_I) and (P_O- P_I) is shown in Figure 4-8. The minimum value of (P_O- P_I) is about -30 Pa which is probably too low to cause any significant gas flow. The values of this variable are always negative showing that the pressure inside the dump is always higher than the pressure above the dump, which would tend to drive pore gas up to the top of the dump. The energy due to (P_O- P_I) varying from -30 Pa to -1 Pa is very small ranging from -0.04 to 0.00 $J{\cdot}g^{-1}$ which is three orders of magnitude less than that due to the maximum and minimum temperature differences with a (T_O- T_I) varying from +20°C to -28°C occurring respectively in August and December, producing a free energy range of +20 to -30 $J{\cdot}g^{-1}$ respectively at these times of the year. As such, the pressure driven energy has barely any noticeable effect on gas velocity and so, the temperature difference is the dominant factor affecting gas flow in reactive waste dumps. According to Phillip et al., (2008), the measured barometric pressure and air velocity are not correlated, but Figure 4-8 does suggest a small degree of correlation with a broad error band. So despite the fact that the outside pressure varies considerably, for example at a time interval of one hour for data from September 2006 and December 2007, where the outside pressure increased to a maximum of 887 Pa in one hour and decreased to a minimum of 543 Pa in another one hour period, at the same time, the internal pressure at 27.4 m down BH 1A changed by a similar value in both cases (i.e., 882, 542). So, despite dramatic changes, equilibrium with the outside pressure occurs rapidly within one hour possibly due to channeling (hot spots) in the cover. The length of time required for a response to barometric pressure changes is determined largely by the dump permeability and only in very fine grained wastes (silts and clays) will the response be prolonged (personal communication, Andy Robertson).

It may be that the duration for the internal pressure to equilibrate with outside pressure will increase in thicker and/or higher waste dumps. As a result, during periods of decreasing outside pressure, (P_O- P_I) may become negatively large in high elevation waste dumps and will decrease the delta free energy to a further negative value. Increased negative free energy will result in positive gas velocity at the bottom of the dump as in Figure 4-3. This means a lower hazard of gas emission at the bottom and perhaps, safer conditions. Of course, the final value of gas velocity is determined by energies derived from both pressure and temperature differences.

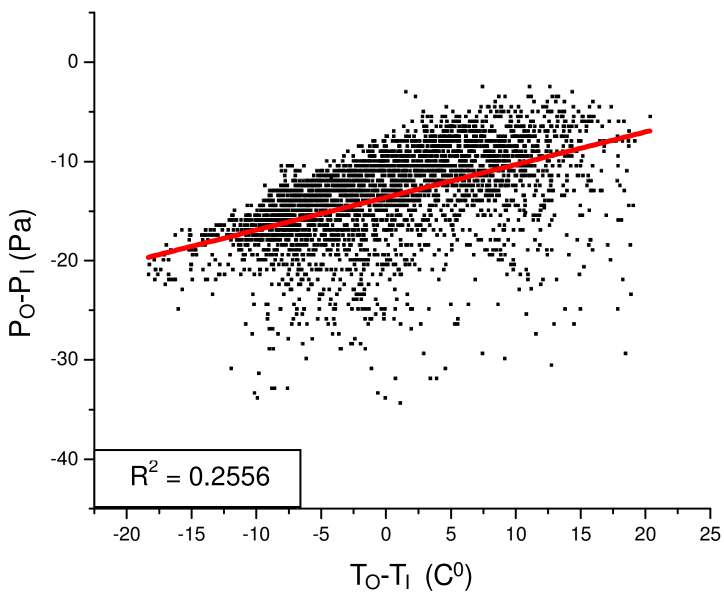

Figure 4-8. Relationship between pressure difference and temperature difference.

The effect of pressure difference is very small in low profile waste dumps (~50 m) such as the Number One Shaft waste dump. According to Wels et al., (2003), the potential for horizontal advection at the toe is higher in dumps with greater height. Advective response would be more important for thicker unsaturated waste rock piles as shown by Massmann and Farier (1992), because with high dumps, the outside pressure at the top of the dump is much lower than the outside pressure surrounding the dump near the bottom and the dump will inhale air at the bottom. Shaw et al., (2002) have mentioned the Chimney Effect: the combination of elevated temperature within rock piles due to ongoing oxidation, and high elevation gradients (490 m high) resulting in high rates of air inflow in the pile. According to Shaw et al., (2002), Sugar Shack South dump at the Questa mine in New Mexico is an example of a dump that shows a Chimney Effect. At this dump, the internal temperature is high at 40 ^{o}C and the oxygen content is higher during winter (6-12%) in comparison to summer (2-5%). The higher oxygen level in winter may be related to a negative (T_O- T_I) value in winter. The carbon dioxide profile in one borehole at Sugar Shack shows the opposite profile to the oxygen pattern in which the level drops to about 2% in the winter and increases to about 4.5% in the summer.

> As a result of (the) chimney effect, higher waste dumps continue to heat up and are not oxygen-deficient. Although the higher internal temperature will cause more gas flow into the waste dump, as…oxidation continues, (this) will affect (a) great oxygen transfer in the pile and increases the leachable contaminant generation (Shaw et al., 2002).

According to Wels et al., (2003), the potential for advective flow is higher in more permeable rock piles with high height to depth ratios, while the gas flow due to temperature differences depends on spatial permeability (coarseness) and the reactivity of dump material which controls the internal temperature. This suggests that higher waste dumps are safer than low profile dumps as air blows in at the dump toe to cause less oxygen-depleted gas generation inside the dump and no emission from the toe which agrees with the findings of the proposed model. Wels et al., (2003) described the oxygen variation in response to atmospheric pressure. When the outside pressure at the sides of the dump increased, compression of the gas phase within the pile occurred leading to entry of fresh oxygen. According to Ritchie, (1994), a wind velocity of 10 $m \cdot s^{-1}$ at a dump with a height of 15m, an area of 25 ha, and a gas-filled porosity of 0.3 causes a pressure gradient of 1 $Pa \cdot m^{-1}$ which can significantly affect gas flow, but comparably less than that of a temperature gradient (gas velocity of $2 \cdot 10^{-5}$ $m \cdot s^{-1}$). Ritchie, (1994) explains that advective gas transport caused by pressure unlike temperature-driven flow, has not been quantitatively measured because temperature gradient lasts for years while pressure gradients only lasts for hours. It is thus concluded in this work that, while in high permeability dumps, barometric pressure changes quickly reaching steady-state throughout the entire dump, temperature changes take considerably longer to reach a new equilibrium.

In White's dump at the Rum Jungle mine in Australia, Harries and Ritchie, (1985) observed a diurnal barometric pressure effect on oxygen concentration in borehole D before the dump was covered in which they noted similarities between the plots of barometric pressure and oxygen content. When barometric pressure decreased by about 500 Pa from 8 am to 6 pm, the oxygen level dropped from 5% to 1%, and when the barometric pressure increased by about 400 Pa from 6 pm to 12 am, the oxygen rose from 1% to 8% at a depth of 10 m in this borehole. According to Ritchie, (2003), this effect was not studied for periods longer than a day. The dependence of oxygen at a depth of 7.5 m on atmospheric pressure as a function of time over 28 hours was clear in borehole A at this dump, where similarity between the two plots strongly suggested semi-diurnal changes in atmospheric pressure caused rapid changes in oxygen and carbon dioxide levels in this borehole before the dump was covered. The energy caused by a pressure drop of 350 Pa led to an 8.5% decline in oxygen within 8 hours, and the energy caused by a pressure rise of 300 Pa caused the oxygen to increase by 8% from 4:30 pm to 22:30 pm (Harries and Ritchie, 1985). It is not known, however, much of the oxygen change was due to any accompanying temperature changes, or how much was due to the pressure difference.

Smolensky et al., (1999), also recognized the effect of barometric pressure on advective flow in the waste dump at the Nordhalde mine in Germany. At this site, the oxygen content in borehole 37 varies with barometric pressure (Smolensky et al., 1999). A pressure increase of 1100 Pa caused the oxygen content at a depth of 7 m to increase from 0% to 18% in about 4 days, followed by a pressure drop of 300 Pa that decreased the oxygen content from 18% back to 0% in 3 days. Over the same time period, the pressure change at a depth of 14 m in the same borehole increased the oxygen level from 0% to 0.8% followed by a decrease from 0.8% to 0%. Note that the thickness of the Nordhalde dump is 80 m with a length of 1450 m and a width of 800 m. It is obvious that temperature changes show a clear seasonal pattern in increasing or decreasing oxygen content in the dump, while the pressure effect is short term and does not show a regular pattern (Smolensky et al., 1999). The claim was made that the pressure effect is more dangerous since it can cause the oxygen content to drop dramatically from 19% to 0% in a few days, showing that a significant advective gas flow has occurred causing oxygen-depleted gas to blow out of the dump.

According to Wels et al., (2003), no detailed study has yet been carried out to precisely determine the net effect of pressure-driven gas flow and so, much more work is needed. It is important to study the net effect of pressure since seasonal variation in oxygen concentrations in the same borehole at the Nordhalde dump has been described as being due to thermally-induced gas convection by Lefebvre et al., (2001(a)). Seasonal variation in internal oxygen content in borehole 36 near the edge of the dump is obvious in this dump (Smolensky et al, 1999), in which during colder periods when $T_O < T_I$ (about 10 ^oC), the oxygen content inside the dump increases from 0 to a level of 8%, while in warmer times when $T_O > T_I$, the internal oxygen content returns to 0% (Smolensky et al, 1999). It is possible that barometric pressure can cause advective flow in dumps which do not have an effective cover. The oxygen content will increase in dumps where the pressure difference between the outside and inside of the dump is very high, e.g., 1000 Pa as with the Nordhalde dump. Currently there is considerable controversy about the effect of dump permeability and cover permeability on advective flow and so, further investigations are needed.

There are no specific studies at any dump that separates out the effect of pressure difference from the effect of temperature difference and little work has been done to demonstrate the specific impact of pressure difference on gas flow. Since the most important feature of all waste dumps is that they are being heated-up from the sulfide reactions, it is reasonable to conclude that temperature differences cause most of the changes in gas flow.

In water wells, with little to no source of heat to cause a significant temperature gradient, it is reasonable to believe that pressure changes cause gas flow. Pressure difference is more significant in breathing water wells and coal mines because of their underground nature.

4.2.2.2 Gas Flow Estimation

It is believed that Δf rather than outside temperature should be used to calculate and predict gas velocity in order to account for both the temperature and pressure effects. However, despite the high correlation of determination shown in Figure 4-3, there is still a significant range of values in the independent variable around the zero velocity situation. The uncertainty in the change of free energy and gas velocity shows that fuzzy rules are perhaps, a better way to estimate risk at any particular waste dump (e.g., pathways changes, measurement errors, heterogeneities, etc.). Table 4-1 shows how it is possible to predict the gas velocity direction and magnitude given a value for delta free energy at different times of the year. These rules derive directly from the curves in Figure 4-4 and 4-5.

Table 4-1. Fuzzy rules to predict gas velocity from free energy difference at bottom of the dump.

Free energy difference between outside and inside of dump ($J{\cdot}g^{-1}$)	***Direction of gas velocity at bottom of the waste dump***			
	Summer	***Fall***	***Spring***	***Winter***
Positive Very High ΔF >32	**NVB**	**-**	**-**	**-**
Positive High 10 < ΔF <32	**NB**	**NB (unlikely)**	**NB**	**-**
Positive Moderate 7 < ΔF <10	**NS**	**NS**	**NS**	**-**
Positive Low 0 < ΔF < 7	**NVS**	**NVS**	**NVS**	**NVS (unlikely)**
Negative Very Low -2 <dF < 0	**PVS**	**PVS**	**NVS**	**NVS**
Negative Low -7 < ΔF < 0	**PVS**	**PVS**	**PVS**	**PVS**
Negative Moderate -10 < ΔF < -7	**PS (unlikely)**	**PS**	**PS**	**PS**
Negative High -32 < ΔF < -10	**-**	**PB (unlikely)**	**PB**	**PB**
Negative Very High ΔF < -32	**-**	**-**	**-**	**PVB**

Negative Very Big - NVB (< -1), Negative Big - NB (-0.7 to -1), Negative Small - NS (-0.3 to -0.7), Negative Very Small - NVS (0 to -0.3), Positive Very Small - PVS (0 to 0.3), Positive Small - PS (0.3 to 0.7), Positive Big - PB (0.7 to 1), Positive Very Big - PVB (>1).

The methodology to estimate the direction and level of gas flow in a waste dump as a function of free energy difference is clear in Table 4-1. In order to proceed with a risk assessment based on this method, internal temperature and pressure measurements of the dump as well as temperature and pressure measurements outside the dump are required.

Measurements of internal temperature and pressure in borehole 1A at 27.4 m depth at the Number One Shaft waste dump were chosen to calculate Δf for this prediction. The internal temperature in shallower boreholes (BH 3A) varies seasonally and is affected by outside temperature more than by the internal reactions. However the internal temperature of other boreholes near the toe in deeper areas (BH 2B in Figure 4-2) do not show such effects and so will yield results similar to boreholes at the centre of the dump. Internal temperatures in the dump show seasonal changes to a depth of about 6 m in bore holes located at the toe which can be attributed to heat escape through the dump surface to the atmosphere. Therefore, temperatures at shallow depths (<6 m) in all boreholes are not representative of the real internal temperature of the dump and are unreliable in predicting the direction of gas velocity. While the driving force for gas convection is related to high temperatures at the dump centre (or perhaps, deeper areas at the toe), applying the internal temperature of boreholes located in such shallow areas should be avoided.

If the assessment is done at a particular time of the year with only a single measured data set, knowledge about maximum monthly atmospheric temperature and the pressure at that time throughout the year allows the system to calculate the direction and value of gas velocity at the bottom of the dump on a temporal basis over the year using the rules in Table 4-1. It is important to measure the outside pressure at the apex of the dump because when outside pressure drops (if the pressure difference is significant) gas escapes from the dump to the outside at the apex, not along the sides of the dump. Risk assessment is less sensitive to the position where the outside temperature is measured, although in calculating Δf, the outside temperature should ideally be measured half way up the dump.

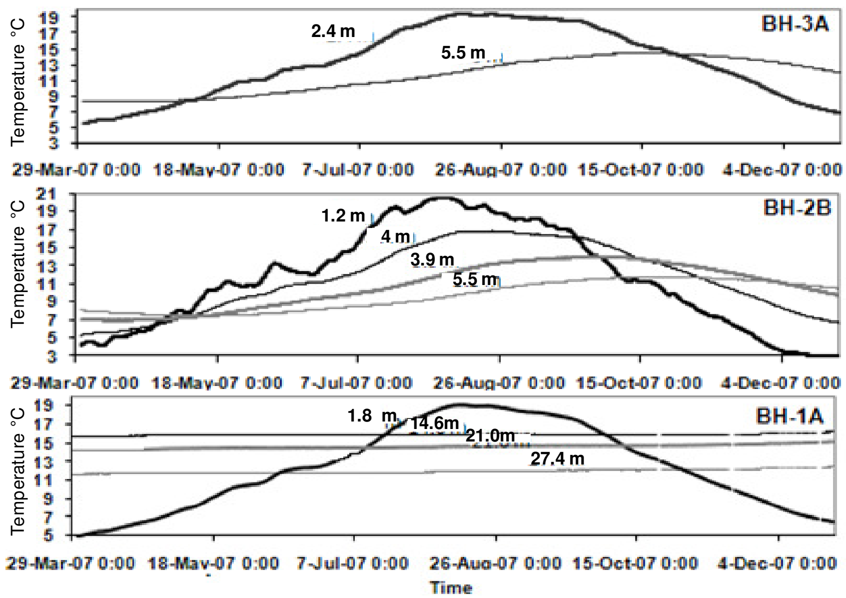

Figure 4-9. Effect of seasonal changes on internal temperature of boreholes 1A, 3A and 2B. location of boreholes are shown in Figure 4-2. (data provided by the Technical Panel of the Sullivan Mine Accident by permission, Teck Metals Ltd)

Since the Number One Shaft waste dump is very heterogeneous with respect to rock size and material reactivity, the internal temperature may fall across a wide range spatially within the dump and so, assuming a single internal temperature is probably unrealistic. However, with current knowledge and sensor capabilities, a single measurement point is likely the most practical way to assess the direction of gas flow. Internal temperature will differ from one dump to another based on many factors related to mineralogy, climate, particle size, water flow, etc. This simplification is correct if the internal temperature is *specific for one* waste dump, but the result only represents the period for which the risk assessment is conducted.

For example, the pivot temperature for change in the direction of gas flow ranges from 5 to 16 °C and depends on the season (Phillip et al., 2008) – see Figure 3-4. Although this range is wide, an average of 11.5°C is apparent. This value is equal to the average temperature measured at 27 m (90 ft) down a borehole at the centre of the dump (1A) from March 2007 to December 2007. At different depths in borehole 1A, average internal temperature varies as follows: 14.6 °C at 21 m, 15.9 °C at 14.6 m, and 14.2 °C at 8.2 m. The peak in internal temperature (15.9 °C) occurs at about 14.6 m depth. The internal temperature of Number One Shaft waste dump varies from surface to depth in other boreholes as well (Figure 4-9). However, note that the central peak temperature of the dump at depth is relatively stable on a yearly basis and continuous measurements of this value over a year are not needed.

To conduct a risk assessment, a single internal temperature can be measured at the centre (middle height) of the dump. The depth of maximum internal temperature varies at different dumps depending on age and reactivity. The temperature at the centre of the dump most likely will not equal the maximum internal temperature as this point will change over the years as the internal reaction zone descends through the dump. In Number One Shaft waste dump, the maximum internal temperature of about 16 °C occurs at a depth above the centre (at about 0.3 x dump height). The pivot temperature that marks the change in direction of gas flow is below the peak temperature at 0.3 but close to the temperature at 0.5 x dump height (about 12°C). Therefore an internal temperature reading at 0.5 x dump height is a better measurement point.

Due to the abundance of oxygen at some points near the edges of the dump, oxidation rates can increase and therefore the internal temperature can reach levels higher than the peak temperature at the centre. This effect was seen in Number One Shaft waste dump, with boreholes 2B and 3A which are closer to the edges of the dump, the internal temperature reached a maximum of 21 °C and 19 °C respectively. An increase in oxidation rates at the edges was also seen at the Nordhalde dump (Smolensky et al, 1999). The maximum internal temperature at the edges of the Number One Shaft waste dump is not close to the pivot temperature for change in direction of gas flow and so, is not useful for risk assessment.

Since the oxidation rate of sulfides in the dump changes over time, one can expect the internal temperature to increase or decrease as reactions either grow or fall in intensity, depending on many variables such as dump age, sulfide content, etc. For example, in the case of the Number One Shaft waste dump, it appears that the internal temperature is currently in a rising mode at the rate of about 2 ^{o}C per year.

4.3. Summary

This chapter has described how atmospheric pressure and temperature changes affect gas flow through a pipe installed to collect effluent from the toe of a waste dump. Combining these effects by taking into account the first and second laws of thermodynamics is proposed for predicting the gas velocity. Temperatures inside and outside a dump are the most important factors that affect gas velocities into and out of a sampling shed. Pressure differences are of a short term nature with three orders of magnitude lower impact than temperature differences for the Number One Shaft waste dump. Pressure plays a role, but to a lesser extent than with a "breathing water well" and other underground soils/rock as temperature gradients are generally much lower in these structures than in a waste dump. Advection at the toe is greater for high elevation waste dumps. The effect of cover permeability and dump permeability on pressure driven gas flow needs more investigation.

Taking free energy changes into account instead of outside temperature alone shows benefit in that both pressure and temperature differences are accounted for. The fact that the graph of gas velocity versus Δf passes through the origin indicates the reliability of this relationship. The method is applicable to assess gas emission from other waste dumps. The dump free energy difference from inside to outside a dump is expected to accurately estimate velocity, i.e., gas emission.

Since the degree of danger changes with climate changes, it is unreliable to simply rely on a random gas measurement in a possible confined space at a reclamation site. Atmospheric pressure and temperature changes occur daily, weekly, monthly, and seasonally. As a result, in a matter of a few hours, the risk of entering a confined space can transform from "safe" to "hazardous". Although such changes have regular patterns (in summer, gas flow is mostly out of the bottom of the dump, while in winter the gas flows out of the top of the dump), during the cooling (fall) and heating (spring) seasons, conditions are unstable and can change daily and/or weekly. This shows the importance of being aware of the existence of such a hazard not only at reclamation sites, but also at other enclosed structures and spaces affected by pressure and temperature changes such as a manhole located in contaminated soil, a "breathing water well", or other naturally confined spaces such as caves. Assessing the risk based on free energy will take into account the seasonal and diurnal changes in temperature and pressure.

Chapter 5

Atmospheric Fuzzy Risk Assessment for Confined Spaces[2]

5.1. Overview

The decisions required to operate a reclamation site effectively and safely with respect to atmospheric danger involve designing the reclamation activities to accomplish one or more of the following:

1. Minimize, eliminate, or control the generation of oxygen-depleted gas in the dump;
2. Minimize, eliminate, or control the emission of toxic gas from the dump;
3. Identify structures or surface anomalies that accumulate or concentrate toxic gas;
4. Eliminate or control the ability of these structures and anomalies to accumulate toxic gas;
5. Control human access to the structures and implement confined space safety practices.

Although these goals may sound straight-forward, the first requirement is to identify (or perceive) that a potential atmospheric risk is high. AFRA has been designed as a logical process to understand and conduct a detailed site assessment to provide this perception.

In this chapter, the key variables that affect gas generation, gas emission, gas confinement, and human exposure are identified. AFRA follows a step-by-step entry of relevant data that determines a Degree of Belief (DoB) that each of these issues is "High" or "A Problem". These elements are collected together to assign a linguistic risk probability to entering an associated confined space.

The system has been verified against six waste dumps from around the world for which sufficient data are available to provide a direct/indirect comparison of prediction and actual

[2] Many parts of this Chaper have been published previously. Meech, J.A., Mohammadi, L., January 2011, Confined Space Atmospheric Risk Assessment, Focus on Tomorrow, WorkSafeBC, pp. 81.

conditions. The comparison in all cases is excellent. Three waste dumps not used to create the system were also examined to test the system against new situations. This validation process also shows excellent agreement with reality in terms of internal temperature and direction of gas velocity estimates.

5.2. Research Problem

To understand how the Sullivan mine accident happened, it is necessary to break down the reclamation activities into their specific contributions that increased the risk of an accident. As demonstrated in Chapter 3, covering the dump during the reclamation activities resulted in the conversion of the ditch into an underground drain – this change was the first element in a chain of events that led towards the accident. The drain acted as a hydraulic conduit for air and pore gas to flow between the dump and the shed and it prevented oxygen-depleted effluent waters from dissolving oxygen from contact with air prior to entering the shed. Neither of these dangers was recognized at the time. While the effluent flow was too low to cause oxygen-depletion at this site, recognition of that danger might have triggered an investigation of the extreme hazard created by the atmospheric connection. Seasonal temperature changes (mainly in the summer) caused oxygen-depleted gas to flow from the dump into the shed (Phillip et al., 2008). Knowledge about these diurnal and seasonal changes is essential in assessing the atmosphere within a confined space.

As well, changes occur within the dump as sulfide minerals continue to oxidize consuming oxygen from the pore gas, generating acid, and producing carbon dioxide from reaction of the acid with carbonate-type minerals. Temperature changes within the dump over time due to sulfide reactions lead to periods of danger followed by dormant behaviour and then followed again by danger over decades and possibly centuries.

At a waste dump, the danger varies hourly as outside temperature changes from high in the daytime to low at night. Reclamation design factors (covers, slope changes, etc.) and dump properties (e.g., sulfide content, water content, particle size, etc.) also play important roles (Mohammadi and Meech, 2011). For example when the cover effectiveness is "High", gas flow into the dump is inhibited which decreases the internal temperature. This will happen for 1 to 3 years after cover placement when the cover is still young. For example, with White's Dump at Rum Jungle mine in Australia, about one year after rehabilitation commenced, the internal temperature at 10 m depth dropped from 49 ºC to 44 ºC, and the oxygen- level in the pore gas declined to <1% (Harries and Ritchie, 1983). Based on Figure 3-4, it was concluded that an increase in outside temperature (or decrease in internal temperature) creates an unobvious and dangerous situation with respect to atmospheric risk at the bottom of a waste dump. Placement of a cover is a cost-effective method to reduce dump oxidation and control ARD generation since it reduces both air and water flows. When a cover becomes eroded, its effectiveness is lessened resulting in higher oxygen inflow to the dump leading to greater rates of sulfide oxidation and higher internal temperatures. Climate plays a significant role, for example – wet periods with a low evaporation to precipitation ratio can cause the cover to saturate with water increasing its effectiveness (Mohammadi and Meech, 2011); with White's Dump, at the end of the wet season the internal temperature dropped 2 to 3 ^{o}C because of an increase in cover effectiveness due to saturation (Harries and Ritchie, 1983).

With a varying environment, one may not recognize an atmospheric danger using a multi-gas meter unless one is aware that certain apparently safe structures may become dangerous at another time. Continuous and regular measurement of oxygen levels is necessary or else a "false perception" of SAFE may result. This may be impractical and as an alternative, a risk assessment tool may prove helpful. Such a system should give designers and operators the knowledge of possible danger before an accident takes place. Recognizing a hazard using a single gas meter measurement is unrealistic as the danger may occur at an unknown point over an unknown time frame, maybe tonight, or next year, or next decade or

100 years from now – AFRA (Atmospheric Fuzzy Risk Assessment) can help evaluate and predict that uncertain risk (Mohammadi and Meech, 2011).

It would be easy to conclude that all sulfide waste dumps pose atmospheric confined space risks, but that is not the case. Some dumps show no effect, such as the North Dump at the Sullivan mine, while others that indicate similar problems have never had an accident because an element in the chain of effects is missing – either no emission, no concentration, or no human exposure. For example, with no covered pathway that connects a shed to bad air in the dump, the shed will likely be safe. Regulations are encouraged to require reclamation designers and operators to conduct an atmospheric risk assessment using AFRA and evaluate if a hazard is present at the beginning of the reclamation work and on a regular basis thereafter. AFRA suggest ways to overcome a hazard and remove it from the site.

5.3. Methodology

5.3.1. Fuzzy Logic Rulebase

AFRA is an Expert System based on Fuzzy Logic. Fuzzy Logic is a methodology able to capture knowledge and perform approximate reasoning similar to how a human copes with uncertain problems when making a decision. Fuzzy Logic can provide structure to an ill-defined problem by gathering vague and dispersed information to input into the decision-making process. Fuzzy Logic in environmental risk assessment has been successfully applied in previous work (Meech and Veiga, 1995; Veiga and Meech, 1997, Ghomshei and Meech, 2000). A number of recent remediation systems have been developed: a system to deal with remediation practices at oil-contaminated sites (Geng et al., 2001); a fuzzy expert system to recommend remediation methods for ARD sites (Balcita et al., 1999); a fuzzy expert system to predict levels of Hg emissions and bioaccumulation risk from artisanal mine sites (Veiga and Meech, 1994; Veiga and Meech, 1995a/b; Veiga and Baker, 2004). These systems all deal with groundwater and soil contamination. AFRA recognizes confined space atmospheric hazards for sulfide mine reclamation sites. Characterizing confined spaces situations using Fuzzy Logic rules has not been done before. Because of the inherent uncertainties involved in such space responses to temporal and environmental changes, this domain is likely to benefit from the use of Fuzzy Logic.

5.3.2. Other Confined Space Systems

It appears that no system has yet been built to evaluate or predict an acute atmospheric hazard. OSHA developed a program called Confined Space Advisor to help with recognizing a confined space (Anonymous, 1997). In this program there is one part that can evaluate a certain work space and give guidelines. The questions that the program asks are simple:

"1- Is the space in question large enough that a worker can bodily enter?"

"2- Is the space configured so that a worker can enter to perform work inside?"

"3- Does the space in question have limited or restricted means of entry and exit?"

"4- Is the space designed for continuous human occupancy?"

The explanation given for "limited or restricted entry and exit" is considerably different from that provided by NIOSH (Pettit and Linn, 1987) and is criticized as being inaccurate. Details of the NIOSH explanation was given in Section 2.3.2 In this program "limited or restricted entry and exit" is defined as "any place where an occupant must crawl, twist, be constrained in a narrow opening, follow a lengthy path or otherwise exert unusual effort to enter or leave, or the entrance may become sealed or secured against opening from inside" (Anonymous, 1997). But there are some cases where a very large enclosed structure such as a house or basement can become a confined space (according to the terminology used in this thesis) or a permit-required confined spaces (according to the terminology used by OSHA) (Jeana et al, 2004). This definition does not cover all the possible structures that may be confined spaces.

The program developed by OSHA was run for the sampling shed at Sullivan mine and it was unable to distinguish the sampling shed as a confined space with "limited entry and exit".

OSHA's system was designed for use in industries that include "agriculture services, oil and gas extraction, food products, tobacco products, textile mill, wood products, chemical products, petroleum refining, rubber products, and leather products". In each of these industries the typical confined spaces are covered and discussed. There is no mention of the mining industry in this program (Anonymous, 1997).

Workplace Hazardous Materials Information System (WHMIS) Canada has developed an electronic training course for confined spaces called "Confined Space Awareness". The course can certify employees after taking such training. The course includes confined space hazards, and pre-entry requirements for confined spaces (http://www.yowcanada.com/course_outlines_csr.asp?source=google&gclid=CIWatv-95qcCFQkFbAodxkJtbA). Recognition of a confined space in this course is based on confined space regulations in Alberta, where a space is categorized as "restricted space" or "confined space". Note that differences in defining "restricted space" and "confined space" consist of crisp answers that do not allow entry of any uncertainty. A Restricted Space is defined in Alberta as a place where the only hazard is getting into and out of the space. There is no need for a permit, for atmospheric testing, or for an attendant. A Restricted Space can become a Confined Space following a new hazard assessment by a competent person prior to entry in which changes in the conditions or the environment suggest additional hazards now exist. The relation between restricted space and confined space is similar to OSHA's definition of confined space and permit-required confined space, so if the place is partially or completely enclosed and not designed for human occupancy and has a limited or restricted entry or exit, it is termed a restricted space in Alberta, but if any type of hazard is added to the space then it is called a confined space. These types of definitions are very helpful and it is recommended to apply such definitions in Bc Mines Act and WorkSafeBC as well.

The US Bureau of Mines developed the SPONCOM computer program to assess the risk of spontaneous combustion in a coal mine. This program is an expert system program that uses geological conditions, coal properties, mining conditions, and mining practices to predict the spontaneous combustion risk. Data are based on information from the literature, mine operators and experts. The geological conditions such as density, coal joints, dikes and channels as well as mining conditions such as degree of floor heave and sloughage are ranked based on known ranking criteria for each property as low, moderate, and high. Based on the rank of each property, the likelihood of spontaneous combustion is output as low, moderate, or high (Smith et al., 1996).

Another program has been built to estimate gas explosion hazards in coal mines. The risk assessment model uses fuzzy mathematics to provide the hazard index of an accident in a coal mine based on a gas (methane, coal dust, or sulfides) explosion. The technique was examined for five faces of a coal mine in Chongqing, China to validate the risk assessment technique (Cao et al., 2006). These programs were designed to predict flammable atmospheres and none of them deal with the atmospheric hazard of confined spaces.

5.3.3. Atmospheric Fuzzy Risk Assessment (AFRA)

A hazard is recognized by AFRA using both a general and detailed assessment of numerous variables observed and measured at a site. The main focus of AFRA is a detailed risk assessment of a sulfide waste dump with the aim to estimate risk due to oxygen-depleted gas emission. The general risk assessment done in AFRA can extend to other gas problems, such as nitrogen monoxide/dioxide and carbon monoxide/dioxide or methane in which conditions for occurrence of such gasses may exist. As such, AFRA can warn about atmospheric hazards from coal waste dumps or from blasting agents. The following sections describe the detailed and general risk assessment processes. AFRA does not account for other types of confined space dangers such as flooding or asphyxiation by collapse of the structure walls, although an extension into that knowledge could be done in the future.

AFRA is written within the Visual Basic.Net 2008 environment allowing customized design of the fuzzy system and making the software portable into different operating systems. Fuzzy logic-based expert systems allow new features to be added with ease by creating different and/or new membership functions, applying different fuzzy mathematics techniques, or by modifying, adding, or removing rules in the future as required. AFRA is flexible, robust and, unlike pre-made fuzzy expert system tools (such as Exsys (http://www.exsys.com/) and LPA VisiRule (http://www.lpa.co.uk/)); there are few restrictions on knowledge transfer since no proprietary software product is required. Visual Basic is one of the most commonly-used programming languages. It is user-friendly and compatible with all PC-based technologies.

The system can function without all the input information and the User is not forced to enter data for each and every variable. There are only four pages of questions – although a further set of questions may be asked if some factors are undetermined. If measurements are available, they can be entered directly, but when not known, ranges or linguistic terms can be chosen instead. Selection of one range involves entering a Degree of Belief (DoB) to represent the certainty (or uncertainty) that the user holds about an entry.

In a detailed risk assessment, the confined space entry risk is synthesized into four major elements: gas generation, gas emission, gas confinement, and human exposure as shown in Figure 5-1.

Fuzzy values of the first three elements give the likelihood of a hazard being present in a particular enclosed structure. By combining this with the Degree of Belief in human exposure, the risk of entering the space is calculated. Both a numerical and linguistic output is generated, although the relationship between the numerical value (on a scale from 10^{-4} to 1.0) and the linguistic term can be changed by the user if desired.

Heuristics is used to model Unsafe and Safe situations at a waste dump. The main focus is on the first two elements, generation and emission but, the latter two are critical in creating conditions for an accident. The first two elements evaluate situations in which oxygen-depleted air or carbon dioxide develops (gas generation) within the pore gas inside a waste dump and then transfers outside the dump (gas emission).

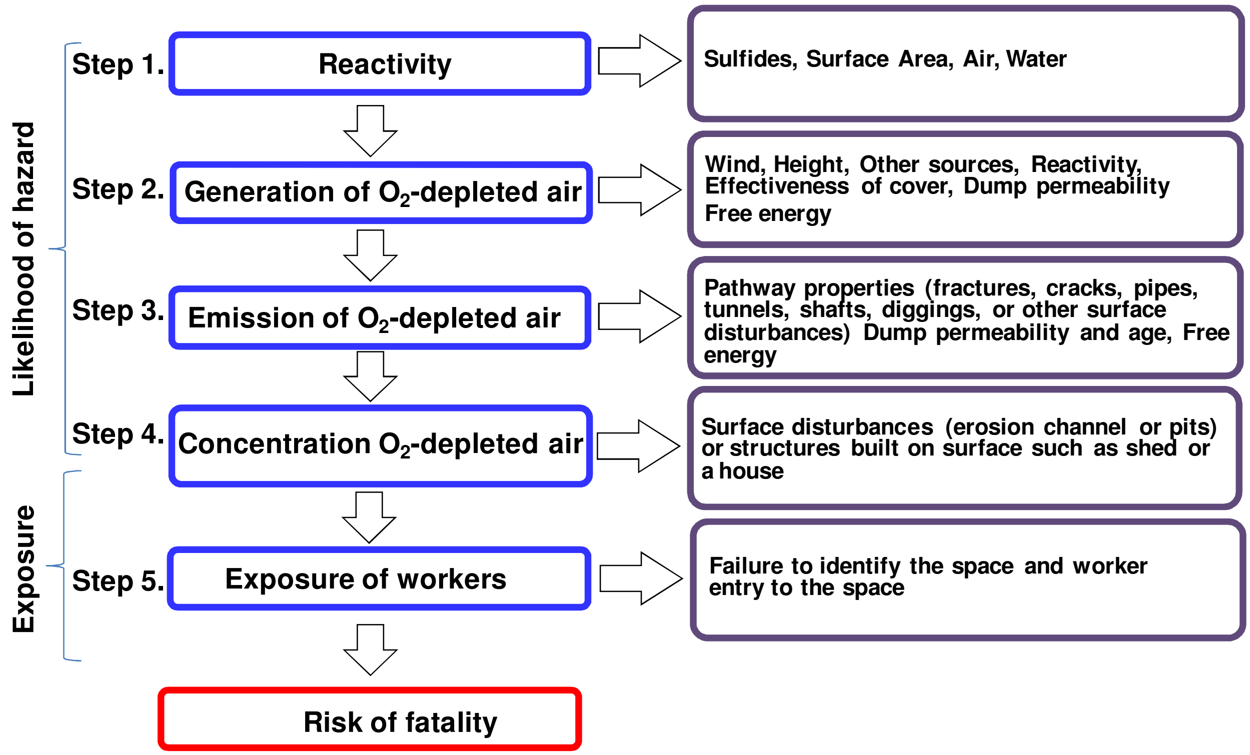

Figure 5-1. Stages in the atmospheric risk assessment

In conducting an environmental risk assessment of a dump, the generation and emission of Acid Rock Drainage (ARD) is evaluated. An analysis is made of the balancing of a dump's AP (acid potential) and NP (neutralization potential) of the minerals in the dump together with the impact on water effluent discharge quality. In AFRA, the process of oxygen-depletion of air (the first element of risk) and the process of oxygen displacement by carbon dioxide coupled with processes that emit such gasses (the second element of risk) are studied. Rather than NP and AP, permeability and the forces of thermal convection and advection that draw air into the dump and allow toxic gas to exit are of interest. Oxygen consumption is characterized by the oxidation rate of sulfides that depends on factors such as sulfide content, water content, pore gas oxygen level, particle size, channeling, etc. Many factors also affect air flow in and pore gas flow out of the dump. Oxygen is depleted from air by reacting with sulfides leading to a temperature increase which in turn enhances convective transport into and pore gas flow out of the dump. The degree of oxygen-depletion depends on a balance between oxygen consumption and oxygen replenishment by convection. The set of variables that characterize these processes are identified by AFRA. Rules were created from knowledge of waste dump behaviour (specifically the Number One Shaft waste dump). The rules were derived from detailed study of waste dumps reported in the literature. Details of these rules with respect to gas flow and the characterization of toxic gas generation and emission can be found in Appendix E.

As Fuzzy Logic is a case-based reasoning approach, the rules attempt to predict oxygen-depletion at six reference dumps from the literature. The software was validated by applying AFRA to three dumps withheld from system development (test dumps). As more sites are tested, more combinations of variables that control atmospheric risk will be covered. The dumps selected for inclusion cover a spectrum of variation in key variables, however not all combinations are yet covered. The multi-dimensional graph in Figure 5-2 shows the levels of variation defined by these dumps. The dumps and their sources are:

1. Nordhalde Dump at the Ronnenburg Mine (U) in Germany
   (Lefebvre et al., 2001(a); Wels et al., 2003; Smolensky et al., 1999),

2. South Waste Dump at the Doyon Mine (Au) in Quebec
   (Lefebvre et al., 2001(a); Wels et al., 2003),

3. Sugar Shack South Dump at Questa Mine (Mo) in New Mexico
   (Wels et al., 2003 and 2001; Lefebvre et al., 2001(b) and 2002; Shaw et al., 2002; Robertson GeoConsultants Inc., 2001)

4. Aitik Mine dump (Cu) in Sweden
   (Stromberg and Bawart, 1999/1994; Ritchie, 2003; Takala et al., 2001)

5. White’s Dump at the Rum Jungle mine (U) in Australia
   (Harries and Ritchie, 1980, 1983, 1986, 1987; Ritchie, 2003),

6. Number One Shaft Waste Dump at the Sullivan mine (Pb/Zn)

(Lahmira et al., 2009)

The test dumps are:

7. Main Waste Dump at Equity Silver Mine (Au/Cu/Ag) in British Columbia
   (Aziz and Ferguson, 1997; Lin, 2010)

8. West Lyell Dump at Mt. Lyell Mine (Cu) in Tasmania
   (Garvie et al., 1997)

9. North Dump at the Sullivan mine (Pb/Zn)
   (Lahmira et al., 2009; Dawson et al., 2009)

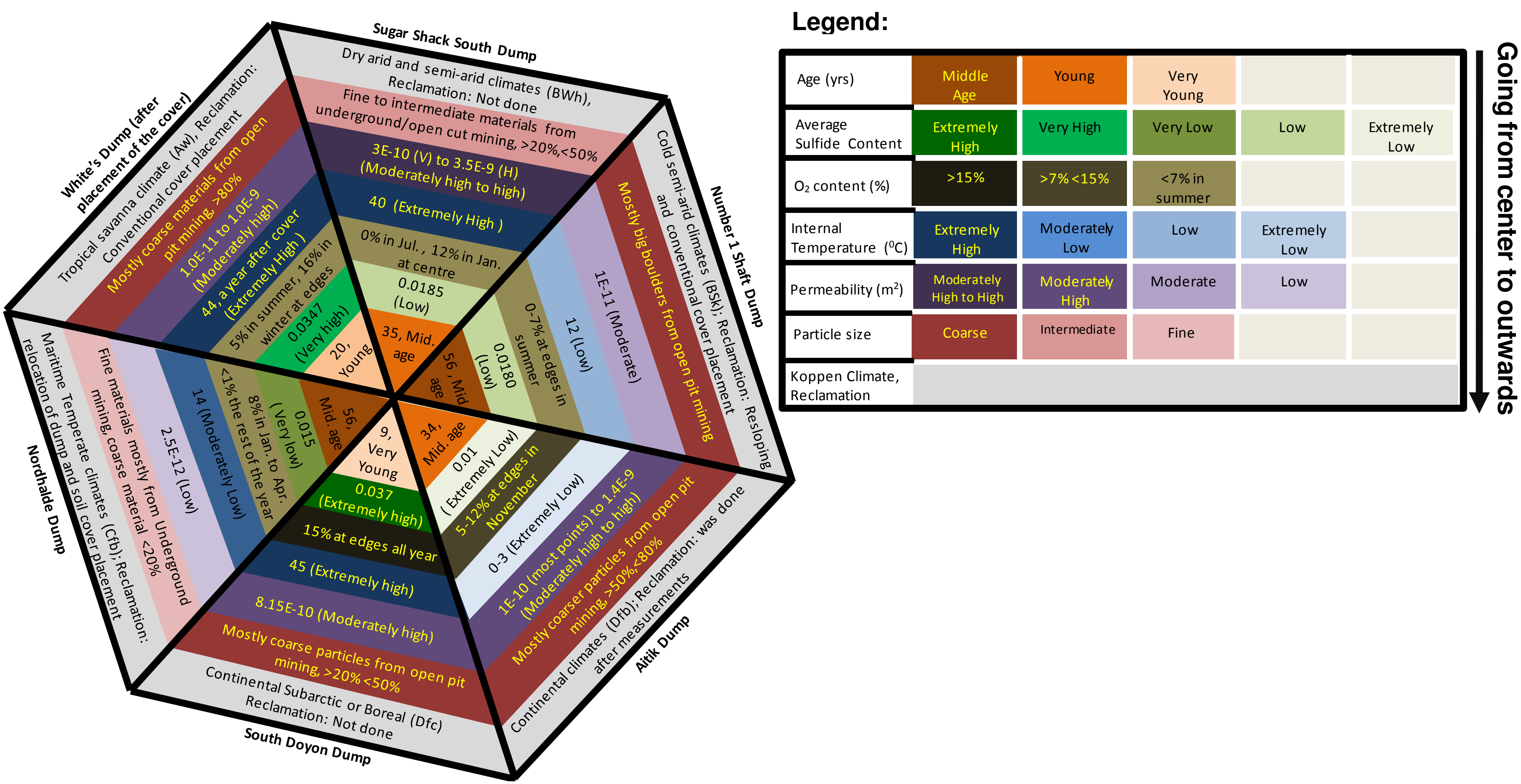

Figure 5-2. Input data for reference waste dumps (fuzzy values are given in parenthesis).

5.3.4. Transition from an Enclosed Structure to a Confined Space

Although an enclosed structure is not dangerous by itself, all such structures can become dangerous confined spaces when gas generation and emission are high. A logarithmic scale is used with linguistic fuzzy sets ranging from 10^{-4} (not a problem) to 1.0 (hazardous) to describe the risk – see Figure 5-3.

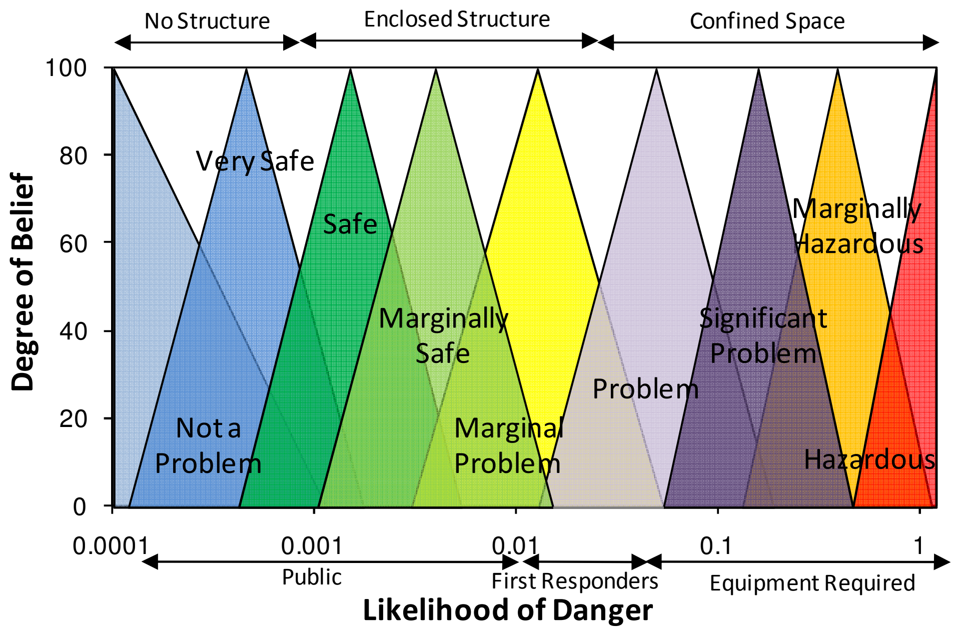

Figure 5-3. Fuzzy sets defining levels of risk for a confined space.

Transition from an enclosed structure to a confined space depends on the assessed risk. Different types of people respond differently to different risks, meaning that a space called Marginal Problem by AFRA may be hazardous to the public, but not to a First Responder whose job involves taking on risk – the very nature of their job must accept a higher level of risk. It is a subjective decision to define a linguistic threshold of acceptable risk for each type of person so a threshold level is requested of each User. Figure 5-3 shows the default setting of the linguistic risk threshold for entry of the public (Marginally Safe); for a paramedic (Problem); while spaces with higher risk (Significant Problem or greater) should be entered only when wearing an appropriate respirator. Gasses generated within a dump are not hazardous unless they are emitted from the dump and then confined within an enclosed structure – at which point the "enclosed structure" has definitely become a "confined space". When assessing atmospheric danger, i.e., the presence or absence of gas generation and gas emission, AFRA will convert an "enclosed structure" to a "confined space" or vice versa respectively. As a result, the atmospheric risk will change when elements are eliminated or added to the situation.

5.3.5. Fuzzy Rules Used Within AFRA

Atmospheric risk reaches its highest value when the possibility of human exposure in the confined space is "high". Enclosed structures at a mine site that might become confined spaces are sheds, sumps, diggings, ditches, storage room or pump house, erosion channels, etc. all of which may confine an emitted gas. A site is considered SAFE when there is no concentration of gas emitted. Although a gas emission may exist, if it is quickly dispersed or diluted with ambient air, no significant hazard is present, but the situation may be problematic. The presence of sampling holes, ditches, coarse soil or rock, segregated rock sizes, cracks or channels, a shaft or well, a pipe, fractures around pipes, drains, or other surface disturbances can alter the emission rate. A site audit and review of past events is necessary to identify pathways that develop over time.

Assessing risk using heuristic formulae (or fuzzy if-then rules) provides a smooth and logical transition from a high to a low risk (or vice-versa) for a single input (or for a combination of fuzzy inputs). AFRA links the different ranges of each variable using piece-wise linear functions to model the multi-dimensional non-linear problem space. This makes the problem easier to understand and the model can be modified quickly as required for new analyses.

A number of fuzzy if-then rules are applied to map gas generation, gas emission, gas confinement, and human presence onto the output risk. Figure 5-4 shows the rules that link the four elements of risk to the final assessed value. For example:

> If enclosed structure is "*Likely Present*" and gas generation is "*Moderate*"
> and gas emission is "*Small*" and presence of people is "*Low*"
> Then confined space risk is "*Marginal Problem*"

Expressions such as "Low" or "Small" are called fuzzy values. The rule-base was initiated based on common sense and then was modified based on information gleaned from the literature on different dumps as well as discussions with a number of available experts. The knowledge gained was used to decide on the level of risk to match each dump with unique degrees of gas generation and emission. In calculating risk, a fuzzy risk value for each element is calculated using a weight factor for each input factor. The degrees of belief (DoBs) of these elements are combined to determine the overall risk. Appendix F contains details of questions asked by the system and typical answers as well as output for each of the nine dumps.

Figure 5-4 shows the complete set of rules that control dataflow from input to final conclusion. Minor variables affect major (or intermediate) variables and their respective risk element through each rule connection. General rules were developed that govern major variables such as reactivity, gas flow, and permeability. The Degree of Belief (DoBs) of the fuzzy value of “high” is used to characterize the major elements of risk. Each variable is described by a number of fuzzy sets to characterize different ranges (i.e., low, medium, and high). Then heuristic formulas and/or weighted inferencing are applied to derive the Degrees of Belief (DoBs) of major (or intermediate) variable from the minor factors. The weighted inference method calculates the DoB of a rule conclusion by the following formula proposed by Meech and Kumar, (1992) and applied by Veiga, (1994):

$$DoB_{conclusion} = \sum_{i=1}^{n} W_i DoB_i \qquad (5\text{-}1)$$

where:

DoB_i = DoB of each factor

W_i = Importance of each factor (a value between 0.0 and 1.0)

DoB in Gas Generation: Low | Moderate | Large

DoB in the Presence of People: None | Low | High

None — Low

Risk		DoB in Gas Confinement		
		Not Present	Likely Present	Present
DoB in Gas Generation	Low	NP	NP	VS
	Moderate	NP	NP	VS
	High	VS	VS	S

None — Moderate

Risk		DoB in Gas Confinement		
		Not Present	Likely Present	Present
DoB in Gas Generation	Low	VS	S	MS
	Moderate	S	MS	MP
	High	MS	MP	P

None — Large

Risk		DoB in Gas Confinement		
		Not Present	Likely Present	Present
DoB in Gas Generation	Low	S	S	P
	Moderate	MS	P	SP
	High	P	SP	MH

Low — Low

Risk		DoB in Gas Confinement		
		Not Present	Likely Present	Present
DoB in Gas Generation	Low	NP	NP	VS
	Moderate	VS	VS	S
	High	S	S	S

Low — Moderate

Risk		DoB in Gas Confinement		
		Not Present	Likely Present	Present
DoB in Gas Generation	Low	VS	MS	MP
	Moderate	S	MP	P
	High	MP	P	SP

Low — Large

Risk		DoB in Gas Confinement		
		Not Present	Likely Present	Present
DoB in Gas Generation	Low	MS	MP	SP
	Moderate	MP	SP	MH
	High	SP	MH	H

High — Low

Risk		DoB in Gas Confinement		
		Not Present	Likely Present	Present
DoB in Gas Generation	Low	NP	VS	S
	Moderate	S	S	MS
	High	S	MS	MS

High — Moderate

Risk		DoB in Gas Confinement		
		Not Present	Likely Present	Present
DoB in Gas Generation	Low	S	S	MP
	Moderate	MP	P	SP
	High	P	SP	MH

High — Large

Risk		DoB in Gas Confinement		
		Not Present	Likely Present	Present
DoB in Gas Generation	Low	MS	P	MH
	Moderate	P	MH	H
	High	MH	H	H

Legend:
H = Hazardous , MH = Marginal Hazard, SP= Significant Problem, P = Problem, MP = Marginal Problem, MS = Marginally Safe , S= Safe ,VS= Very Safe NP = Not a Problem

Figure 5-4. Fuzzy Associated Memory Map for Confined Space Risk as a function of gas generation, gas emission, gas confinement, and exposure of humans.

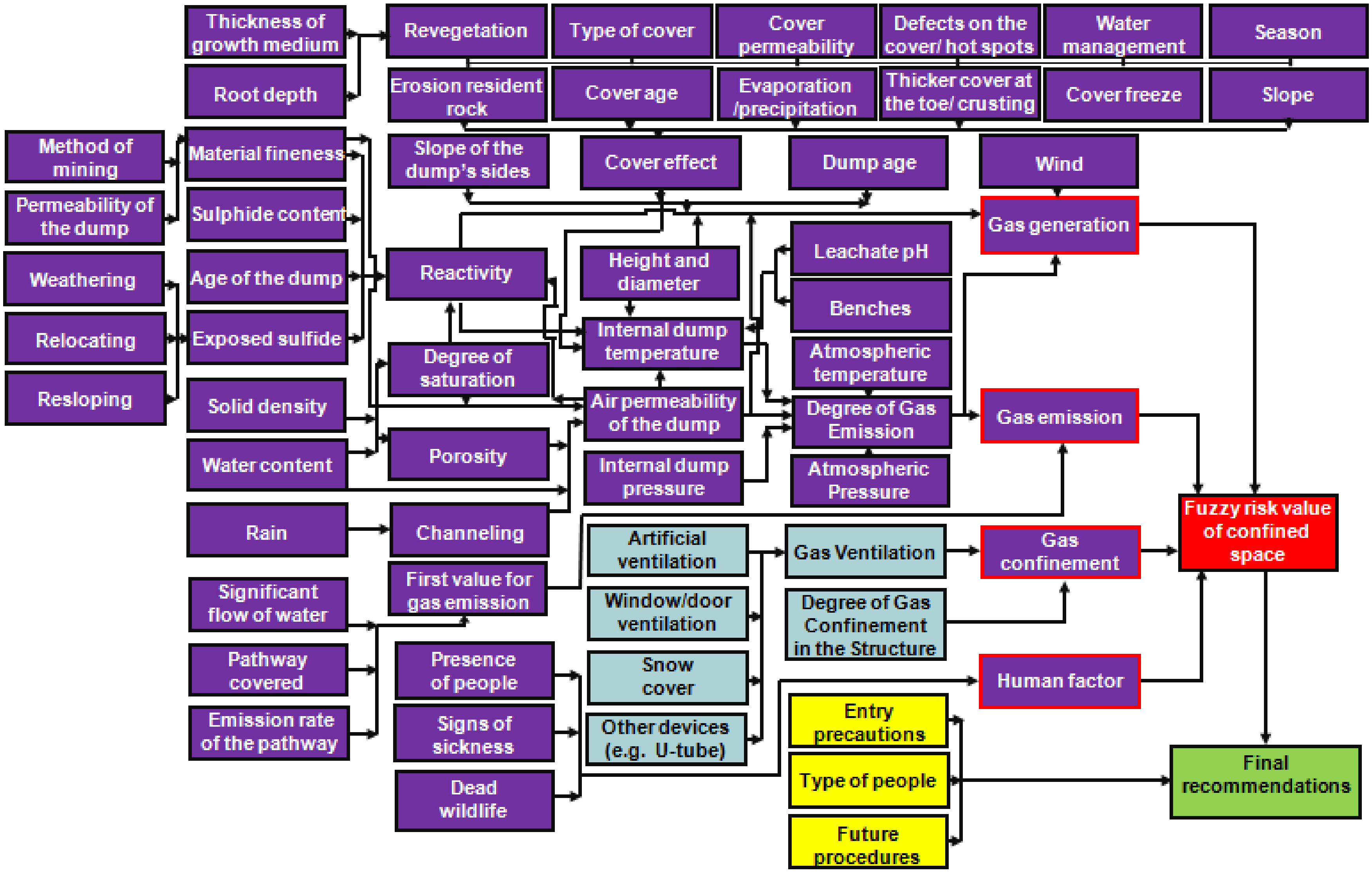

Figure 5-5. Overall Flowchart of AFRA.

The major parts of a fuzzy rule-based expert system include Fuzzification (input fuzzy set definition), Inferencing (interpreting outputs from the inputs applying the rule-base) and Deffuizification (output fuzzy set deffinitions) units (Meech, 1999). The first unit is called Fuzzification wherein membership functions which are local descriptions of input variables are assigned a Degree of Belief (DoB). A membership function gives the DoB to a description of a discrete variable using linguistic terms such as "high", "medium", and "low". In the Inference unit, a conclusion is made from input facts and fuzzy rules. Fuzzy rules are expressions of the form - IF A THEN B - where A and B are labels of fuzzy sets each characterized by a designated membership function. The premise part of each rule partitions the input space into fuzzy regions that overlap with other rule-defined regions, while the conclusion or output part describes how the system behaves in each region. In the Inferencing unit, depending on the input values, some of the fuzzy rules stored in the rule-base will fire.

After the inputs are fuzzified, the degree of belief (DoB or μ) for each part of the premise for each rule is defined on a scale from 0 to 1 (or 0 to 100). If the rule premise has more than one part (in the example in Figure 5-6, there are two parts), a fuzzy operator is applied to obtain the net degree of truth of the rule premise. The fuzzy operator for an OR conjunction is the maximum DoB in the premise parts while for an AND conjunction, the minimum DoB is chosen. In this example, the AND (minimum) conjunction is applied to calculate the net degree of truth - e.g., for the first rule this value is 20%, while for the second rule the value is 10%. The net degree of truth is then assigned to the fuzzy set of the rule conclusion to reshape it. This process is called implication. Implication is done by shortening the output (or conclusion) fuzzy set to the value of the corresponding net degree of truth of the rule premise multiplied by the variable weight. For implication, every rule has a weight (between 0.0 and 1.0). In the example in Figure 5-6, the weights for the rules have values of 1.0. The conclusion fuzzy set in this example is a Gaussian set - although often a fuzzy singleton is chosen for simplicity without any loss in accuracy.

If two or more rules with similar fuzzy set conclusions are active, the maximum DoB of these rules will be projected onto the fuzzy set in question. The output fuzzy set is the combination of conclusion fuzzy sets which are then defuzzified to a discrete value using a weighted average equation as shown in Figure 5-6. This method is not computationally intensive and produces results only slightly different from other techniques such as "area-centroid" or "mean of maximum".

If data is unavailable for a variable (such as wind velocity), fuzzy linguistic sets are chosen to show the relative velocity (on a scale from 0 to 10). These linguistic variables include heavy winds, light-but-frequent winds, and other terms in-between.

The weights of the effect of minor/major variables and the heuristic formulae used to assess each risk element are listed in Tables 5-1 through 5-6.

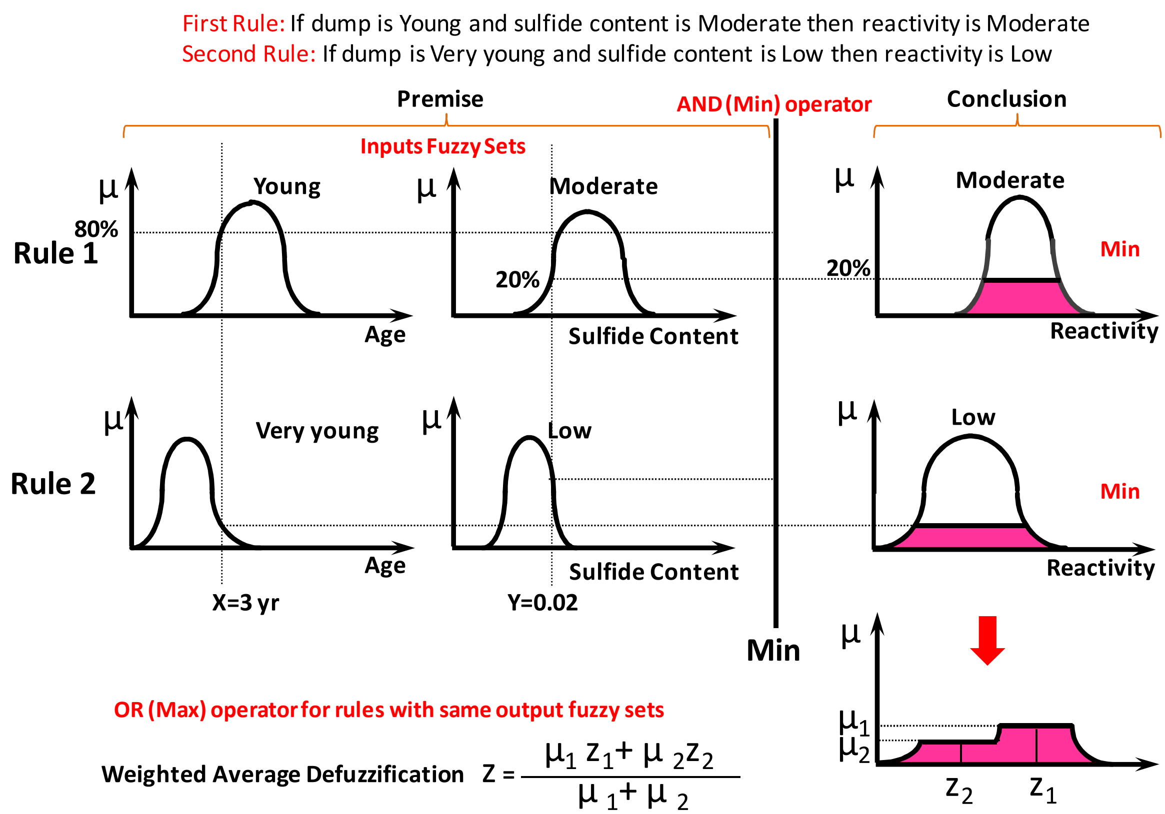

Figure 5-6. Two-rule fuzzy expert system (inferencing and defuzzification) (Grima, 2000, adapted and changed by permission).

5.3.6. Detailed Risk Assessment Architecture

In AFRA, a list of possible enclosed structures at a reclamation site is given to the User to choose one or many. Then, possible pathways that may connect the waste dump to each structure are entered by the User. Some elements of risk are specific for each structure (e.g., exposure and confinement), while other properties such as dump permeability, reactivity, internal temperature, cover properties are specific for the dump and so, are common for all structures depending on the degree of homogeneity of the dump (see Figure 5-7). A final confined space risk is determined for each enclosed structure. The output is given numerically and linguistically accompanied by recommendations and suggestions about future risk.

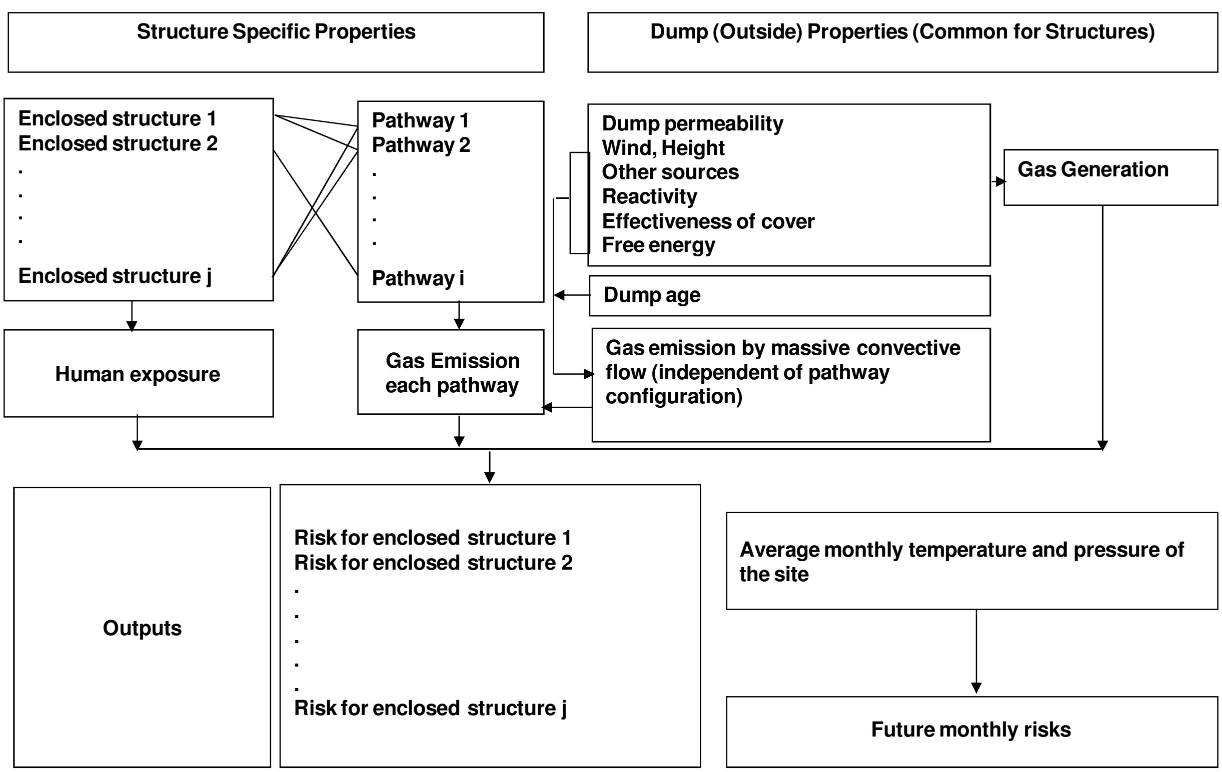

Figure 5-7. Structural architecture of AFRA.

The calculated risk is adapted to a final risk level using an adaptation factor (α) as in Equation 5-2 (Veiga, 1994):

$$Risk_{final} = 100*(Risk_{initial} / 100)^{\alpha} \quad (5\text{-}2)$$

The value of the adaptation factor depends on input parameters such as observations of dead wild life around the enclosed structure, people entering the space showing signs of sickness, or people possessing a confined space entry permit, and future plans for worker protection. The adaptation factor is applied as an exponent to the initial estimated risk value. Adaptation provides considerable elasticity to the risk prediction. As shown in Figure 5-8, the adaptation factor (α) can vary logarithmically from 100 to a value approaching 0, with 1.0 representing no adaptation. When α approaches 0, even a small initial Degree of Belief is amplified significantly. When α approaches 100, even a small amount of uncertainly will move the final Degree of Belief close to 0. In AFRA, the value of α is restricted to a range from 0.6 to 20. If the system is satisfied that future plans and site observations show that a confined space is recognized and mitigation step implemented, the risk estimate is reduced. However, should AFRA believe that recognition of the problem is unclear, the final degree of belief in a "high" risk level is elevated.

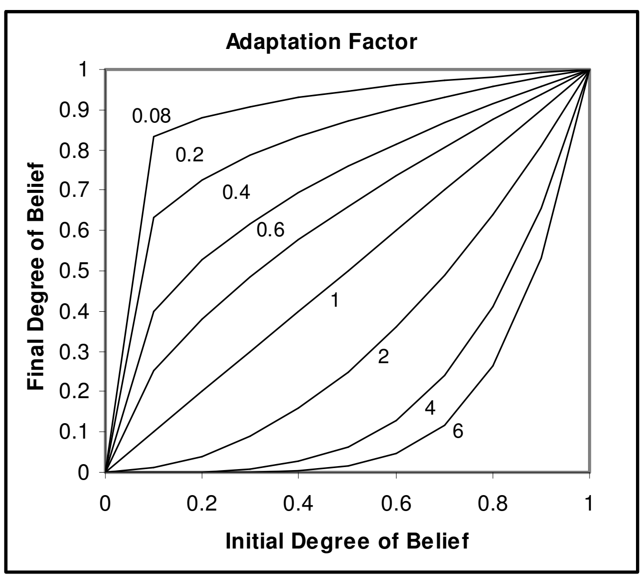

Figure 5-8. Diagram showing different adaptation factors.

The user is warned when the outside temperature lies above the internal temperature. If the outside temperature for all months of the year is not provided or available, the system can use site climate type according to Köppen’s climatic classification (Peel et al. 2007) to estimate the maximum outside temperature (climate type can also be used to verify humidity which helps to estimate changes in cover effectiveness). Given the maximum yearly outside temperature the extreme condition (highest risk) at the site is estimated. If gas emission at this extreme is "Low", there is minimal or no concern about site results for the rest of the year. The assessment results and input values are stored in an Excel spreadsheet as well as an ASCII file for future analysis or modification.

5.3.7. Gas Emission

Table 5-1 shows that the DoB in "high" gas emission depends on climatic changes (temperature and pressure) which determine the free energy difference across the dump surface, the dump configuration, the dump age, and the design of each pathway to the structure. The Δf ranges in Table 4-1 are applied to interpret the fuzzy value for gas velocity at different seasons, although additional ranges are used to choose the weight for gas velocity values to estimate the gas generation and emission DoBs (see Table 5-1).

Depending on the pathway effectiveness to transfer gas outside, a value from 0 to 100 is assigned. This term is called PathDoB(i) - where i represents each pathway. When the dump is inhaling air, danger may still arise if O_2-depleted water flows into the structure. This will deplete oxygen in the structure if the flow rate to air volume ratio is high enough and influx of fresh air is low (see Section 3.3.2) (Mohammadi and Meech, 2011). Gas emission DoB increases if sufficient effluent water runs through the pathway. The dump effluent DoB is represented by PathEffluentDoB(i). This DoB derives from flow data entered by the User from knowledge of ARD effluent samples which are generally collected monthly. The extent to which a pathway is covered will isolate water and air from the atmosphere before they reach the structure. This effect is represented by PathCoverDoB(i). Equation 5-3 combines these factors to calculate the effect of pathway properties on gas emission – the variable name is PathwayEmissDoB(i).

$$\text{PathwayEmissDoB(i)} = \text{Min}(100, (\text{PathDoB(i)} + 0.2*(\text{PathCoverDoB(i)} + \text{PathEffluentDoB(i)}))) \quad 5\text{-}3$$

As there may be more than one pathway, the Maximum of the various PathwayEmissDoBs is considered as the final value of the pathway influence on the DoB in "High" gas emission to each enclosed structure. The variable is MaxPathwayEmissDoB(j) (as in Equation 5-4), where j represents different enclosed structures at the site:

$$\text{MaxPathwayEmissDoB (j)} = \text{Max (PathwayEmissDoB (i))}, \text{ where i, j} = 0,\ldots, n \quad 5\text{-}4$$

The effect of pathway properties on gas emission together with other physical factors determines the final gas emission value. The overall gas emission to each enclosed structure (j) is determined by Equation 5-5. In Equation 5-5, "PermWeight" is the weight applied to permeability, "GasVelocityWeightforEmiss" is the weight applied to the effect of gas velocity direction, and "AgeWeightforEmiss" is the weight applied to the effect of the dump age on gas emission. The values for these weights are specified in Table 5-1.

$$\begin{aligned}\text{DoBforGasEmissionn(j)} = \text{Max}(&\ 0, \text{Min}(100, (\text{DoBperm} * \text{PermWeight} + \\ &\text{DoB GasVelocityWeightforEmiss} * \text{GasVelocityWeightforEmiss} + \text{DoBAge} * \\ &\text{AgeWeightforEmiss} + \text{MaxPathwayEmissDoB (j)} * \text{Weightfor MaxPathwayEmissDoB})))\end{aligned} \quad (5\text{-}5)$$

Table 5-1. Weights to calculate DoB in "High" gas emission at dump bottom.

Inputs	Fuzzy Values	Range	Weight
Free energy difference between outside and inside of dump (J/g)		>44	0.95
		31 to44	0.8
		25 to 38	0.7
		18 to 31	0.6
		12 to 25	0.5
		6 to18	0.4
		3 to12	0.3
		1 to 6	0.2
		-2 to 3	0.18
		2 to -3	0.1
		-1 to -6	0.05
		-3 to -12	-0.1
		-6 to -18	-0.2
		-12 to -25	-0.3
		-18 to -31	-0.5
		-25 to -37	-0.8
		<-37	-1
DoB for Each Range of Permeability at Edges at the Bottom (m^2)	Very Low	1E-13 to 1E-12	-0.2
	Low	1E-13 to 1E-11	-0.1
	Moderate	1E-12 to 1E-10	0
	Moderately high	1E-11 to 1E-9	0.1
	High	1E-10 to 1E-8	0.2
	Very High	1E-9 to 1E-8	0.25
	Undetermined	DoB in Table 5-2	0.25
Age		<2 yrs	-0.8
		>2yrs	0.01
Maxpathway (%)		>70	0.2
		<70 >50	0.1
		<50 >20	-0.3
		<20	-0.8
DoB for Gas Emission at the Bottom of the Dump	Min ((DoB Free energy difference * W Free energy difference + …+ MaxPathway * W MaxPathway), 100)		

5.3.8. Permeability

The gas permeability of a waste dump is a difficult parameter to measure and/or estimate, yet it is fundamental in establishing the degree to which gas and air flows through the dump surface. Waste dumps generally consist of coarser material and large boulders with a range of permeability from as high as 10^{-9} to as low as 10^{-12} m^2 (Ritchie, 1994), on the other hand, tailings dams consist of very fine material and have a lower permeability (10^{-11} to 10^{-13} m^2). Permeability also varies across the dump surface, so measurements must be taken at various points to ensure a good average value is recorded. When a dump is covered with soils, clays, or glacial till, the objective is to create a less permeable surface to minimize air and water infiltration. Table 5-2 lists the factors considered important in estimating the DoB of "High" dump permeability.

Table 5-2. Weights to calculate DoB in "High" permeability

Factor	Fuzzy Value	Range	Weight
Method of dumping	End dumping		0.3
	Truck dumping		0.2
	Push dumping		0.2
	Use of dragline or bucket excavator		0.1
Percentage of coarse material at the base of the dump (> gravel size)	Undetermined	0%	0
	Low	0-20%	-0.5
	Moderate	20-50%	-0.2
	High	50-80%	0.10
	Very High	>80%	0.25
Water saturation	High	>0.75	-0.3
	Moderate	0.4-0.75	-0.22
	Low	0.2-0.4	-0.2
	None	0-0.2	-0.1
If saturation level is unavailable then use mass water content	High	>10%	-0.3
	Moderate	5-10%	-0.22
	Low	<5%	-0.2
	None	<2%	-0.1
Channeling	Present		0.08
Horizontal layering or prevention of high permeability channels	Present		-0.3
Dump materials from processing plant	Present		-0.08
Dump materials from blasting	Present		0.08
Opencut mining	Present		0.08
Underground mining	Present		-0.70
DoB for "High" permeability	Max(Min((DoB Method of dumping * W Method of dumping +…+ DoB Underground mining * W Underground mining, 100),0)		

Air permeability is estimated heuristically in AFRA from variables such as: method of mining and dumping; percentage of coarse material at the dump toe, water saturation (or water content), channeling, and type of dump material. The weights shown in Table 5-2 were derived during validation of the model to fit results to the six reference dumps.

5.3.9. Gas Generation (Oxygen-Depletion)

Table 5-3 indicates that the DoB in "High" gas generation depends on the cover, dump permeability, and material reactivity – all of which affect reactions that deplete O_2 from air.

At the Number One Shaft waste dump, the oxygen concentration varies from 0% at the centre of the dump to a maximum of 20.6% at its edges (Phillip et al. 2008). Figure 5-9 shows the oxygen ranges and their corresponding fuzzy values.

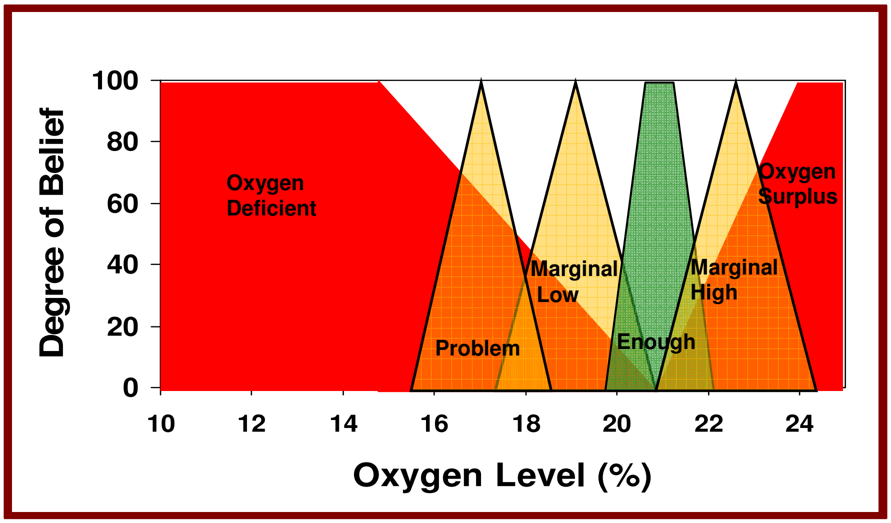

Figure 5-9. Fuzzy representation of oxygen level.

An oxygen value below 19% is unacceptable for permanent human occupancy, so it is very likely that air blowing out of an effluent pipe at dumps like this one will exhibit an oxygen level below this value. When oxygen was blowing from the pipe at Number One Shaft dump, it was below 8% all the time (Figure 3-7) – definitely "oxygen-deficient". This occurred despite the fact that many boreholes showed "Marginal Low" oxygen concentrations at the dump edges because of a higher permeability at the bottom due to end-dumping together with the wedge shape of the dump making it shallower at the edges leading to higher oxygen contents.

The weights in Table 5-3 were derived initially by common sense judgement and then modified to adapt to the expected behaviours of each of the six reference dumps. Similar to gas emission, the free energy difference between the inside and outside of the dump determined from temperature and pressure measurements also affects gas generation. In this case the effect of a negative free energy was reduced (lower weights than for gas emission) to account for a lower influx of air in winter versus the absolute value of the outflow in summer.

Other variables of importance to gas generation include permeability at the edges of the dump, reactivity of materials, cover effectiveness, dump height, the presence of wind, and other sources of gas generation such as carbonates which create CO_2. The reactivity weight trend may seem counter-intuitive showing a decline in generation as the material becomes more reactive. However, there are multiple effects of reactivity through the impact on internal temperature (free energy) as well as interactions with the presence of water and the quantity of sulfides, so this trend is designed to mute the final trend of reactivity on gas generation.

A 1.5 m deep "low permeability" cover was placed on Number One Shaft waste dump, but this did not stop convective gas flow especially at the toe where the cover may help intensify gas influx, because of topography and the effluent pipe pathway. "High" permeability dumps with a low-permeability cover are likely more hazardous regarding oxygen-deficient air. Although the fuzzy value of hazardous gas generation in some "High" permeability dumps may be "Low", when gas is blowing out through a specific pathway, the danger may be "High".

When the sulfide content is "Low" (0.015-0.02), and the waste dump has a "High" permeability, oxidation is inhibited by lack of sulphide, despite oxygen being widely available. In this situation, gas generation is "Low". If the site is located in an area of high winds, advection may be high for high elevation dumps (Wels et al., 2003) so more oxygen can enter and the oxygen level in the dump will be "Enough" to sustain oxidation in the central core.

The Number One Shaft waste dump has passed its neutralization stage, yet the CO_2 level in gas blowing out of the dump measured as high as 5% which is an additional hazard in its own right. The amount of carbonate rock in the dump varies from 0.1 to 0.7%. In some boreholes, carbon dioxide varied from 4 to 10% during August and 0 to 5% during November 2007.

Table 5-3. Factors affecting "High" gas generation (oxygen-depletion within the dump)

Inputs	Fuzzy value	Ranges	Weight
Free energy difference between outside and inside of dump (j/g)		>44	0.95
		31 to44	0.8
		25 to 38	0.7
		18 to 31	0.6
		12 to 25	0.5
		6 to18	0.4
		3 to12	0.3
		1 to 6	0.2
		-2 to 3	0.1
		2 to -3	0.08
		-1 to -6	0.05
		-3 to -12	-0.05
		-6 to -18	-0.1
		-12 to -25	-0.15
		-18 to -31	-0.2
		-25 to -37	-0.3
		<-37	-0.4
DoB for each range of permeability at edges (%)	Very Low	1E-13 to 1E-12	0.1
	Low	1E-13 to 1E-11	0.05
	Moderate	1E-12 to 1E-10	0
	Moderately high	1E-11 to 1E-9	-0.15
	High	1E-10 to 1E-8	-0.2
	Very High	1E-9 to 1E-8	-0.25
	Undetermined	DoB in Table 5-2	-0.25
Cover effectiveness (%) (DoB in Table 5-5)	Very High	80-100	0.6
	High	60-80	0.3
	Moderate	60-40	0.2
	Low	40-20	0.1
	None	0-20	0
DoB for reactivity (%) (DoB in Table 5-4)	High	>60	1
	Moderate	<40	1.4
	Low	<20	1.6
Height (m)	Short	<50 m	0
	Moderately High	50-100 m	-0.025
	High	100-400 m	-0.05
	Very High	>400 m	-0.08
DoB for each range of wind (%)	Not Windy		0
	Light Winds		-0.03
	Heavy Winds		-0.05
	Frequent Heavy Storms		-0.08
DoB other sources	DoB of other sources of hazardous gas generation in the enclosed structure		
DoB for "High" oxygen-depleted gas generation from dump (%)	Min(DoB Free energy difference * W Free energy difference + ... + DoB Wind* W Wind), 100)		
Total DoB for "High" gas generation (%)	Max(DoB other sources, DoB for "High" oxygen-depleted gas generation, 100)		

5.3.10. Dump Reactivity

Reactivity is a term that describes how rapidly oxygen is consumed from the air in a waste dump (Wels et al, 2003). Reactivity is a function of dump age, sulfide content, particle size, water saturation, and extent of weathering as listed in Table 5-4.

The difference in oxygen concentration at the slopes of a dump and its centre is due to high reactivity that causes the pore gas to become oxygen-deficient. If reactivity is low, oxygen will be brought to even deeper levels in the dump and if reactivity is not too small, the chance of heat being retained is high leading to high temperatures inside the dump (Wels et al, 2003). As the dump heats up, the influence of bacteria to sustain oxidation reactions by controlling the ratio of ferric to ferrous ions in water will dominate yielding higher temperatures with low oxygen levels in the pore gas.

Another factor affecting exposed sulfide is water infiltration which washes the surface of the rock removing reactant products. More important than infiltration, there must be at least 2% water content to meet the reaction requirement – below this level; oxidation virtually ceases (private conversation, Ward Wilson). While water is needed for oxidation, saturation is not required. When the fuzzy value of degree of saturation is "None", this has a very high weight in lowering the estimate of internal temperature. When the degree of saturation is well above the critical level of 2%, the DoB in a "high" internal temperature is unaffected - see Table 5-4.

Many of the factors affecting dump reactivity depend on the method of dump construction. For example, underground mining or dump relocation and resloping generates finer, more uniform waste rock with higher exposed sulfides which in turn leads to higher internal temperatures. Age affects the reactivity of a waste dump. Older dumps will be more reactive mainly because bacterial activity is established and the internal temperature has become elevated.

Table 5-4. Factors affecting waste rock dump reactivity.

Inputs	Fuzzy Values	Range	Weight
Sulfide content	Extremely High	>0.035	1
	Very High	>0.03 <=0.035	0.9
	High	>0.025 <=0.03	0.8
	Moderate	>0.02 <=0.025	0.7
	Low	>0.015 <=0.02	0.6
	Very Low	>0.01 <=0.015	0.2
	Extremely Low	<= 0.01	-0.2
	None	0	-0.8
Percentage of exposed sulfide (ave. particle size)	Low	<20%	-0.07
	Moderate	20-50%	0.02
	High	>50%	0.03
Water saturation (if not measured, use Water content)	None	<0.2	-1
	Low	0.2<	0.02
	Moderate	0.4<	0.02
	High	0.75<	0.03
(OR) Water content	None	<2%	-1
	Low	<5%	0.02
	Moderate	5-10%	0.02
	High	>10%	0.03
Percentage of fine grained materials	High	>20% finer than sand	0.08
	Moderate	>7 <20%	0.02
	Low	>2 <7% finer than sand	0
	Very Low	<2% finer than sand	-0.01
Weathering or Slaking	Highly weathered	> 20% is weathered to fine	0.04
	Slightly weathered	>2% is weathered to fine	0.03
	Not weathered	< 2% is weathered to fine	-0.02
Permeability	Very Low	1E-13 to 1E-12	0.3
	Low	1E-13 to 1E-11	0.25
	Moderate	1E-12 to 1E-10	0.2
	Moderately High	1E-11 to 1E-9	0.15
	High	1E-10 to 1E-8	0.1
	Very High	1E-9 to 1E-8	0.05
	Undetermined	DoB for "High" permeability inTable 5-2	0.05
Age		> 181 yrs	-0.13
		171 - 193 yrs	-0.1
		162 - 181 yrs	-0.05
		150 - 171 yrs	0.005
		137 - 162 yrs	0.04
		121 - 150 yrs	0.1
		106 - 137 yrs	0.18
		92 - 121 yrs	0.2
		78 - 106 yrs	0.18
		71 - 92 yrs	0.1
		64 -78 yrs	0.04
		57 -71 yrs	0.005
		45 - 64 yrs	-0.05
		30 - 57 yrs	-0.055
		15 - 45 yrs	-0.06
		4 -15 yrs	-0.1
		8 - 30 yrs	-0.12
		4 - 8 yrs	-0.13
		0 - 4 yrs	-0.15
If percentage of coarse and fine materials in undetermined -Underground mining			0.08
If percentage of coarse and fine materials in undetermined -Open Pit mining			-0.02
Resloping	Was done		0.04
Relocation	Was done		0.05
Mining with blasting (as it affects exposed sulfide surface) - considered if permeability is undetermined			-0.02
Waste material from processing plant - considered if permeability is undetermined			0.08
DoB for "High" reactivity	Min((DoB Sulfide content * W Sulfide content + ...+ DoB Material from processing plant * W Material from processing plant), 100)		

5.3.11. Cover Effectiveness

The factors that affect the effectiveness of the cover to reduce permeability are listed along with their weights in Table 5-5. These factors include: type of cover; thickness of the growth medium; depth of established root system; age of the cover; evaporation:precipitation ratio; cover permeability; water infiltration rate; hydraulic conductivity of the compacted layer; slope angle; various defects in the cover (crusting, hotspots, etc.); thickness at the toe; freezing in winter; water management practices; and use of erosion-resistant rock. The more effective the cover at minimizing influx of water and air, unfortunately the more dangerous may be the atmospheric hazard.

Best practice reclamation activities aim to minimize gas and water flow into the dump. Hence rehabilitation is done by covering a dump surface with clay and/or soil to reduce water infiltration; reshaping the slope to reduce erosion; and planting suitable growth material (revegetation). Temperature profiles measured within a covered waste dump shows that sealing can reduce and, in some extreme cases, stop pyrite oxidation (Harries and Ritchie, 1987). Placement of a cover is a cost-effective method to reduce dump oxidation and control ARD generation since it reduces both air and water flows.

Lundgren, (2000) studied the effect of cover on oxygen concentration within two centuries-old waste dumps in Sweden. One was covered with about 0.5 m of glacial clay compacted in 3 lifts, while the second was covered with a concrete-type layer consisting of cement slurry with coal fly ash grouted into a 0.25 m thick layer of crushed aggregate. Before covering, the oxygen concentration of air in the dump was close to 21% throughout. Time-variations were small and related mainly to shifting wind direction and the presence of snow and ice, despite intense oxidation of sulfides taking place in the dump due to its very high permeability.

After covering, the oxygen concentration in both dumps immediately dropped to low levels remaining consistently at 0.5%. Some zones of higher concentrations were still seen indicating leakage paths resulting from cover imperfections around monitoring installations. A seasonal variation was observed even in this cold climate with variations from 0 to 5%. The peak level occurs in winter even though the covers are saturated with moisture, showing that even when sealed with a "perfect" cover (i.e., cemented), convective flow is still active, although it is not enough to cause elevated oxygen content or "low" gas generation within the dump.

At the Number One Shaft waste dump, the oxygen concentration was "low" (0 to 14%) in August 2007. Covering this "high" permeability waste dump with "low" permeability material (glacial till) stopped air from entering and exiting freely by convection.

The type of cover is the most important factor affecting cover effectiveness. These include:

- store and release (or evapotranspiration) cover (highly effective if saturated)
- capillary barrier cover (must maintain near-saturation conditions)
- conventional or low hydraulic conductivity cover - clay or geosynthetic membranes
- simple soil cover (cheapest, but least effective)
- water cover (most effective, if water level > 2 m)
- concrete-like cover (very effective, but can degrade or crack)

Oxygen ingress reduces exponentially with cover thickness (Wels and O'Kane, 2003). When a proper cover is installed, air will not flow freely into the dump even if a pipe is installed at the bottom of the waste dump – while it can flow into the dump, it cannot move too far as the seal limits outflow. However such a pipe can still act as a pathway for pore gas movement out of the dump when it exhales.

Cover age is important. Aging of the cover leads to deterioration and loss in effectiveness. In mine sites subject to heavy rain fall, permeability will decrease after heavy rains retarding air inflow (private conversation, Ward Wilson). Crusting may occur in older waste dump (>70 yrs) which are more reactive, e.g., Sullivan North dump. Crusting may initially impede air flow, but as the crust cracks, enhanced infiltration may result.

High permeability waste dumps with a low-permeability cover are more hazardous regarding oxygen-deficiency since gas can flow out of the dump if it finds a pathway. The cover acts as a seal leading to oxygen-deficiency ("High" gas generation in the dump) although the internal temperature may not rise as much when there is no cover. So with the internal temperature falling below the outside temperature, convection can move the gasses out of the dump from the base. So although covers are beneficial and cost-effective for rehabilitating a waste dump by reducing the flow of air and water, a "higher" atmospheric risk arises because of "high" gas generation and emission.

Table 5-5. Factors affecting cover effectiveness to control oxygen transfer (adapted from O'Kane and Wels, 2003)

Inputs	Range	Characteristic		Thickness	Fuzzy value	Weight
Cover type	Store and release cover (evapotranspiration)	Saturated		> 2m		0.9
				2-1 m		0.8
				<1m		0.7
		Partially saturated		> 2m		0.7
				2-1 m		0.6
				<1m		0.5
		Not saturated		> 2m		0.5
				2-1 m		0.4
				<1m		0.3
	Capillary barrier cover	Completely saturated		> 2m		0.3
				1-2 m		0.2
				<1m		0.1
		Nearly saturated		>2m		1.0
				1-2 m		0.8
				<1m		0.6
		Partially saturated		>2m		0.7
				1-2 m		0.5
				<1 m		0.4
		Not saturated		> 2m		0.5
				1-2 m		0.3
				<1m		0.1
	Conventional low hydraulic conductivity cover	Active clay	saturated	> 1.5 m		1
				<1.5m		0.9
			partially saturated	> 1.5 m		0.8
				<1.5m		0.7
			not saturated	> 1.5m		0.6
				<1.5		0.5
		Stable clay	saturated	>1.5m		0.8
				<1.5 m		0.7
			partially saturated	>1.5 m		0.6
				<1.5m		0.5
			not saturated	>1.5m		0.4
				<1.5 m		0.3
		Geo-membrane-		>1.5m		0.9
				<1.5 m		0.8
	Simple soil cover					0.7
	Water cover					1
	Concrete-like cover					0.9
Root depth					Shallow	-0.08
					Intermediate	-0.05
					Deep	0.05
Thickness of growth medium					Thicker	-0.08
					Intermediate	-0.05
					Thinner	0.05
Cover age	< 6 months				Very young	0.1

Inputs	Range	Characteristic	Thickness	Fuzzy value	Weight
	6 months to 3 yrs			Young	0.06
	2 to 6 yrs			Moderately young	0.03
	4 to 8 yrs			Moderately old	-0.06
	6 to 12 yrs			Old	-0.08
	>12 yr			Very old	-0.1
Evaporation /precipitation	> 10%			-	-0.02
	> 5%			-	-0.01
	< 5%			-	0.05
Cover infiltration rate (Percentage of rainfall)	< 5%			Low	0.3
	5-10%			Moderate	-0.1
	>10%			High	-0.4
Cover permeability (m^2)	<1E-12			Low	0.3
	1E-10 to 1E-12			Moderate	-0.1
	>1E-10			High	-0.4
Hydraulic conductivity of the compacted layer (m/s)	<1E-9			Low	0.3
	1E-9 to 1E-5			Moderate	-0.1
	>1E-5			High	-0.4
Season	Wet season (or wet season has just ended)				0.08
	Dry season (or dry season has just ended)				-0.08
Slope	<20			Low	0.08
	20-40			Moderate	0.02
	>40			High	0.01
How does the user rank the effectiveness of the cover?				None	- 1
				Low	-0.2
				Moderate	0.08
				High	0.3
Crusting				Present	0.1
Defects in cover				Present	-0.08
Hotspots				Present	-0.08
Thicker cover at the toe				Present	0.08
Does the cover freeze?				Present	0.08
Water management solution, i.e. diversion channels				Present	0.08
Erosion resistant rock	Adds to the life of the cover			Present	0.08
Degree of Belief in "High" performance of cover	Max(Min((DoB cover type * W cover type +...+ DoB Thicker cover at the toe * W Thicker cover at the toe), 100),0)				

5.3.12. Internal Temperature

Since internal temperature together with atmospheric temperature is the most important factor that drives pore gas out of a dump, it is necessary that AFRA be given data on internal dump temperature. At least one internal measurement is needed, although the position (height) in the dump is important since a temperature gradient will exist. If internal temperature measurements are not currently available, AFRA can still function and provide an estimate of risk by attempting to predict the internal temperature. Factors used by AFRA to calculate the internal temperature are listed along with their weights in Table 5-6. In addition to temperature, pressure is also useful although the position (height in the dump) of temperature measurement can be used to predict the difference in pressure between the inside and outside of the dump.

The central problem is to obtain internal temperature and pressure profiles. These can only be obtained by drilling at least one borehole through the dump. If the top pressure (P_{atmT}) and bottom pressure (P_{atmB}) are available, then pressure in the dump can be estimated from the relationship P_{Dump}= Average(P_{atmT}, P_{atmB}) for periods of time in which atmospheric pressure does not change abruptly since within pressure changes reach equilibrium in about one hour.

AFRA can infer the internal temperature using other factors. These include: position in the dump where average temperature conditions are considered to exist; reactivity of dump material; permeability at the edges of the dump; dump height and height:width ratio; presence of benches; presence of fumeroles; slope of dump sidewalls; cover age and effectiveness; effluent pH; and dump age. Some of these factors increase temperature and some decrease temperature as shown in Table 5-6. The output is given as a fuzzy value varying from "extremely high" to "extremely low" with each term covering a range of about 5 ^{o}C.

The weights were adjusted to match reported measurements for the six reference dumps used to create AFRA. These validation and verification results are given in Section 5.5.

Table 5-6. Factors affecting internal temperature.

Inputs	Effect	Fuzzy Values	Ranges	Weight
Level in the dump at which the internal temperature is preferred to be estimated	Varies		>0.10 < 0.20 Height	Reactivity * 0.92
			>0.20 < 0.35 Height	Reactivity * 1.00
			>0.35 < 0.50 Height	Reactivity * 0.92
			>0.50 < 0.70 Height	Reactivity * 0.85
Location in the dump where the internal temperature is estimated	Varies	Edges		Reactivity * 1.20
		Center		Reactivity * 1.00
Reactivity (DoB from Table 5-4)	Positive		100	2
			95-100	1.25
			92-95	1.15
			90-92	1.1
			85-90	1.05
			80-85	1
			75-80	0.95
			70-75	0.9
			65-70	0.85

Inputs	Effect	Fuzzy Values	Ranges	Weight
			60-65	0.4
			50-60	0.2
			40-50	0.1
			30-40	0.05
			20-30	-0.1
			10-20	-0.2
			<10	-0.3
Permeability at edges	Positive	Very Low	1E-13 to 1E-12	-0.20
		Low	1E-13 to 1E-11	-0.10
		Moderate	1E-12 to 1E-10	0.00
		Moderately high	1E-11 to 1E-9	0.10
		High	1E-10 to 1E-8	0.20
		Very High	1E-9 to 1E-8	0.25
		Undetermined	DoB from Table 5-2	0.25
Height	Positive		<50 m	-0.05
			50-100 m	0.00
			100-400 m	0.15
			>400m	0.20
Benches	Positive	Present		0.1
		Not present		-0.1
Fumaroles	Positive	Present		0.2
Height:width ratio (h/x)	Negative	x>>h	(>7)	0.01
		h=x	about 1	0.0
		X<h	(<7)	-0.01
Dump slope	Positive	Steep	>30 ^{0}	0.10
		Moderately Steep	20-30 ^{0}	0.05
		Gentle	<20 ^{0}	0.0
Cover age (when the cover is just placed (<1 yr) the cover doesn't affect internal temperature. Effect is high when cover is young 1-5 yrs, When cover is > 7 yrs it loses effectiveness due to erosion)	Factor (A) is multiplied by the weight for cover effectiveness		<1yr	A=0.20
			1-3yr	A=2.00
			3-5yr	A=1.80
			5-7 yrs	A=1.70
			7-10 yrs	A=0.90
			>10yrs	A=0.80
Cover and crusting DoB for "High" effectiveness - Table 5-5)	Negative	None	0-20	0.000*A
		Extremely Low	20-30	0.125*A
		Very Low	30-40	0.070*A
		Low	40-50	0.050*A
		Moderate	50-60	-0.025*A
		High	60-70	-0.170*A
		Very High	70-100	-0.200*A
pH (acidic) effluent	Positive	Low	> 4	-0.10
		Moderate	3-4	0.05
		Highly acidic	2-3	0.15
		Extremely acidic	<2	0.20
DoB for internal temperature	Max(Min ((DoB Reactivity * W Reactivity + ... + DoB pH* W pH), 100),0)			
Estimation of internal temperature based on ranges of DoBs for internal temperature		Extremely High	95-100	>40 °C
		Very High	90-95	35-40 °C
		High	80-90	30-35 °C
		Moderately High	70-80	25-30 °C
		Moderate	60-70	20-25 °C
		Moderately Low	50-60	15-20 °C
		Low	30-50	10-15 °C
		Very Low	15-30	5-10 °C
		Extremely Low	<15	2-5 °C

5.3.13. Gas Confinement

An emitted gas must be trapped in one place without being vented for the hazard to be realized. Any enclosed structure existing on the dump surface or in a working place that can accumulate oxygen-depleted air can create a dangerous condition. A sump, manhole, large pipe, space with internal baffles, surface depression, tank, shed, tunnel, well house, pump house, basement, storage room, steep surface, trench, and even an erosion channel (see Figure 5-10) are all possible sites to confine and accumulate gas at a mine reclamation site.

Figure 5-10. Erosion channel at a rehabilitation site (Matsui et al., 2004, by permission).

Table 5-7. Initial degree of belief in confinement for different enclosed structures.

Structure	DoB in Confinement	Structure	DoB in Confinement
Large Pipe	100	Pump House	80
Place with Internal baffles	100	Basement	60
Depression on the ground	70	Storage Room	80
Tank	100	ARD settling pond	60
Sump	90	Room	50
Manhole	90	Steep surface	40
Shed	60	Trench	80
Tunnel	60	Erosion Channel	80
Well House	80	Depression on	80

The initial degree of belief in whether these structures confine a gas is set by default using the values in Table 5-7. Gas Confinement is also affected by artificial ventilation or other devices used for gas control such as a U-tube on the effluent flow pathway. If there is no confined structure or the structures are not large enough for a human to enter, the hazard of gas emission from the surface is estimated. Surface emissions can pose a hazard to a person bending down or lying on the ground. Gasses emitted from a waste pile are quickly dispersed or vented at the surface over a short distance under most circumstances. Wind velocity, surface topography and geometry as well as temperature inversions can play important roles in dissipating or intensifying the danger however. Other factors, such as snow covering a structure and the presence of a door or window will also affect the Gas Confinement DoB. A number of rules are used to calculate the effect of these factors on effective ventilation of a confined space. Some of these rules are as follows:

If 'Artificial ventilation' is None
and 'Window and door ventilation' is None
and 'Snow cover' is None
and 'Other devices' are None
then 'Effect of ventilation' is Very Low

If 'Artificial ventilation' is Moderately Enough
and 'Window and door ventilation' is None
and 'Snow cover' is None
and 'Other devices ' are None
then 'Effect of ventilation' is Low

If 'Artificial ventilation' is Enough
and 'Window and door ventilation' is Enough
and 'Snow cover' is Small
and 'Other devices' are None
then 'Effect of ventilation' is Very Low

If 'Artificial ventilation' is None
and 'Window and door ventilation' is Enough
and 'Snow cover' is Large
and 'Other devices' are Quite Effective
then 'Effect of ventilation' is High

If 'Artificial ventilation' is Moderately Enough
and 'Window and door ventilation' is Enough
and 'Snow cover' is Large
and 'Other devices ' are None
then 'Effect of ventilation' is Moderate

If 'Artificial ventilation' is Enough
and 'Window and door ventilation' is Enough
and 'Snow cover' is Large
and 'Other devices' are Quite Effective
then 'Effect of ventilation' is Very High

These rules together with others are combined to formulate an "alpha" factor similar to that shown in Equation 5-2 to adjust the initial DoB in Confinement.

5.3.14. Human Exposure

People can be exposed to the atmosphere inside an enclosed structure either by entering the structure, or by extending their head into the structure, or by bending down or lying or falling on the ground. If a structure (j) is large enough for a human to enter, then the Degree of Belief in Human Exposure is calculated using Equation 5-7. If the structure is not large enough to enter, then the DoB of Human Exposure is only due to head exposure:

DoB HumanExpose(j) = Max(DoB exposure by entering (j), DoB exposure by entering in the future (j), DoB head exposure (j), 0) 5-7

5.4. Simplified Representation of the Rules in AFRA

The following examples show pertinent output from AFRA; however, there are many additional sub-factors and rules that affect the risk estimate. All rules are active at all times in an analysis, albeit to different degrees. In these examples, permeability is assumed high enough (>1E-10 m^2) to allow air or gas to flow freely in and out of the dump.

1. High reactivity (average age, high sulfide content, “no cover” or “ineffective cover” (age (>5 yrs) or eroded cover, high fine particles)
   → High internal temperature and higher internal temperature than outside
   → Air flows in at the bottom edges while pore gas rises from the centre to the top of the dump (gas emission is low)
   → Oxygen content inside the dump is moderate because of a balance between high reactivity and gas inflow
   → A buried pathway connects the atmosphere in the dump to a shed
   → The shed has no open window and artificial ventilation
   → Shed is in use by people
   → **Risk is low (e.g. A Problem)** at this time as O_2-depleted gas does not find a pathway to flow from the dump to the shed.

2. High sulfide content
   → High reactivity
   → High internal temperature and lower internal temperature than outside
   → Gas sinks from top to centre and flows out of bottom edges (gas emission is high)
   → Oxygen content in dump is very low because of high reactivity and gas outflow

→ A buried pathway connects the atmosphere in the dump to a shed
→ The shed has no open window or artificial ventilation
→ Shed is in use by people
→ **Risk is very high (e.g. Hazardous)** as highly O_2-depleted gas blows into an unventilated confined space.

3. Young age (>2 >50 years) or Old age (>160 years), low sulfide content, effective cover (young age: 1-3 yrs) and few fine particles
   → Low reactivity
   → Low internal temperature and lower internal temperature than outside
   → Gas sinks from top to centre and flows out bottom edges, negative gas velocity (gas emission is high)
   → Oxygen content in dump is moderately low because of balance between low reactivity that consumes less O_2 and low gas inflow because of effective cover
   → A buried pathway connects the atmosphere in the dump to a shed
   → The shed has no open window or artificial ventilation
   → Shed is in use by people
   → **Risk is high (e.g. Marginally Hazardous)** since O_2-depleted gas is blowing into an unventilated confined space.

4. Low sulfide content → Low reactivity
   → Low internal temperature, but higher internal temperature than outside
   → Gas rises to top from centre and air flows into dump bottom (gas emission is low)
   → Oxygen content in dump is moderately high because of low reactivity of dump material and higher air inflow
   → A buried pathway connects the atmosphere in the dump to a shed
   → The shed has no open window or artificial ventilation
   → Shed is in use by people
   → **Risk is very low (e.g. Marginal Problem)** at this time since O_2-depleted gas is not blowing into an unventilated confined space and oxygen-depleted gas generation is not high.

5.5. Validation and Verification of the AFRA Model

Comparisons of the estimated internal temperature range with actual measurements for each of the reference and test dumps are shown in Table 5-8. In each case the measured value falls within the range predicted by AFRA which shows that the system is able to estimate internal temperature of the nine waste dumps with considerable accuracy.

To compare the effects of gas generation and gas emission on risk at each of the dumps, the two other elements (gas confinement and human exposure) were each considered high at 100%. So it is assumed that an ARD collection sump exists at the bottom of each dump connected to the pore gas in the dump through a buried pipe and an underground drain. Table F-1 in Appendix F shows the answers to question related to the enclosed structure (sump in this case), while Table F-2 demonstrates the answer to the questions related to properties of the pathway (pipe in this case).

Table 5-8. Estimated and measured internal temperatures in reference and test dumps.

Dump	Internal Temperature (°C)[1]	
	Estimated by AFRA	Measured
Nordhalde	10-15	14
Doyon	>40	45
Sugar Shack South	>40	40
Aitik Mine	2-6	0-3
White's Dump	>40	44 (one year after cover)
Sullivan No. 1 Shaft	10-15	12 (two years after cover)
Equity Silver Main	>40	52 (four years after cover)
West Lyell	35-40	38
Sullivan North	30-35	33 (eight years after cover)

[1] For details see Table F-10 in Appendix F.

Table 5-9 is a summary of the key findings predicted for each of the reference and test dumps used to build AFRA. Four of the dumps (Doyon, Sugar Shack South, Aitik, and West Lyell) either have no cover in place or the cover is old and judged completely ineffective. Dump reactivity is judged to be 100% high for Doyon, White's Dump, and Sullivan North with the Number One Shaft dump having 78% belief in high.

Gas generation is fully certain for the Nordhalde dump and for Number One Shaft dump. Both of these dumps show predicted gas velocities that are negative as does the Aitik dump. Although White's dump shows 100% gas generation belief, its emission belief is only 27%. The combination of these factors leads to risk values that are at least "A Problem" in all of the dumps. Number One Shaft dump and Nordhalde dump are judged to be "Hazardous" while Aitik, White's and North dumps are each a "Significant Problem".

Table 5-9. Summary of reference and test dump assessment assuming 100% confinement and 100% human exposure.

Dump	Cover effectiveness[1]	Dump reactivity[2]	Gas velocity[3]	Gas generation[4]	Gas emission[5]	Risk Value	Linguistic Risk Term
Nordhalde	74	48	Negative Small	100	63	0.53	Marginally Hazardous
Nordhalde (winter)	74	48	Positive Big	49	18	0.16	Problem
Doyon	0	100	Positive Big	31	15	0.15	Problem
Sugar Shack South	0	78	Positive Big	23	18	0.15	Problem
Aitik Mine	0	19	Negative Big	75	86	0.47	Significant Problem
White's Dump	100	100	Positive Very Small	100	27	0.33	Significant Problem
Sullivan No. 1 Shaft	89	78	Negative Very Big	100	100	0.90	Hazardous
Sullivan No1. Shaft (May)	89	76	Negative Big	100	73	0.60	Marginally Hazardous
Equity Silver Main	100	70	Positive Big	64	18	0.16	Problem
West Lyell	0	83	Positive Big	36	18	0.16	Problem
Sullivan North	100	100	Positive Very Small	100	24	0.31	Significant Problem

[1] For details see Table F-4 in Appendix F
[2] For details see Table F-5 in Appendix F
[3] Assuming a pipe and sampling shed exist – for details see Table F-6
[4] For details see Table F-7 in Appendix F
[5] For details see Table F-8 in Appendix F

The estimates of gas velocity direction during the warmest time of the summer for Number One Shaft dump and North dump at Sullivan mine show results comparable to the measurements. At Number One Shaft dump, when the outside temperature is 32°C, the gas velocity is about -1 m/s). This agrees with AFRA's estimation of gas velocity of "Negative Very Big" for an outside air temperature of 32°C. According to Dawson et al., (2009), monitoring of the North dump seepage collection system has not shown any significant oxygen-depletion or carbon dioxide-elevated gas emission in comparison to the Number One Shaft dump. This agrees with AFRA's estimation of a gas velocity at the North dump of "Positive Very Small" for an outside temperature of 32^{o}C.

There are no gas velocity measurements for any of the waste dumps in the literature and therefore it was not possible to compare gas velocity direction with real data for the remaining dumps. However by comparing AFRA's risk assessment results with oxygen content measurements at these dumps, a useful verification of the magnitude of the estimated gas generation can be made. A comparison of seasonal changes in oxygen content can be used to infer if gas or air is flowing into or out of the dump respectively. Such a comparison reported by Smolensky et al., (1999) allows conclusions about the direction of convective gas/air flow in the Nordhalde dump. According to Smolensky et al., (1999), during the late autumn and early winter the oxygen profile in Nordhalde dump shows an increase in oxygen content, for a borehole near the edges of the dump. At this dump, AFRA estimated a gas velocity value at the bottom of the dump of "Positive Big" during the winter resulting in a gas emission belief of only 18%. During the summer, the gas velocity was estimated as "Negative Small", resulting in a gas emission belief of 63%. These results are in accord with oxygen levels in summer (0%) and winter (8%) in this dump (Smolensky et al., 1999).

The results presented in Table 5-10 represent three possible scenarios for each of the reference and test dumps. The worst case scenario for all dumps involves the presence of a sampling shed connected through a buried pipe to an underground drain (similar to the situation in May 2006 at the Sullivan Mine Number One Shaft waste dump). Note that all the dumps are at least problematic should a sampling shed and pipe pathway be installed. The Nordhalde dump is "Marginally Hazardous" with the Aitik Mine dump, White's dump at Rum Jungle, and Sullivan North each classified as a "Significant Problem". As would be expected, the Sullivan Number One Shaft dump is classified as "Hazardous" with almost full certainty.

Table 5-10. Atmospheric Risk of reference and test dumps for different scenarios.

Dump	Risk with 100% confinement and 100% human exposure	Risk with 100% confinement and 0% human exposure	Risk with 0% confinement And 0% exposure and no pathway
	Worst Case	**Moderate Case**	**Best Case**
Nordhalde	0.53 (Marginal Hazard)	0.21 (Significant Problem)	0.02 (Marginal Problem)
Doyon	0.15 (Problem)	0.06 (Marginal Problem)	0.0002 (No Problem)
Sugar Shack South	0.15 (Problem)	0.07 (Marginal Problem)	0.00019 (No Problem)
Aitik Mine	0.47 (Significant Problem)	0.21 (Significant Problem)	0.019 (Marginally Safe)
White's Dump	0.33 (Significant Problem)	0.11 (Problem)	0.009 (Marginally Safe)
Sullivan No. 1 Shaft	0.90 (Hazardous)	0.50 (Marginally Hazardous)	0.05 (Marginal Problem)
Equity Silver Main	0.16 (Problem)	0.06 (Marginal Problem)	0.008 (Safe)
West Lyell	0.16 (Problem)	0.08 (Marginal Problem)	0.00018 (No Problem)
Sullivan North	0.32 (Significant Problem)	0.13 (Problem)	0.012 (Marginally Safe)

The Moderate Case reflects continued use of the confined space as a sampling shed although proper confined space procedures are now in place and the shed can only be entered by someone wearing proper SCBA equipment with a person watching from outside the shed. The Number One Shaft waste dump is still considered hazardous, although the Nordhalde dump is now reduced to a Significant Problem.

The Best Case scenario is where there is no enclosed structure connected to the dump, humans are not exposed to a possible hazard, and the pathway has been eliminated. In this situation, four of the dumps are now rated as No Problem, and three are Marginally Safe, while the Number One Shaft waste dump has been reduced to a Marginal Problem.

In fact, this is what has taken place at the Sullivan Number One Shaft waste dump. The shed has been removed and a U-tube has been built to prevent emission of gas through the pipeline. The reason the site is still considered a Marginal Problem by AFRA relates to the fact that an accident did indeed occur at this site.

The results show that complete elimination of Emission and/or Confinement elements can switch a potentially dangerous problem into a potentially safe one.

5.6. Risk Assessment under Different Climate Conditions

It is important to examine the sensitivity of the risk assessment process to changes in climate conditions. The question asked is: how would the Number One Shaft waste dump behave if it was located in a different part of the world? Four scenarios have been examined using Köppen's climatic classification system (Peel et al., 2007):

1. AF - tropical wet with no dry season
2. Bwh - Subtropical desert, low latitude
3. Cfc -Marine west coast, mild with no dry season, cool humid summer
4. Dfd - Subarctic - severe winter, no dry season, cool summer

Table 5-11 shows the estimated risk under different climate conditions during the summer for entering a sump at the toe of the Sullivan Mine Number One Shaft waste dump in 2006, which is connected to the dump by a buried pipe and is in use by workers. In this assessment it is assumed that no internal temperature measurements are available and the evaporation to precipitation ratio and water saturation values of the cover are Undetermined. As can be seen, for an arid, hot climate (Arizona) and a very wet, hot climate (Brazil) the risk is assessed as "Hazardous". Without measurements, the temperate climate conditions generate a "Marginally Hazardous" risk. For the very cold, sub-arctic-like climate (Yukon), the risk of this situation is only a "Significant Problem".

Table 5-11. Estimated risk for different climates during the summer with no internal temperature measurement for entering an enclosed structure similar to that at the toe of Sullivan Mine Number One Shaft waste dump in 2006, which is connected to a dump by a buried pipe and in use by Workers.

Climate Type	Atmospheric Temperature in Summer (ºC)	Gas Generation DoB	Gas Emission DoB	High Reactivity DoB	Estimated Internal Temperature (ºC)	Cover Effectiveness	Direction of Gas Velocity	Risk
Very wet and hot: AF – Tropical wet climate with no dry season (i.e., Brazil)	31	100%	100%	76%	10-15	100%	Negative Very Big	0.896 – Hazardous
Very dry and very hot: Bwh – Subtropical desert, low latitude desert (i.e., Mexico, Arizona)	40	100%	100%	76%	15-20 [a]	90 % [b]	Negative Very Big	0.896 – Hazardous
Temperate, moderately wet: Cfc – Marine west coast –mild with no dry season, cool humid summer (i.e. Norway)	22	100%	79%	76%	10-15	100%	Negative Big	0.641 – Marginally Hazardous
Very cold and wet: Dfd – Subarctic – severe winter, no dry season, cool summer	8	100%	25%	76%	10-15	100%	Positive Very Small [c]	0.316 – Significant Problem

[a] Increase in internal temperature is due to reduced cover effectiveness

[b] Lower cover effectiveness due to lower saturation in a dry climate

[c] Despite the fact that the gas velocity is Positive Very Small, the hazard is still considered a Significant Problem to ensure a conservative approach.

5.7. Cyclic Behaviour of a Reactive Waste Dump

No atmospheric accident similar to that which occurred at the Sullivan Mine reclamation site has ever occurred anywhere else in the world. As such, the results of this project cannot be compared directly with another study since atmospheric investigations of waste dump behaviour is a relatively young field of research. Further studies of other waste dumps need to be conducted to provide more evidence about atmospheric risk. The industry appears to have been fortunate not to have seen a similar incident at another dump site. The following analysis describes our belief as to why other waste dumps have not shown an atmospheric hazard in the past. The reason may lie in the fact that there are several cyclic behaviours exhibited by a waste dump with respect to oxygen-depleted air being blown out the bottom of the dump into an associated confined space. These include:

1. Diurnal: Safe at night / Dangerous in day time

Each day as the temperature cycles from hot in the daytime to cool at night, the dump may transition from blowing to sucking - this will occur if the maximum internal dump temperature lies between the daytime maximum and night time minimum temperature;

2. Seasonal: Safe in winter / Dangerous in summer

In the summer, the minimum night time temperature may lie above that of the maximum internal dump temperature - in this case the dump will blow toxic gas throughout the entire day. On the other hand, during the winter, the maximum day time temperature may lie below the maximum internal dump temperature - in this case the dump will suck in air at the bottom throughout the entire day.

3. Decadal: Safe(r) when the maximum internal temperature has reached its maximum value / Dangerous when it is transitioning either up to or down from this value.

Initially, there is a low reaction rate of sulfides with oxygen so the pore gas is not depleted of oxygen and high convective flow is not yet established. But as the dump temperature rises due to internal heat generation from the oxidation reactions, more air is sucked in through convection and the rate of reaction intensifies (especially as sulfiferous and ferriferous bacteria begin to accelerate the surface reactions) – the pore gas becomes depleted of oxygen and dangerous. As years pass, the maximum internal dump temperature continues to rise, perhaps climbing to a level above the maximum diurnal temperature in the summer. When this occurs, the dump will suck in air at the bottom all the time and no danger will exist in a confined space connected to the bottom of the dump. As the mineral surfaces continue to oxidize, eventually the sulfides approach the point of depletion and the maximum internal dump temperature will begin to fall. As it passes below the maximum diurnal temperature in summer, the dump will begin to exhale toxic gas at the bottom of the dump once again thus recreating the hazard. Eventually the reactions will stop altogether and the pore gas will no longer be depleted of oxygen, hence the danger is now gone forever. Exactly when each of these transitions occur is difficult to predict with any degree of accuracy, but it will depend on the sulfide content, the reactivity of the sulfides, the dump permeability, the flow of water through the dump, and atmospheric conditions that include temperature and pressure changes, among many other variables. Depending on the outside and internal temperatures, the danger can be conceptualized as follows (estimated for the Number One Shaft Waste Dump based on historical information):

0 - 10 years	Initial period with rising danger
10 - 60 years	Maximum danger - extremely hazardous
60 - 80 years	Declining danger - transitioning from hazardous to a problem
80 - 150 years	Constant reduced danger - internal temp > max. outside temp
150 - 170 years	Rapid increase in risk - internal temp falls below max. outside temp
170 - 180 years	Maximum danger returns - extremely hazardous
180 - 190 years	Declining danger - transition from hazardous to safe (pore gas O_2 levels rise)
190 - onward	Site is safe - no oxygen-depleted gasses are generated or emitted

Recognize that the temporal boundaries between these projected risk levels are fuzzy concepts which vary significantly by changes in the site setting and waste dump properties.

Currently many of the dumps that have been reviewed in this thesis appear to be at the stage of reduced danger due to their extremely high internal temperatures and so; most of these dumps do not show an atmospheric risk. Of course, this stage is followed by rapid increase in atmospheric risk if confinement and exposure exists. Dumps with high sulfide content may reach this stage as early as 20 years old.

Figure 5-11 shows the idealized risk and internal temperature over time for low, typical, and highly reactive waste dumps. In this assessment, the internal temperature changes as the dump ages. The maximum outside temperature is assumed to be 32 °C each year to ensure the evaluation detects the maximum likelihood of risk in that year (although warmer conditions could prove more hazardous). Figure 5-11 (c), presents a conceptual graph of the decadal variations in maximum internal temperature and the corresponding risk for Number One Shaft dump. In this assessment, the internal temperature was estimated by varying the age of the dump and considering all the real dump properties as given in Appendix F and has been presented idealasticly. The Number One Shaft waste dump was about 66 years old when the accident took place in 2006, although this is really an estimate since the dump is very heterogeneous and was in use off and on over its life to closure; reaction rates may not have varied uniformly over the years as AFRA assumes. The maximum internal temperature was about 16 °C in 2010 and from measurements taken between 2006 and 2010; this appears to be increasing at the rate of about 1.5 to 2 °C per year. If this rate of increase continues, by 2030 the maximum internal dump temperature will probably reach about 36 °C, and remain at this steady state value for about 60 years (perhaps longer). In 2090, the reaction rate will begin to decline as the sulfides become depleted. The internal temperature is estimated to then begin dropping by about 3 °C per year until a final equilibrium temperature of 10 °C is reached at which point all atmospheric danger at the site may be gone. This might occur around 2140 or so.

In the early years (<5 yrs) the risk is a "Marginal Problem". At this stage, although gas generation is "None", the DoB in a "Low" gas emission is 81%. Gas emission is not "None" since it is assumed the dump is connected through a buried ARD collection pipe to an enclosed structure at the bottom of the dump in which water flow is significant. If gas generation and emission were both "None" instead of one being "Low", the risk level would be "Very Safe". Here, a "Low" gas emission in combination with "High" values for confinement and human exposure gives a risk value much higher than "Very Safe". If the confined structure did not exist (which would yield "No" concentration and exposure) the risk would be "Not a Problem".

Between 5 to 50 years of age, oxidation increases and the pore gas oxygen level declines to a very low value. The internal temperature increases and convective air flow is established with internal temperatures below the outside temperature. As such, risk increases to "Hazardous".

Between 50 to 80 years, the internal temperature continues rising until it exceeds the maximum reported outside temperature of 32 °C causing the risk to decline to a "Significant Problem". From 80 to 150 years the internal temperature reaches its maximum (about 32 °C) and flow reversal occurs year round – at this point, the risk is judged to be "A Problem". At 150 to 170 years, the internal temperature begins to drop due to a decrease in dump reactivity as the sulfides become depleted causing the risk to increase to "Hazardous" once again. From 170 to 190 yrs the danger starts to decline as the sulfides become depleted. At a very old age (>200 yrs) the sulfides in the dump are completely depleted and so, the pore gas is no longer oxygen-depleted, i.e., "No" toxic gas is generated. Although the internal temperature is lower than the maximum atmospheric temperature which may continue to induce air emission from the toe, the risk is a "Marginal Problem" since the pore gas oxygen level will have increased to that of normal air. It must also be understood that spatial differences in these transitions may occur at different times due to dump heterogeneities.

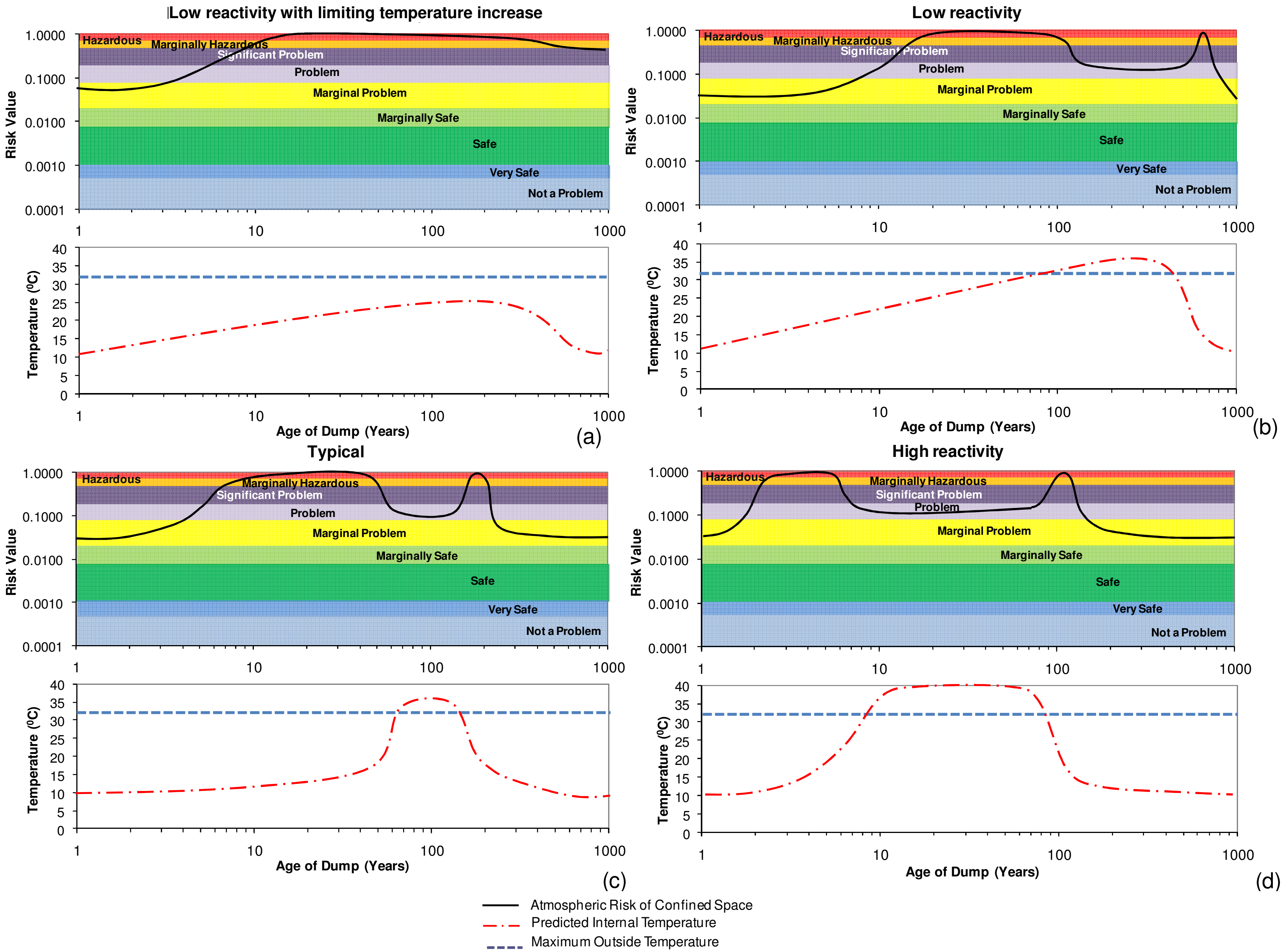

Figure 5-11. Idealized risk and internal dump temperature over time for various reactivities. It is assumed that heat is retained to an extent sufficient to eventually reach an internal temperature above the maximum outside temperature except for (a) which represents the case of a slow rate of temperature increase to a level below the maximum outside temperature.

Figure 5-11 (a) represents the risk for a dump with a low reactivity along with a limited temperature increase due to other factors such as a more effective cover and geometrical properties of the dump (e.g., gentle slopes and shorter height). In this dump, it may take longer (about 200 years) for the internal temperature to reach its maximum value of 25 °C. If the reactivity of the dump is low but has a faster internal temperature increase, due to a lack of cover, then in the same amount of time, the internal temperature may increase to around 35 °C see Figure 5-11 (b). In a dump with a much higher reactivity, the internal temperature may reach its highest value speedily (about 10 years or less) - Figure 5-11 (d).

The yearly trend of the internal temperature can help in future risk analysis. A cooling dump initially becomes more hazardous while a heating one will eventually become safe for some considerable time. For the reference dumps this information is in Table F-6 in Appendix F.

A sensitivity analysis was done for Number One Shaft waste dump to show how the confined space risk value varies when the values for gas emission, gas generation, gas confinement and human exposure change from "Low" to "High" - the results are presented in Figure 5-12. Gas emission changes were studied by considering three different sets of internal temperatures. Gas generation, gas confinement, and human exposure have been tested at three levels [0% (Low) 50% (Moderate) and 98% (High)]. The outside temperature is assumed to be at the highest measurement reported for Kimberley B.C (about 32 °C). In this table, gas emission varies for different internal temperatures: for T = 12 °C, Emission belief = 100%, for T = 30 °C, Emission belief = 51%, while for T = 38 °C, Emission belief = 18 %. The results show that as the values of the four elements of risk vary from "Low" to "High", the level of risk changes smoothly from "Not a Problem" to "Hazardous".

After discovering the existence of a risk, management measures should be implemented. These measures are learned from regulations, through other effective methods, or because of past accidents. The best practices may be passive or active ventilation or a confined space entry procedure suggested for the site. The lowest level of risk management is simply placing warning information at the site.

The first step in managing risk is to ensure that any person who enters a dangerous confined space is aware of the possible problem and has the proper authority and equipment to survive should that problem actually exist - i.e., HUMAN EXPOSURE The second step in eliminating RISK is to eliminate the danger. In the case of a confined space this can be done in a number of ways. The space itself can be removed - i.e., CONCENTRATION; its connection to the source of the toxicity can be removed - i.e., PATHWAY. The ability of the toxic gas to enter a pathway can be eliminated - i.e., EMISSION. And finally, the source of the toxic gas can be eliminated - i.e., GENERATION. Any of these actions will eliminate the RISK of death. However, step 1 which ensures awareness and preparedness does not preclude a misunderstanding or a failure on the part of a person to follow proper procedures, so even if properly done, the possibility of death still exists to a certain degree. With step 2, each of the individual actions may not be completely possible. For example: - removing the confined space may not be practical if it serves a proper function - i.e., sampling ARD; the connection demands a pipeline for the ARD to flow, but it can be designed to avoid the collection of a toxic gas in the structure (use of a U-tube or venting pipe); controlling emission and generation involve complex issues related to the properties of the dump, its cover, and the associated environment. Achieving success with actions aimed at these elements is unlikely.

Once the RISK of an identified confined space at a reclamation site has been eliminated or minimized the analysis must move to possible emission and concentration of the toxic gas in an ***unrecognized*** confined space. This might include a surface depression, an erosion channel, a bore hole, a small excavation or trench, or one of many other types of pathways. The summer is more dangerous at the toe of the dump while in winter, emissions can occur on the upper walls or top surface of the dump. A further unrecognized state might take place at some point in the future, decades from the present time in which a house or structure is erected on the dump with a basement or cellar or well-head because the memory or knowledge about the hazard has been forgotten or mislaid. It is for this latter reason that a regular atmospheric risk assessment must be done whenever a change in the environment or design of the site has taken place. Surface erosion or fallen trees or uprooted shrubs may create a new confined space situation that should be evaluated.

The residual risk after implementing these changes should be assessed. After the design process, performance evaluations should be done to understand if the redesigned system meets the requirements to reduce or eliminate the risk.

DoB in the Presence of People	DoB in Gas Generation	Risk: Internal Temp.	DoB in Gas Confinement L (0%)	M (50%)	H (98%)
Low (0%)	Low (0%)	12	0.001	0.027	0.072
		30	0.0005	0.015	0.023
		38	0.0003	0.008	0.012
	Moderate (50%)	12	0.040	0.172	0.240
		30	0.015	0.091	0.103
		38	0.008	0.055	0.059
	High (98%)	12	0.078	0.243	0.464
		30	0.023	0.103	0.157
		38	0.012	0.041	0.066
Moderate (50%)	Low (0%)	12	0.005	0.104	0.151
		30	0.002	0.077	0.089
		38	0.001	0.039	0.047
	Moderate (50%)	12	0.118	0.238	0.358
		30	0.09	0.173	0.199
		38	0.050	0.115	0.130
	High (98%)	12	0.236	0.422	0.706
		30	0.103	0.199	0.2646
		38	0.059	0.128	0.159
High (98%)	Low (0%)	12	0.007	0.163	0.449
		30	0.002	0.077	0.130
		38	0.001	0.041	0.066
	Moderate (50%)	12	0.164	0.384	0.697
		30	0.09	0.180	0.257
		38	0.054	0.115	0.159
	High (98%)	12	0.440	0.697	0.800
		30	0.160	0.289	0.4386
		38	0.084	0.163	0.228

NP	VS	S	MS	MP	P	SP	MH	H

Legend:
H = Hazardous , MH = Marginal Hazard, SP= Significant Problem, P = Problem, MP = Marginal Problem, MS = Marginally Safe , S= Safe ,VS= Very Safe NP = Not a Problem

Figure 5-12. Sensitivity analysis for various internal temperatures at No.1 Shaft Waste Dump assuming a maximum atmospheric temperature of 32 °C. Output in each rule box represents the risk value estimated by AFRA. Values are interpolated when moving from one box to the next. The values shown are the risk at the centre position of each box.

5.8. General Atmospheric Fuzzy Risk Assessment

For a general assessment regarding the nature of the waste materials, the presence of confined structures or human activities at the site, AFRA simply decides if there is an atmospheric risk to human health. The risk at this stage is assessed based on the degree of certainty that a confined structure or a source of hazardous gas exists (user defined); and the magnitude of danger based on possibility of death due to exposure (predefined for each hazard). A number of waste materials may be present that can create an atmospheric hazard at reclamation sitr. These are listed so a user can choose those that are known or considered to be present. For example sump or well head or drill holes, erosion channels, ditches, and/or drains, or pit or hole caused by trees falling on the waste dump surface can create confined structures in which hazardous gas can accumulate, water in tailing pond/waste dump water is O_2 deficient and can cause O_2 deficiency, soil around maintenance facilities after closure is contaminated with oil and gas and can create atmospheric hazards in confined space nearby and any pit or manhole created in soils in a dangerous confined space also blasting activities agents or residues can create atmospheric hazards.

This part of the system is referred to as Source Identification and Recognition and is at the heart of the general risk assessment technique. Source investigation needs a good understanding about the kinds of reactions that may occur within different materials and the types of gasses that might be generated. To comprehend the sources, the literature for gas generation from soils and mined materials as well as previous confined space accidents and their regulations were reviewed. The Atmospheric Confined Space Manual based on Appendix C is embedded within AFRA. This involved classification of hazardous gas or enclosed structure presence into four groups: minerals and soils, organic materials, operations and activities, and other suspect places. Each group contains a list of materials in the form of hyperlinks. Gasses related to each are recognized from user input and further investigation and/or use of proper respirators is recommended.

5.9. Summary

The major outcome from this research has been the creation of a fuzzy methodology to perform an atmospheric risk assessment at a waste dump reclamation site. The design of this "expert system" can help prevent an accident similar to the Sullivan tragedy if atmospheric risk assessment is made a prerequisite in conducting reclamation work. An effectiveness evaluation was done to verify that the system meets the requirements of risk assessment at six mine sites used as input to the development process. The system was validated against three sites that were not used as input. Prediction of internal temperature using a thermodynamic model has demonstrated success in matching measured temperature levels.

Four risk elements (generation, emission, confinement, and human exposure) are considered the steps to generating a dangerous and potentially unrecognized confined space. The failure to recognize danger from a sampling shed connected directly to pore gasses at the base of a waste dump may have been due to the cyclic nature of the emission and confinement steps. These cycles occur on a daily, seasonal, and long-term (yearly) basis. The cyclic nature can mask the danger for many years after the dump begins to oxidize.

There is currently no convenient analytical way to calculate sulfide oxidation rate in a dump (Lefebvre et al., 2001a) and so, field measurements are needed to provide valid data. However, AFRA can use inference equations to interpret an approximate value of reactivity to estimate the internal temperature range and apply this to the thermodynamic model to estimate gas flow and eventually evaluate the risk. Internal temperature depends on the degree of saturation (or water content), reactivity, permeability, cover effectiveness and age, dump age and geometry and pH. The system allows a User to enter values for these intermediate variables, or if not available, it will infer these values from other parameters.

Chapter 6

Compact Version of Confined Space Risk Assessment

During the Sullivan mine incident, two of the victims were paramedics. Their deaths were ultimately a failure to recognize they were responding to a confined space accident. An additional goal of this research was to develop an application for a hand-held Pocket PC to provide first-responders with immediate answers pertaining to a particular confined space situation. The application, called AFRA CE, was built in .Net Compact Framework V.2 and can run under Windows mobile 5.0. It can be converted to .Net Compact Framework V.3 or 3.5 in Visual Basic .Net 2008, so it can be run in Windows CE, Pocket PC 2003, Windows Mobile Professional, or Standard 6 OS. AFRA CE takes user input to assist in decision-making prior to entering an accident scene for the purpose of rescue. It is also a training tool for paramedics, fire-fighters, and police officers to become familiar with confined space situations so when they respond to an accident site, they understand the need for multi-gas meters and appropriate respirators. The application is only useful in assessing the presence of an atmospheric hazard. Rescuers are encouraged to learn about the cause of the accident to determine the equipment needed to conduct the rescue safely. Other dangers with confined space are listed in AFRA CE as part of a training manual but the system does not provide advice on other types of hazards.

The risk assessment for the hand-held device is done by answering questions – each question being part of a hierarchy of questions to quickly affect the Degree of Belief about "entering" or "not entering" the space without proper safety equipment. A concise manual on confined spaces is embedded within the system to aid users in accessing information rapidly on confined spaces and the types of materials responsible for hazardous gas generation. A definition of a confined space is provided along with a complete list of confined space examples. The system guides the user in understanding which type of hazardous gasses might be generated from different types of organic materials, minerals (including warning about waste dumps), and from activities such as welding, etc. However, no claim is made that AFRA CE covers all possible atmospheric hazards in all industrial workplaces. AFRA CE is only designed to help with atmospheric hazards and as such, it is assumed that the rescuer is responding to a situation involves an enclosed structure. Since the enclosed structure is present (Concentration) and the rescuer is about to become exposed to it (Human Exposure), only the Degree of Belief in the presence of an atmospheric hazard in the enclosed structure is important in deciding to "enter" or "not enter" the space.

Figure 6-1 shows the flowchart of AFRA CE, in which inputs are combined to calculate the DoB to not enter the space without SCBA. Appropriate advice is provided for each situation to generate an awareness of the risk to the rescuer. Table 6-1 shows how the initial User Belief (DoB_i) in the presence of an atmospheric hazard can change according to factors that indicate the possibility of a problem. After calculating the final DoB in the presence of an atmospheric hazard from the user's answers to questions such as: "Has the accident happened recently?" and "Is the victim obviously still alive?", the DoB in "not entering" the space is calculated – see Table 6-2. In all cases, if a Self-Contained Breathing Apparatus (SCBA) or air–supplied respirator is available, the rescuer should use it. If such equipment is not available, then depending on the DoB certainty level to not enter the space, the advice given is:

Advice 1:	0-20	- Enter,
Advice 2:	20-40	- Maybe okay to enter,
Advice 3:	40-70	- Maybe better not to enter,
Advice 4:	70-90	- Better not to enter,
Advice 5:	90-100	- Do not enter.

Note that the victim's condition (dead or alive) has a double effect on the decision because not only does it affect the DoB in the presence of a hazard, it also affects the DoB to not enter the space. This is because in many confined space accidents, the victim dies quickly after exposure to the hazard. So if the victim is dead, there is no point to immediately enter the space without the correct equipment. As well, if the accident happened more than 20 minutes before arrival, then rushing into the enclosed structure for rescue without SCBA is not wise since the victim is likely already dead. Note that in all rescue attempts, the safety and life of a rescuer is considered more important than that of the victim. Rescuers should not do something that places themselves in jeopardy especially if the action is unnecessary. As a result, when uncertainty exists in the decision to enter or not enter the space, the answer is leaning more towards recommending that the space not be entered, e.g., Advice 3 and 4.

Appendix G shows the results of testing AFRA CE for certain situations. In all examples, it is assumed that the user has already answered the initial questions as follows:

1. Is it obvious that a non-atmospheric effect is the cause of this accident? (Ans. No or Uncertain)
2. Is the accident definitely due to an atmospheric hazard? (Ans. Uncertain - DoB varies for each instance as shown in the examples in Appendix G)
3. Has another rescuer lost consciousness? (Ans. No)
4. Do you have SCBA? (Ans. No)

With Advice 1 to 4, if the rescuer has decided to enter, he/she should wear a full body harness attached to a life line. At least one additional person (attendant) should stand outside and ensure the rescuer is responding frequently during the rescue. If the attendant does not hear a response from the rescuer, the rescuer should be pulled out of the space immediately using the life line. In decision 5, it is recommended that the rescuers wait until they have access to the proper equipment before entering the space. Firefighters are usually equipped with oxygen tanks and other necessary tools, but might arrive on the accident scene after police or paramedics. Therefore, it is recommended for police officers and paramedics to wait until firefighters arrive. Although this decision may not save the victim (if the victim was alive on first arrival), the rescuer will not lose her or his own life by rushing (perhaps needlessly) into the space without proper equipment.

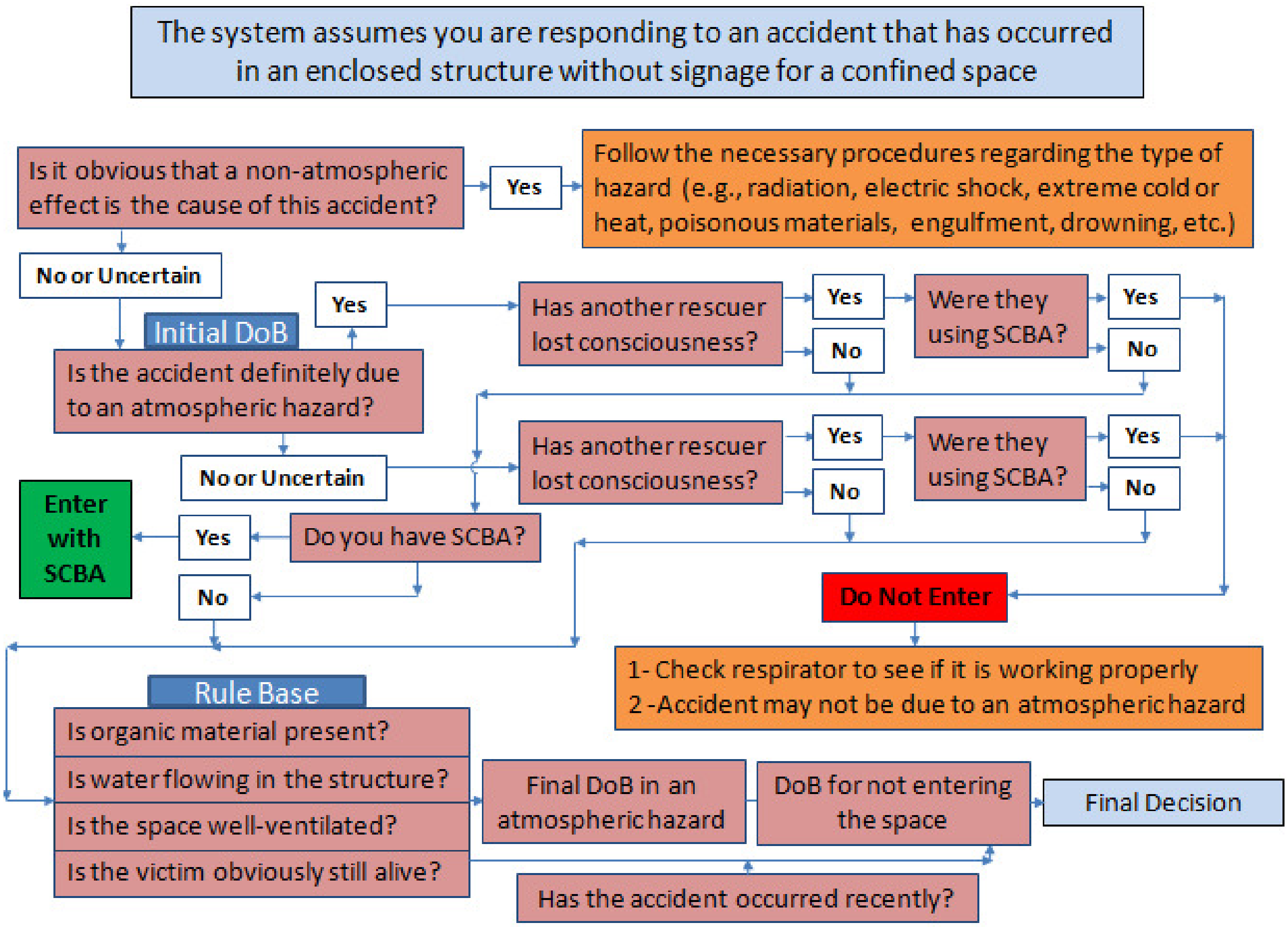

Figure 6-1. Overall Flowchart of AFRA CE.

The examples shown in Appendix G indicate that the initial DoB in an atmospheric hazard expressed by a User may be strengthened or weakened depending upon the answers to the simple questions presented to the user. Each question and answer has its own unique weight to affect the final DoB in either a positive or negative way.

In all cases, the rescuer should bear in mind that they do not have to follow the Advice given by AFRA CE as it is their own responsibility to make the final decision. The software only provides logical suggestions based on user input. The developers of this system do not accept responsibility for any consequences resulting from the use/misuse of AFRA CE.

Table 6-1. Factors affecting the DoB in the presence of an atmospheric hazard.

Factor	**Answer**	**Weight**
Victim condition	Alive (100)	-0.2
	Dead (0)	0.3 * (100 – Ans.)
Proper ventilation	Yes (100)	-0.3
	No (0)	0.1 * (100 – Ans.)
Water present	Yes (100)	0.2
	No (0)	-0.05 * (100 – Ans.)
Organic material present	Yes (100)	0.2
	No (0)	-0.05 * (100 – Ans.)
$DoB_{atm\ hazard}$	$Min(Max((DoB_{initial} + \sum Weight_i * Answer_i),0), 100)$	

DoB_{intial} is the intial DoB in an atmospheric hazard as expressed by the user.

Table 6-2. Factors affecting the DoB in not entering the space without SCBA.

Factor	**Answer**	**Weight**
Has the accident occurred recently (within last 20 minutes)?	Yes, or do not know (100)	0
	No (0)	0.1* (100 – Ans.)
Victim condition	Alive (100)	-0.1
	Dead (0)	0.2* (100 – Ans.)
DoB in not entering the space without SCBA	$Min(Max((DoB_{atm\ hazard} + \sum Weight_i * Answer_i),0), 100)$	

Chapter 7

Concluding Chapter

7.1. Conclusion

A detailed analysis of the Sullivan Mine confined space accident was done in Chapter 3 to recognize the direct and indirect factors contributing to the accident. The accident was compared with other similar confined space accidents, where the temporal changes of temperature and pressure caused the "bad" air to flow in to the confined structure. All of the analysis was conducted with a view to creating a tool to assist in the design of mine reclamation programs that can recognize the factors that contributed to this hazard in order to prevent future accidents.

Climatic pressure and temperature changes can affect the atmospheric condition of a confined space. As such, a confined space can switch from being safe in one instance to being unsafe in another. This effect has been only mentioned in few confined space regulations. In Chapter 4, a thermodynamic model was built based on laws of thermodynamic that calculates the free energy change based on temperature and pressure differences inside/outside of the dump. Gas emission into an enclosed area at different times of the day and year can be predicted given the change in delta free energy. Such a model has never been built for confined spaces and perhaps can be applied at other confined space situations such as breathing coal mines. This methodology is helpful at such places where it is not safe to simply rely on a random gas measurement due to the fact that in a few hours, days or months the confined space risk can transform from "safe" to "hazardous". In Chapter 4, the effect of pressure differences on gas flow has been studied in Number One Shaft Waste Dump. This effect at different waste dumps has been reviewed in the literature. Pressure difference in waste dumps is dependent on height and permeability and often times is of a short term nature. Pressure plays a role in dumps but to a lesser extent than in "breathing water wells" and other underground soils/rock. Cover plays a significant role in pressure effect on gas flow in waste dumps.

In Chapter 5 it was shown that confined space problems at reclamation sites involve exposure of humans to oxygen-depleted air usually accompanied by high levels of carbon dioxide. This toxic gas danger results from a chain of mechanisms that occur in sequence leading to the death of virtually any and all exposed humans. These stages are Gas Generation within the dump, Gas Emission from the dump, Gas Confinement (or Concentration) in a confined space, and Human Exposure in the confined space. The risk of a confined space accident depends on the magnitude of these four elements which interact and affect each other.

Gas Generation (oxygen-depleted air) occurs in virtually all sulfide-bearing waste dumps through reaction of sulfide minerals (pyrite and others) with oxygen dissolved in water and other ion species derived from early reactions. The water only needs to percolate through the dump at relatively low rates for these reactions to be sustained. The source of oxygen derives from influx of air into the pore volume which is controlled by diffusion at the centre of the dump and by advection/convection near its edges. As the reaction proceeds, air and water become depleted of oxygen and the internal temperature rises drawing in air at higher flow rates. Convection may actually reach the central regions.

Gas Emission depends on many factors. Air may be drawn in at the top of the dump and toxic gas emitted through the toe (usually quickly diluted and dispersed) when the dump's internal temperature is below that of the atmosphere. This direction is reversed when the atmosphere is cooler than the dump (i.e., at night perhaps, and in the winter months). On these occasions, air is drawn in at the toe and emitted from the top of the dump. Difference in free energy between inside and outside of the dump is recognized to be correlated with direction of air movement. Of course a direct connection is needed to cause the oxygen-depleted air or carbon dioxide to an enclosed structure. For example in Sullivan Mine tragedy the sampling shed was safe before covering the toe-drain which created a direct connection between air in the shed and air in the dump.

Gas Confinement can take place in an enclosed structure near to the point of emission which could be a pipe or a surface depression. If the accumulation remains undiluted, a confined space hazard exists that must be permit-required for entry. As well, oxygen-depleted water can be emitted through a buried conduit which can also act to deplete oxygen from the air in an attached confined space that it enters.

Human Exposure to the toxic gas can occur in a number of ways. In the case of the Sullivan Mine tragedy, gas accumulation took place inside a shed covering a sump installed to collect samples of the Acid Rock Drainage every month. Sampling had been done in this shed for about five years prior to the accident and entry into the shed occurred without incident two weeks prior to the accident. Failure to identify the danger is central to all types of confined space accidents – in this case, this failure occurred by the site operators as well as the individuals who entered the shed and died.

In Chapter 5 it was shown that certain reclamation activities that are implemented to protect the aquatic environment from Acid Rock Drainage (ARD) and Metal Pollution actually enhance the effects of one or more of these mechanisms. These activities include: installation of a cover to seal the dump to reduce infiltration of water and air; conversion of an open ARD collection ditch to an underground drain; installation of a sampling shed to monitor the ARD effluent; and creation of a hydraulic connection between the sampling shed and pore gas in the dump.

In Chapter 5 an atmospheric fuzzy risk assessment tool (AFRA) has been devised to assist in recognizing atmospheric hazards of confined spaces at a mine reclamation site before the danger can cause death. The hazard can then be mitigated either through redesign of the reclamation practices or by adhering to proper confined space entry procedures (permit-required, proper signage, oxygen-meter, and use of proper respirators, etc.). AFRA is a fuzzy-logic rule-based expert system developed from three sources: from knowledge gained from the

Sullivan Mine accident; from atmospheric emission studies on other waste dumps reported in the literature; and from discussions with recognized experts in the field. Fuzzy logic provides a way to conduct a dialog between a user and the system using linguistic terminology and to report the findings in a common sense way that is easy to understand and adjust. It is considered that a non-numeric method is more likely to be accepted for use by mine personnel. The model was verified against six waste dumps used to derive the rules of thumb within the system. Another three dump reports not seen before creation of the system were used to validate the system's ability to predict behaviour of previously unseen dumps. Verification and validation of AFRA shows excellent agreement with actual measurements at the chosen dumps.

In Appendix C, possible gasses that can be emitted from mine wastes and soils especially at mine reclamation sites as well as previous atmospheric related confined space accidents were reviewed to develop an Atmospheric Confined Space Manual (Especially for Gasses from Mines and Soils). This manual which contains important parts of existing confined space regulations is very complete in helping people with recognizing the danger at workplaces especially at mine sites. The electronic version of the manual is embedded within AFRA as under the category called "A list of possible gasses in confined spaces" and is a complete reference which relates possible gasses to different sources, designs or activities at different sites.

Although society and industry seems to have a good understanding of the reasons for different types of confined space accidents, these tragedies continue to occur. A key factor in preventing such accidents is sharing knowledge about how elements of each situation combine to result in a hazard. Investigating and focusing on the causes of the accident although useful, is insufficient. The goal must apply knowledge in a way to prevent future accidents at the same site as well as elsewhere. Otherwise the knowledge is simply stored in books and reports as plain statistics. AFRA can transfer lessons from the Sullivan Mine accident in regard to confined space atmospheric hazards and apply this knowledge to assess risk at other dump sites. AFRA recognizes confined space atmospheric hazards for sulfide mine reclamation sites. This is while it appears that no system has been done yet to assess the acute atmospheric problems especially at mine sites.

Regarding these issues, changes have been suggested by the Technical Panel of the Sullivan Mine Incident to eliminate and manage atmospheric hazards at the Number One Shaft Waste Dump site, e.g., placement of a cover to seal the oxygen-depleted gas, and decoupling enclosed structures from dump pore gas. A U-tube was installed on the buried pipe and the sampling shed has been removed from the site.

AFRA is a tool that can help people understand why the atmosphere within a confined space can change from safe to hazardous in a matter of minutes, but it is important to take multiple gas measurements at different times of the day and year. Since accidents such as this one have never happened before in an ARD sampling shed, designers and operators of reclamation sites are unlikely to have this problem or its causes "front of mind". When a structure has been entered safely without any problem on numerous occasions, it is unlikely that someone will consider assessing the oxygen level in the air within the space. AFRA is able to predict an oxygen-depletion hazard even when the space is currently safe. It can offer advice about design changes or climatic changes that may convert an enclosed structure into a dangerous confined space. This will force users to think about possible problems before it is too late - things that no one considers important unless warned beforehand.

7.1.1. Contributions

The major contributions of the thesis are:

- Applying thermodynamic laws to understand the combined effects of climatic pressure and temperature changes on the atmospheric risk of an enclosed structure near a waste dump.
- Recognizing oxygen-deficient water as a source that can cause oxygen-depletion in an enclosed structure near a waste dump.

- Developing and testing an atmospheric fuzzy risk assessment tool (AFRA) based on fuzzy logic to recognize atmospheric risk at an enclosed structure around a sulfide waste dump.
- Providing a possible explanation as to why an accident similar to that which occurred at the Sullivan Mine has not been seen elsewhere (see Section 5-7).
- Recognizing that certain reclamation activities potentially increase the atmospheric risk.

7.2. Recommendations

The terminology used in the field of confined spaces is extremely confusing, varying by jurisdiction and agency. In Chapter 5, this thesis suggests a simplified approach to improve understanding. Any structure that is enclosed should be deemed an enclosed structure. Any enclosed structure that has the potential to become hazardous should be designated a confined space that requires a permit to control entry. Two terms can encompass all situations: "enclosed structure"; and "confined space". The former is safe, the latter is hazardous. The transition from one term to the other is the central focus of risk assessment procedures such as that performed by AFRA.

During the conduct of this research, the Mines Act (2008) regulations were revised by the Ministry of Energy, Mines and Petroleum Resources – two years after the accident. Yet there is still no mention of atmospheric hazards at mine reclamation sites in the confined space section of this Act. There is insufficient definition and regulations about confined spaces in the BC Mines Act. In fact there is no specification of the possibility of oxygen-deficiency at sulfide mine reclamation sites in the BC Mines Act and any mining-related regulation throughout the world (Mohammadi and Meech, 2011). This oversight must be addressed so mine operators and mine inspectors are informed about this potential hazard that may exist during the operating phase of a mine and following closure.

Few confined space regulations acknowledge that a change in atmospheric temperature or pressure can transform a safe enclosed structure into a deadly confined space. This issue should be stressed in all confined space regulations, notifications, and brochures. As well gasses from remediated mines can create a hazard either at the site or by travelling through the ground into people's homes or any other enclosed structure. The thesis draws the attention of society to the existence of these types of hazards. The possible pathways for such gas migrations were reviewed in Appendix C. Many houses are built near remediated coal mines, others may be built near remediated mines in the future. Assessment should be done to examine soil surfaces, water, and enclosed areas (nearby houses and yards) for the presence of methane, carbon dioxide, and oxygen-depleted gas. If any hazardous gas is present then its extent and sources should be assessed and if necessary, it should be managed (Mohammadi and Meech, 2011).

A brief analysis of previous confined space accidents that included their detailed cause and location has been done by a few organisations such as NIOSH. Such a resource can help to explain which types of atmospheric problems are possible in certain workplace based on past experience. This is important in preventing future confined space accidents. Finally having one single regulation for confined spaces for all industries can result in omission of site-specific atmospheric hazards. A customized confined space regulation is needed for each industry that should be accompanied by an specific risk assessment methodology. AFRA is a risk assessment tool specific for mine reclamation sites.

AFRA is available free-of-charge through a UBC web site (www.mining.ubc.ca/AFRA). It can be downloaded for use by mining companies, government agencies, and/or safety professionals. It should be a requirement to use this tool to evaluate reclamation practices at all mine sites and a reevaluation of risk should be mandated whenever a change occurs in the environment, design, or operation of the site. First Responders (paramedics, fire-fighters, and police officers) should be encouraged to download the associated educational tool on confined space situations. The tool can be placed on a hand-held device for reference purposes to assist a First-Responder in deciding to enter or not a suspect site.

The Sullivan mine tragedy should focus people's attention on the fact that insufficient time is spent on studying hazards at reclamation sites, especially when these dangers are associated with new reclamation techniques designed to protect the environment. Continued risk assessment is needed to investigate atmospheric hazards in industry. It is crucial to investigate possible ground faults and to amend mine regulations regarding atmospheric problems instead of waiting until the next "first accident" occurs.

7.3. Future Work

The proposed methodology is applicable to other workplaces by changing consideration of the types of hazardous gasses generated and emitted. The four major elements of atmospheric risk are the same in all confined space accidents across all industries. The differences involve the degree to which different variables affect each risk element and the type of toxic gas. These depend on the type of operation, design and modifications, climatic conditions, technologies, and types of materials.

For example, with breathing water wells, gas generation is due to low-oxygen levels from displacement by nitrogen and carbon dioxide. Gas emission is influenced by barometric pressure changes much more than by temperature changes. Air moves into the well when the pressure rises. Problems of this kind can be modelled by a structure similar to AFRA. A thermodynamic model similar to that used in AFRA can model the effect of barometric pressure on gas flow in breathing water wells. There are other examples in the literature that could benefit from using a similar expert system structure to solve their problems, such as reclaimed coal waste tips and sites above underground coal mine operations.

Tools such as AFRA can take available knowledge and distribute it to workplaces to help prevent similar accidents from occurring. The most important lesson learned from the Sullivan Mine accident is that each new technology, material, or operation should be retested from different contexts of health and safety before application. Assessment should continue throughout the life of the structure should any change occur at the site.

AFRA is based on knowledge of current waste dumps in the literature that have been instrumented and studied. As more sites are tested, better understanding of the risk will be achieved and other combinations of variables that control atmospheric risk can be included. The weights and rules can be updated as understanding of these new waste dumps is achieved. this analysis has focused on structures located at the toe of a dump. Danger also exists in a reverse manner with structures built on top of a dump. Further attention must be given to regulation and policies about housing construction on top of dumps that might take place decades after closure.

The last issue that affects human health and can make a work place more convenient for the workers is "communication requirements". This is a key factor in managing risk and should be considered in safety guidelines at reclamation sites. In evaluating the risk for confined spaces the presence of good emergency response and communication between closed mines and emergency services is important and will significantly reduce risk. Controlling worker access to the workplace as well as proper and efficient emergency response may stop additional fatalities or prevent the first from occurring.

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Appendices

Appendix A Statistics on Confined Space Fatalities

Table A-1. Confined-space accident deaths from 1980 to 2009 in the United States characterized by event and exposure and presented in numerically. Data from 1989 and before are from NIOSH (Suruda et al., 1994) while data after 1992 are from Dep't. of Labour statistics. Death from drowning is not considered from 1992 (U.S. BLS, 2010). (Data in both NIOSH (by CDC) and BLS are public domain and do not need specific permission)

Event or Exposure	Inhalation, oxygen-deficiency, engulfment and drowning in enclosed, restricted, or confined spaces	Depletion of oxygen in enclosed, restricted, or confined spaces(code 384XXX)	Inhalation in enclosed, restricted, or confined space (code 3411XXX)	Depletion of oxygen from cave-in or collapsed materials (383X)	Total
1980	83	Not classified	Not classified	Not classified	83
1981	86	Not classified	Not classified	Not classified	86
1982	68	Not classified	Not classified	Not classified	68
1983	52	Not classified	Not classified	Not classified	52
1984	87	Not classified	Not classified	Not classified	87
1985	58	Not classified	Not classified	Not classified	58
1986	62	Not classified	Not classified	Not classified	62
1987	45	Not classified	Not classified	Not classified	45
1988	61	Not classified	Not classified	Not classified	61
1989	68	Not classified	Not classified	Not classified	68
1990	Not classified	Not classified	Not classified	Not classified	-
1991	Not classified	Not classified	Not classified	Not classified	-
1992	Not classified	13	51	0	64
1993	Not classified	3	43	4	50
1994	Not classified	3	44	3	50
1995	Not classified	10	35	0	45
1996	Not classified	12	56	0	68
1997	Not classified	5	25	0	30
1998	Not classified	7	27	0	34
1999	Not classified	0	23	0	23
2000	Not classified	5	22	0	27
2001	Not classified	13	25	0	38
2002	Not classified	10	20	0	30
2003	Not classified	7	27	0	34
2004	Not classified	9	13	Not classified	22
2005	Not classified	0	21	Not classified	21
2006	Not classified	4	15	Not classified	19
2007	Not classified	Not classified	32	Not classified	32
2008	Not classified	Not classified	17	Not classified	17
2009	Not classified	Not classified	11	Not classified	11

Table A-2. Asphyxiation in different industries in 1984 in 47 states of US between 1984 and 1986 (data from Bureau of Labor Statistics Survey of OII) "Reproduced by permission from BMJ Publishing Group Limited. [from Asphyxiation and Poisoning at Work in the United States 1984-86, Suruda, A.J., Agnew, J., v 46, 541-546, 2011] ".

Industry	Mechanical	Simple Asphyxiation	Toxic gasse s	Oxygen deficiency	Solvents	Other	Report incomplete	Total	No. of Employees in 1984 (million)	Rate per million workers
Agriculture	3	0	0	0	0	1	0	4	933.8	1.68
Construction	3	6	4	8	6	0	0	27	4345	2.44
Oil/gas	1	8	11	4	2	0	0	26	612.7	16.64
Manufacturing	20	26	13	7	11	6	5	88	19412	1.78
Services	1	2	7	2	5	1	1	19	20761	0.36
Trade, wholesale and retail	10	1	12	4	5	0	1	33	22134	0.58
Transport	3	1	3	1	5	1	0	14	2673.1	2.05
Utilities	1	4	7	0	0	0	0	12	898.9	5.24
Other	0	0	8	1	1	0	0	10	7213.3	0.54
Total	42	48	65	27	35	9	7	233	78983.8	1.16

Table A-3. Death from inhalation and oxygen-deficiency in a confined spaces in mining industry in U.S (U.S. BLS, 2010). (Data in BLS is public domain and do not need specific permission)

Year	Depletion of oxygen in enclosed, restricted, or confined spaces(code 384XXX)	Inhalation in enclosed, restricted, or confined space (code 3411XXX)	Depletion of oxygen from cave-in or collapsed materials (383X)	Total
1992	0	0	0	0
1993	0	0	4	0
1994	0	6 private mining	3	6
1995	0	4 private mining	0	4
1996	0	5 private mining	0	5
1997	0	0	0	0
1998	0	0	0	0
1999	0	3 mine and quarry	0	3
2000	0	0	0	0
2001	0	0	0	0
2002	3 mining private industry	0	0	3
2003	0	4 Natural resources and mining	0	4
2004	0	4 Natural resources and mining	0	4
2005	0	0	0	0
2006	0	0	0	0
2007	0	7	0	7
2008	0	4	0	4
2009	0	0	0	0

Table A-4. Work-related fatalities in Manitoba, 1995-2005 (WCB, 2006, adapted by permission).

Cause of Work-Related Fatalities in Manitoba		**Number of Fatalities**	**Percentage of Fatalities**
Occupational Disease Fatalities	Heart disease	15	4%
	Other Cancer	16	4%
	Asbestosis and Mesothelioma	96	25%
	Other diseases	19	5%
Acute Hazard Fatalities	Mobile Vehicle	113	30%
	Machinery Contact	17	5%
	Excavation and Structural Failure	28	7%
	Explosion/Fire/Electric Current	21	6%
	Confined Entry	6	2%
	Other Acute- Hazards	45	12%
Total	**-**	377	100%

Table A-5. Number of confined space related fatalities in British Columbia based on number of claims accepted for fatal benefits by subsector and the year in which it was accepted (WorkSafeBC, 2010 (a), data are extracted by permission).

Sector/ Subsector	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Agriculture														3[w]	
Amusement Facilities															
Canadian Pacific ltd. (Rail and Mining)												1[s]			
Construction trades			1[d]												
Fishing								1[n]							
Food products								1[o]							
Heavy manufacturing	1[a]		1[e]												
Hotel and restaurants			1[f]												
General retail					1[j]										
Logging															
Misc. Manufacturing															
Mineral products															
Mining (not coal)															
Municipalities					1[k]										
Oil and gas well drilling			1[g]											1[x]	
Other services		1[b]									1[q]			1[y]	
Petroleum, Coal, Rubber, Plastic and chemical products							1[l]						1[v]		
Provincial government												2[t]			
Pulp and paper			2[h]												
Road and Construction							1[m]								
Sawmill		1[c]													
Technical Services												1[u]			
Transportation and related services									4[p]					1[z]	
Trucking			1[i]												
Wood and paper											1[r]				1[zz]
Total	1	2	7	0	2	0	2	2	4	0	2	3	1	3	1

a A welder was exposed to paints, solvents and fumes and the cause of death was heart attack
b A 27 year old tireman died by CO poisoning when he parked his car in lot and left the motor running
c Vapours from lumber irritated lungs of one mill worker. Cause of death: complications of severe bronchial asthma.
d Sealer died applying concrete sealant within a cement structure when an explosion and then a fire occurred.
e A welder was welding an aluminum fuel tank into a boat when an explosion occurred

f	Guide buried in an avalanche while heli-skiing
g	a labourer was exposed to CO in well- building site
h	2 worker was found dead in a confined space possible asphyxiation
i	A guide and his client were caught in an avalanche
j	A guard asphyxiated by propane heater in an enclosed room
k	A contractor collapsed in bottom of manhole, asphyxiated from methane gas
L	A 55 year old labourer was buried in a collapsed excavation
m	A 45 year old welder entered barge- lack of oxygen in hold caused worker collapse
n	A 34 year old fisherman died by a exhaust fumes that were blown by wind into the boat and caused carbon monoxide exposure
o	A 47 year old owner fell into wine fermentation tank and overcame by carbon dioxide fumes and drowned
p	A 47 year old welder, 36 year old yard helper, 46 year old lead hand and a 38 year old shop foreman entered watertight void space of barge and was overcame by oxygen-depleted air (Anoxia)
q	A 52 year old production worker died in chemical explosion
r	A worker died by exposure to cedar dust which resulted in cedar dust asthma, he died of respiratory failure
s	A 50 year old project manager died by oxygen-deficiency In a sampling shed
t	A 44 years old and a 21years old paramedics died in sampling shed because of oxygen-deficient air
u	A 48 year old technical engineer died in a sampling shed by oxygen-deficiency
v	A 25 year old operator died when equipment failed and released uncontrolled flow of H_2S
w	A 55 years old farm worker was working in pumphouse of brown water containment pond. Pipe came apart and sludge released, creating an oxygen-depleted , hazardous atmosphere
X	A 60 years old equipment operator tumbled into a water-filled pit. Worker was trapped in cab and drowned
Y	A 60 years old carpet cleaner died while two persons cleaning carpets using a gas engine powered cleaning unit (compressor). Cause of death: carbon monoxide poisoning
z	A 32 years old vacuum truck operator died while a storage tank exploded. Worker was thrown against an adjacent building.
zz	75 years old Pipefitter died of exposure to chlorine gas which caused asthma

Table A-6. Oxygen deficiency fatalities in BC 1997-2009 in all sectors (WorkSafeBC, 2010 (b), data are exztracted by permission)

The sector	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Number of fatalities
Agriculture Jobs, not Labourers												6		6
Art, culture technical jobs	1							1						2
Childcare; home support							1							1
Construction Trades										1				1
Forestry, mine ,fish not labourer				1			1	1	1					4
Health technical occupations										2				2
Other managers										1				1
Other sales and service		1			1			1						3
Other Trades		3		4					1	2	3			13
Primary production labourers						1								1
Private Service Jobs											1			1
Manufacturing supervisors							1							1
Manufacturing machine operator	1				1	1	1	1						5
Registered nurses		1												1
Science professionals	1					1								2
Science technical jobs						1				2				3
Trade, transport, contractor, supervisor	2						1							3
Trade, transport labourers	1	1	1				1							4
Transport Equipment Operators										1				1
Total														55

Appendix B Calculating Oxygen-depletion in the Sump by Oxygen-Deficient Water (No Leakage)

B.1. No Leakage of Air in to the Shed and Sump.

$P = 102\ kPa$

$T = 20^0 C = 293K$

$\rho(O_2) = 1.429 g / L$

X_{gt} $O_2\%$ *in the air at time t*

C_0 *Initial dissolved* O_2 *in water flowing to the sump* (mg / L)

C_t *Dissolved* O_2 *in water in the sump at time t* (mg / L)

C_t * *Saturated dissolved* O_2*concentration at time t* (mg / L)

C_{t-1}' *dissolved* O_2 *in water in the sump* (mg / L) before mixing with new water flow volume (with $C_0 = 1$) at time t - 1

C_{t-1} *dissolved* O_2 *in water in the sump* (mg / L) after mixing with new water flow volume (with $C_0 = 1$) at time t - 1

Water flow rate $= 2000\ L / hr = 33.33\ L / \min$

Water flow in one minute $= 33.33\ L$

Water level in the sump $= 0.5m$

Sump area $= 2 * 1.2\ m^2$

Sump depth $= 2.5m$

Volume of water in the sump $= 0.5 * 2 * 1.2 = 1.2m^3 = 1200\ L$

Air volume in the sump $= 2 * 2 * 1.2 = 4.8\ m^3 = 4800\ L$

$A/V = (2*1.2)/(2*1.2*0.5) = 1/0.5$

$K_L(293K) = 32.3 cm / hr = 0.00538\ mm / \min$

$K_H = 9.73 * 0.0001 * EXP(1799/293) = 0.451493305 mg / L - kPa$

$P_{gt} = P * X_{gt}$

$P_{gt} = 102 * 0.2095 = 21.369 kPa$

$C*_t = K_H * P_{gt}$

$dC / dt = K_L (A / V)(K_H P_{gt} - C)$

$$\int_{C'_{t-1}}^{C_t} dC / (K_H P_{gt} - C) = \int_0^t dt * K_L (A / V) = Ln(K_H P_{gt} - C)\Big|_{C'_{t-1}}^{C_t} = K(A / V)t$$

Dilution by new water flow:

$C_{t-1}' = ((1200 - 33.33)C_{t-1} + 33.33\, C_0)/1200$

$$= Ln(K_H P_{gt} - C'_{t-1}) - Ln(K_H P_{gt} - C_t) = K_L (A/V)t$$

$$= Ln\frac{(K_H P_{gt} - C'_{t-1})}{(K_H P_{gt} - C_t)} = K_L (A/V)t$$

$$= Ln\frac{(C_t * - C'_{t-1})}{(C_t * - C_t)} = K_L (A/V)t$$

$$= C_t * - C'_{t-1} = e^{K_L (A/V)t}(C_t * - C_t)$$

$$C_t = \frac{C_t * (e^{K_L (A/V)t} - 1) + C'_{t-1}}{e^{K_L (A/V)t}} mg/L$$

O_2 taken by the water in each min (g) = $((C_t - C_{t-1})/1000)*1200$

O_2 in sump air in time t (g) = $4800 * X_{gt} * 1.429$

O_2 in the air in time one = $4800 * 0.21 * 1.429 = 1440.43g$

Remaining O_2 in the sump in time t(g) = (O_2 in sump air in time t) - (O_2 taken by the water in each min)

X_{gt} (%) = Remaining O_2 in the sump in time t(g) * 100/(1.429(g/L) * 4800(L))

B.2. Considering Gas Flow from the Pipe into the Sump

$A = 0.125\ (m^2)$

v_t = Gas velocity at time t (m/s)

$Q_t = Av_t$, Gas flow rate at time t (m^3/s)

$V_{pt} = Q_t * 60$ (s), volume of gas at time t (m^3)

V_{sump} = Sump volume

X_{g0t} = O_2 content in sump before air mixes with the gas at time t, (%).

X_{gt} = O_2 content in sump after air mixes with the gas at time t, (%).

X_{pt} = O_2 content in the gas blowing into the sump from the pipe, (%).

$$X_{g0t} V_{sump} + X_{pt} V_{pt} = X_{gt} V_{sump}$$

Given the X_{gt} The rest of the calculation is similar to B - 1.

Appendix C Atmospheric Confined Space Manual (Gasses from Mines and Soils)

Note: Format of this manual is borrowed from BHP-Billiton safety manual.

C.1. Atmospheric Confined Space Manual

While all of details given in all regulations are useful none of the regulations are a complete source for all of the information. In this section the important parts of the existing regulations are reviewed and combined together to form a document which is as complete as possible to help with identification of confined spaces. Also, the possible gasses that were recognized in this section and can create a hazardous atmosphere at mine reclamation sites are included in this document. Some parts of this manual that have been described previously, are repeated in the manual mainly due to the importance that manual has to stand on its own. Also, the format of the manual is different from the rest of thesis so that one can take this part of the thesis and use it in their work place.

C.1.1. Intent

To eliminate the risk of fatalities and injuries arising from confined spaces in surface and underground mining as well as transport, storage, production, disposal and reclamation activities.

C.1.2. Application

This manual is written to prevent fatalities in confined spaces that involve exposure of humans to hazardous atmosphere that can cause immediate death. Typically, these accidents involve asphyxiation due to the emission of a hazardous gas into an unventilated enclosed structure.

This protocol applies to all controlled activities at a mine site and to all its employees, contractors, and visitors when involved in controlled activities.

C.1.3. Definitions

A bump test Uses a known concentration to verify if an instrument is responding correctly. The equipment shall be calibrated and bump-tested according to the frequency specified by the manufacturer (calibration may be needed every 30 days while bump-testing is typically done daily at the start of the shift) (Confined Space Entry Program- A Reference Manual, 2005, by permission).

Hazards in a confined space Confined spaces may contain a hazardous atmosphere (toxic gasses, asphyxiants, poisoning gasses and agents (inhalation/skin) and oxygen-deficiency) and mechanical hazards (entrapment and engulfment in unstable materials and/or moving parts of equipment). Confined spaces may contain other hazards such as non-ionizing and ionizing radiation, electric shock/electrocution, noisy environment, fire/explosion, head impact, heat stress, constrained movement, eye impact, poor visibility, cold stress, falling objects, drowning and hazards such as slips, trips or falls, materials release through the lines, electrical or mechanical machinery activation can cause injury to the workers, objects falling (Confined Space Entry Program- A Reference Manual, 2005; Confined Space Hazards, Part III, 1979; Hazards of Confined Spaces, 2004).

Confined space A confined space is one that is not designed for human occupancy for permanent or extended periods of time. Most of the time entering and exiting such a space is restricted or difficult and is typically entered temporarily on regular or irregular basis to complete a particular work task (OSHA, 2004). Confined space refers to any enclosed area or structure that prohibits the natural ventilation in which the possibility of a dangerous atmosphere exists or can occur after the work starts. When a hazard is added to an enclosed structure like this, it will become extremely dangerous permit-required confined space. Enclosed structure is any space that is open in maximum three side (out of the 6 sides). A room with a closed door and windows is closed in all sides while a trench which is open in two sides and the top has only three closed sides.

Any structure built on top of a confined space or located adjacent to a confined space may contain the same hazards as confined space. Therefore, it is necessary that all confined structure and structures connected to them be examined for hazard (especially atmospheric hazard) evaluation. This type of structure is simply called an enclosed structure in this thesis and manual.

A place having any of these characteristics is a confine space:

Limited entry and exit due to size or locations The size of the openings is as small as 18 inches in diameter, and is difficult to move through easily and it may contradict with getting the needed equipment such as respirators, life-saving equipment in or out of the spaces when rescue is needed. In some open-topped confined spaces such as pits, degreasers, excavations, and ships' holds openings may be very large. Access to these spaces may require the use of ladders, hoists, or other devices, that make the escape from such places very difficult in the case of emergency (Pettit and Linn, 1987). This term is defined by WorkSafeBC as a place which does not need to be small, tight or fully enclosed space to be considered a confined space, it can be large or small and may not be enclosed on all sides and be partially enclosed, workers may be able to move freely inside the space (Confined Space Entry Program- A Reference Manual, 2005).

Not designed for continuous worker occupancy Confined spaces are designed mostly to store the product, enclose materials and processes or transport products or substances rather than for the worker to enter and work in them in the routine basis. Therefore they contain danger due to chemical or physical hazards to workers who occasionally enter them for inspection, maintenance, repair, cleanup, construction or sampling (Pettit and Linn, 1987). This often means the space is not normally ventilated (Confined Space Entry Program- A Reference Manual, 2005). Some confined spaces like the sampling shed in Sullivan mine are entered "in regular basis".

Permit-required confined space A permit-required confined space is a place that has *any one* of the characteristics of a *confined space* (plus) within which the contained atmosphere can become dangerous to human health mostly because the air may not move freely due to the design and does not have natural ventilation: lack of oxygen leading to asphyxiation; high oxygen-level leading to fire; emission of a toxic, flammable, or explosive gas; emission of air contaminants (fumes, dusts, or mists) that can pose an immediate threat to life or interfere with a person's ability to escape unaided from the space; threat of engulfment from surrounding bulk-material and/or water flooding into the space or collapse of the side walls or any other hazard exists that can cause serious burning, poisoning, engulfment, fracture, damage of the occupant. Accumulation of water can occur or in such a space can drown a human occupant, or water can flow in to cause consumption of oxygen by dissolution in the water or emit other dissolved hazardous gasses. Change in climatic conditions can also be added to those that can transform a non-permit required confined space to a permit required one. When such hazards are identified, entry of a human into the space requires a permit and specific protocols must be followed to eliminate or minimize the threat (changed from OSHA, 2004 (some of the hazards have been added to this definition)). The drop in barometric pressure may cause the gasses to come into the confined spaces from the surrounding walls. These kinds of manholes may have been entered previously without any problem (Pettit, 1994). Permit required confined spaces might experience temporal changes due to pressure and temperature fluctuations throughout the year (different seasons, months, weeks or even days and nights). Temperature and pressure changes (caused by climatic conditions) control gas emission direction into/out of the enclosed area in different times. Therefore, the confined spaces can change between safe and unsafe conditions all the time. It is very possible that a permit required confined space be measured to be safe by mistake. The snow or freezing can block small openings that were providing marginally safe conditions before and convert the space to a dangerous confined space. This type of structure is simply called a confined space in this thesis and manual.

Note - By including the possibility of drowning (which in fact was the first thought of the second victim who found the first casualty), this definition could have been applied a long time ago to the Sullivan water-sampling shed. According to this definition, a pit or excavation in the ground with a depth more than a certain amount should be considered a confined space because of limited access and limited ventilation and/or rapid influx of water. This depth depends on the climatic conditions and/or the existence of significant water flow.

Example of a potentially safe enclosed structure – any room in a house (usually have natural and artificial ventilation)

Example of a potentially dangerous enclosed structure– A tank without any organic, inorganic waste materials, water or rust which is open on the top.

Examples of a permit-required confined space (enclosed structure with hazard)

- a cellar containing a water well;
- any trench or ditch (deeper than 1.52 m) in the ground (usually have cave-in and atmospheric hazards);

- a tunnel in high organic content black shale or mudrock;
- a pump house that contains a pipe with organic sludge inside;
- a well house built over a freshwater well;
- a tunnel or shaft within sulfide-bearing soil;
- a chamber in which welding work is to be conducted;
- a room being cleaned with toxic chemicals;
- a garage with an operating engine
- a room or storage place on top of a contaminated soil-reclaimed coal/sulfide mine or their waste rock.
- a basement of a house that is atmospherically connected to a water well with high dissolved natural (or from coal mine) methane content;
- a manhole, digging or a basement near blasts;
- well known permit-required confined spaces (Pettit and Linn, 1987; CCOHS, 2002; Confined Space Entry Program- A Reference Manual, 2005): "boilers, cupolas, degreasers, furnaces, pipelines, pits, sumps, pumping stations, reaction or process vessels, septic tanks, sewage digesters, sewers, silos, storage tanks, ships holds, wells, tunnels, underground utility vaults, vats, ventilation and exhaust ducts, truck or rail tank cars, manholes, cold storage, aircraft wings, culverts, open ditch, kilns, storage bins, water reservoirs, double hulls or other similar places, manure pits, water reservoirs, hoppers, vaults, and pumping stations. "

C.1.4. Reasons for Inclusion of This Protocol

Confined space accidents are extremely insidious and accidents of this kind often occur in mining (whether reported or not). Confined space accidents take place at high frequency in many apparently innocent situations around the world. According to statistics collected by NIOSH on these accidents in North America over the past quarter century, of all industrial sectors, mining/oil/gas has a considerably higher rate than all other industries. However, it should be recognized that no industry is free of these tragic occurrences with events happening even in the rather commonplace activities of public administration, retail trade, the service sector, and real-estate, insurance, and finance.

Although confined space hazards are well-known and well-understood features of underground mining, all other facilities and processes in a mine should be investigated for confined space hazards. The risk associated with transport, storage, production, and processing facilities as well as disposal and reclamation sites during the operation and following closure of a mine should be studied.

Confined space accidents often involve multiple deaths as rescuers fail to recognize the danger and succumb to the same exposure as the first victim(s). Of all types of hazards, a confined space is the most difficult for an individual to recognize especially when the problem involves oxygen-depletion. There is nothing visual to provide warning; there is no odor and no noise. Death is quick and the victim rarely understands that a danger exists and will become unconscious within 10 to 40 seconds depending on the degree of oxygen-depletion. It is a painless death, but one that in virtually all cases is preventable, if proper procedures is followed (Mohammadi and Meech, 2008).

Apart from atmospheric hazards, death may also occur as a result of physical hazards, where a worker can be crushed, struck by a falling object, or buried within a bulk material. As the mining regulations regarding to blasting fumes control which is another atmospheric threat to underground and surface mining is not at all sufficient, and such activities can cause confined space accidents, in this protocol a comprehensive guideline for fume migration mitigation from blasting to confined spaces is included. However an independent manual for blasting is needed. It is necessary to ensure that policies are implemented to manage the risk associated with any kind of enclosed area. The causes and contributing factors to a confined space accident are:

- Not being able to recognize confined spaces and their hazards;
    - Lack of understanding of chemicals, soils, and contaminants that can cause a hazardous atmosphere in an enclosed area;
    - Dangerous nature of confined spaces; no odor, smell and nothing visible;
    - Previous safe conditions in the confined space; no accident in its life.
- Insufficient or lack of training of workers about entry into a confined space;
- Improper emergency response or improper use of respirators or supplied air;
- Equipment failure;
- Insufficient rules and regulations about dealing with a confined space.

C.2. Plant and Equipment Requirement

1. All operations, structures, and facilities should be investigated for the presence of a confined space, and should be reassessed in the event that a change in operation, design, or the environment takes place. The type of material present (organic or inorganic) as well as the configuration of each structure can lead to a permit-required confined space procedure being required at the site. A review of past confined space accidents with the type of equipment in question either in the mining industry or in other industries can lower the risk by enhancing knowledge within the work force.
2. A toxic or flammable atmosphere can form in a confined space as a result of reactions with liquids and solids inside a confined space or within the soil surrounding the space. Formation may or may not be due to the type of work being conducted within the space.
3. The nature of the work, such as welding or liquid nitrogen operations, that is done in a space that would not normally be classified as a permit-required confined space may convert it to one.
4. Appendices C.5 and C.6 show confined space risk assessment and permit entry forms.
5. Appendix C.7 contains a list of many conditions that can lead to oxygen-depletion in a confined space.
6. Appendix C.8 contains a list of many relevant toxic and flammable gasses as well as the conditions in which they may form within a confined space.
7. Appendix C.9 shows the guidelines for blasting activities.
8. Appendix C.10 describes gas migration pathways at mine reclamation sites.
9. Appendix C.11 shows the health effect of different concentrations of hazardous gasses and their explosive limits and the necessary actions to be taken at different observed methane concentrations.

10. Implementation of any new or innovative technology, design, operation, or change may contain new and undefined ways that can make an identified confined space dangerous. So all unforeseen risks should be identified and predicted before a tragedy occurs.
11. When focusing on solving one procedural problem, engineers may cause some safety problems with their new plans, therefore risk should always be assessed for a confined space danger in any new plan.

C.3. Procedural Requirements (Confined Space Entry Program- A Reference Manual, 2005, Adapted by permission)

1. A written entry permit shall be required that states all necessary procedures to eliminate or minimize the risk of all identified hazards (see Appendices C.5 and C.6).
2. The permit and its contained procedures shall be posted in a prominent location at the site.
3. After a new set of conditions occur in the space, a new written procedure that includes control measures for all associated risks shall be followed.
4. Work in the space shall not continue if the procedure doesn't account for any changed conditions.
5. Confined spaces shall be tagged and isolated – this also includes de-energizing of potential or electrical energy in any mechanical or electrical systems respectively.
    - Training programs shall be implemented to help workers identify a confined space and its dangers. This training shall include knowledge about the properties of harmful air contaminants and symptoms of exposure. The following training elements shall be included: How to identify and follow entry permits;
    - How to use and respond to air-testing device alarms;
    - How to follow isolation and lockout procedures;
    - How to use mechanical ventilation systems: appropriate placement of the inlet/outlet of the ventilator so enough fresh air moves into the space to achieve a safe contaminant level;
    - How to use personal protective equipment and do a seal-check for face-sealing respirators;
    - How to communicate with standby person(s); and
    - How to perform an emergency exit and conduct safe rescue procedures.
6. The atmosphere in the confined space shall be tested and appropriate respiratory protection used:
    - Confined spaces shall be tested not more than 20 minutes prior to entry or any ventilation performed to remove any explosive, toxic, or oxygen-deficient/enriched atmosphere;
    - Testing results shall be recorded and posted at all entry points into the confined space;
    - An adequately trained worker shall carry out the atmospheric test before opening hatches or starting ventilation to identify an explosive atmosphere;
    - The hazardous atmosphere shall not be vented into adjacent areas occupied by workers;
    - Care shall be taken to avoid creating a spark which could cause an explosion when there is an explosive gas within the space;
    - Testing shall be conducted after the required precautions to examine if the atmosphere is now safe for a worker to enter;
    - A continuous gas monitor shall be used if an atmosphere 20% above the LEL might develop;

- The monitor should be calibrated in clean outside air. If the oxygen level differs from 20.9%, the oxygen sensor or calibration procedure may be faulty;
- If humidity is high, the manufacturer’s special instructions should be followed;
- The tester shall know how to use a hand pump and probe or extension tubes to test the atmosphere from outside the space;
- The tester shall know the allowable limits of exposure for each contaminant;
- The tester shall know how to obtain readings from a continuous monitor;
- The tester shall be able to use substance-specific monitoring equipment;
- The tester shall be able to read immediately accurate, reliable, and specific readouts and have the ability to obtain peak readings;
- All monitoring equipment shall be calibrated according to the frequency specified in the manufacturer’s instructions and must be bump-tested or spanned as required;
- The level of oxygen shall be tested first since oxygen-deficiency can cause serious injury or death and may affect the flammability reading on a monitor;
- In a moist or wet atmosphere, the probe shall be pointed downward and water droplets wiped from the probe since many oxygen meters are affected by high humidity;
- It is important to understand the cause of oxygen-depletion even to a small amount before a worker may enter the space. For example presence of many toxic gasses that are extremely dangerous can cause a small displacement of oxygen;
- The presence of water flowing through or in the vicinity of the confined space with direct contact with the atmosphere in the space can lead to a depressed oxygen level depending on the degree of dissolved oxygen saturation of the water and on the relative flowrate to air volume ratio;
- Self-Contained Breathing Apparatus (SCBA) or a supplied-air respirator with escape bottle may be used before entry to raise the oxygen level to at least 19.5%;
- Flammable gasses, vapors, and dusts in a confined space can cause explosion. Tests shall be done for flammable gasses such as methane, hydrogen, ethane, and propane if such gasses are suspected;
- To recognize toxic and/or flammable gasses or vapors, a monitor should be used with the ability to measuring both concentration and flammability;
- Measuring devices shall be used for dusts such as coal and grain that may explode when they reach a certain concentration level in air.

7. Workers shall not enter if flammability is greater than 20% of the LEL. Hot work in the space shall not be done if the LEL is above 1%.
8. The records of confined space risk assessment, and approved entry permits with measured tests shall be kept for at least five years.

C.4. People Requirements (Confined Space Entry Program- A Reference Manual, 2005, Adapted by permission)

1. The employer shall assign a qualified person to identify and make a list of confined spaces in each workplace (The risk assessment forms are in Appendix C.6).
2. A qualified person shall complete a suitable and sufficient risk assessment based on hazards listed in Appendices C.7 and C.8.

  - The qualified person shall "have training and experience in recognizing, assessing, and controlling the hazards of confined spaces".
3. The employer shall prepare and implement a written entry program, which includes (see Appendix C.6):
    - Assigned responsibilities to specific job titles and their requirements;
    - Risk assessment for each workplace that may have a confined space;
    - Demonstrated due diligence in the selection of the qualified person to undertake the hazard assessment and production of confined space entry procedures;
    - Whenever a seriously deficient confined space hazard assessment or work procedure is encountered, this indicates that the author was not qualified to do the hazard assessment and/or develop the written confined space entry procedure;
    - Work start time and end time should be controlled on the site so that proper action is taken as soon as someone is lost on the site (this may happen in the case where an unrecognized confined space danger exists);
    - If a worker is lost and does not return, the employer shall immediately contact 911 before beginning any search and rescue action since a confined space accident may have occurred;
    - Untrained workers shall not be sent to the site to search for the lost worker since a confined space accident may have occurred.
4. The employer shall ensure that all confined space hazards are managed in a safe manner:
    - There may be ways to reduce the need to enter the confined space or to reduce the time a worker spends inside the confined space (e.g., using automated system for flushing and cleaning tanks or by using remote control cameras to inspect hard-to-see areas).
    - The employer shall ensure instruction and training are effective and that retraining occurs often enough for workers to remain competent.
5. The employer shall assign responsibility to administer the confined space program to an entry supervisor who:
    - Has the authority and means to ensure the program is implemented effectively;
    - Ensures procedures are implemented as written and all monitoring equipment is available;
    - Will work with joint health and safety committees and with the qualified person who prepared the risk assessment and the safe work procedures;
    - Ensures any procedural changes are made if required.
6. All entry, stand-by, and rescue-personnel, and persons that authorize entry shall:
    - Hold a current confined space training certificate issued for successfully completing a training course in confined space safety within the past 2 years;
    - Have appropriate physical competence to undertake the assigned work (such as inspection, repair, testing, cleaning, etc.);
    - Know the specific hazards of the confined space;
    - Understand the written safe-work procedures to perform their duties, including safe entry as well as working inside the space;
    - Be trained to immediately leave the confined space when
        - the standby person indicates evacuation is necessary,
        - the continuous monitor alarm goes off, or
        - an unsafe work environment develops.
7. The training program often takes place in a classroom setting:
    - Training may include a mock or simulated setting, where the worker can demonstrate ability using the specific procedures and equipment. (e.g., use a specific monitoring device, apply locks, place ventilation equipment appropriately)

- Workers attending the program shall be educated about the hazards types that may exist and the effects of exposure;
- Training shall include a section on equipment required for entry;
- Records of all instruction and training shall be kept;
- For each workplace, the training will be specific to the specific hazards.

8. Instructors of a confined space training program shall be qualified to know:
    - Hazards of confined spaces;
    - Applied work practices and techniques ;
    - Ventilation needed for the type of work being done;
    - Duties and responsibilities of the supervisor of entry; and
    - Duties of the workers entering the space, and standby personnel;
    - Have knowledge about monitoring requirements, entry permits, and safe limits for hazardous gasses and agents.
9. If a change occurs in the conditions from those in place when the risk assessment was done, then the circumstances must be reviewed by the entry supervisor and discussed with the qualified person to possibly update the entry procedures.
10. The risk assessment and written confined space entry procedures must be prepared by a qualified person who has one of the following qualifications:
    - "Certified industrial hygienist (CIH)
    - Registered occupational hygienist (ROH)
    - Certified safety professional (CSP)
    - Professional engineer (P.Eng.)
11. The entry supervisor shall ensure that the following are done for each entry at the site:
    - Entry is avoided unless necessary;
    - Testing and inspections have been conducted according to written procedures prior to entry;
    - Workers follow the precautions and control measures according to the written safe work procedures and all work procedures are reviewed to maintain safety;
    - Other precautions required by OHS Regulations, such as traffic control, are followed;
    - Only authorized workers who are trained enter a confined space;
    - A confined space entry permit is completed and posted at the entrance of the confined space;
    - Workers are removed from the space if changes occur during entry.

C.5. Assessment in the Work Place

Table C-1. Risk assessment table in the workplace (ANU, 2008, adapted by permission).

Number	Description	Location	Potential Hazards	Entries per year	Signage Entry permits			Contact Person
a-bbb-cc					Signage	Entry Permit	Control Entry/Exit	
1-205-44	ARD Sampling Shed	No. 1 Shaft Waste Dump	oxygen-Depletion (can be shown by a code)	12	✓	✓	✓	Safety Officer

C.6. Entry Permit (ANU, 2008, adapted by permission; Pettit and Linn, 1987, no permission is requierd, http://www.facilities.colostate.edu/files/forms/safety/CH-18.Confined.Space.pdf, adapted by permission).

IN THE EVENT OF AN EMERGENCY, STAND-BY AND RESCUE PERSON SHOULD CALL 911. IF THE CONDITIONS OR PROCEDURES SPECIFIED ON THIS PERMIT CHANGE, STOP WORK IMMEDIATELY AND NOTIFY THE SAFETY OFFICE. NO ONE SHOULD RUSH INTO A CONFINED SPACE TO ATTEMPT A RESCUE WITHOUT BEING TRAINED, WITHOUT PROPER BREATHING EQUIPMENT, AND WITHOUT KNOWING WHAT HAS CAUSED THE ACCIDENT.

Date of entry ....Time of Entry..

Is entry necessary?..

Confined space identification number...

Location of confined space...

Description of confined space..

Equipment to be worked on..

Description of the Work to be performed ....

Anticipated time to complete work...

Material or chemicals located and/or brought to the confined space and their MSD's must be stated...

All equipment located or to be brought to the confined space should be named

....

Anticipated hazards..

Entry personnel...

Attendants ....

Qualified person completing risk assessment..

Plans to control measures to remove/minimize hazards/risks:	**Acceptable Conditions**		
Has lockout/tagout procedures been done, if applicable?	**N/A**	**Yes**	**No**
Does the space require hot work permit? (If yes, answer the followings)	☐	☐	☐
Are combustibles removed from the site up to 15 m?	☐	☐	☐
Are applicable fire extinguishers easily available on site?	☐	☐	☐
Is atmosphere free from all dangerous gasses?	☐	☐	☐
Is there any safe access and exit in the space?	☐	☐	☐

Testing

Are the atmospheric testing devices properly calibrated?	☐	☐	☐
Has the confined space been tested for atmospheric hazard?	☐	☐	☐
Is oxygen level at least 19.5% and not more than 21%?	☐	☐	☐
Are toxic, flammable/explosive or O_2-displacing gasses/vapors present?	☐	☐	☐

Atmospheric checks: Oxygen .... % O_2 19.5 % to 23.5 %
Explosive .... % L.F.L. ‹10 L.E.L./L.F.L.
Toxic .... ppm 0-35 ppm CO
0-10 ppm H_2S

Atmospheric tester's initials................. Time...

Monitoring

Will the atmosphere in the space be monitored while work is ongoing?	☐	☐	☐
Continuously?	☐	☐	☐
Periodically? (State the interval.....................................)	☐	☐	☐

Note: Atmospheric conditions in the space may be safe at the time of entry, but may change rapidly because of the work procedure or products stored or generated within the space.

Cleaning

Has the space been cleaned before entry is made?	☐	☐	☐
Was the space steamed and allowed to cool?	☐	☐	☐
Has the place been clean up for dust?			

Ventilation

Has the space been ventilated before the entry?	☐	☐	☐
(Specify mechanical or natural ventilation only...)			
Will ventilation be continued during entry?	☐	☐	☐
Is ventilation sufficient for dust collection?			
Is the air supply for ventilation of the space free of Combustible or toxic agents?	☐	☐	☐
After ventilation and isolation, was the place re-tested before entry?	☐	☐	☐

Atmospheric Tester's Initials.................... Time and day...

Oxygen: .... % O_2
Explosive:............% L.E.L
Toxic: ....PPM

Please list the potential physical/chemical hazards been checked (Check all of the following hazards: Temperature Spark-producing, Radiation, Spilled Liquids, Entrapment, Electrical equipment, Noise, Irritant, Chemical Absorption, Mechanical Equipment, Vibration, Entry and Exit Limitation, Engulfment, Corrosive agents)

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Isolation

Has the system been isolated?	☐	☐	☐
Have pumps/lines/lines under pressure been blocked, disconnected?	☐	☐	☐
Has electrical equipment been double-insulated / locked out/grounded or?	☐	☐	☐
Have disconnects been used when needed?	☐	☐	☐
Has mechanical equipment been blocked, locked, and deactivated?	☐	☐	☐

Are ladders, scaffolds and work platforms safe to prevent falls?	☐	☐	☐
Requirements			
Clothing/Equipment			
Are special clothing and personal protective equipment required (e.g. gloves, overalls, chemical suit, ear plugs/muffs, hard hat, safety boots, goggles, safety glasses)? (If yes specify ....)	☐	☐	☐
Is special equipment required (e.g. rescue equipment such as safety harnesses and lifelines for entrants and attendants, mechanical retrieval/hoisting equipment, lifting gear communications equipment, motion detector, fire extinguisher, first aid kit, torch etc.)? (If yes specify ....)	☐	☐	☐
Are special tools required (e.g., electrical equipment/lighting/non-sparking)? (If yes specify ....)	☐	☐	☐
Respiratory Protection			
Is respiratory protection required (e.g., air-purifying, supplied air, air lines, self-contained breathing apparatus, etc.)? (If yes specify ....)	☐	☐	☐
Are the needed respirators available at the worksite?	☐	☐	☐
Is the worker able to fit through opening of the space with a respirator?	☐	☐	☐
Training			
Have entrant(s), attendant(s), and rescue personnel (if applicable) successfully completed required training?	☐	☐	☐
Have you been trained to use respirator properly?	☐	☐	☐
Have you received first aid/CPR training?	☐	☐	☐
Have you been trained in confined space entry?	☐	☐	☐
Standby/rescue			
Will there be a standby person on the outside that is in communication with the entrant?	☐	☐	☐
Is the standby person be able to hear or see the entrant?	☐	☐	☐
Has the standby person been trained to perform a rescue?	☐	☐	☐
Are safety lines and harness required to remove the person?	☐	☐	☐
Have company rescue procedures been devised for emergencies?	☐	☐	☐
Are workers familiar with emergency rescue procedures?	☐	☐	☐
Do you know who to notify and how to do so in emergencies?	☐	☐	☐

I have reviewed the work authorized by this permit and I declare that the confined space is safe for entry to do the described work if all needed specified precautions are fully taken

Entry/Exit Supervisor signature and name .... Date and Time ....

All personnel entering and working in the confined space MUST sign below

SIGN ON: I have been notified of the safety precautions to be taken while entering/working in the confined space according to this permit. I have been trained to work in confined spaces and consider this site safe to enter.

Sign on Entry .... Print name ....
Date and Time .... ID No ....

EXIT STATEMENT: Work is now completed (or suspended), all personnel have evacuated the confined space, and the confined space may now be secured and this permit is not applicable anymore.
Entry/Exit Supervisor signature and name .... Date and Time ....

All personnel exiting the confined space MUST sign below
SIGN OFF: I have left this confined space. I am aware that I am required to SIGN ON again if I want to re-enter.

Sign on Exit.................................... Print name ....
Date and Time.................................... ID No..

This permit is now cancelled. Any re-entry or work in this confined space requires a new Confined Space Entry Permit.

C.7. Processes that Cause Oxygen Depletion

1. Oxygen at low levels is an asphyxiant and at high levels (>21%) causes spontaneous combustion or explosion (Hazards of Confined Spaces, 2004).
2. Any combustion of organic fuels (propane, methane, and other organic materials or minerals) can deplete oxygen from unventilated air. This can happen in a room heated by gas or solid fuels if the combustion products are not vented from the room (Hazards of Confined Spaces, 2004; Confined Spaces Hazards, Part III, 1979). The combustion products are carbon dioxide, carbon monoxide and water vapor.
3. Microbial activity (yeasts, moulds, bacteria, algae) consume oxygen and often produce toxic gasses as by-products of metabolism (generally carbon dioxide) (Hazards of Confined Spaces, 2004; Konhauser and Bertola, 2007; Confined Spaces Hazards, Part III, 1979).
4. Oxidation of steel, iron, pyrite, or pyrrhotite reduces the oxygen content of a confined space (Hazards of Confined Spaces, 2004; Confined Spaces Hazards, Part III, 1979).
5. Damp activated carbon in the atmosphere or in a filtration tank can consume oxygen from the air (Confined Spaces Hazards, Part III, 1979).
6. "Oxygen-depletion can also occur in ballast tanks, boilers, double hull vessels, utility vaults, septic tanks, vats, manure pits, wine storage tanks, reaction vessels, storage tanks, fuel tanks, tank cars, tank trucks, and kilns" (Hazards of Confined Spaces, 2004).
7. Welding inside any confined space can decrease the level of oxygen (Hazards of Confined Spaces, 2004; Confined Spaces Hazards, Part III, 1979).
8. Oxidation of sulfide minerals (such as pyrite, Sphalerite, Galena and Tetrahedrite, Arsenopyrite, Marcasite, Chalcopyrite, Pyrrohotite) in an active mine or reclamation site can cause oxygen-depleted air.
9. Oxygen-depleted water can cause oxygen-depleted air when it comes into contact with enclosed air.
10. Other gasses, vapour, fume, or mist can physically displace the oxygen and diminish the oxygen levels. Inert gasses such as nitrogen, carbon dioxide and argon or helium, can displace the oxygen and cause asphyxiation. Heavy flammable gasses such as methane, propane, butane and other hydrocarbons that stay in the depressions of the confined space can also replace oxygen and cause oxygen-deficiency, from:

    http://www.osh.govt.nz/publications/series/hb-24-oxygendepletion.html
11. In high altitude also the amount of oxygen available to breathe reduces (Clean Air, 2007).
12. Enrichment of oxygen can be caused by leak from oxygen lines or welding equipment. Ventilation of the space with oxygen instead of air can also cause oxygen enrichment (Clean Air, 2007).

C.8. Common Materials that Cause Asphyxiation, Poisoning or Explosions in Confined Spaces and Places/Industeries that Contain These Materials

C.8.1. Acetylene

Explosive, flammable, asphyxiant (Hazards of Confined Spaces, 2004)
- Leaking from welding equipment (Hazards of Confined Spaces, 2004)

C.8.2. Ammonia Fume (NH_3)

Is toxic and occurs at the following places or conditions:
- Cleaning a tank with some cleaning fluids will release ammonia fumes (Confined Spaces Hazards, Part III, 1979)
- Anaerobic fermentation to form fertilizer in a manure pit forms ammonia (http://www.cdc.gov/niosh/90-103.html).
- In mineral processing ammonia may form from the residual nitrogen products like NO_2 from blasting in a muck rock
- Ammonia and ammonium are high at streams like sewage or stratified lakes because of protein decomposition, or in coastal areas which has high C content sediments at water and sediments interface (Konhauser and Bertola, 2007).
- Ammonium is high in marine sediments.
- waste water treatment systems where ammonium is being removed from agricultural soil may (Konhauser and Bertola, 2007). Ammonium is transferred to ammonia at pH greater than 7.5 (Barbarick, 2006).Organic nitrogen in the soil that cannot be used by plants is transformed by soil microorganisms to ammonium (NH_4^+). The ammonium is positively charged; therefore it sticks to clay materials which are negatively charged (Barbarick, 2006).

C.8.3. Argon (Ar)

Displaces oxygen, may accumulate at bottom (Hazards of Confined Spaces, 2004).
- Welding (Clean air, 2007)
- Replaces the oxygen to kill bacteria as part of a cleaning process (Hazards of Confined Spaces, 2004; Confined Spaces Hazards, Part III, 1979)

C.8.4. Cadmium

Causes Cadmium poisoning and occurs:
- Cutting cadmium-bearing material with an oxygen propane torch (Confined Spaces Hazards, Part III, 1979)

C.8.5. Carbon Dioxide (CO_2)

Carbon dioxide can dissolve in water according to Henry's law and form a solution of carbonic acid which has a pH of 5 (Hess and White, 1989).

$$CO_2(gas) \longleftrightarrow CO_2(aqueous) \quad K_h = \frac{aCO_2}{PCO_2} \tag{C-1}$$

$$CO_2(aqueous) + H_2O \longleftrightarrow H_2CO_3 \quad K = \frac{aH_2CO_3}{aCO_2} \tag{C-2}$$

$$CO_2(gas) + H_2O \longleftrightarrow H_2CO_3 \quad K_{CO_2} = \frac{aH_2CO_3}{PCO_2} \tag{C-3}$$

$K_h = Henry's\ Law\ Constant$

$K = Hydration\ Constant$

$K_{CO_2} = Equilibrium\ Constant\ for\ the\ Combined\ Reaction$

In the stage where carbon dioxide becomes hydrated, carbonic acid represents only 0.17% of the whole dissolved carbon species. The carbonic acid similar to other acids such as hydrogen sulfide or sulfuric acid can react with carbonate rocks such as dolomite or calcite. This reaction shows a competition between carbonic acid and bicarbonate ion. These processes can occur in groundwater located in carbonate rocks (Hess and White , 1989).

$$CaCO_3 + CO_2 + H_2O \longleftrightarrow 2HCO_3^- + Ca^{2+} \tag{C-4}$$

$$CaMg(CO_3)_2 + CO_2 + 2H_2O \longleftrightarrow 4HCO_3^- + Ca^{2+} + Mg^{2+} \tag{C-5}$$

Many studies have shown that the sink for carbon dioxide from unsaturated zones is the atmosphere (Hendry et al., 2001; Solomon and Cerling, 1987). For example, Hendry et al., (1993) showed that 2% of the carbon dioxide produced in a 3.2 m thick sandy unsaturated zone under high recharge conditions was removed by the recharging groundwater while Solomon and Cerling (1987) determined that about 4% of the carbon dioxide produced in an unsaturated zone was removed by the recharging groundwater to the atmosphere.

As was shown in Appendix D, carbon dioxide is emitted by carbonate dissolution in sulfuric acid that is released from pyrite oxidation. The other source of carbon dioxide is Microbial aerobic respiration and oxidation of organic matter in the subsurface. Rates of aerobic microbial degradation of organic matter and contaminants in the subsurface are greater than anaerobic degradation (Hendry et al., 2002).

carbon dioxide is present in coal seams can have the same origin as nitrogen. It is not present in shallow levels as much as nitrogen due to its more solubility in water. carbon dioxide in the coal seam comes from various sources other than the dissolved air in surface water. Coal oxidation also produces carbon dioxide. Most of the carbon dioxide in the coal seam is told to be from pneumatolytic gasses - emitted from solidifying magma during mineral formation – and it becomes a major problem in deeper mines. carbon dioxide unlike methane is 1.53 times denser than air and therefore tends to accumulate at lower portions of the mines. 5% of carbon dioxide will decrease the oxygen level to 14.08 % - see Equation C-6. Also carbon dioxide is toxic as at 5%, it will cause shortness of breath and annoys the nostrils and eyes (Hargraves, 1983). According to NIOSH Pocket Guide to Chemical Hazards IDLH for carbon dioxide is 4%. carbon dioxide stimulates the respiratory system at 3% and will cause unconsciousness at 10% According to U.S. OSHA TLV of carbon dioxide for healthy adults during an eight-hour work day should not exceed 5,000 ppm (0.5%). This is not because it replaces the oxygen outside, but because it actually replaces the oxygen in the lungs. If the concentration of carbon dioxide in the lungs increases, then, it displaces oxygen from the haemoglobin. So, less of oxygen is available to the

body. This state of oxygen deprivation is called ASPHYXIA (http://www.madsci.org/posts/archives/2006-06/1149301161.Bc.r.html; http://www.engineeringtoolbox.com/co2-comfort-level-d_1024.html).
Note: if the carbon dioxide in air increases to 10%, it will not bring the oxygen level below the safe level (19%) by displacement unless it concentrates at depth since it is heavier than air.

$$\rho_{CO_2} * \Delta V_{CO_2} = \rho_{O_2} * \Delta V_{O_2} \qquad \text{(C-6)}$$
$$1.977 * 0.05 = 1.429 * \Delta V_{O_2}$$
$$\Delta V_{O_2} = 6.9\%$$

The amount of seam carbon dioxide increases with depth, and causes major outburst hazard when extracting the coal. 7 workers have died in Metroplitian colliery as a result of carbon dioxide outburst between 1895 and 1954 (Lunarzewski and Battino, 1984). In coal seam gasses can release during the coal extraction. Lognwall mining can cause more problems because of its high capacity of extraction (Eltschlager et al., 2001 (a)). Gasses in coal seam are seemed to be kept in by more complex processes than compression - e.g. by applying pressure of about 4 MPa only a small fraction of gas is sorbed to the seam only by compression. The sorptive capacity of the coal is the function of the temperature, pressure and gas composition, i.e. carbon dioxide has two to three times more sorption capacity than CH_4 or at 75^{o}C sorptive capacity is about 1.5 times more than its value at 20^{o}C. Also the black coal has higher rank and has more sportive capacity and less porosity. As the hydrostatic stress over the coal increases from 0 to 10 MPa the coal permeability decreases from 0.05 to 0.00001 millidarcys which will increase the sportive capacity. The release of gasses from the seam is noisy and rapid and the temperature of released gasses is usually cold relative to the ambient air in a coal mine. It is interesting that when the coal is being extracted the intervening strata permeability will change because of relaxation. The gasses in the seam will release in the direction of the extraction and their flow will decrease by time to zero (Hargraves, 1983).
Many actions have been taken to as a solution for carbon dioxide outburst. The change in cutting the coal from horizontal to vertical and instantaneous shortfiring was implemented after these accidents. Later on infusion shortfiring was introduced as a solution. They also drilled small boreholes on the face to vent them under free flow. Back in 1980s they measured the gas pressure in the coal seam by emission value meter where the value of 0.2 cm^3/g per min was a safe emission value for an outburst. Curves specific for each colliery that relates the coal gas seam to the volatile mater of the coal that are used to estimate the gas seam is very useful (Lunarzewski and Battino, 1984). Lunarzewski and Battino, (1984) have talked about pre-drainage of carbon dioxide gas as a major for controlling outburst of this gas. In the previous pre-drainage methods, carbon dioxide emission was monitored ahead of the face to decide about implementing the shortfiring. The drainage of the gas based on free-flow was another method. But because of low permeability of coal and short gas free flow in pre-drainage time this method was not reliable enough (Lunarzewski and Battino, 1984). In 1981, a pre-drainage of coal gas under suction was examined in 6 heading of the Metroplitian colliery in Sydney. The gas was drained from the heading and was vented in return headings. The gas analysis showed that the gas contained 98% O_2, 1.5% CH_4, 0.4% N_2 and 0.1% O_2. Although this gas was inert it was suspicious that the gas mixes with outside atmosphere and reaches to explosive level due to

methane. However, further investigations showed that when the oxygen amount in the gas is kept below 12%, the drainage can be continued safely. The carbon dioxide diffusion into the air of the return heading was also measured for safety purposes. Their result showed that heading under suction pre-drainage did not need shortfiring as the level of gas seam has dropped to an acceptable level.
Other gasses also can also exist in coal mines. Helium occurs in coal mines from a pneumatolytic origin. Its amounts can reach to values higher than hundreds of part per billion is some mines (Hargraves, 1983). Coal seam gas does not contain any oxygen. Therefore the ventilated mine air should have a 20.93% oxygen as of the natural air. However these value should be deducted 0.21% for each 1% of inert gas present at the mine. Lower rank coal oxidizes faster and therefore will cause more oxygen-depletion (Hargraves, 1983). Also, sulfur and nitrogen oxides as well as carbon monoxide can be introduced to the mine by diesel engines (Hargraves, 1983). The other problem with coal mines is fires that is caused by endogenous heating of the coal by auto-oxidation of pyrite. Fire in underground mines as a result of endogenous heating is extremely difficult to control. Sealing the adjacent spaces to protect them from fire heat is one controlling major. However the sealed void space may get heated enough to catch another fire. This sometimes will engulf the whole mine and lead into closure. The coal heating will cause toxic CO emissions. Removal of CO caused by fire is difficult task after the fire was extinguished (Banerjee, 1995). Partial oxidation of coal also may produce small amounts of CO (Hargraves, 1983). Banerjee, (1995) has talked about the effectiveness of bio-technology in hindrance of the oxidation of pyrite in coal to prevent fire, and also the effectively of bio-technology in filtering out the produced CO from fire.

Places where carbon dioxide can occur are as follow:

- Can form on surface of reclaimed or underground sulfide/ coal mines. The gas being trapped in people houses / storage places or any other structure will cause health hazards (Jeana et al., 2004).
- Abandoned underground lead and zinc sulfide underground mines hosted in carbonate rock located in quartzite and argillite country rock can produce oxygen-deficient and carbon dioxide elevated air.
- Is used to prevent corrosion of vessels (boilers or storage tanks) by displacing oxygen. The vessel will be oxygen-deficient (Confined Spaces Hazards, Part III, 1979)
- Fermentation generates carbon dioxide that displaces oxygen. This occurs in brewing and winemaking (Confined Spaces Hazards, Part III, 1979).
- Is used to provide a pressure head for tapping-off beverages. Carbon dioxide may leak and displace oxygen. This can occur in the hospitality industry (Work safe alerts, 1998).
- Anaerobic fermentation in a manure pit can cause emission of this gas (http://www.cdc.gov/niosh/90-103.html).
- Degassing of carbon dioxide from groundwater passing through carbonate rocks can cause atmospheric hazard due o elevated carbon dioxide concentration. If acid mine drainage pass through carbonate rocks like karstic limestone its dissolved carbon dioxide concentration will increase. The exsulotion of carbon dioxide from water will bring its concentration well above IDLH in confined spaces. Because the underground conduits are most likely filled completely with water, the water with elevated carbon dioxide that travels under the ground does not find any way for dispersion. However in some cavities under the ground that are partially filled with water, dissolved carbon dioxide will accumulate on the empty area

(white, 1988). The elevated carbon dioxide caused by a mechanism described above is a threat for peoples' houses built above these empty areas.
- Carbon dioxide can accumulate in caves and other vertical solution openings built in limestone. Other toxic flammable gasses from leaks from pipelines, storage tank or solid waste can e confined in underground openings and may leak to people's houses and be confined in their basements (white, 1988).
- Carbon dioxide that exsolve from the water in tranquil settling ponds in acid rock drainage treatment plants can be dangerous.

C.8.6. Carbon Monoxide (CO)

is toxic and asphyxiant and is produced under any of the following conditions:
- CO is produced by incomplete combustion of organic materials such as wood, coal, gas, oil and gasoline, (e.g., in welding, generators, or equipment that is run by internal combustion) (Confined Spaces Hazards, Part III, 1979).
- Forms by microbial decomposition of organic material in sewers, silos and fermentation tanks (Confined Spaces Hazards, Part III, 1979)
- Spontaneous combustion of the coal in coal mines (Hargraves, 1983). CO can migrate to the surface from the fractures on top of the reclaimed mine area. Co trapped in rooms or any other manmade or natural structure of the ground can form a permit- required confined space.
- Occurs from blasting and can migrate through the soil get confined in house's basements or other confined spaces days after the blast (Mainiero et al., 2007).
- Also, CO although is much less toxic than NO_2 it can stay unchanged in the ground after blast and be released in loading operation (Mainiero et al., 2007).
- Partial oxidation of the coal may produce small amounts of CO (Hargraves, 1983).

C.8.7. Chlorine (Cl_2)

Toxic, lung and eye irritant, may accumulate at bottom (Hazards of Confined Spaces, 2004)
- Household and commercial bleaches, detergents can contain this gas. If contacts combustible materials fire and explosion results (http://www.ccohs.ca/oshanswers/chemicals/chem_profiles/chlorine/basic_chlorine.html).

C.8.8. Hydrogen (H_2)

This gas is explosive and:
- "Contact between aluminum or galvanized metals and corrosive liquids" (Hazards of Confined Spaces, 2004)

C.8.9. Hydrogen Sulfide (H_2S)

Low temperature sulfide minerals (less than 100^oC) are formed by sulfate reduction. Pyrite which is the most relevant sulfide mineral is formed by Fe (II) reaction with pore water sulfide (HS^-). Fe (II) is formed by the biological reduction of Fe (III) in soils and diffuses down to reach sulfide ion. While, sulfide ion is formed in sulfate reduction zone and forms iron monosulfide with Fe (II). The iron monosulfide reacts with other partially oxidized sulfur phases such as polysulfides (S_x^{2-}) or thiosulfate ($S_2O_3^{2-}$) to form pyrite (Luther, 1991). This clarifies why there is always a positive correlation between sulfide minerals and organic carbon in fine-grained anoxic sediments such as

marine shales (Raiswell and Berner, 1986). This also justifies the biological origin of sulfur in many sedimentary sulfide deposits (Konhauser and Bertola. 2007). It is said that H_2S from oil and gas field is precipitated as pyrite and this mitigates H_2S threat naturally. However, if the sandstone in the field is clean and has limited iron then H_2S can still be present on the sands (Worden et al., 2003). Therefore, the presence of pyrite on sediments on top of the oil and gas wells is used to evaluate H_2S hazard.
Major source for biological S and H_2S is SO_4^{2-} from sea water (Lloyd, 2006). The anaerobic production of H_2S from SO_4^{2-} is carried out by sulfate-reducing bacteria under anoxic conditions in pore water of sediments and stagnant basins (seas, lakes, etc.) (Millero, 1986):

$$SO_4^{2-} + 2H^+ \rightarrow H_2S + 2O_2 \quad \text{(C-7)}$$

The presence of different forms of sulfur in sediments and the kinetic of its reactions depend on the pH (Millero, 1986). For example sulfide is present in the pore water in soils, sediments and other aerobic environments in alkaline conditions (pH>7) (Canfield, 1989).

$$H_2S \longleftrightarrow HS^- + H + \longleftrightarrow S_2^- + H^+ \quad \text{(C-8)}$$

H_2S is a hazardous gas that can form in many confined spaces mostly as an activity of Sulfur Reducing Bacteria (SRB). Also, hydrocarbons fuel in storage tanks of the machinery are a good place for sulfur reducing bacteria growth. The microbial biofilms can cause corrosion in fuel tanks or oil ridge utilities (Hill, 2002). The corrosion occurs because of the SRB activity that produces ions such as HS^- and S^{2-}, which are highly corrosive to steel and blackens yellow metals. Black remains of ferrous sulfide are the result of the activity of these bacteria. When ferrous sulfide acts as cathode and drives electron from anodic pitting (the corroding surface of metal) it will cause the reaction to continue even after the SRB is killed (Hill, 2002). H_2S between 30 and 100 ppm smells sweet, and above this level it anaesthetizes the nose. This is extremely dangerous because it gives a wrong impression that the gas dissipated while in reality it is on fatal level (Hill, 2002). H_2S is extremely flammable, toxic and causes lung failure, it also may accumulate at bottom of confined spaces (WorkSafeBC, 2004). The SRB is active in anoxic conditions that sufficient organic matter and sulfate exist. These bacteria cannot survive in oxic conditions (Konhauser and Bertola, 2007).
Wherever SRB is present in a confined space danger of H_2S exists. In a closed tank space, H_2S equilibrate between water- air phases in a way that a few ppm of H_2S in water will cause this gas's concentration to reach lethal levels in the atmosphere. Sometimes cleaning the tanks (disturbance of sulfide) will stimulate the dormant bacteria (in a previously measured safe tank) and causes dramatic H_2S generation which was not expected (Hill, 2002). The exchange of H_2S in water-air interface of these environments is dependent on the water salinity, temperature and pH (Millero, 1986).
There are a number of bacteria called reductant photosynthetic bacteria that are classified by their colors which can also produce H_2S. These bacteria involve in anaerobic and aerobic oxidation of H_2S and include: 1- green sulfur bacteria 2- green nonsulfur bacteria, 3- purple sulfur bacteria, 4- purple nonsulfur bacteria and 5- helicobacter (Ormerod, 1992). Among these the green sulfur bacteria lives in anaerobic sulfide rich environments. These bacteria assimilate carbon dioxide and use H_2S as their predominant source of sulfur (Imhoff, 1992). These bacteria form in

stratified lakes and shallow marine sediments. One species of these bacteria (chlorobium) oxidizes H_2S to form sulfate as follow (Konhauser and Bertola, 2007):

$$3H_2O + 6CO_2 + 6H_2O \longrightarrow C_6H_{12}O_6 + 3SO_4^{2-} + 6H^+ \tag{C-9}$$

The bacteria form elemental sulfur as an intermediate element of the reaction. The same bacteria will use the elemental sulfur as a sulfur source if the H_2S is limited (Kelly, 1974).

The green nonsulfur bacteria forms in aerobic conditions such as hot springs, marine intertidal and hypersaline environments (Ward et al., 1989). They form under anoxic conditions with H_2S, H_2 and Fe(II) as electron donors (Pierson and Parenteau , 2000) and are associate with sulfur purple bacteria. However when the oxygen amount changes to fully aerobic conditions the color of bacteria changes from dull green to orange (Konhauser and Bertola, 2007).

$$12H_2 + 6CO_2 \longrightarrow C_6H_{12}O_6 + 6H_2O \tag{C-10}$$

Due to less sensitivity to oxygen, the purple sulfur bacteria is located on upper layer of sulfur green bacteria zone. These bacteria need H_2, $S_2O_3^{2-}$, or Fe^{2+} as reducers (electron donors) and form blooms mostly on deeper portions of lakes and marine waters (Camacho et al, 2000). Some species of these bacteria (Thiocapsa reseopericina) form pink reddish booms in dark places such as swages where the organic concentration is high (Pfennig, 1978). The colors as a result of the activity of these bacteria is visible and can help with distinguishing of the presence of H_2S at some cases).

H_2S hazard in oil tanks and oil contaminated soils is not mentioned neither in confined space manual of WorkSafeBC or BC Mines Act (2008). WorkSafeBC only mentions the H_2S hazard from sewer or gas line or rotting materials inside a space. Fatalities related to H_2S still occur in places such as landfills which are well known for emitting this type of gas. This shows the need for including the conditions and possible places of occurrence of this type of gas in confined space regulations. Although it is not likely to encounter H_2S at mine due to minerals (microbial activities in gypsum deposits), the hazard of this gas still exists due to other factors such as oil contaminated soil around maintenance shops in mine sites.
SRB are prevalent in (Konhauser and Bertola, 2007; Fenchel, et al, 1998; Lloyd, 2006):

- Manure pits, waterlogged soils, brackish water, polluted waters and sewage effluents,
- Anoxic marine sediments.
- estuarine tide
- Volcanic gasses with SO_2 in lower amounts
- In underground aquifers and in mineral water springs (at Aix-la-Chapelle, Harrogate and Llandrindod Wells).
- Oil and gas field.
- Around geothermal spring waters from Reykjavik.
- Yellowstone National Park.
- Lower depths of the Black Sea and in the ‘black smoker’ volcanic emissions.

- manure pits, waterlogged soils, brackish water, polluted waters and sewage effluents
- Mine wastes (not specified probably coal)
- Used for biotreatment of ARD from sulfide waste rock

Other sources of H_2S are as follow:

- Hydrogen sulfide is generated by specific kind of sulfur reducing bacteria (SRB) in anoxic conditions in the presence of sufficient organic materials (Konhauser and Bertola 2007). For example in the anaerobic (anoxic) conditions in pore water of sediments and stagnant basins (seas, lakes, etc.) (Millero, 1986). H_2S is produced from SO_4^{2-} by SRB. Also H_2S can form from decomposition of organic S by oxidation with H_2 or H_2O or Conversion of $S_2O_3^{2-}$ to $H_2S+SO_4^{2-}$ in the presence of water or anaerobic reduction of SO_4^{2-} or $SO_3^{2-}$with hydrogen (Konhauser and Bertola 2007).
- Hydrocarbon fuels in storage tanks of the machinery are a good place for SRB growth and therefore the H_2S (Hill, 2002).
- Oil and gas field (from kerogen and breakdown of oil) (Orr, 1977). H_2S from oil and gas field is precipitated as pyrite and its threat is mitigated. However, if the sandstone is clean and has limited iron then H_2S can still be present on the sands (Worden et al., 2003)
- Sometimes cleaning the tanks (disturbance of sulfide while cleaning sludge in manure pits, ship hold barge or tanks) will stimulate the dormant bacteria (in a previously measured safe tank) and causes dramatic H_2S generation, which was not expected (Hill, 2002; http://www.cdc.gov/niosh/90-103.html).
- High sulfur coal mines and coal waste. This gas can have pneumatolytic source, but can also be produced by decomposition of sulfurs with acidic water. Helium also, occurs in coal mines from a pneumatolytic origin. Its amounts can reach to values higher than hundreds of part per billion is some mines (Hargraves, 1983).
- Thermochemical sulfate reduction (TSR) is sulfur deposits is the other source for H_2S production (Orr, 1977), for example H_2S production from microbial activities in gypsum and anhydrate deposits that are formed along within native sulfur deposits (Alonso-Azcarate, 2001). According to Tritlla et al., (2000) gypsum and anhydrate can form along with dolomite in native sulfur deposits.
- The microbial biofilm can cause corrosion in fuel tanks or oil ridge utilities because of the SRB activity that produces ions such as HS^- and S^{2-} which are highly corrosive to steel and blacken yellow metals. Black remains of ferrous sulfide are the result of the activity of these bacteria. When ferrous sulfide forms, the corrosion will continue even after the SRB is killed (Hill, 2002).
- H_2S between 30 and 100 ppm smells sweet, and above this level it anaesthetizes the nose. This is extremely dangerous because it gives a wrong impression that the gas is dissipated while in reality it has reached to its fatal level (Hill, 2002).
- Sewers and landfills(Hazards of Confined Spaces, 2004)
- Treatment plants(Hazards of Confined Spaces, 2004)
- Tanks or piping that contain sulfur dioxide from which it could leak (Confined Spaces Hazards, Part III, 1979)
- Rotting pulp in tanks, pulp and paper mills (Hazards of Confined Spaces, 2004)
- Fermentation of grain in silos (Hazards of Confined Spaces, 2004)

C.8.10. Nitrogen (N_2)

When the surface water having air inside enters the soil and rock, it loses its oxygen content as it goes downwards to the ground. The oxygen in the dissolved air will be consumed to oxidize organic matter as well as coal and generates carbon dioxide, and thus the nitrogen will be remained untouched. Nitrogen is an inert gas, so it causes oxygen-deficiency problem. This oxygen-deficient mixture is called blackdamp, which is mostly present in the shallow seams at coal mines. 10 pound of the nitrogen per acre is added to the soil by rain in a year (Barbarick, 2006). Apart from surface water, nitrogen can enter to the soil from plant residues, animal manures and commercial fertilizers. Nitrogen sometimes is added to the soil in the form of ammonium and nitrogen oxides, which are the products of combustion engines, and nitrogen oxidization by sunlight. The organic matter in the soil formed by the residue of the plants contains 5% nitrogen. Cattle manure contains about 10 to 40% nitrogen per ton (Barbarick, 2006). Processes below summarize the five main processes that dominate nitrogen transformations in the soil (Barbarick, 2006) –see Figure C-1.

Mineralization - Organic nitrogen in the soil that cannot be used by plants is transformed by soil microorganisms to ammonium (NH_4^+). Ammonium occurs at natural pH. The ammonium is positively charged and sticks to clay materials which are negatively charged (Barbarick, 2006).

Nitrification - In warm soil that is well drained, ammonium transforms to nitrite (NO_2^-) and then nitrate (NO_3^-) and becomes available for plants in the presence of oxygen and nitrifying bacteria. This form of nitrogen will not stick to the clay and will find its way downwards (Barbarick, 2006; Konhauser and Bertola, 2007). Nitrifying bacteria is present in streams such as sewage or stratified lakes where ammonia and ammonium are high because of protein decomposition. This process in coastal areas which have high carbon sediments and are close to water, occurs at water and sediments interface (Konhauser and Bertola, 2007).

$$NH_4^+ + 2O_2 \longrightarrow NO_3^- + H_2O + 2H^+ \qquad \text{(C-11)}$$

Immobilization- Ammonium and nitrate will transfer back to organic nitrogen by microorganisms during their organic material decomposition process (Barbarick, 2006). This process takes place in soils with residues of organic materials, which are high in carbon content (such as wheat straw, corn and saw dust). If enough nitrogen is added to the soil, then the above process will be stopped (Barbarick, 2006). Ammonia can also combine with nitrite in an anaerobic condition in the presence of "anammox" bacteria to form nitrogen. Nitrite is a product of nitrate reduction and can occur in anoxic conditions such as marine sediments as well as wastewater treatment systems where ammonium is being removed from agricultural soil. This is an important reaction that produces nitrogen in stratified water columns. Ammonia can diffuse upwards from deep anoxic waters and form nitrogen with nitrite (Konhauser and Bertola, 2007).

$$NH_4^+ + NO_2^- \longrightarrow N_2 + 2H_2O \qquad \text{(C-12)}$$

Denitrification - in poorly aerated soils, the microorganisms use the oxygen in nitrate in anaerobic condition and decompose nitrate to nitrogen oxide and nitrogen gas (Barbarick, 2006). The nitrification in marine sediments is coupled with denitrification without any stratification between them. Denitrifiers are capable of completely converting organic matter to carbon dioxide and nitrogen in the presence of nitrate. It has been shown that denitrification can oxidize 12-16*10^9 mol/day of organic carbon (3% of all anaerobic sedimentary carbon oxidation).

Decomposition of the organic materials with nitrite becomes more significant when oxygen to nitrate ratio become smaller (Konhauser and Bertola, 2007).
Volatilization - is the process where ammonium is transferred to ammonia at pH greater than 7.5 (Barbarick, 2006).

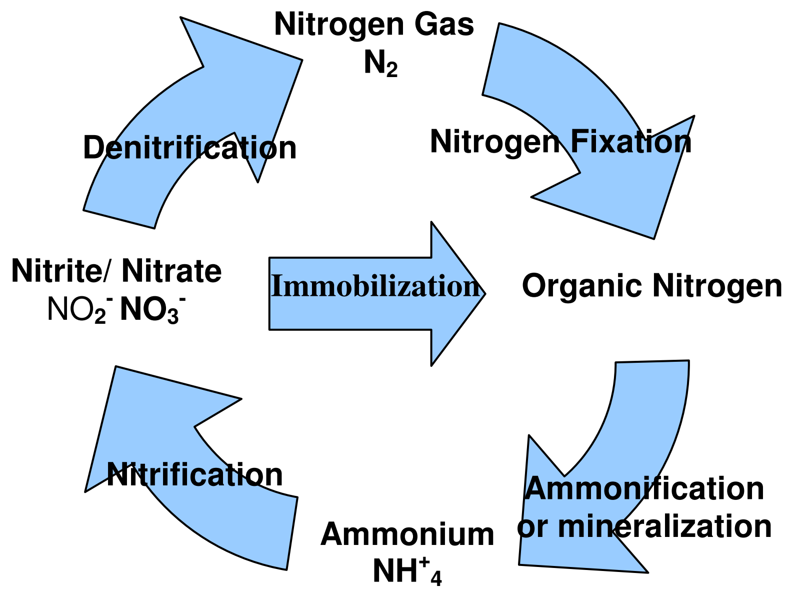

Figure C-1. Nitrogen cycle in soil
(Barbarick, 2006, adapted and changed by permission).

- Is used for inerting to prevent chemical reactions (possible explosions or corrosion). This will prevent rusting in vessels such as boilers and storage tanks (Confined Spaces Hazards, Part III, 1979)
- As shown in the asphyxiation in breathing water wells, nitrogen can transfer from soil to pits, ditches and wells in the ground due to barometric pressure drop and cause oxygen-deficiency (Hill, 2002).
- Is used to provide a pressure head for tapping-off beverages in hospitality industry. The nitrogen may leak and displace oxygen (Work safe alerts, 1998)

C.8.11. Nitrogen Dioxide (NO_2)

This gas is toxic, causes severe lung irritation, may accumulate at bottom of confined spaces. IDLH for NO_2 according to NIOSH, is 20 ppm and its permissible exposure limit according to OSHA is 5 ppm (Mainiero, et al., 2006).

- Occurs in high temperature metal smelting process (http://www.worstpolluted.org/projects_reports/display/61).
- Occures in welding (Confined Spaces Hazards, Part III, 1979)
- Because of the released toxic fumes (A red or orange colored cloud NO_2) up to IDLH levels (see Appendix C.9) blasters should wait for the gasses to dissipate before allowing anyone to return to the blast area (Barnhart, 2003; Lawrence, 1995; Mainiero, et al., 2006).

- The wind direction should be monitored before blasting and if there is a risk that the wind brings gasses to a place where people live, blasting should be postponed (Mainiero, et al., 2006).
- NO_2 from blasting is easily dissolve$_d$ in wa$_t$er, and is absorbed by moist surfaces. Although this factor will lower the NO_2 concent^{r}ation, the NO oxidization in the presence of air can form more NO_2 (Mainiero, et al., 2006) (see Section C.9 in this Appendix for more information)

C.8.12. Nitrogen Oxide (NO)

IDLH for NO according to NIOSH is 100 ppm and permissible
exposure limit for NO according to OSHA is 25 ppm (Mainiero, et al., 2006).

- NO unlike NO_2 dissolves little in water, therefore it is more possible that it stays unchanged in the muck pile of rock without dissipation (Mainiero et al., 2006). Because of lack of oxygen in the rocks NO stays unchanged and stays on the site. Lazarov, et al., (1975) measured NO_x concentrations at the depth of 1.5 to 10m in the muck pile 100 hours following a blast, the NO_x concentration ranged from 30 to 250 ppm and fell to safe levels in 2 to 6 hours. According to Mainiero, et al., (2006): "Miners must be aware that the NO_x released during the mucking operation has potential to cause serious injury or death" (see Section C.9 in this Appendix for more information)

C.8.13. Methane (CH_4)

Methane in natural gas and coal bed gas has a thermogenic source. Coal and natural gas have formed from decomposition of buried organic matter in sediments which were subjected to progressively higher temperature regimes. Although, carbon dioxide or methane which form in other sources such as landfills and marsh have the microbial origin. Methane from different sources can be distinguished by the isotopes of its hydrogen and carbon. Methane with microbial origin forms while the organic matter decomposes in the presence of oxygen and methane generating bacteria (archaebacteria). This process also forms carbon dioxide, methane and low oxygen content air and is prevalent in organic rich soils. Carbon dioxide and methane can be generated in also in an anaerobic condition from organic material in the presence of methanogenic bacteria, a process called methanogenesis. Methanogenic bacteria can form methane from carbon dioxide reduction in marine environments and fermentation of acetate in freshwater settings as well (Eltschlager et al., 2001 (a)). Half of the organic carbon is converted to methane by anaerobic reaction, in the presence of bacteria called archaea (Konhauser and Bertola, 2007).

$$4CH_3OH \longrightarrow 3CH_4 + CO_2 + 2H_2O \tag{C-13}$$

$$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O \tag{C-14}$$

Methanogenic bacteria can survive in a wide temperature range (0-110 ^oC) and will die quickly when exposed to oxygen. These bacteria are prevalent in swamps, water-logged soils, tundra, marine sediments, hydrothermal vents, landfills, and sewages where the anoxic sulfate deficient environment exists (Konhauser and Bertola, 2007). Low Eh anaerobic environments, such as confined groundwaters are also suitable for methane formation (Bishop and Lloyd, 1990). The methanogens will convert methyl containing compounds to methane. Some other methanogens oxidize ethanol, butanol and propanol to methane. Methanogens can coexist with sulfate- reducing bacteria which justifies the coexistence of methane with H_2S. Methanogens cannot break down aromatic compounds or long chained fatty acids (more than two carbons). The other bacteria (such as Acetobacterium woodii and Clostridium aceticum) will ferment these materials to substances such as acetate and hydrogen that will be readily consumed by methanogens. This process happens in anaerobic sludge digestion, where the fermentive bacteria convert large polymers to carbon dioxide and hydrogen and make them ready for the use of methanogens. In sludge, 70% of the methane is produced by directly converting the methyl compound of the acetates by methanogens, while the rest of it comes from the use of carbon dioxide and hydrogen from fermentation process (Konhauser and Bertola, 2007). In methanogenesis other electron acceptors such as O_2, NO_3^-, Mn^{4+}, Fe^{3+} and SO_4^{2-} are used sequentially to oxidize organic matter (Gooddy and Darling, 2005).

Thermogenic methane is generated by metamorphism of the vegetable matter to anthracite under the pressure (water table and higher sediments pressure). In this process the organic materials (oil in reservoir and non-reservoir rocks, carbonaceous shale, coal unit and organic matter in sediments) crack under the pressure and high temperature regimes (> 165 ^oC) to form methane. During coal metamorphism, methane will travel to higher permeable sediments or may be kept in coal bed under the pressure of above rock layers. Each gram of coal may have 21 Cm^3 of sorbed methane in its micropores, which are 21 times more than coals volume. The micropores can build a large surface as much as 200-300 m^2 in each gram of coal. The gas can also be stored in the coal in macropores such as joints, cracks and fractures (Eltschlager et al., 2001(a)). When extracting the coal the firedamp which is mostly methane is emitted. Methane, carbon dioxide and H_2O are the products of coal metamorphism under underground temperature and pressure conditions. But, when the coal reaches to late stages of metamorphism and black coal (coal with high bituminous) forms the production of carbon dioxide and H_2O becomes less significant while the methane is still being produced. Methane content of high bituminous rank is around 15 m^3/tonne in deep mines. The methane content of the coal increases by depth. Methane is not toxic but it can cause oxygen-deficiency as it is an inert gas. 5% methane will drop the oxygen level to about 19.8% - see Equation C-15. Methane is lighter than air and tends to gather near the roof (Hargraves, 1983).

$$\begin{aligned} \rho_{CH_4} * \Delta V_{CH_4} &= \rho_{O_2} * \Delta V_{O_2} \\ 0.55 * 0.05 &= 1.429 * \Delta V_{O_2} \\ \Delta V_{O_2} &= 1.92\% \end{aligned} \qquad \text{(C-15)}$$

Methane is explosive if is between 5-15%, in an air containing 12% or more oxygen. When methane constitutes 9.5% of the air the combustion is very favorable and will consume all the methane in the air and will produce carbon dioxide and H_2O, if methane constitutes more than 9.5% of air, CO, C and H_2 can be generated (Eltschlager et al., 2001(a)).

Thermogenic methane is also found in oil shales. The release of methane during mining of these fossil fuels caused many problems for mining companies. The methane content in oil shale from a Piceance Basinin in Western Colorado in a mining zone has been measured. The mean methane content resealed from a sample (drilling cores) was measured to be 0.0316, 0.114, and 0.195 cm^3/g after 3, 40, and 125 days respectively (Schatzel et al., 1987).

Methane gas associated with oil shale sand causes secondary explosion in underground blasting. The oil shale is marlstone made of dolomite, quartz and calcite. This sandstone contains an organic material named kerogen. Oil shale mine rocks have increased carbon dioxide concentration, decreased oxygen level and increased methane concentration. The oil shale samples that contained bitumens and pyrite had more methane content (Schatzel et al., 1987). Kerogen is heated at temperatures above 200 ^oC to get the oil in the form of vapor and other gasses. These gasses are then condensed and form a fuel (Weiss et al., 1995). The ore dusts in sulfide mines can also cause explosion regarding to the dust concentration, particle size, and kerogen or sulfur content in the ore. When oxygen is available the combustible dust from oil shale, sulfide ore and coal can cause an explosion in confined areas. The underground blasting is the ignition source for this explosion. After the explosion, large quantities of dust and high-temperature gas and particles release due to the rock fracturing. The wind of this explosion stirs up the dust sitting on different parts of the mine. These dusts become in contact with the fire and cause a secondary explosion. The ignitibility of the dust depends on the particle size and kerogen content. Because of the explosive dusts in oil shale sands, the Mine Safety and Health Administration feels the need about the additional regulation than only using existing metal and non metal mine safety regulation for oil shale mining (The standard for explosives for metal and non-metal mines is 30 CFR 15) (Weiss et al., 1995). This is while Mines Act only mentions the explosion hazard of sulfide dusts in its section 6.31.1 or coal dust in section 6.44.1 at any underground mine. Sulfide dust in oil shales and secondary explosion hazard associated with them should also be mentioned in Mines Act. In surface mining, there is no evidence that such dusts may cause explosion. Although in confined areas, specific condition may exist that causes the dusts to cause explosion and as a result it is important to be aware of the explosion hazards on coal, sulfide and oil shale sands.

The other source of methane is abiogenic which is not yet well understood. This kind of methane is present in Canadian Shield and in other ultramafic-mafic environments. It is said that hydrogen may be involved in inorganic processes of methane formation (Sherwood et al., 1988). See Table C-3 in Appendix C.11 for upper and lower explosive limits of methane. Methane occurs in:

- Coal seams (Eltschlager et al., 2001 (a))
- Microbial biodegradation of organic materials (e.g. rotting organic wastes in sewers or tanks or anaerobic fermentation to form fertilizer in a manure pit) (Hazards of Confined Spaces, 2004; http://www.cdc.gov/niosh/90-103.html)
- Dissolved methane in water wells near coal mine causes problem in nearby houses (Eltschlager, 2001 (b))
- Methane migrates through the soil to houses near coal mines (Eltschlager, 2001 (b))
- The high organic content mudrock together with slow water flow rate movement causes high dissolved methane concentration. The methane consuming bacteria populated at walls of the well and any other civil construction like an earth dam build on mudrock will produce carbon dioxide and oxygen-depleted gas from the methane bearing water (Gooddy and Darling, 2005; Baker, 1986).

C.8.14. Sulfur Dioxide (SO_2)

Is toxic, and severe lung irritant, may accumulate at bottom of places and occurs (Hazards of Confined Spaces, 2004):

- In high temperature metal smelting process (http://www.pollutionissues.com/Re-Sy/Smelting.html)

C.8.15. Other Contaminants in Confined Spaces

- Evaporation of liquids may produce hazardous atmospheres such as liquid fuel in a tank producing vapors (Hazards of Confined Spaces, 2004). Solvents such as acetone, ethanol, toluene, turpentine, xylene, trichloroethane, dichloroethane and methyl chloroform can spill by improper use or disposal and form a toxic atmosphere (Hazards of Confined Spaces, 2004; Confined Spaces Hazards, Part III, 1979). Vinyl chloride is a carcinogenic substance (Confined Spaces Hazards, Part III, 1979).
- Calcium carbide in contact with water forms acetylene that can catch fire. Small amounts of unstable compounds such as acetylene-metal compounds, peroxides, and nitrates cause spontaneous chemical reactions and explosions. In a dry state, these compounds have the potential to explode upon percussion or exposure to increased temperature (Confined Spaces Hazards, Part III, 1979).
- Gasses which are lighter than air can rise in a closed tank and develop a flammable concentration. The byproducts of work procedures such as spray painting can generate flammable or explosive conditions within a confined space (U.S. Department of Labor, 2011).
- A flammable atmosphere can form from pyrophoric substances (carbon, ferrous oxide, ferrous sulfate, iron, etc). Deposits of these pyrophorics are found in tanks used in chemical and petroleum engineering work and will spontaneously ignite when they come in contact with air (Confined Spaces Hazards, Part III, 1979). The presence of these substances should be investigated in mining to predict possible reactions that can cause an unknown hazardous atmosphere to form.
- Combustible dust forms when grain products, nitrated fertilizers, fine-grained chemical products are being loaded or unloaded. The electrostatic charge which accumulates on surfaces can produce a spark. This spark forms at low humidity (below 50%) and may explode the dust (U.S. Department of Labor, 2011).
- Chemicals from the inner surface of a confined space can be desorbed from a container and can form a hazard after the material is removed. After filling a container with water and draining the water, the container may still contain an explosive mixture of gas and air (U.S. Department of Labor, 2011) .
- Coal and grain dust can explode after reaching a critical level (Confined Space Hazards, Pt. III).
- Other air contaminants in confined spaces (Confined Space Entry Program - Reference Manual, 2005) are as follows: "1- Styrene, if there is fiber-glassing, 2- Sensitizers, when using any products such as epoxies or urethanes, 3- Isocyanate, contained in paints or coatings, 4- Dusts, particularly allergenic dusts, wood dust, and grain dust, at contaminant levels with the potential for explosion, 5- Benzene or other hydrocarbons in contaminated soil, 6- Other contaminants may be found inside the space or brought into the space through ventilation".
- Irritants such as chlorine, ozone, hydrochloric acid, hydrofluoric acid, sulfuric acid, nitrogen dioxide, ammonia, and sulfur dioxide. Secondary irritants include benzene, carbon tetrachloride, ethyl chloride, trichloroethane, trichloroethylene, and chloropropene (U.S. Department of Labor, 2011).
- Open-top contaminated water tanks that appear to be harmless may contain hydrogen sulfide formed by vaporization of sulfide-bearing waters (Confined Spaces Hazards, Part III, 1979).
- The dust from bins or grain silos or sugar in the plants can cause explosion (http://www.grecon-us.com/html/dust_explosions.htm; Hazards of Confined Spaces, 2004).

- Combustible dust from oil shale and sulfide ore or coal can explode depending on concentration, particle size, and sulfur content with an explosive power similar to a coal dust explosion (Weiss et al., 1995).
- Grouting mixtures containing iron or aluminum may cause oxygen-deficiency. Mixtures containing iron cause oxygen-deficiency in less than 24 hours through release of hydrogen. Mixtures containing Al release only a small amount of hydrogen consuming little oxygen, however, under certain conditions, enough hydrogen might be released to produce an explosion (Barrett, 1969).
- Backfill material containing pyrrhotite is a source of oxygen-depletion in underground mining which has been well-studied with recommendations given for water flow and height of fill material in each separate lift to reduce the risk of this hazard (Bayah et al, 1984).
- "Dusts of various metals, such as magnesium, zirconium, titanium, aluminum, chromium and manganese are ignitable and explosive when suspended in carbon dioxide as they form carbonic acid in water (NIOSH Pocket guide) ".
- Elevated amounts of helium, carbon dioxide, carbon disulfide, sulfur dioxide, carbonyl sulfide (COS) and hydrogen sulfide gas is measured on the pore gas in the soil on top of the sulfide deposits containing pyrite and chalcopyrite (Hinkle and Dilbert, 1984). Elevated levels of SO_2 (up to 2284 ppb), COS (up to 391 ppb) and CS_2 (up to 79 ppb) in wet conditions were measured in copper deposit in Arizona for soil gasses. The generation of COS and CS_2 is related to the presence of dissolved organic mater in groundwater (Hinkle et al., 1990).

C.9. Guideline for Blasting Fume Migration Control to Residences

Blasting operation will produce toxic gasses (CO, NO_2) regardless of the type of the explosive (Santis, 2001). ANFO is a common blasting material that is made of ammonium nitrate and fuel oil. When ANFO ignites it will produce water, nitrogen and carbon dioxide through the following reaction (Dick et al., 1983):

$$3NH_4NO_3 + CH_2 \longrightarrow 7H_2O + CO_2 + 3N_2 \quad \text{(C-16)}$$

Surface blasting may be accompanied with release of toxic levels of these gasses to the atmosphere, as surface mines may use up to two million pounds of blasting agent in a single shot, which forms a red or orange coloured cloud due to the presence of NO_2 (Barnhart, 2003; Lawrence, 1995). Commercial explosives have 0.5 to 10% CO (0.0062 to 0.031 m^3 per a kilogram of properly mixed explosive) which is a lot more than their NO $_{(1)\,(2)}$ content (Mainiero et al., 2006). However, the released CO concentration to the atmosphere is not considerable. Other gasses such as hydrogen and methane may also form in large or small quantities (Harris et al., 2004). According to Martel et al., (2004) theoretically each kilogram of explosive should emit 10 to 24 L of CO. This amount consists 1 to 3% of all the generated explosion gasses (Martel et al., 2004) - see Table C-2. The incorrect proportion of the fuel oil or inadequate primer is the main reason for producing toxic gasses such as CO and NO_2 (Mainiero, et al., 2006). IDLH for NO_2 and NO according to NIOSH is 20 ppm and 100 ppm and permissible exposure limit for these according to OSHA is 5 ppm and 25 ppm respectively (Mainiero, et al., 2006). Because of the released toxic fumes, blasters wait for the gasses to dissipate before allowing anyone to return to the blast area. Even in some mines the wind direction will be monitored before blasting and if there is a risk that the wind brings gasses to residential areas, blasting will be postponed (Mainiero, et al., 2006).

Table C-2. Theoretical volume of carbon monoxide from commercial explosives at detonation state (Katsabanis and liu, 1993, adapted by permission).

Explosive	CO (mol/kg)
ANFO	0.48
Emulsion explosives	0.81
ANFO (Al 5.4%)	1.60
ANFO (Al 6.5%)	1.73

NO_2 is easily dissolved in water, and is absorbed by moist surfaces. This fact will reduce the amount of NO_2 concentration, although NO oxidization in the presence of air can form more NO_2 (Mainiero, et al., 2006). NO unlike NO_2 dissolves a little in water, therefore it is more possible that it stays unchanged in the muck pile of rock without dissipation (Mainiero et al., 2006). Because of lack of oxygen in the rocks NO stays unchanged and stays on the site. Lazarov, et al., (1975) measured NO_x concentrations at the depth of 1.5 to 10m in the muck pile 100 hours following a blast. NO_x concentration ranged from 30 to 250 ppm and fell to safe levels in 2 to 6 hours. According to Mainiero, et al., (2006): "Miners must be aware that the NO_x released during the mucking operation has potential to cause serious injury or death". Also, CO although is much less toxic than NO_2 it can stay unchanged in the ground after blast and be released in loading operation (Mainiero et al., 2007). CO is slightly soluble in water and is slightly lighter than air (97%) and is very stable (Rowland III and Mainiero, 2000). This makes CO more likely to travel through the soil.

The source of CO and CO_2 is fuel oil which has a thermogenic origin. This will help us to detect the source of elevated CO or CO_2 in nearby houses and other confined structures by isotopic analysis (Eltschlager et al., 2004). High content of the fuel oil will generate excess CO, while low content of it will lead into excess NO_2 generation (Mainiero et al., 2006). Other important factors for toxic gasses being produced are: lack of confinement during blasting, reactivity of the explosives with the rock, incomplete product reaction, insufficient water resistance, poor formulation, improper use and explosives ageing which will cause ingredients to leak out of the packaging and their compositions changes (ISEE Blaster's Handbook; Mainiero et al., 2007). For example the blasting agent may flow into cracks and crevices around the borehole and therefore won't detonate properly because the width of the cracks and crevices may be below the critical diameter (Mainiero et al., 2007) – e.g. large scale surface mine blasting do not detonate properly in boreholes of 1-inch diameter. Incomplete detonation of the blasting agent leads to excessive toxic fumes (ISEE, 1998). This could be prevented by the use of packaged product or borehole liners (Mainiero et al., 2007). Rowland III and Mainiero (2000) have graphed the relationship of different percentages of fuel oil in ANFO to the volume of produced carbon oxides, nitrogen oxides and ammonia. They have also graphed the effect of oxygen balance as well as water content on these gasses. An ANFO mixture of 94% ammonium nitrate, 6% fuel oil is close to optimum from viewpoint of minimum toxic fumes production. Adding aluminum or rock dust to ANFO does not affect the fumes production of carbon monoxide, while adding rock will increase the NO_x production (Rowland III and Mainiero, 2000). Placing stemming plugs on top of the blasthole to prevent mixing of the blasting agent with drill cuttings or rocks is one way to control this problem (Mainiero et al., 2007). Blasting in wet boreholes with an explosive that is not water resistant such as ANFO will cause excessive NO_x production. In such cases, use of blasting agents that are packaged or emulsion blasting agents which are water resistant are recommended (Mainiero et al., 2007).

Surface mine blasting emits CO and CO_2 and causes oxygen-deficiency that can cause accumulation of this gas at high concentration in nearby residences. Blasts in surface mining are supposed to be vented in an open atmosphere and dissipated into the atmosphere

(Eltschlager et al., 2004). However since 1988, at least eleven incidents of stray CO migration from blasting sites have been reported in both construction and mining industry, mostly because of the confined designs of the blasts which is devised to prevent flyrock (Eltschlager et al., 2004). There were 30 cases of CO poisoning and one fatality due to CO. Of these accidents, all occurred in residences and one happened in a manhole (Santis, 2001). The confined design of the overburden of the blasts causes the gasses to be trapped in the ground and under the pressure of blasting they find pathways through least resistance features in rocks, such as pores and fractures or manmade structures, i.e. buried pipelines and other utilities that has caused weakness in the rock (Eltschlager et al., 2004). In 5 of the accidents the blast was located about 6 to 15 m of the underground confined space, while 3 of the them were 30.3 to 46 m away, and 1 was about 120 to 150 m away (Santis, 2001).

None of the blasts in blasting related accident in section 3.4.5 were excavated immediately. It is believed that the sedimentary formations, trenches filled with porous materials, fracture zones, water paths and other unconsolidated materials have facilitated the gas migration to houses. Other structures such as nearby sumps, underground utility lines, a french drain, and cracks in the foundation act as routs for gas entry to houses (Mantel et al, 2001; Santis, 2001; Harris and Mainiero, 2004). Houses with concrete foundation and no basement in same vicinity of the blasting near other affected housed did not show elevated CO (Harris et al., 2004). In 2000 a family was reported poisoned by CO poisoning in Pennsylvania. CO from blasting in surface coal mine had migrated to their house about 122 m through the fractures in the rock and was concentrated in their basement up to 640 pmm. The fractures were conducted to the hand –dug well (8.5 m depth closed by a cap) near their house which was atmospherically connected to the basement of the house through the drain. Some reasons to the CO migration were: a) not excavating the blast immediately, b) under-shooting to protect nearby residences from flyrock, c) presence of an opening through the well from which the gas had transferred into the house, d) the house being located near to the blasting area as well as e) an outcrop of the coal seam below the affected house. h) Heavy stemming had forced the fumes into the fractured sandstone that was extended to the well (Eltschlager et al., 2001(a)). The porosity and permeability of the rock or soil affects the travel rates and pathways directions. These gasses migrate both by advection; a pressure difference driven movement, and diffusion; a concentration difference driven movement. Diffusion causes the gasses to move underground even when the pressure caused by blasting has been equalized. The barometric pressure in some cases can play role in directing gas migration through pathways (Eltschlager et al., 2004). The traveled gasses can accumulate in confined spaces such as sewages, pipeline trenches, or basements of homes (Mainiero, et al.,2007). Sometimes regarding to the existing pathways (pathways may be created by broken rock from an earlier blast or a pathway caused by the movement of rock layers on a hillside) gasses will move only in one direction preferentially (ISEE, 1998; Eltschlager et. al. 2001 (b)).

OSHA has emphasized on following the confined space entry procedures when entering into trenches, manholes and vaults and other confined spaces located nearby blasts (Mainiero et al., 2007) – such a rule does not exist in a reference manual and regulation and guidelines for confined spaces in WorkSafeBC or BC Mines Act, 2008. In US a guideline and practices were recommended for controlling the adverse effect from blasting fumes in 2001, in which a few mitigating plans were devised for stopping CO migration to houses. In 2002 for preventing a CO migration from trench blasting in sewage construction near houses in Bristow, excavating the entire blasted trench up to the bed rock immediately after blasting was recommended. Even one trench (4.6 to 7.6 m) between the homes and the blasts were left void to make a gap to prevent gas migration from future blasting to homes. However after this plan the CO was still detected at homes (Harris et al., 2004). Applying negative pressure on the ground soil around the confined space will mitigate the problem readily (Santis, 2001).

Trench blasting causes more problems than surface mine blasting. This is because of the heavily confined structure of the trenches to prevent flyrock to nearby dwellings which will inhibit gas dispersion (Harris et al., 2004). Martel et al., (2004) have tried three methods to investigate the best procedure to minimize the migration of CO through rocks to nearby houses in Quebec:

First test - a) first they excavated all the debris (overburden and broken rock) after each blast, and filled it up with the excavation materials again, b) changed the sequence of blasting c) placed 5 vents, d) used of packed aluminum ANFO instead of granular one. In their test, immediately after the blast, CO had migrated up to 6-8 m in the direction of family joints in rock and up to 12 m by advection in the broken rock of trench in comparison to 20 m migration in their earlier test that did not include any of the aforementioned provisions. After 2 to 3 days CO migrated up to 10 m by diffusion through the soil while in test without any provision after 3 days gasses were traveled up to 28 m by diffusion.

Second test - a) they excavated the overburden completely, b) changed the sequence after each blast, c) completely excavated the broken rocks after each blast to evacuate the CO and make a free face for next blast ventilation, d) used smaller primer charge in each borehole, e) completely excavated the last blast to eliminate the media from which gas was migrating by diffusion to the fractures caused by blasting and find its way to houses. After the test gasses migrated only up to 5-10 m by advection but in less concentration than the previous test. After one day there was no increase in the distance of CO migration by diffusion and after three days the CO concentration was decreasing.

Third test - a) changed blasting sequence b) used small primer c) excavated a small trench in the broken rock to pump air between the broken rock right after explosion with a vacuum truck. After the test, CO traveled up to 5-10 m in fractures by advection. The migration of CO in the broken rock trench was half of its migration in test without previsions, and its concentration dropped. 6 days after the blasts CO was still migrating to one of the houses. However if more pumping was done this would have not happened.

Among three methods the second one was effective and safe while the third one was not as reliable and effective and it needed monitoring. The first method was recognized to be the least efficient (Martel et al., 2004). Other ways were recommended by Mianiero et al (2006) to protect the neighbors from blasting CO: "1. Minimize the quantity of toxic fumes produced by correct blasting and formulation 2. Determine where the fumes may go so workers and neighbors may inform to evacuate, 3. Prevent the fumes from moving towards workers and neighbors, 4. Monitor the air near workers and neighbors so they can be relocated if fumes appeared, and 5. Ventilate structures or confined spaces until CO falls below a hazardous concentration. "

C.10. Gas Migration and Pathways in Reclaimed Mines

The geochemistry and geology of the site used for exploration is helpful for atmospheric hazard risk assessment in mines. A number of factors that control ore formation mostly by controlling the fluid movement are an example of this. Such factors are shale edges (depositional margins of shale units), limestone and dolostone transitions, reef complexes, solution collapse breccias, faults, and basement topography. Pathways themselves are the product of hydrological or tectonic activities and are likely to control the movement of underground gas (or fluids containing them) (Mohammadi and Meech, 2011). They also act as the rout for conducting gasses to places where human live and/or bring them to the groundwater aquifer which is in use of human. This is more of a concern if the deposit is formed in carbonate rock, i.e. lead and zinc Mississippi Valley Type (MVT) deposits that form in dolostone and less commonly in limestone or sandstone. This is because karsting that forms in carbonate rocks can make another type of pathway.

In the surface of sulfide mines the natural breaks such as joints and faults are ways that expose the mineral surface to water and air and cause oxidation and oxygen-depletion. Oxygen-depleted air can be emitted from this fractures or faults. The rock structure and characteristics (porosity and permeability) changes will determine gas movement from one area to another. Gasses can follow the same patterns as that of the groundwater in the ground - via secondary porosity and permeability. For example the geological structures such as faults may stop gasses from movement and trap them in the intersection of permeable unit with an impermeable one, or folds and bedding plane such as anticline can trap gasses, e.g. methane, in top of the fold where a low permeable cap has covered the permeable unit. Fractures such as stress relief joints can also help with gasses, e.g. methane, traveling (vertically or horizontally) (Eltschlager et al., 2004).

Pipes that bring underground water in upper surfaces in an open pit mines to the bottom of the pit are likely to contain oxygen-depleted gas and elevated carbon dioxide as they contain effluents coming from the sulfide orebody (although the ore is not exposed to air)- note that these pipes are big enough that human may enter into them for repair or inspection therefore they should be permit required confined spaces, there are lots of pipes like this for water transfer e.g in Britaina Mine.

Eltschlager et al., (2001 (a)) has investigated the pathways for methane emission to houses nearby coal mines. His study is very helpful as the same pathways can exist and control other hazardous gas emission from other mine sites. In this section, parts of his study that highlights the possible pathways for methane emission from an underground coal mine is summarized. Methane can travel from gas wells to nearby ground water systems located at upper levels, or it can build a small reservoir under the ground. Then it can find way to houses and structures, trough cracks in the floor or fractures around buried pipes or is transferred by dissolved water and cause explosion of well houses, ignition of spigots and well heads, human suffocation, fires at surface cracks, kill surface vegetation and cause cracking in the pavement (Eltschlager et al., 2001 (a)).

Large amount of gas can still stay in coal mine after the closure. Gasses can emit under the effect of ground water movement (lowering the piezometric level), or because of the pressure from subsidence in mines. Also, mine subsidence can create fractures that will expose the coal strata and facilitate methane emission (Mohammadi and Meech, 2011). Raising underground water or flooding the mine can also move the methane upwards by displacing it. In abandoned coal mines gasses can migrate to the surface via voids, fractures, shafts, drifts, and borings, or they move slowly through low permeability soils (Tauziède et al., 2002; Eltschlager et al., 2001 (a)). Then gasses can concentrate up to hazardous limits in confined spaces. Surface reclaimed coal mines have caused many accidents because of methane emission. There was a case where a young student lit a cigarette near a closed coal mine portal. The methane leak from the portal caused an explosion and seriously burned the student - the methane concentration was 7%. The risk associated with methane explosion should be assessed by monitoring before drilling into the abandoned mine (Eltschlager et al., 2001 (a)). Mine plan and reclamation program information part in Mines Act (2008), in sections 10.6.5 and 10.7.21, refers to securing the openings such as shafts, raises, stope openings and adits. It only refers to taking measures to control inadvertent access and/or subsidence of the materials such as capping, e.g. by reinforced concrete or fill it with other material. There is no mention to the possible explosion due to fire or spark at the endings of the such openings.

Methane can migrate to people’s houses and cause problem. In this case the risk of methane should be assessed in houses by interviewing the landlord, observing the situation and test for atmospheric methane. If the conditions are safe now, they may change in the future and the periodic monitoring should take place. If the methane was above 1%, place should be evacuated and ventilated (Eltschlager et al., 2001 (a)). Necessary actions that should be taken at different levels of methane are shown in Table C-3..

Then the extent and sources of the gas should be assessed. Geological maps, mine maps, topographic maps, hydrologic studies and historical reports on methane emission and migration is used in assessment of the risk in houses. Site audit, interviews with local people is effective. The areas well beyond the site should also be investigated for hazard. There were some examples where methane from a landfill leaked in to the glacial drift and propagate thousands of feet away from landfill into people's houses. The ground water and soil methane content can become elevated at wells near coal mines or landfills (Eltschlager et al., 2001 (a)). Dissolved methane in water from various sources (e.g. groundwater) can bring explosion hazard into confined spaces. If the local partial pressure of methane in subsurface rises above its atmospheric partial pressure of $\sim 1.75\times10^{-5}$ bars, the amount of dissolved methane will increase proportionally. When the atmospheric partial pressure for methane is re-established, e.g. by water being exposed to atmosphere, methane will be outgassed until the extremely low background composition is reached. The released methane has the risk of explosion hazard when it discharges into a confined space, e.g., a building or excavation (Gooddy and Darling, 2005).

Harder et al., (1963) has plotted the dissolved methane concentration in confined spaces receiving water from a fresh water aquifer with methane concentration of 127 ppm which is locates 213 m under the ground. They have assessed the risk of methane reaching to explosive limit (5%) in the shower stall from water. According to their graph, in a shower stall with 2 m^3 volume, 34.4 m^3 of water can increase methane up to 1%. They have made a range of graphs demonstrating the methane concentration for different space volumes receiving different volume of water.

Methane in the soil is not dangerous unless in gathers in a confined space. It is because there is no source of ignition in the soil; however soil can act as conduit for methane migration. The source of methane in the soil should be investigated (leaky gas pipe or underground storage tank, landfill, buried organic matter, coal mine…) (Eltschlager et al., 2001 (a)). Methane coming from a deep oil and gas reservoir can leak to upper underground water aquifers from the defect in casing (crack in grout of the annulus) of the oil and gas wells. This can be controlled by grout and cement injection, well plugging or abandonment of the well. In landfills methane can migrate up to 457 m from the source to confined spaces or water wells. Passive and active ventilation of the landfill is used as a mitigation plan. Shallow venting trenches may also be effective. Passive vent cannot be as effective as active ones (vacuum air), because methane pressure in the landfill is not enough to be ventilated by convention and natural barometric pressure drops. For controlling methane from closed underground coal mines, grouting the fractures is not economical. Ventilating the mine and keeping the source of the gas under negative pressure is a better way, although it requires long term monitoring and is high maintenance. Dilution is also another method for controlling methane. Vents are designed in different forms for open shaft, collapsed shaft, backfilled shaft and abandoned portals (Eltschlager et al., 2001 (a)).

C.11. Dangerous Limits of Explosive and Toxic Gasses

Table C-3. Lower and higher limits for explosive gasses (http://www.oshasafety.com/H2S.htm; Eltschlager et al., 2001(a)).

Flammable gasses	Lower explosive limit (LEL) (%)	Higher Explosive Limit (HEL) (%)
Methane	5.00	15.00
Hydrogen	4.00	74.20
Carbon Monoxide	12.50	74.20
Hydrogen Sulfide	4.3	46.0

Table C-4. Adverse health effects of different concentrations of toxic gasses and O_2 (Material safety Datasheets, 2006; http://www2.worksafebc.com/i/posters/pdfs/2009/ws_09_02.pdf; http://www2.worksafebc.com/i/posters/2009/WS%2009_03.html).

O_2	CO	H_2S	CO_2	Ammonia	Chlorine
O2>21%-- Flammable atmosphere O_2<20.5% - Recommended alarm setting 14%<O2<17%-- produce impaired judgment, deeper breathing, loosing muscular coordination, dizziness, fatigue and collapse. 12-16% Oxygen -- Breathing and pulse rate increased, muscular coordination slightly disturbed. 10-14% Oxygen -- Emotional upset, abnormal fatigue, disturbed respiration. 6-10% Oxygen -- Nausea, vomiting, collapse, or loss of consciousness. At 10% the victim will loss consciousness and will die in 8 minutes. He will understand it but is not able to move or ask for help (Hill, 2002). Below6% -- Convulsive movements, possible respiratory collapse, and death.	All exposure levels: Over-exposure to Carbon Monoxide can be indicated by the lips and fingernails turning bright red. 13-25 ppm -- Recommended alarm setting 25 ppm -- 8 hours time weighted average 100 ppm -- 15 minute short-term exposure limit 200 ppm -- Slight symptoms (i.e. headache) after several hours of exposure. 300-650 ppm -- Severe headache; nausea and vomiting; and confusion and collapse. 400 ppm -- Headache and discomfort experienced within 2-3 hours of exposure. 700 – 1000 -- Coma and convulsions. 1200 ppm – Immediately dangerous to life and health (IDLH) 1,000 -2000 ppm -- Heart and lungs depressed. Fatal if not treated. >2000 ppm -- Rapidly fatal.	0.3-30 ppm -- Odor is unpleasant. 5-10 ppm - Recommended alarm setting 50 ppm -- Eye irritation. Dryness and irritation of nose, throat. Slightly higher than 50 ppm -- Irritation of the respiratory system. 100-150 ppm -- Temporary loss of smell. 200-250 ppm -- Headache, vomiting nausea. Prolonged exposure may lead to lung damage. Exposures of 4-8 hours can be fatal. 300-500 -- Swifter onset of symptoms. Death occurs in 1-4 hours. 500 ppm -- Headache, excitement, staggering, and stomach ache after brief exposure. Death occurs within 0.5 - 1 hour of exposure. > 600 ppm Rapid onset of unconsciousness, coma, death. > 1000 ppm Immediate respiratory arrest.	10% (100,000 ppm) -- Unconsciousness or death. Maximum 5,000 ppm – 8 hr time-weighted average (TWA) is allowed 2500 - 5000 ppm -- adverse health effects expected 1000 - 2500 ppm -- general drowsiness 600 - 1000 ppm -- complaints of stiffness and odors < 600 ppm -- acceptable levels 350 - 450 ppm -- normal outside levels	25 ppm -- 8 hours time weighted average 35 ppm -- 15 minute short-term exposure limit 300 ppm – Immediately dangerous to life and health (IDLH) 13-25 ppm -- recommended alarm setting	0.5 ppm – 8 hours time weighted average 1 ppm – 15 minute short-term exposure limit 10 ppm – Immediately dangerous to life and health (IDLH) 0.25-0.5 ppm -- Recommended alarm setting

For further information about chemicals in the workplace refer to OSHA's Standard Number 1926.55 App A which has a Threshold Limit Values of Airborne Contaminants Gasses, vapours, fumes, dusts, and mists at:
http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=1062

NIOSH Pocket Guide to Chemical Hazards also has the IDLH Exposure limits for chemicals. In this Pocket Guide the proper respirator is also recommended by NIOSH and OSHA for each chemical at: http://www.cdc.gov/niosh/npg/

Appendix D Hazardous Gasses from ARD in Sulfide/ Coal Mines

Sulfides minerals (e.g. marcasite, pyrite and chalcopyrite) produce acid rock drainage (ARD). Pyrite is the most important mineral in producing ARD at mine sites. Yet, pyrite in the sediments such as shale and sandstone is more reactive than the hydrothermal pyrite (Hammack et al., 1988). When pyrite oxidizes, sulfate and acidity are released (see Equation D-1). As the reaction continues, each mole of ferrous ion consumes one mole of acidity to form ferric ion. Therefore, Oxidation of one mole of pyrite is equivalent to production of four mole of acidity (Konhauser and Bertola, 2007):

$$FeS_{2(s)} + 3.5O_{2(g)} + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad \text{(D-1)}$$

$$2Fe^{2+} + 0.5O_{2(g)} + 2H^+ \rightarrow 2Fe^{3+} + H_2O \quad \text{(D-2)}$$

In the presence of oxygen and water, pyrite oxidizes to ferrous ion and sulfuric acid. Ferrous ion will form ferric ion in the presence of oxygen and sulfuric acid, and once the dump is well-populated with T. ferrooxidans and other acidophilic microbes, the ferric levels can increase the rate of generation by several orders of magnitude (Nordstrom and Southam, 1997).The ferric iron is readily transferred away from active pyrite oxidation zone and wont contact with any sulfide mineral in the site. Ferric ion then hydrolyses the water and precipitates as iron hydroxide (e.g. jarosite). This process adds more acidity to the water (Konhauser and Bertola, 2007).

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ \quad \text{(D-3)}$$

Further on pyrite starts to be oxidized by dissolved ferric ion:

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{3+} + 2SO_4^{2-} + 16H^+ \quad \text{(D-4)}$$

Sulfide minerals, water from rain and oxygen supply in the vadose zone of the sulfide waste or heap as well as the carbon from carbon dioxide influx from the surface meet all the needs for the sulfide - oxidizing microorganisms. Acidithiobacillus ferrooxidans (formerly known as Thiobacillus ferrooxidans) establish themselves in sulfide-bearing waste (tailing or waste dump) within two weeks of colonization accelerate the reaction. Although these bacteria start their activity in fine-grained pH-natural gray sulfide bearing tailings, they turn them yellow acid producing residues through time. In anoxic and acidic environment with the absence of these bacteria, ferrous iron is stable in the above reaction. Once the environment becomes more alkaline and aerated the oxidation and hydrolysis begins in the presence of these bacteria. Therefore, periodic rainfalls cause more ARD generation as they cause aeration and remove oxidation products to expose new pyrite surfaces. Even when oxygen is not present to oxidize pyrite, the bacteria is able to oxidize elemental sulfur or hydrogen to reduce Fe^{3+} and generate acidity (Konhauser and Bertola, 2007):

$$S^{0} + 6Fe^{3+} + 4H_{2}O \rightarrow 6Fe^{2+} + 8H^{+} + SO_{4}^{-2} \qquad \text{(D-5)}$$

Although here the bacterium reduces the sulfur to generate acidity, it does not form hydrogen sulfide. Hydrogen sulfide is generated only by specific kind of sulfur reducing bacteria in anoxic conditions in the presence of sufficient organic matter (see Appendix C.9). The above reaction takes place at the center of anaerobic waste dumps or heaps that does not receive oxygen. The ferric iron is provided by aerobic bacterial activities at the surface (Konhauser and Bertola, 2007). ARD becomes significant when acid is accumulated in sulfide waste's pore water. This can be caused by the waste dump becoming sealed during the winter because of freezing. During the spring melt when the ice is melt and drainage unplugged then acid will be discharged. The opposite condition is also true, the heavy rainfalls can wash the acidity so the pH stays around neutral and this will reduce the microbial population and thus the ARD will become less for a short time as the bacterial colonies can come back in 6 months. On the ground that receives ARD (pH of 2 to 4) an ochreous color surface is built because of the Schwertmannite (Fe_8O_8 $(OH)_6$ SO_4) and jarosite ($MFe_3(SO_4)_2(OH)_6$) precipitation. This yellow surface forms because of the oxidation of the Fe^{2+} in contact with fresh water (the same color as the ARD sampling sump).

At higher alkalinity, the neutralization occurs which will result in iron hydroxide or goethite formation (Konhauser and Bertola, 2007). When carbonate minerals such as calcite (or dolomite) are present at the site, CO_2 is produced through following reactions (Konhauser and Bertola, 2007):

$$CaCO_{3(s)} + 2H^+ \rightarrow Ca^{2+} + H_2CO_3 \qquad \text{(D-6)}$$

$$CaMgCO_{3(s)} + 4H^+ \rightarrow Ca^{2+} + Mg^{2+} + 2H_2CO_3 \qquad \text{(D-7)}$$

$$H_2CO_3 = H^+ + HCO_3^- \qquad \text{(D-8)}$$

$$HCO_3^- = H^+ + CO_3^{2-} \qquad \text{(D-9)}$$

$$H_2CO_{3(s)} \rightarrow H_2O + CO_{2(g)} \qquad \text{(D-10)}$$

The neutralization of strong acid with carbonate will increase the concentration of carbon dioxide. Therefore, P_{CO2} of water becomes greater than that of the atmosphere and it exsolve from the water in tranquil settling ponds (Pearson and McDonnell, 1975). Although this helps with acid neutralization, it elevates the carbon dioxide level of the surroundings. Consumption of 1 mol of oxygen by pyrite oxidation with carbonate buffering may produce (Lee et al., 2003):

1- 0.2 mol of CO_2 in gneissic waste rock where mean sulfide content is 0.1 wt.% and mean inorganic and organic carbon contents are 0.1 and <0.05 wt.% respectively ;

2- 0.5 mol of CO_2 in lake sediments where mean sulfide content is 0.01 wt.% and mean inorganic and organic carbon contents are 0.5 and 0.7 wt.% respectively;

3- 0.7 mol of CO_2 in forest soil where mean sulfide content is below detection limit and mean inorganic and organic carbon contents are 0.5 and 1.4 wt. % respectively.

Rates of oxygen consumption and carbon dioxide production is about one order of magnitude greater in lake sediment than in gneissic waste rock due to higher organic carbon content. This fact shows that distribution of oxygen-depleted and carbon dioxide elevated gas in waste dumps which are constructed on the dewatered lake sediments is more significant (Lee et al., 2003).

If water with elevated carbon dioxide from the above reactions is traveling under the ground carbon dioxide may not find a way for dispersion, because the underground conduits are most likely filled with water. In some cavities under the ground that are partially filled with water, dissolved carbon dioxide will accumulate on the empty area (White, 1988). The elevated carbon dioxide caused by above mechanism is a threat for elevated carbon dioxide at peoples' houses built above these empty areas. This problem can occur in caves as well. The air-filled-caves built in limestone as well as vertical solution openings may act as a storage place for carbon dioxide and other hazardous gasses. Gasses can accumulate in these confined areas from various sources such as leaks from pipelines, storage tank or solid waste. Toxic flammable gasses may leak to people's houses and be confined in their basements (White, 1988). An understanding of the chemical kinetics of carbonate dissolution and carbon dioxide equilibrium at water air interface is important in understanding the carbon dioxide exsolution from water contaminated by carbon dioxide (Hess and White al., 1989).

The degassing of carbon dioxide from the groundwater coming from carbonate rock can cause an atmospheric hazard. Sometimes ARD is in close relation with caves formed in karstic limestone. For example Mississippi valley lead and zinc type minerals which are formed in limestone can have this type of problem. This makes the ARD remediation more important from the view point of atmospheric hazard with carbon dioxide. Some fatalities related to carbon dioxide emission from same reactions have been reported in the literature. Accident caused by methane bearing water seepage in a dam at Carsington, U.K. is an example of this – see Section 3.4.1.

ARD in waste dumps is not the only source for oxygen-depletion and carbon dioxide generation. Alteration at active or reclaimed underground or open pits also can generate these gasses. The relation between carbon dioxide and oxygen-depleted air in the pore space on top of sulfide ores with a carbonate gangue has been studied by Lovell and Hale (1983) and Watmuff and Morris, (1993). Alteration at active or reclaimed underground or open pits can generate these gasses along with elevated amounts of He, CO_2, CS_2, SO_2, COS and H_2S (Hinkle and Dilbert, 1984). Among all of these gasses oxygen-depletion and CO_2 levels appear to be the main causes of serious hazard in enclosed structures on top of such altered zones.

Watmuff and Morris (1993) found CO_2 anomalies at top of the sulfide deposits in South Africa. Study of the soil samples from Bell porphyry deposit near Tucson, Arizona showed elevated amounts of helium, carbon dioxide, carbon disulfide, sulfur dioxide, carbonyl sulfide and hydrogen sulfide (Hinkle and Dilbert,1984). The minerals in this deposit were pyrite, chalcopyrite, and chalcocite at the depth of 10-40 m (supergene zone) beneath the leached cap. Samples were taken from 0-5 cm above the deposit after removing surface debris. The results by Hinkle and Dilbert (1984), show high CO_2 (0.08 to 0.35%) and depleted oxygen above alteration zones. In 16 of the 30 samples oxygen was measured to be 9-10% and in 11 of them it was 6-8%, and in the rest of the samples it was 12-17%. Hydrogen sulfide at low levels was detected at 4 of the 30 samples and was 100-240 ppb. Of these samples, 3 were above alteration zone. Carbonyl sulfide was also detected between 140-570 pbb. Carbon disulfide amount was between 100-1000 pbb in 17 of the samples, and sulfur dioxide was detected in 9 of the samples in the range between 300-1000 ppb (Hinkle and Dilbert, 1984). Hinkle and Dilbert (1984) refer the elevated SO_2 detection to aridity of the area which allows SO_2 to reach to the surface before changing to SO_4^{2-}. Ball et al., (1985 and 1990) examined CO_2 and oxygen-depletion in many sulfide deposits. In all of the studies, gas anomalies showed decrease in arid seasons or arid areas (Ball et al., 1990). However, sulfide deposits in South Africa did not show any anomaly of these gasses in dry season where no oxidation was occurring (Watmuff and Morris 1993). Lovell et al., (1982) referred the reduction of CO_2 and oxygen-depleted gas anomaly to the lower sulfide oxidation rate under reduced water table conditions. The soil moisture controls biological activities in soil which controls the oxidation rate (Lovell et al., 1982).

Oakes and Hale (1985) demonstrated elevated amount of COS about 1500 ppt, above sulfide oxidized mineralization. COS showed anomalies around 500 ppt with background of 200 ppt in arid and semi-arid areas. However the anomalies exceeded this value and reached up to 750 ppt when COS in the background was 100-500 ppt. COS anomalies did not show coordination with rises in organic content in the soil. CO_2, O_2 and CH_4 have been measured over a Crandon massive sulfide deposit (Wisconsin) (McCarthy et al., 1986). Deposit is covered by 65 m glacial drift. Methane showed anomalies as high as 25 times more than the background (930 ppm). Oxygen was depleted up to 4.5%, and CO_2 showed elevated levels up to 3.8%, and no H_2S, CS and SO_2 were detected. SO_2 is highly soluble in water and readily converts to SO_4^{2-} (McCarthy et al., 1986). High methane concentration was related to 2.45% carbon that was present in the area and the black shale in Crandon deposit (May and Schmidt, 1982). Taylor et al (1982) stated that CS_2 and COS are the dominant sulfur gasses from sulfide minerals (pyrite, chalcopyrite, sphalerite and galena). They found anomalies of these gasses at oxidized sulfides at vitro. Hinkle et al (1990) examined the drill cores from Santa Cruz copper deposit in Arizona for soil gasses. They examined the gasses in finely grained crushed samples that have been weathered artificially (without the presence of any bacteria). They found elevated levels of SO_2 (up to 2284 ppb), COS (up to 391 ppb) and CS_2 (up to 79 ppb) in wet conditions. Hinkle et al., (1990) summarized the probable reactions responsible for COS generation as follow:

$$4FeS_2 + 15O_2 + 8H_2O \longrightarrow 2Fe_2O_3 + 8H_2SO_4 \quad \text{(D-11)}$$

$$O_2 + 2H_2SO_4 + 2FS_2 \longrightarrow 4S + 2FeSO_4 + 2H_2O \quad \text{(D-12)}$$

$$\frac{1}{2}O_2 + CO_2 + 2S \longrightarrow COS + SO_2 \quad \text{(D-13)}$$

or

$$\frac{1}{2}O_2 + COS + 2S \longrightarrow CS_2 + SO_2 \quad \text{(D-14)}$$

Stedman et al., (1984) removed the organic matter in the samples by rinsing it in HCl and acetonitrile (CH_3CN), then again washed the sample with HCl and boiled it in water for 20 min. their results showed that the generation of COS and CS_2 is related to the presence of dissolved organic material in groundwater. They also examined the effect of bacteria by sterilizing the samples. Results showed that bacterial activity has no essential effect on the production of COS and CS_2. SO_2 or H_2S were not observed in their experiments.

Based on Material Safety Data Sheets from Arkema Inc., Carbon Disulfide (CS_2) is a hazardous chemical which is flammable, skin irritant, toxic and causes nervous system effects. At levels greater levels than 400 ppm it is immediately dangerous to life or health (Lentini and Armstrong, 1997). Carbonyl Sulfide is a colorless flammable and toxic gas. High concentration of this gas (>1000 ppm) can cause sudden collapse and death (Hazardous Substances Data Bank. 1994). COS and CS_2 in sulfide dumps concentrations seems to be negligible at sulfide waste dumps.

Oxygen-depletion and carbon dioxide hazard from altered zones of the sulfide deposits in Table D-1 are not a danger. This is because these gasses will disperse in the atmosphere. A problem occurs if the pit, ditch, tunnel or manhole in the ground confine these gasses.

Table D-1. Pore gas in soil above mineral deposits.

Ore deposit	Mineralization	Gangue	ΔO_2[a]	CO_2	Overburden	reference
Long rake	Sphalerite fluorite and barite deposit mineralized in limestone	Fluorite barite	~3.5%	~2%	15 m shale, 5 m glacial till	Ball, et al. 1985
Cae Coch, Gwynedd	Massive sulfide ore located in pyrite and quartz. Carbonate veins (mostly gypsum) has intruded the ore body	Quartz	~6%	~1.5%	Pyritic black shale	Ball, et al. 1985
Teign Valley Devon	Sphalerite, Galena and tetrahedrite	Barite and Quartz	-	2% - background is 0.2-0.5%	2-4 m of brown earth and Head	Ball, et al. 1985
Hemerdon Devon	Tungsten and tin mine consisting Wolframite, arsenopyrite and cassiterite	Granite dyke	~5%	~9%	Head and regolith	Ball, et al. 1985
Dalny mine, chakari, Zimbabwe	Gold mineralization in Quartz carbonate sulfide stringers	hosted in shear zone within Archaean mafic greenstone	~0.4%	~0.2-0.8%	More than 1 meter of red-brown ferralitic clay rich residual soil covered by 0.3 m waterlogged soils	Ball, et al. 1990
Ashnati mine, Obuasi, Ghana	Gold mineralization with pyrrohotite and arsenopyrite bearing quartz stockwork	Massive quartz reefs and sulfide-carbonate rich shear zones	~0-3%	~1-3%	5 m or residual ferruginous soils	Ball, et al. 1990
Ngwako Pan mineralization, Lake Ngami, Botswana	Stratiform copper deposit, with calcareous argillite, chalcocite, bornite and chalcopyrite	Sandstone	-	~0.1-0.8%	Various thicknesses of unconsolidated sands with calcrete	Ball, et al. 1990
Johnson Camp, Tucson, Arizona	Low grade Cu-Zn- sphalerite, chalcopyrite and Bornite in Tertiary quartz monzonite stock intruded into Paleozoic sediment	Metamorphosed limestone	~ 0.75% - background is 0.1-0.3%	~0.9% - background is 0.1-0.3%	Pediment gravel and Alluvium	Lovell et al., 1982
Ash Sha'ib, Jaddah, Saudi Arabia	Cu-Zn Sulfide	Precambrian amphibolites, hornfels gneisses, calc-silicates and dolomite	0.2-0.5% - Background is ~0.05%	0.2-0.25% - Background is ~0.05%	Unconsolidated wadi sediments (comprise mainly of sand) 4-8 m thick	Lovell et al., 1982
Witvlei, south west Africa Namibia	Chalcopyrite with Cu mineralization (2%)	Sedimentary sequence of conglomerate, grits, sandstone, arkoses, siltstone, and claystone	~0.3-0.5% background is 0.05-0.2%	~0.4-1% background 0.05-0.2%	2 m Kalahari sand	Lovell et al., 1982

a **Depletion of O_2 from 21%**

Appendix E Literature Knowledge Acquisition for Gas Generation and Emission

E.1. Convective and Diffusive Gas Flow in Waste Dumps

In attempting to understand how pore gas flows into and out of a dump, one must examine the rate-controlling mechanism in the oxidation of contained sulfide minerals as well as the consumption of carbonate minerals by generated acid emissions. The reaction in waste dump is controlled by dissolved oxygen, ferric ion, and water (Ritchie, 1994). The oxygen level is a function of waste composition and variation together with cover permeability (Harries and Ritchie, 1987) which controls air diffusion and water transport into the dump. According to Collin, (1987): there are four transport mechanisms in the waste dump:

1- Gas transport due to pressure difference, called advective flow
2- Gas transport due to temperature difference called convective flow (or sometimes called advective flow as well)
3- Gas transport because of concentration difference called diffusive flow
4- Gravitational transport of water which brings dissolved oxygen into the dump

Oxygen transport is a major rate-limiting factor in sulfide mineral oxidation. Sulfide oxidation within the dump generates heat that accelerates oxygen (air) transfer into dumps with high permeability by a process called thermal convection (Lefebvre, 2001(a)). In the early years of the dump, air diffusion is the main transport mode. The zone where diffusion is rate-controlling is a relatively short distance (Ritchie, 1994) and can be diminished by covering the dump with a layer of impermeable clay or glacial till. Oxygen consumption generates a gradient between gas in the dump and the outer atmosphere (Lefebvre et al., 2001(a)). When the dump is constructed, most oxidation occurs near the sides of the dump and over time the main oxidizing zone moves into the centre.

While diffusion control is limited to a surface zone of a few meters, advection (from thermal gradients, wind-pressure gradients, and barometric pumping) can move air deep into a pile (Wels et al., 2003). As time passes, heat accumulating from oxidation by this diffusive air establishes convective flow conditions in high-permeability dumps (Ritchie, 1994). During fall and winter, upper dump temperatures fall below those in the interior and oxygen gas levels increase at the bottom by convection as the central warm air rises, pulling in fresh cold air at the toe (Lefebvre et al., 2001(a)). Mineral reactivity and quantity, coarseness, and spatial variations affect convective flow (Wels et al., 2003).

Sulfide oxidation increases the dump temperature. The increase in temperature will cause changes in pressure and gas composition which will induce more gas flow. The gas flow will then increase the temperature of a dump to the point that the dump "pulls" even more air (oxygen) into the dump. This process is called self-acceleration of sulfide oxidation by Lefebvre et al, (2001(a)). Therefore convection leads to increased air flow into the dump (depending on the sulfide content more oxygen than needed for oxidation may be self-supplied), but this inflow may be limited to small areas on the slopes of the dump (Sracek et al., 2006; Lefebvre, 2001(a)).

Ritchie, (1994) considered convection due to an internal temperature gradient as a major mechanism drawing air in at the bottom. Heat given off internally provides a temperature gradient. His model considers a dump as three idealized regions depending on the type of reactions – see Figure E-1. The outer region contains completely oxidized stable material. The second region is where pyrite oxidizes by dissolved oxygen in water. The inner boundary of this region is where dissolved-oxygen in water is so low, direct action on pyrite stops and so, in the inner region accelerated oxidation by ferric ion occurs. Carbonate buffering reactions occur in both regions, the extent depending on the amount of neutralizing minerals. These neutralizing reactions are much faster than pyrite oxidation.

Oxidation rate as a function of depth has been modeled ideally by Ritchie (1994) for an uncovered dump with high quantities of pyrite–see Figure E-2. During the early years (perhaps as long as 40), the first zone does not exist and oxidation proceeds due to high oxygen levels in both the infiltrating air and water although the rate is relatively slow. Over time, the first zone forms and high oxygen levels in air and water are retained ever deeper in the dump. The point of the peak reaction rate descends into the dump as time passes and oxidation at depths of 20m or more is evident even after 100 years. For example according to Cathles and Schlitt (1980), when the White's dump was constructed, most of the oxidation probably occurred near the side of the dump but through years the main oxidizing zone moved further into the dump.

This model has limitations in understanding gas emissions from a dump. The effects of conditions such as pressure, temperature, wind, and precipitation (rain and snow) must be accounted for in order to predict acute health hazards. Air flow in and out of a dump is a complex phenomenon that varies greatly at different locations on the surface and at different times.

Internal temperatures can vary greatly depending on material heterogeneity in different zones. With high reaction rates in zone 2 and 3 from high sulfide levels (20 to 80 %), these internal regions may reach 85°C (Wu et al., 2005) causing significant vertical convective flow that draws air in through the side walls and at the toe.

The temperature profile in borehole 1A in Number One Shaft Waste Dump shows the pick in internal temperature at region 2 at the middle of the dump - see Figure E-3. The atmospheric temperature changes affect the temperature of the waste dump near surface, while the temperature variation is similar for different seasons at depth. Oxygen concentration remains below about 6% in all depths in borehole 1A, while carbon dioxide is about 7%.

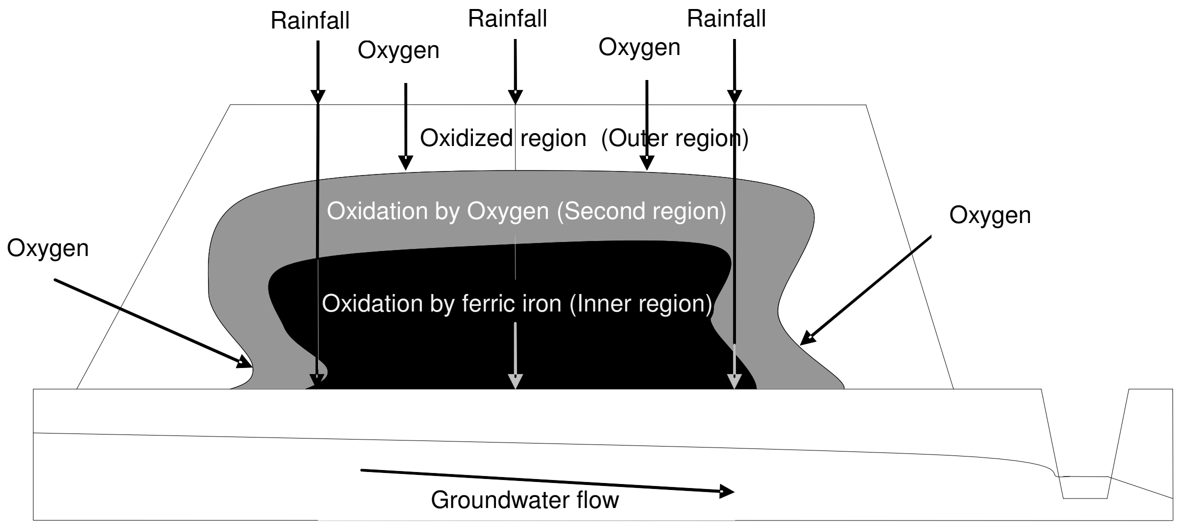

Figure E-1. Oxidation rate at a sulfide waste dump (depth and time after construction) (Ritchie, 1994, adapted by permission).

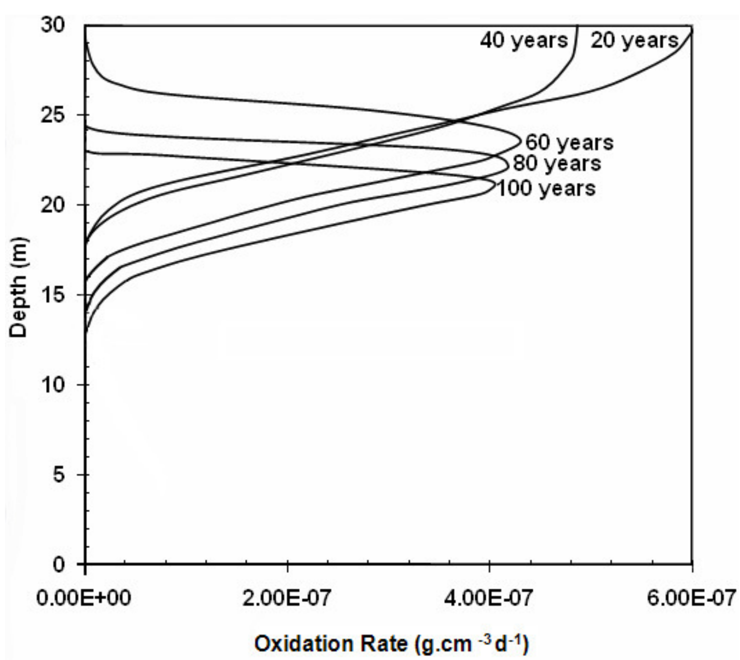

Figure E-2. Depiction of the three reaction zones in a sulfide waste dump (Ritchie, 1994, adapted by permission).

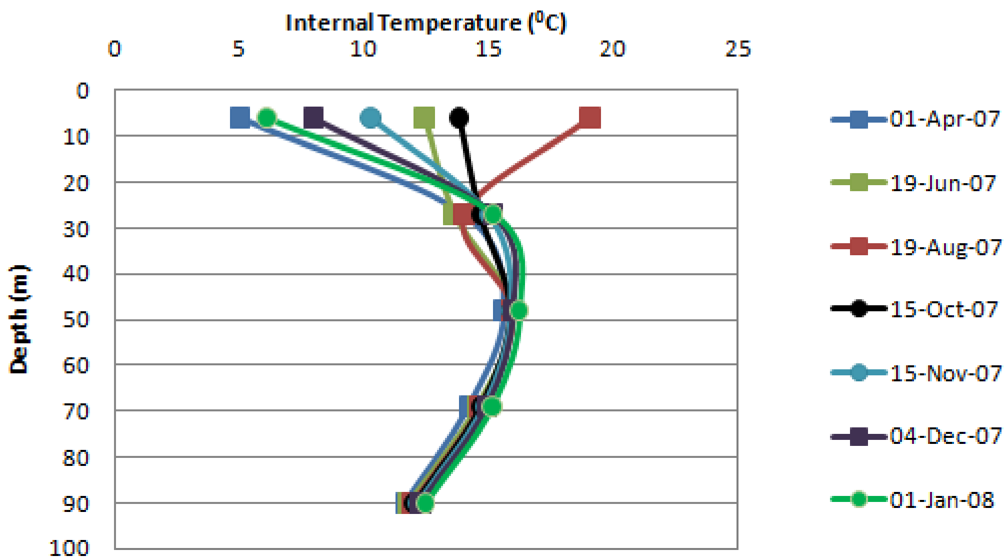

Figure E-3. Temperature profile in borehole 1A in No. 1 waste dump (data were provided by technical panel of the Sullivan mine accident, Teck Metals Ltd.).

E.2. Gas Generation and Emission

Depending on flow direction, convection can either bring more oxygen into the dump or can create more oxygen-depleted air within the dump (by not supplying enough air for oxidation) which if it finds a way out, will blow to the outside. So, the extent of gas emission and sometimes gas generation at the top and bottom of the dump depends on the direction of convective flow (Mohammadi and Meech, 2011). If convection moves air into the dump at the bottom, hazardous gas emission will be "Low" for an enclosed structure located there but "High" for structures erected on top of the dump. In this case, gas generation is independent of emission (either "Low" or "High" depending on the reactivity of the dump material) even if gas movement into the dump increases oxygen content and heat generation within the dump. The increased heat will move even more fresh air (hence oxygen) into the bottom of the dump by convective flow as the hot gasses rise through the dump to the upper surface (Lefebvre et al., 2001(a)). On the other hand, if convection causes gas to flow out of the bottom of the dump, then gas generation and emission values will both be "High" for a structure located at the bottom of the dump (Mohammadi and Meech, 2011). In this case, if the pore gas becomes trapped in an enclosed structure and if the probability of human exposure is "High", then the atmospheric risk is definitely "Hazardous".

However, if either gas generation or emission is "Low", then the risk might become a "Marginal Problem" because of other risk elements. Although danger is less apparent in this case, fewer elements are needed to cause unacceptable level of risk than when no risk elements are present. This feature gives the model the ability to respond quickly and adjust to future changes (climatic, operations, and design) at the site. It must be recognized that the direction of convective flow is controlled by pressure and temperature changes outside the dump (at the top and bottom) and within the dump. Modeling must consider these variables and their variations temporally and spatially. Obviously, the exact opposite effects are likely to be observed for an enclosed structure located on the top of the dump.

The oxygen level in the pore gas is determined by a balance between oxygen-depletion due to oxidation (which depends on the intrinsic oxidation rate of the sulfide surfaces) and the rate of oxygen supply into the dump. These two factors define the extent of the main sulfide oxidation region within the dump where temperatures elevate (Ritchie, 1994; Lefebvre et al., 2001(b); Sracek et al., 2004). For example, in the Nordhalde dump, as one moves from the centre to the edges of the dump, the oxidation rate increases because oxygen is at a higher level in the pore gas at the slope boundaries generating a more extensive oxidation zone that over time slowly moves into the dump from the edges (Figure E-4) (Smolensky et al, 1999).

Seasonal changes in atmospheric temperature determine the gas flow direction (Phillip et al., 2008). Seasonal effects on gas flow can be seen in the Nordhalde dump (Figure E-5) where during the cold season (when the internal temperature is higher than outside) the flow direction (into the dump) increases oxygen concentration within the dump, i.e., a situation of low hazardous gas emission and generation. The difference in the outside and internal temperatures provides the driving force for gas movement and will differ from one waste dump to another depending on permeability and reactivity. Sometimes the driving force for gas flow is stronger and remains active for a longer period of time such that the oxygen concentration may actually move up to 19-21% and appear to be non-hazardous. At Nordhalde, the oxygen level never exceeds 8% because of high reactivity and low permeability – "High" reactivity consumes oxygen quickly while "Low" permeability inhibits significant gas flow.

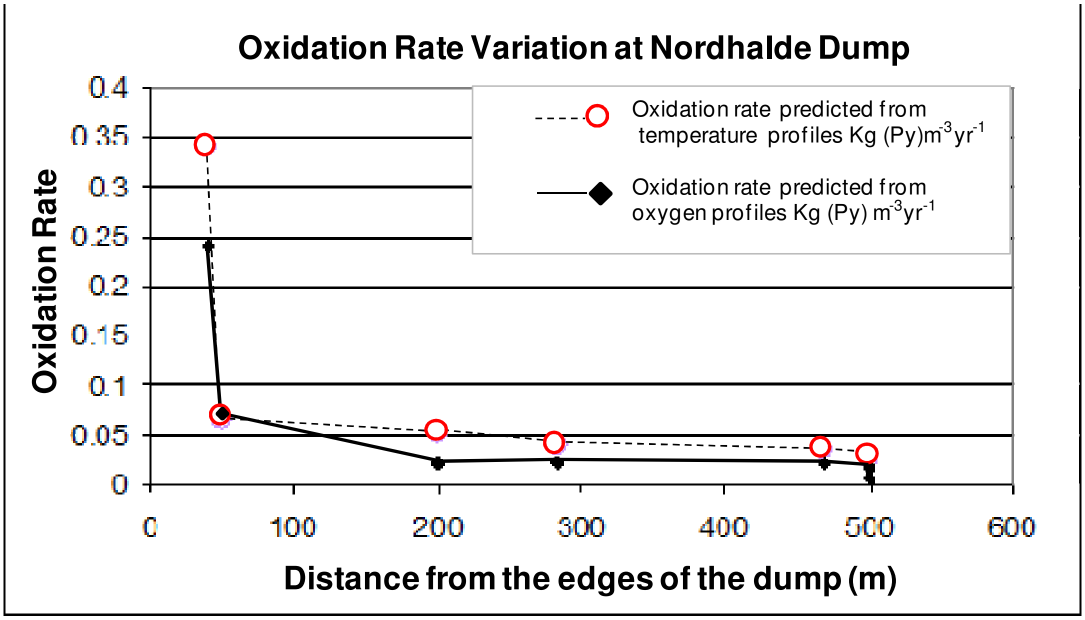

Figure E-4. Oxidation rate declines when moving from the edges of the waste dump (Smolensky et al, 1999, adapted by permission).

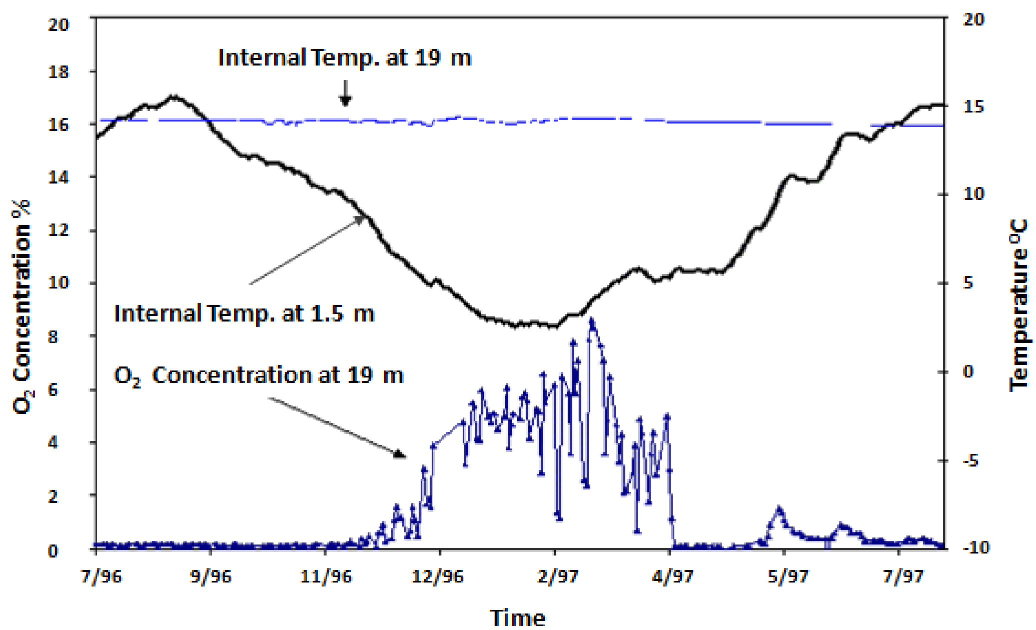

Figure E-5. Oxygen levels and temperatures in borehole 36 (near the edge) in Nordhalde dump (Smolensky et al, 1999, by permission).

Taken together, temperature differences and changes, "Low" permeability, and “High” reactivity in the Nordhalde dump increase the fuzzy value of "Low" for hazardous gas generation to "Moderate". The reactivity of the Nordhalde dump is "High" because it has "Moderate" sulfide content and contains fine materials (due to Low permeability).

At West Mt Lyell Dump the average sulfide content of the materials is 5% (Garvie et al., 1997). The north arm of the West Lyell Dump has an area of 25 ha and is up to about 90 m high. Oxygen and temperature profiles were measured at 9 probholes in this waste dump to investigate the oxidation rate. The measurements were done for the period of August 1993 to July 1994. According to Garvie et al., (1997) throughout most of the dump the oxygen concentration were close to the atmospheric value, which was because the mine was located in the area in Tasmania which was subject to westerly winds. The wind driven advection was responsible for sustaining the oxygen amount at the dump. An upper estimate for the oxygen consumption rate based on temperature profiles in this dump was 0.18 kg (O_2) $m^{-3}y^{-1}$ (Garvie et al., 1997), this rate according to Ritchie (1994) is "High" and it could be the result of extremely "High" sulfide content in the dump."High" oxidation rate in the dump can cause "High" internal temperatures (35 - 40 ^oC) which in return causes "High" oxygen concentration within the dump. Therefore, "High" sulfide content although causes oxygen-depletion and "High" gas generation, since it causes "Higher" internal temperature it induces more gas inflow which eventually causes "Lower" oxygen-depleted gas generation and emission at the toe of the dump.

Waste dumps are also sources of carbon dioxide which creates another hazard by displacing the oxygen and causing toxicity. The amount of acid generated is equal to the amount of acid neutralized by carbonates after the first 1.5 to 3 years depending on how much lower the rate of acid consumption is at natural pH. After this time a transition from natural pH to acid conditions may occur. Calcite can significantly be reduced in particles smaller than 5 to10 mm in a few years. The remaining calcite is present at the waste rock even when the acid condition is developed. Silicate weathering extends the transition time compared to calcite dissolution as the only source of alkalinity. In longer transition times (as a result of slower sulfide oxidation over time), the contribution of silicates over time will become important (Stromberg and Banwart, 1999). Because of the large reservoir of silicates this will continue until all the sulfides are consumed.

Although till cover may contain a "High" carbonate level, because of its shallow depth, it does not contribute to a high carbonate level in dump material. Although waste dumps which consist of glacial till can have an elevated risk of carbon dioxide accumulation at the surface. In such a situation even a small digging can raise a problem. In some fully-neutralized waste dumps carbon dioxide can vary from 20-60% (Hockley et al., 2000). The carbon dioxide level at White's Dump is 5% which is "High". In this dump much of the overburden materials consist of carbonaceous slates and graphitic schists which give the dump a dark gray color (Harries and Ritchie, 1980).

E.3. Intermediate Factors

E.3.1. Permeability

Permeability indicates the flow of gas and fluid to react with sulfide and generate heat (Wels et al, 2003). Many writers believe that convection is not a significant mechanism in waste dumps with permeability of less than 10^{-10} m^2 (Pantelis and Ritchie, 1991; Bennett et al., 1989). Instead it is believed that convection is significant in dumps with a permeability of 10^{-9} m^2. The permeability of the Nordhalde dump among all dumps examined was lower than that which these authors believed prevented the onset of thermal convective gas flow. However the oxygen profile for the a dump in Nordhalde mine in Germany shows seasonal changes that are caused by convective oxygen-flux changes according to Lefebvre et al., (2001(a)) – see Figure E-5. Therefore the permeability of the Nordhalde dump appears sufficient to allow high gas flow in and out of the dump. As such, it can be concluded that convective flow is established at the base of all waste dumps but may vary seasonally in direction.

Analyzing different waste dumps it was concluded that for the base of waste dumps regarding to their range of water content and porosity the effective air permeability is higher than $1*10^{-12}$ m^2. The method of dumping also affects the gas and water flow into the dump. End dumping method in many dumps causes very high effective gas conductivity at the base of the waste dump. Less water content is indicative of the bigger particle size and thus higher hydraulic and air conductivity, mainly because higher water content (or water saturation) is the result of capillary effect in smaller size particles. The use of face dumping causes gravitational sorting of the materials, causing the rubbles to gather at base. Face dumping forms layers of coarse and fine materials, where the coarse materials at the base allow the oxygen rich air to blow inside the dump and the fine layer provide water flow. The warm oxygen-depleted gasses can blow out of the dump from inclined coarse materials (chimney effect) (Wels et al, 2003).

Although the permeability of a dump is usually high enough to move oxygen in and gas out of the dump, decreased permeability can slow gas emission as observed at the Nordhalde dump. This effect of permeability is projected in oxidation rate and therefore on the internal temperature estimation. To effectively reduce convective air movement, covers with permeabilities of 10^{-13} m^{-2} are often used (Wels et al., 2003). Permeabilities as low as the permeability at mine tailings will inhibit the free convective flows and will cause in lower oxygen content than the waste dumps. However, oxygen transport to the centre of the dump can still occur by diffusion even in a high permeability waste rock piles that has previously established convective gas flow (Ritchie, 1994; Lefebvre et al., 2001(b), Sracek et al., 2004, Wels et al., 2003). According to Kuo and Ritchie (1999), in dumps with a high width-to-height ratio, diffusion dominates gas transport into the centre of the dump while convection is the main mechanism at the extremities or edges.

Lefebvre et al., (2001(a)) have applied a method that was introduced by Brooks and Corey (1964) for unsaturated soil to estimate the effective air permeability given the capillary properties of the waste rock. Using this approach, they were able to derive the capillary parameters by Rawls and Brakensiek (1985) method given the porosity and clay percentage of the waste materials. Therefore in order to estimate the effective air permeability by this method, only water content (or water saturation), porosity and clay and sand percentage were needed. This method is not applied in this thesis due to the fact that it is very sensitive to correct percentage of clay and sand. Because usually waste dumps contain a large range of particle sizes it is not possible to acquire the accurate value of these variables from the user. Instead undetermined air permeability can be estimated heuristically based on variables such as method of mining and dumping, percentage of coarse materials at the base of the dump, water saturation (or water content), channeling and type of the dump materials.

Visual examination of truck loads with waste rock and measured particle size distribution can be indicative of the percentage of particles larger than 2 dm and boulders of up to several meters in size. When these large particles comprise about 20–50% of the dump then permeability is higher. In waste dumps where the channeling has occurred there will be more gas and water flow into the dump that shows that the dump has higher permeability. Different factors such as use of horizontal layering or prevention of high permeability channels at inclined surfaces within the dump will reduce the permeability and convective flow and will decrease the oxidation rate (Wels et al., 2003). Degree of compaction and grain size distribution affected by method of dumping are two factors that have significant effects on the movement of water and gasses within waste rock piles (Morin et al, 1991). There are 4 major dumping methods categorized by (Morin et al, 1991):

1- End dumping, dump trucks deposit the waste rock directly across the crest of the pile.

2- Push dumping, trucks or conveyors dump the waste rock near the crest then the rocks are pushed over the crest with bulldozers.

3- Free dumping, first stacks (heaps) of 2 m height are made then the surface is levelled and compacted.

4- Dragline or bucket excavator are used to transport and handle the waste. This method is common in large-scale open pit coal mining.

Each of these methods has an impact on segregation of the materials and therefore they affect air permeability at the base. In method 1, three zones of different grain size can often be distinguished: an upper zone consisting of fine particles, a lower zone consisting of coarse material and a transition zone of intermediate, non-uniform grain size material. This method increases the permeability more than the other dumping techniques. The height of the slope does not seem to influence this distribution, although in general, material segregation is less noticeable for lower dump heights (Morin et al, 1991). In method 2, coarse materials are found at the base of the slope, but there is less segregation at the top of the dump. For example, in method 2, 40 per cent of the coarse material reaches the foot of the slope (compared to approximately 75 per cent for method 1), because of lower initial angular velocities of the coarse material when it is pushed rather than dumped over the crest (Morin et al, 1991; Fala et al., 2003). Method 2 also increases the permeability at the base but has less effect than the method 1. In method 3, segregation is less pronounced, and the material remains denser than in the first two methods. Method 3 is often used to initiate the construction of a rock pile, and is later replaced by method 1 or 2 when the pile is high enough. When a dragline or bucket excavator is used, (method 4), segregation is further reduced since the grain size distribution tends to be more uniform. In some cases, weak segregation can occur if the grain size distribution is non-uniform (Morin et al, 1991). Method 3 and 4 are less abundant than the first two other methods. These methods do not increase the permeability. Most waste dumps are constructed by end- dumping and to lesser extent push dumping.

Water content or saturation

The value for water content or water saturation is important in determining reactivity and permeability. If water saturation is undetermined it can be estimated given the water content, solid density, and porosity based on a number of formulas presented by Lefebvre et al., (2001(a)). In Table F-3 in Appendix F, undetermined water content was estimated for the reference and test dumps. Porosity, water saturation and bulk density are related by Equations E-1 and E-2 (Lefebvre, 2001(a)).

$$\rho_b = (1-n)\rho_s + n\rho_w S_w \qquad \text{E-1}$$

$$w = \frac{n\rho_w S_w}{(1-n)\rho_s} \qquad \text{E-2}$$

In Equation E-2, mass water content (w) is usually measured in the laboratory, mainly because it can be measured on reworked material whose density and porosity (n) are unknown. Porosity n and water saturation S_w are difficult to measure or estimate. Density of the solids ρ_s can be measured by laboratory tests. Also, the gravimetric geophysical survey can be used to estimate the global density ρ_b. Given all these parameters, the above two equations can be used to drive the values for porosity and water saturation (Lefebvre, 2001 (a)).

While rain can increase the water saturation of the cover, most likely it will not be able to change the internal water saturation of the waste dumps. For example according to Daniel et al., (1983), in white dump the moisture content within the dump does not change significantly through wet/dry seasons in the northern territory as the moisture content only changes in 2 m from the surface.

E.3.2. Reactivity

The difference in oxygen concentration at the slopes of the dump and its centre is due to direction of gas flow and high reactivity that causes the air to become oxygen-deficient when it reaches the centre of the dump. If the reactivity is slow the oxygen will be brought to deeper levels in the dump. In this condition oxygen will survive to deeper levels of the dump and if the reactivity is not too small, the chance of heat being isolated will be high. This will lead to higher temperature inside the dump (Wels et al, 2003). The difference is also because areas near the edges of the dump are more oxidized than at the centre and hence the reaction is impeded due to low oxygen levels at the centre (Ritchie, 1994). However, at this stage the influence of bacteria to sustain the oxidation controlled by the ratio of ferric to ferrous ions in the water may dominate yielding high temperatures with low oxygen level in the pore gas. This effect is apparent at the South Doyon waste dump (Borehole 4 located at its centre) which had "Low" oxygen concentration and hot conditions (Lefebvre et al, 2001 (a)). At the Oxygen levels in borehole 5 located at the center of this dump show about 6% during winter when air flows into the dump at the toe. The internal temperature at Doyon is as high as 40 ^{o}C, yet lower than the edges which approaches 65 ^{o}C. This shows that reactions at the centre are still significant even when the oxygen is almost completely consumed (Lefebvre et al, 2001(a)). In Sugar Shack South dump which has considerably lower reactivity than that of Doyon (Lefebvre et al, 2002), when air reaches the centre, it still has oxygen concentration greater than 0%. Although sulfide reactions can continue without oxygen from pore gas, oxidation rate might have been faster when oxygen is available and the high oxidation rate in the central region is generally related to oxygen supply by convection which is much higher than by diffusion at most dumps.

Temperature and oxygen profiles show more variability when convection is the dominant mechanism, where the temperature peaks at a shallow depth which is often accompanied by a peak in oxygen level in the pore gas (Timms and Bennett, 2000). When diffusion dominates, both oxygen and temperature profiles show similar peak points with an increase in temperature and decrease in oxygen concentration from surface to depth (Timms and Bennett, 2000) (e.g., site 7 and site TBT at the Doyon dump, Wels et al., 2003). Observation of such pick especially at Nordhalde dump further supports the conclusion that all dumps are sufficiently permeable for mass transport of air/gas by convective flow (Lefebvre et al, 2001a).

Another factor affecting exposed sulfide is the water infiltration rate which washes the surface of the rocks and removes reactant products. High evaporation and run-off causes lower infiltration rates. If channeling exists on the dump surface it is incorrect to assume high exposed sulfide surfaces due to high infiltration rates because channeling water does not pass through the waste dump (Morin, 1991), although it may create hot spots. As a result only 15-30% of the surface area inside the dump is washed in these cases (Morin, 1991). Run-off depends on the geometry and cover of the dump. Methods of dump construction are important in assessing permeability. For example, channeling results from end-dumping. Visual observations can help recognize channeling effects - large cavities and pores observed on a dump surface is indicative (Morin, 1991). Premature snow melt on the surface of Number One Shaft Waste Dump caused by upward movement of hot gasses also indicates internal channeling. A high hydraulic conductivity of 10^{-3} m/s indicates channeling is the main water transport mechanism at the site (Morin, 1991).

In assessing ARD, an annual precipitation of 25 cm per year is regarded as a threshold value below which the dump will not have any water infiltration and no leachate emissions (Savci and Williamson, 2002). This will occur in arid climates where annual precipitation is about 22 cm in wet months and 0.20 to 0.25 cm in dry months (Savci and Williamson, 2002). At windy sites, evaporation will be higher and infiltration lower with colder months usually twice as windy in arid climates (Savci and Williamson, 2002). According to Hutchison and Ellison, (1992) conditions that produce no leachate (seepage) or negligible quantities are those cases where percolation (net infiltration) rates are extremely low 3.14 cm/yr and will produce no or negligible quantities of leachate.

The net Infiltration rate at the waste rock stockpile in Ajo mine was predicted to be around 0.33 to 0.61 cm per year. Based on the net infiltration threshold value, it is unlikely that the potential future or existing waste rock stockpile at the Ajo mine have the potential for future discharge to the underlying aquifer, although the water content at waste rock stockpile Ajo mine varies between 1-6% (Savci and Williamson, 2002). This shows that if a waste dump does not have potential for discharge in aird and semi-arid areas, the sulfide oxidation will not stop because of the lack of moisture as the water content in these areas is likely >2% which is enough for the oxidation.

Water content for the particles with sizes of 0.1, 0.6 and 2 mm is 19.9-22.0, 17.2-23.6 and 1.6-2.2% respectively. Hollings et al., (2000) selected 0.6 and 2 mm size particles to test the effect of varying water content on the oxygen consumption rate, in order to understand the effect of grain size and water content on the oxygen consumption. They conducted a kinetic test on 5 different grain sizes of sulfide materials for low sulfide waste rocks (about 0.5 wt % S). The oxygen consumption rates decreased with increase in particle size. Also if the water content is between 5-10% then the oxidation rate (oxygen consumption) showed the highest value, for particles between 0.6 mm and 2 mm. Reaction rates with zero water content were predictably low (Hollings et al., 2000). In his study the average oxygen consumption rate was measured as follow:

0.1 mm (fully drained) → 1.73E-09 (mol O_2 kg^{-1} s^{-1}),
0.6 mm (fully drained) → 2.62E-10 to 7.01E-10 (mol O_2 kg^{-1} s^{-1}),
0.6 mm (water content of 5-20%) → 1.21E-9 to 1.48E-9 (mol O_2 kg^{-1} s^{-1}),
2mm (water content of 0-10%) → 4.53E-10 (mol O_2 kg^{-1} s^{-1}),
2 mm (Fully drained) → 3.05E-10 to 7.16E-10 (mol O_2 kg^{-1} s^{-1}),

13mm → 2.43E-09 (mol O_2 kg^{-1} s^{-1}),

25 mm → 4.53E-10 (mol O_2 kg^{-1} s^{-1}),

Shortly after emplacement of the cover on White' dump, it was assumed that there was effectively no percolation of water through the dump. This was because cover was designed to reduce the amount of water percolating through the dump to less than 5%. Measurements of the amount of water collected in lysimeters under the covers have confirmed this low infiltration rate (Harries and Ritchie, 1987). Net infiltration is the water that is not extracted by evapotranspiration and moves to the soil zone and infiltrates into the underlying waste rock. This shows that even with a very effective cover water content stays "moderately enough" for oxidation to continue. This shows that effective covers will not decrease the water content to the amount that stops the oxidation. Especially because under unsaturated flow conditions typical in dry climates water will flow through finer rocks than the coarser materials (Newman et al., 1997; Swanson and O'Kane, 1999).

Many of the factors affecting dump reactivity depend on the method of dump construction and the method of mining. Also resloping of the dump during rehabilitation sometimes can crush the coarser materials and increase the exposed sulfide (personal correspondence with Mark Phillip). As a result resloping and reshaping of the waste dump will increase the reactivity.

Oxidation rate is higher if more than 15% of the dump is made of particles with diameters less than 0.1 mm (Holling et al., 2000). The particle size rate dependence and particle size distribution are such that in waste rock where 27% of the total mass has diameters less than 0.25 mm, this amount will accounts for 80% of both sulfides and silicates weathering. The fraction of the smaller materials has much more influence on the oxidation rate than the larger particles. The corresponding time for oxidation of larger particles is much longer. The turn over time for fine particles for sulfide oxidation is more than a decade and is considerably longer for larger particles, for silicates this time is hundreds of years (Holling et al., 2000).

Even at constant sulfide content, the oxygen consumption rate is directly proportional to the surface area. The rate for the 13 mm fraction doubles that of the 25 mm particle. The rate of oxygen consumption for the 0.1 mm particles is only 10 times more than that of the 25 mm particle. The influence of the fine size particles on oxygen consumption rates is of importance in waste rock piles. The large particle sizes (>0.2m) have a minor influence on pyrite oxidation rate relative to small particles (Morin and Hutt, 1994). Morin and Hutt, (1994) suggested that for a bulk density of 1800 kg/m^3in waste rocks having 80% large fragments and 20% small particles by mass the large size fraction would compromise only 6% of the surface are. While the 0.1 mm particles and smaller particles will constitute 99% of the surface area. Therefore, usually the waste dumps made of granite stockpiles (e.g. Diavik Minesite) have lower oxidation rate (3* 10^{-13} kg (O_2) $kg^{-1}s^{-1}$) (Ritchie, 2003). While waste dumps made of brittle Sericite schist have higher oxidation rate (e.g. Doyon South dump) (Lefebvre et al., 2001 a). This is mostly because Sericite schist is more fragile and breaks into smaller particles which increase the exposed sulfide.

A chamber test was done by Sracek et al, (2006) on fresh particle sizes that range from 0.5 – 5 cm and were collected directly from blasting in south Doyon waste dump. The test was done to see the effect of particle sizes on oxidation rate. Some samples were also taken from the slope of the waste dump and were oxidized. Oxidation rate based on oxygen consumption measurements have been calculated in the laboratory. The results show that in particle sizes between 0.4-0.6 cm, the oxidation rate is about 1.2 ± 0.44 * 10^{-7} mol (O_2) kg $^{-1}s^{-1}$, and for particles between 1-4.5 cm, the oxidation rate is about 3.9 ± 0.46 * 10^{-8} mol (O_2) kg $^{-1}s^{-1}$. The effect of particle size to increase oxidation rate is limited by the amount of the oxygen available. For a waste dump where the particles are small and pyrite is mostly free, the amount of pyrite available is too high relative to the oxygen available; therefore, the reaction rate will not change for the smaller sized particle waste dumps as the pyrite is being oxidized (Lefebvre et al., 2001(a)).

If bacteria is present the oxidation rate is independent of oxygen partial pressures (Ritchie, 1994). Age is another factor that affects the reactivity of the waste dump. Older dumps will be more reactive. Mainly because the bacterial activity is established at the waste dump and also internal temperature of the waste dump has increased and has started the convective flow, unlike early ages of the dump (< 2yrs) which gas flow mechanism is mostly diffusion (Kuo and Ritchie, 1999). For example in White's Dump at Rum Jungle in the early stages (<2 years) the dump had not yet established convective flow (Ritchie, 1994).

Another factor affecting the oxidation rate is the pH, according to (Ward et al., 2004) pH< 4 is important in accelerating the oxidation rate. The oxidation rate at pH<4 varies depending on the diffusion in particle sizes of pyrite grains. Mineralogy is not the most important factor is determining the sulfide oxidation rate. Organic matter and clay coating will reduce the oxidation rate (Bush and Sullivan 1997, Bush, 2000). High organic matter will inhibit the pyrite oxidation by forming complexes with Fe^{3+}, but meanwhile it consumes the oxygen (Bronswijk et al 1993).

E.3.3. Cover

The effect of cover in different situations is demonstrated as cover effectiveness. If the water cover is used and mine waste is submerged under the water, the cover is very effective and the risk of oxygen-depleted gas generation will be zero (Wels and O'Kane, 2003). One kind of cover is a "conventional (or low hydraulic conductivity)" which is made of clay or geosynthetic membranes. A number of protective soil covers are needed to protect this kind of cover from environmental elements. Generally a low hydraulic conductivity layer is used as an oxygen barrier. Therefore if the clay layers stay unsaturated the cover will fail and oxygen will be transferred into the rock (Wels and O'Kane, 2003).

The other kind of cover is capillary barrier cover. This effect is created when fine-textured materials are placed over the coarser materials. The underlying coarser materials will not let the water to drain from the upper layer. However if the top fine-textured layer becomes saturated then the water will percolate down to the waste dump (Wels and O'Kane, 2003). Therefore, if the cover is always under saturation it will perform better.

The other form of covers is the "store and release (or evapotranspiration cover)". This kind of cover will retain and store the infiltration water as moisture for subsequent evapotranspiration. This is mostly done by keeping the water at the surface through plants roots. The plants formed at the surface at this case will stop the erosion. The efficiency of the covers differs from one site to another due to solar effects (Wels and O'Kane, 2003). For example in a sulfide waste dump (with high sulfide content) located in a sub-tropical climate with a mean annual rainfall of 1400 mm (90% occurring in 5 months), and with an evaporation of 2500 mm, dry cover was used. This kind of cover was selected because of the high evaporation at the site. The cover was made of clay as a barrier to control water flow and oxygen diffusion. The kind of the clay minerals used can affect the net percolation to the waste rock materials. For example percolation for stable clay is higher than the percolation for active clay. Also the percolation decreases by increase in cover thickness. The percolation is around 1% (as a percentage of rainfall) for active clay with thickness of 2 m, to 8% for the same clay with thickness of 1 m. Also the oxygen ingress reduces exponentially with an increase in cover thickness (Wels and O'Kane, 2003). According to Wels and O'Kane (2003), a layer with 2 meter growth medium and the compacted active clay will reduce the oxygen ingress to the waste dump. Oxygen ingress for a 1 m compacted active clay is $1*10^9$ $Kg/m^2/yr$ while for the same cover with the thickness of 2 m the oxygen ingress is around $1*10^4$ $Kg/m^2/yr$ (Wels and O'Kane, 2003).

Therefore the type of the cover is important to evaluate the availability of oxygen for sulfide oxidation. A use of non-reactive cover materials to isolate reactive materials from the zone of active flow will reduce the advective gas flow (Wels et al., 2003). Also low cover permeability depends on whether the aim is to control the water flow or air flow. A less permeable cover

($3*\ 10^{-13}\ m^2$) is able to stop the air flow, while the same cover will fail to control the water infiltration (this cover will have a hydraulic conductivity of $3*10^{-6}$ m/s). However, the hydraulic conductivity of $1*10^{-9}$ to $1*10^{-10}$m/s is needed to stop the water infiltration (Wels et al., 2003). Therefore study of the effectiveness of the covers is very important in estimating the oxygen-depletion at dumps. The type of cover can have an effect on the water content. The reclamation that utilizes 1 m uncompacted till cover will allow 40% infiltration and of course will increase the water content. While a combination of clay covers which is the most efficient cover will reduce the water infiltration rate. The compacted clay cover will allow approximately 5% infiltration (Aziz and Ferguson, 1997).

Also thicker cover should be used at the toe of the waste dump. This usually is hard due to the slope at the sides of the dump. At steeper dumps this task is harder.

Aging of the cover is also important. Aging of the cover can cause more air flow into the dump which can increase the internal temperature back to what it was before the placement of the cover. Cover deterioration was mentioned by Timms and Bennett (2000) in White dump, where 12 years after the placement of the cover, infiltration rate had increased from below 5% of the rainfalls to values ranging from 5-10 % of the rainfall. The increase in infiltration rate shows that the performance of the cover regarding to the control of the water flux has been deteriorated (Timms and Bennett, 2000). Therefore the extent of defects in the cover is important in the overall performance of the cover. Also wet periods with a low evaporation to precipitation ratio can cause the cover to saturate with water increasing its effectiveness. For example, with White's Dump, at the end of the wet season the internal temperature dropped 2 to 3 ^{o}C because of an increase in cover effectiveness due to saturation and oxygen concentration dropped to less than 1% (Harries and Ritchie, 1983). This is because air cannot pass through waste rocks or clay covers quite easily by diffusion through water because diffusion rate of air through water is very low. If 80% or more of the pore space within a cover is filled with water, the diffusion rate of air through air will be greatly reduced (Matsui et al., 2004).

E.3.4. Internal Temperature

If the range of sulfide oxidation rate is available it may be a good indicator of the range of internal temperatures inside the dump. For waste dumps, there is currently no analytical way to calculate sulfide oxidation rate (Lefebvre et al., 2001(a)) and so, field measurements are needed to provide valid data. Conventional numerical methods for estimating the oxidation rate are only applicable for fine grained homogenous materials such as tailings where diffusion is the main gas movement mechanism. In such materials it is possible to estimate the intrinsic oxidation rate given the sulfide content, and grain size distribution (Scharer et al., 1994). The bulk rates of oxidation in these materials can be calculated by diffusion transport model (Nicholson et al., 1989; Elberling and Nicholson et al., 1996, Ritchie 1994). But in waste rocks the sulfide minerals are embedded in big bulk materials with nonreactive matrix and as a result not all the pyrite is exposed. In such materials diffusion is not the only dominant oxygen transport mechanism. According to Wels et al., (2003) modeling of the multiple processes that affect convective gas flow is not as easy as diffusive gas flow. This is because the convective gas flow is a highly non- linear process which involves many interdependent processes that affect gas transport. The laboratory tests for oxidation rate are valid for places where particle sizes are small and oxygen transport is dominated by diffusion. For waste dumps there is a need to make field measurements of the oxidation rate in order to achieve valid data. This is because of the unique configuration of the sulfides in a waste rock (percentage of exposed sulfide), pockets with higher sulfide content and reactivity as well as the wide range of size distribution. Also oxidation rate values can be affected by the scale of measurements and tests. For example the chamber test results for oxidation rate in the center of waste dumps are usually one order of magnitude higher than the oxidation rate measured from oxygen and temperature profiles in the dump (Sracek et al, 2006). The data based on crushed rock samples in humidity cell and column tests give different result than field data collected in waste rock piles, because the increase in the scale of mineral weathering can lower the oxidation rate. Note that temperature and oxygen profiles at the field are used to calculate the oxidation rate and will give better results. Temperature and oxygen profiles have been used by Sracek et al., (2006) to calculate the pyrite oxidation rate because pyrite oxidation consumes oxygen and produces heat. According to Lefebvre et al., (1992) the function fitted to the curvature of temperature profile allows the calculation of generated heat which can be used to drive the oxidation rate. But having access to oxygen and temperature profiles is hard itself and if available can directly be used for the atmospheric risk assessment. Therefore, if internal temperature measurements are not available, in can be predicted from other factors in the waste dump heuristically.

Waste dump geometry has an effect on airflow as well (Wels et al., 2003). For controlling the ARD, Wels et al., (2003), have recommended some measures during the design and construction phase of the waste. Recommendations included control of air flow to lower the oxidation rate mainly by selective placement and design of the internal structure of the waste dump, for example encapsulating of reactive waste rock between non-reactive waste (Wels et al., 2003). According to Wels, et al (2003) benches even though do not represent large modifications on the surface of the waste dump, they can increase gas flow into the waste dump. Steep slopes (>43^0) also in faced-dumped rock piles increase the oxygen transfer in to the piles. For mitigating this problem, waste dump are resloped to minimize the benches and the slope (Wels et al., 2003). Numerical modeling by Wels et al., (2003) has shown that resloping will significantly decrease the gas flow.

Dumps with long slopes and low thickness (<100 m) will achieve very high convective flow. As a result such dumps maintain a high internal temperature even with a moderate sulfide content (>0.01 and <0.02). Sugar Shack South dump is an example of this situation – it was end-dumped on the slope of a mountain and stands over 450 m with a thickness of about 100 m. Convective air flow has caused very high internal temperature (40 ^{o}C) although the sulfide content is only about 0.019 in this dump (Lefebvre, 2001(b)).

Apart from the effect of age on gas emission and generation, age has an indirect effect in estimating internal temperature through reactivity as well. Waste dump should be old enough to have elevated temperatures at deeper surfaces so not only convection starts but also the generated heat will be retained. This is because the reaction surface will move towards the center as the waste dumps ages.

Appendix F Input Ranges of Reference Dump Properties for AFRA.

Note - Variables in gray color are assumed values. Also, the DoB is 100% where the values do not appear.

Table F-1. Selected confined structure (sump is this case) properties

Question about the confined structure properties	Answer (Yes, No, Uncertain)
Does the confined structure have an entrance that is big enough for a human to enter?	100
How likely is it that the person may expose their head into the structure?	0
Are people entering this confined structure?	100
Is it likely that people will enter the structure in the future because of changes in design or operation?	100
Does the confined structure contain any source of hazardous gas generation?	0
Is it likely that hazardous gasses leak from the structure to another confined structure which is atmospherically connected to it?	0
Does the confined structure has "signage" and/or requires a "confined space entry permit"?	0
Is the structure located higher than the mid-slope bench of the waste dump? (Higher the mid waist of the waste dump)	0
How likely is it that the structure will become more confined in the future due to changes made in its design?	0
Do people who enter the confined structure have authorization for confined space entry?	0
Do the people who enter to the confined structure have asthma or any other respiratory problems?	0
Have the people entering the confined structure ever felt dizzy and nauseated inside the Acid Rock Drainage (ARD) sump or any other confined structure?	0
Have you ever seen dead wildlife inside or around the confined structure?	0
Does the structure become covered by snow?	0
Is there an operating fan present in the confined space?	0
Are there windows and doors present at the confined structure?	30
Are other hazardous gas control devices (such as U-tube) present at the site?	0

Table F-2. Selected pathway (pipe is this case) properties.

Question about the pathway properties	Answer (Yes, No, Uncertain)
Is there a noticeable flow of water from the pathway?	100
Are the water and air pathways destined for the confined structure, running along a significant length of path exposed to the atmosphere? (Either this can happen when a water or air passing on the pathway are open to the atmosphere or when they leave a covered pathway they run in an open atmosphere).	0
Is the pathway located higher than the mid-slope bench of the waste dump?	0

Table F-3. Estimation of undetermined permeability.

Dump Site	Determined Permeability (m^2)	Undetermined Permeability (m^2)					Water content	Undetermined Water content				Measured Water content
		% fines <2 mm DoB	Channeling DoB	Processing plant/blasting materials	Method of mining and dumping	%coarse >70 mm DoB		Water Saturation	Solid Density	Porosity	Bulk Density	
		Permeability estimate by weighted combination of important factors					Water Saturation	Estimated Mass Water Content				
Nordhalde Dump	2.5E-12 (effective air permeability)	>20%, 100	30	Blasting 30%	underground 70, open pit 30 end dumping 100	<20%, 100	UN	0.63	2751	0.30	UN	UN
		1E-12					0.63	0.098				
Doyon Dump	8.15E-10 (effective air permeability)	2-7% 100	100	Blasting 100	open pit 100 end dumping 100	20-50%, 100	0.098	0.42	2800	0.33	1918	0.098
		3E-9					0.42	0.074				
Sugar Shack South	3.0E-10 (V) to 3.5E-9 (H)	>20% 100	30	Blasting 100	open pit 50, Underground 50, end dumping 100	20-50%,80	UN	0.35	2740	0.33	UN	UN
		9E-10					0.35	0.063				
Aitik	1.0E-10 to 1.4E-9	>20% 100	30	Blasting 100	open pit 100 end dumping 100	50-80% 100	UN	Very low	2800	0.35	UN	UN
		7E-10					Very low	UN				
White's dump	1.0E-11 to 1.0E-9	2-7% 50	30	Blasting 100	open pit 100 end dumping 100	> 80% 50	0.11	Est. 0.46	2800	0.40	1862	0.110
		2E-10					0.46	UN				
Number One Shaft	1.0E-11 to 1.0E-9	2-7% 50	100	Blasting 100	underground 100 end dumping 100	>80% 100	0.08	0.24	2800	0.33	UN	0.080
		4E-9					0.24	0.042				
North Dump (reserved for testing)	Low	>20% 100	30	Blasting 100	underground, 100 end dumping 100	<20%100	Low	Low	UN	UN	UN	UN
		1E-12					UN	UN				
Main dump at Equity Silver Mine	Undetermined	UN	30	Blasting 100	underground 50, open pit 50 end dumping 100	UN	UN	UN	UN	UN	UN	UN
		5E-10					UN	UN				
West Lyell waste dump	Undetermined	UN	30	Blasting 100	open pit 100 end dumping 100	UN	UN	UN			UN	UN
		4E-9					UN	UN				

Table F-4. Estimation of cover effectiveness.

Dump Site	Cover type			Thicker at the toe	Cover defects	Revegetation		Permeability, Infiltration rate, or Hydraulic conductivity	Cover Age **	Crusting or thick layer of ice	Time of Cover Installation Start to End	Effectiveness Estimate Input by User	Climate Type [a]	E:P ++ Ratio	Season	Humid/ Dry	Hot Spots	Diversion Channel	Cover Freeze	Erosion resistant material	DoB in High Effectiveness
	thickness	saturation	Clay			Root depth	Growth medium thickness														
Nordhalde Dump	Simple soil cover			Yes	Yes	UN		Moderate	UN	30%	UN	High	Cfb	UN	Summer	H	30%	50%	100%	50%	74%
	-	-	-			UN	UN														
Doyon Dump	UN (assumed no cover was installed)												Dfc	Low	Summer	H	-	50%	0%	50%	0%
Sugar Shack South Dump	No cover												BWh	High	Summer	D	-	50%	0%	50%	0%
Aitik mine Dump	Simple soil cover (half dump)			No	Yes	Not done		UN, UN, UN	0[†]				Dfb	Low, <5	Summer	H	30%	50%	100%	50%	54%
	>1m	-	-			-	-														
White's Dump	Conventional cover			Yes	No	Done		Low	~ 1 yr	100%	Sept. 1983 - UN	High	Aw	5 – 10	Summer	H	100%	50%	50%	50%	100%
	100% <1.5	saturated	stable			Interm.	UN														
Number One Shaft Dump	Conventional cover (till)			No	Yes	Not done		5E-13	6 months - 3 yr	0%	2005	60% High	BSk	>10	Summer	D	100%	50%	50%	50%	89%
	100% <1.5	Not tention saturated	stable			-	-														
Main Dump at Equity Silver	Simple soil cover			No	Yes	Present		UN -**<5%- low**	4 yrs	30%	1990 -1997	UN	Cfb	< 5	Summer	H	30%	-	-	-	100%
	-	High	-			Shallow	0.3 m														
West Lyell Waste Dump	No Cover												Cfb	High	Summer	H	30%	-	-	-	**0%**
North Dump	Conventional cover			No	100%	Present		Low, 100%	~9 yr	100%	cover 1997, vegetate 1998	High	BSk	>10	Summer	D	30%	50%	50%	50%	100%
	100% =1.0	Not tention Saturated	Stable			Interm.	Thin														

++ Evaporation : Precipitation Ratio

† Installed after measurements. In estimations, cover effect was not considered. ** Cover age at time of measurements

[a] Dfc - Continental Subarctic or Boreal (taiga)
BWh - Dry arid and semi-arid climates
Aw - Tropical savanna climate

Cfb - Maritime Temperate climates or Oceanic climates with westerly winds
Dfb - Warm Summer Continental or Hemiboreal climates
BSk - Cold semi-arid climates

Table F-5. Estimation of dump reactivity

Dump Site	Sulfide Content	Permeability	Water Saturation	Resloping	Relocation	Exposed Sulfide	fine materials, DoB	Dump Age **	Time of measurements	Dump Material	Weathering	High Reactivity
Nordhalde Dump	0.015	2.50E-12 †	0.62	Done	Not done	>50%, 50%	>20%, 100	56	June 1997	Underground	UN	48%
Doyon Dump	0.037	8.15E-10 †	0.42	Not done	Not done	UN	2-7%, 100	9	July 1993	Blasting	UN	100%
Sugar Shack South Dump	0.0187	7 E-10	0.35	Not done	Not done	UN	>20%, 100	35	July 2000	Blasting	UN	78%
Aitik Mine Dump	0.01	Moderately high 1.0E-10 to 1.4E-9	Low	Not done	Not done	UN	>20%, 100	34	Nov. 1991 ***	Blasting	UN	19%
White's Dump	0.0347	2E-11	0.46	Done	Not done	UN	2 -7%,100	34	Nov. 1984	Blasting	UN	100%
Number One Shaft Dump	0.018	1E-11 to 1E-9	0.24	Done	Not done	UN	2-7%, 100	56	July 2007	Blasting	UN	78%
Main Dump at Equity Silver Mine	0.0185	1E-11 to 1E-9	0.2	Done	Not done	UN	UN	13	June 1994	Blasting	UN	70%
West Lyell Waste Dump	0.027	4E-9	0.2	Not done	Not done	UN	UN	58	July 1994	Blasting	UN	83%
North Dump	Very-High 0.030-0.035	Low	Low, 100%	Done	Not done	UN	>20%, 100	91	July 2007	Uniform <2.5 cm	UN	100%

† Effective air permeability ** Dump Age at time of measurements *** O_2 profile was measured. Internal temperature time of measurement is undetermined.

Table F-6. Estimation of gas velocity

Dump site	Outside Temperature (°C) ** / Outside Pressure at top of the dump at time of Max T (Pa)	Central Internal Temperature of the dump / Central Internal Pressure at same time	Δf caused by ΔT	Δf caused by ΔP	Total Δf (J/g)	Gas Velocity at base of dump †	Internal Temperature Trend	Oxygen measurements
Nordhalde Dump	18	14	7.700	0.017	7.740	Negative Small	Pseudo steady state	<1% the all year in the edges, except for Jan to Apr
	97,000	97,020						
Nordhalde Dump (January)	-8	14	-22.08	0.017	-22.097	Positive Big	Pseudo steady state	8% in Jan. to Apr. 1997 at edges
	97,000	97,020						
Doyon Dump	20	45	-25.120	0.017	-25.140	Positive Big	Pseudo steady state	15% at edges all year
	97,020	97,000						
Sugar Shack South Dump (no cover)	24	40	-16.080	0.017	-16.080	Positive Big	Cooling	3-7% in Sept. 1999, 2-5% in July 2000
	97,020	97,000						
Sugar Shack South Dump (no cover) (January)	-6	40	-46.23	0.017	-46.23	Positive Very Big	Cooling	6-12% in Jan 2000 at centre
	97,020	97,000						
Aitik Mine Dump	15	3	23.270	0.017	23.310	Negative Big	Undetermined	No measurements available
	97,020	97,000						
Aitik Mine Dump (November)	3	3	0.016	0.017	0.033	Negative Very Small	Undetermined	5-12% at edges in November
	97,020	97,000						
White's Dump	38	45	-7.125	0.017	-7.090	Positive Very Small	Cooling after covered. 10 years later, dump began to heat	5% in Jan. (summer)[b] and 16% in Aug.(winter)at edges 0% at the centre all year
	97,020	97,000						
Number One Shaft Waste Dump	32	12	39.025	-0.005	39.020	Negative Vey Big	Heating 2°C/year (2 years after cover)	0-5% at edges in August
	86,210	86,215						
Number One Shaft (May - time of the accident)	20	12	15.458	-0.008	15.450	Negative Big	Heating 2°C per year (2 years after cover)	2-19% in June
	86,344	86,352						
Main Dump at Equity Silver Mine	22	52	-30.150	0.017	-30.120	Positive Big	Cooling	2-5% at the center in January
	97,020	97,000						
Main dump at Equity Silver Mine (January)	-4	52	-56.267	0.017	-56.25	Positive Very Big	Cooling	5-7% at the center in summer
	97,020	97,000						
West Lyell Waste dump	22	38	-16.080	0.017	-16.046	Positive Big	Undetermined	0 to 20% (most times) at edges Varies dramatically due to pods of high oxidation rate material (No seasonal variation at O_2 content)
	97,020	97,000						
North Dump	30-35 (32)	33	-1.005	-0.005	-1.010	Positive Very Small	Undetermined	No measurements available
	86210	86215						

* values shown in pale grey have been assumed † negative velocity means gas is blowing out from the base of the dump

** for all dumps maximum temperature in the summer is applied, unless other time in the year is specified.

Table F-7. Estimation of gas generation

Dump Site	Gas Velocity	Wind Conditions	Dump Height (m)	Climate type [a]	Dump mixed with garbage	Reactivity	Dump Permeability	Cover Effectiveness	Gas Generation in summer	Oxygen measurements
Nordhalde Dump	Negative Small	Frequent Heavy storms	80	Cfb	No	48%	2.50E-12 †	74%	100%	8% in Jan. to Apr. 1997 at edges, <1% the rest of the year
Doyon Dump	Positive Big	Frequent Heavy storms	35	Dfc	No	100%	8.15E-10 †	0%	31%	15% at edges all year
Sugar Shack South Dump	Positive Big	Not windy	450	BWh	No	78%	3.5E-9 (Hor) to 3.0E-10 (Ver) (7E-10)	0%	23%	3-7% in Sept. 1999, 2-5% in July 2000 6-12% in Jan 2000 at centre
Aitik Mine Dump	Negative Big	Not windy	20	Dfb	No	19%	Moderately high 1.0E-10 to 1.4E-9	0%	75%	UN
Aitik Mine Dump (November)	Negative Very Small	Not windy	20	Dfb	No	19%	Moderately high 1.0E-10 to 1.4E-9	0%	29%	5-12% at edges in November
White's Dump (1 year after cover)	Positive Big	Heavy winds	20	Aw	No	100%	2.0E-11	100%	100%	5% in Jan. (summer)[b] and 16% in Aug.(winter)at edges 0% at the centre all year
Number One Shaft Dump (2 years after cover)	Negative Very Big	Light winds, 50%	50	BSk	Yes	78%	1E-11 to 1.0E-9	89%	100%	0-7% at edges in summer
Main Dump at Equity Silver (4 years after cover)	Positive Big	Less frequent Heavy winds	~80	Cfb	No	70%	1E-11 to 1E-9	100%	64%	5% at edges and 10% at the center in summer
West Lyell Waste Dump	Positive Big	Frequent Heavy storms	90	Cfb	No	83%	4E-9	0%	36%	0 to 20% (most times) at edges Varies dramatically due to pods of high oxidation rate material (No seasonal variation at O_2 content)
North Dump (8 years after cover)	Positive Very Small	Light winds, 50%	50	BSk	No	100%	Low	100%	100%	No measurements available

† effective air permeability

[a] Dfc - Continental Subarctic or Boreal (taiga)
BWh - Dry arid and semi-arid climates
Aw - Tropical savanna climate
Cfb - Maritime Temperate climates or Oceanic climates with westerly winds
Dfb - Warm Summer Continental or Hemiboreal climates
BSk - Cold semi-arid climates

[b] In Northern Territories, Australia, daytime temperatures average between 30 to 35 °C year round.
The dry season (May – October) has sunny days while the wet season (November – April) is hot and humid with tropical storms.
Away from the coast, there are four distinct seasons: Winter (Jun-Aug) warm days and cool nights
Summer (Dec-Feb) very hot with temperatures in the high 30s

Table F-8. Estimation of gas emission

Dump Site	Pathway (assumed except Number One Shaft Dump)			Dump Permeability	Gas Velocity	"High" gas emission through the pathway
	Location	Water flow	Extent covered			
Nordhalde Dump	Pipe bottom	Yes	100%	2.50E-12 †	Negative Small	63%
Doyon Dump	Pipe bottom	Yes	100%	8.15E-10 †	Positive Big	15%
Sugar Shack South	Pipe Bottom	Yes	100%	3.5E-9 (Hor) to 3.0E-10 (Ver) (7E-10)	Positive Big	18%
Aitik Mine Dump	Pipe Bottom	Yes	100%	1.0E-10 to 1.4E-9	Negative Big	86%
White's Dump	Pipe Bottom	Yes	100%	1E-11 to 1E-9	Positive Very Small	27%
Number One Shaft Dump	Pipe Bottom	Yes	100%	1E-11	Negative Big	100%
Main Dump at Equity Silver Mine	Pipe Bottom	Yes	100%	1E-11 to 1E-9	Positive Big	18%
West Lyell Waste Dump	Pipe Bottom	Yes	100%	4E-9	Positive Big	18%
North Dump	Pipe Bottom	Yes	100%	Low	Positive Very Small	18%

† effective air permeability

Table F-9. Risk Assessment for warmest seasonal period in time

Dump Site	Gas Generation (%DoB in high)	Gas Emission (%DoB in high)	Gas Confinement [a] (%DoB in high)	Human Exposure [a] (%DoB in high)	Risk Value	Risk Assessment
Nordhalde Dump (summer)	100	63	100	100	0.5346	Marginal Hazardous
Nordhalde Dump (winter)	49	18 (82% low)	100	100	0.16536	Problem Exists
Doyon Dump	31 (69% medium-low)	15 (85% low)	100	100	0.1511	Problem Exists
Sugar Shack South Dump	23 (77% medium-low)	18 (82% low)	100	100	0.1528	Problem Exists
Aitik Mine Dump	75 (25% medium-high)	86 (14% medium-low)	100	100	0.4768	Significant Problem
Aitik Mine Dump (November)	29 (71% medium-high)	47 (53% medium-high)	100	100	0.2410	Significant Problem
White's Dump	100	27 (73% medium-low)	100	100	0.3369	Significant Problem
Number One Shaft Waste Dump (summer)	100	100	100	100	0.9000	Hazardous
Number One Shaft Waste Dump (during the accident period – May 2006)	100	73	100	100	0.6033	Marginally Hazardous
Main Dump at Equity Silver Mine (summer)	64 (36% medium-high)	18 (82% low)	100	100	0.1826	Problem Exists
Main Dump at Equity Silver Mine (winter)	48 (52% medium-high)	18 (82% low)	100	100	0.1647	Problem Exists
West Lyell Waste Dump	36 (64% medium)	18 (82% low)	100	100	0.1607	Problem Exists
North Dump	100	24 (76% low)	100	100	0.3122	Significant Problem

[a] These values are assumed in order to compare the overall risk of all 11 scenarios (confinement and exposure are human controlled issues)
[b] Gas velocity is not a positive-big value because the low permeability of the dump decreases gas emission

Table F-10. Estimation of undetermined internal temperature

Dump Site	Reactivity	Height (m)	%DoB Fumaroles	Slope	Permeability	Benches	Height/Width Ratio	Effluent pH	Cover Effectiveness	Position of Max. Internal Temperature		Estimated Internal Temperature	Actual Internal Temperature
Nordhalde Dump	48%	80	30	Gentle	2.50E-12 †	Yes	0.100	2.7	74%	0.23 Height	Edges	10-15	14
Doyon Dump	100%	35	30	20-30°, 50%	8.15E-10 †	Yes	0.070	<2	0%	0.50 Height	Center	>40	45
Sugar Shack South Dump	78%	450	100	26°	3.5E-9 (Hor) to 3.0E-10 (Ver) (7E-10)	Yes	4.090	UN	0%	0.50 Height	Center	>40	40
Aitik Mine Dump	19%	20	30	20-30°	Moderately high 1.0E-10 to 1.4E-9	Yes	0.100	4.1	0%	0.50 Height	Center	2-6	0-3
White's Dump	100%	20	30	18°	1.0E-11 to 1.0E-9	Yes	0.040	2-2.6	100%	0.50 Height	Edges	>40	44 (1 yr after cover installation)
Number One Shaft Waste Dump	78%	50	30	25°	1E-11 to 1.0E-9	Yes	0.1	UN	89%	0.50 Height	Center	10 -15	12 (two years after cover)
Main dump at Equity Silver Mine	70%	~80	100	20°	Moderately high 1E-11 to 1.0E-9	Yes	~0.160	2.6	100%	0.20 Height	Center	>40	52 (four years after cover)
West Lyell Waste dump	83%	90	30	UN	4E-9	Yes	0.191	UN	0%	0.33 Height	Center	35-40	38
North Dump	100%	50	30	21°	Low (1E-12)	Yes	0.10	~2.8	100%	0.50 Height	Center	30-35	33 (eight years after cover)

† Effective Air Permeability

Appendix G Examples of Predictions by AFRA CE

The Accident Has Recently Occurred	Victim alive	Water Present	Ventilation Present: Organic Material Present No	Ventilation Present: Organic Material Present Yes	Ventilation Not present: Organic Material Present No	Ventilation Not present: Organic Material Present Yes
No	Yes	No	0	0	0	5
No	Yes	Yes	0	0	5	30
No	No	No	30	45	60	85
No	No	Yes	45	70	85	100
Yes or do not know	Yes	No	0	0	0	0
Yes or do not know	Yes	Yes	0	0	0	20
Yes or do not know	No	No	20	35	50	75
Yes or do not know	No	Yes	35	60	75	100

0-20, Enter	20-40, Maybe okay to enter	40-70, Maybe better not to enter	70 – 90, Better not to enter	90 – 100 , Do not enter

Figure G-1. AFRA CE Output for an Initial DoB in an atmospheric hazard of 0% (NO) as expressed by the User.

The Accident Has Recently Occurred	Victim alive	Water Present	Ventilation Present – Organic Material Present: No	Ventilation Present – Organic Material Present: Yes	Ventilation Not present – Organic Material Present: No	Ventilation Not present – Organic Material Present: Yes
No	Yes	No	0	0	10	35
No	Yes	Yes	0	20	35	60
No	No	No	50	75	90	100
No	No	Yes	75	100	100	100
Yes or do not know	Yes	No	0	0	0	25
Yes or do not know	Yes	Yes	0	10	25	50
Yes or do not know	No	No	40	65	80	100
Yes or do not know	No	Yes	65	90	100	100

0-20, Enter	20-40, Maybe okay to enter	40-70, Maybe better not to enter	70 – 90, Better not to enter	90 – 100 , Do not enter

Figure G-2. AFRA CE Output for an Initial DoB in an atmospheric hazard of 30% as expressed by the User.

The Accident Has Recently Occurred	Victim alive	Water Present	Ventilation Present – Organic Material Present: No	Ventilation Present – Organic Material Present: Yes	Ventilation Not present – Organic Material Present: No	Ventilation Not present – Organic Material Present: Yes
No	Yes	No	0	15	30	55
No	Yes	Yes	15	40	55	80
No	No	No	70	95	100	100
No	No	Yes	95	100	100	100
Yes or do not know	Yes	No	0	5	20	45
Yes or do not know	Yes	Yes	5	30	45	70
Yes or do not know	No	No	60	85	100	100
Yes or do not know	No	Yes	85	100	100	100

0-20, Enter	20-40, Maybe okay to enter	40-70, Maybe better not to enter	70 – 90, Better not to enter	90 – 100, Do not enter

Figure G-3. AFRA CE Output for an Initial DoB in an atmospheric hazard of 50% as expressed by the User.

The Accident Has Recently Occurred	Victim alive	Water Present	Ventilation Present – Organic Material Present: No	Ventilation Present – Organic Material Present: Yes	Ventilation Not present – Organic Material Present: No	Ventilation Not present – Organic Material Present: Yes
No	Yes	No	20	45	60	85
No	Yes	Yes	45	70	85	100
No	No	No	100	100	100	100
No	No	Yes	100	100	100	100
Yes or do not know	Yes	No	10	35 – 2	50 – 2	75
Yes or do not know	Yes	Yes	35 – 2	60 – 2	75	90
Yes or do not know	No	No	90	100	100	100
Yes or do not know	No	Yes	100	100	100	100

0-20, Enter	20-40, Maybe okay to enter	40-70, Maybe better not to enter	70 – 90, Better not to enter	90 – 100 , Do not enter

Figure G-4. AFRA CE Output for an Initial DoB in an atmospheric hazard of 80% as expressed by the User.

The Accident Has Recently Occurred	Victim alive	Water Present	Ventilation Present: Organic Material Present – No	Ventilation Present: Organic Material Present – Yes	Ventilation Not present: Organic Material Present – No	Ventilation Not present: Organic Material Present – Yes
No	Yes	No	39	64	79	100
No	Yes	Yes	64	89	100	100
No	No	No	100	100	100	100
No	No	Yes	100	100	100	100
Yes or do not know	Yes	No	29 – 2	54 – 2	69	90
Yes or do not know	Yes	Yes	54	79	90	90
Yes or do not know	No	No	100	100	100	100
Yes or do not know	No	Yes	100	100	100	100

0-20, Enter	20-40, Maybe okay to enter	40-70, Maybe better not to enter	70 – 90, Better not to enter	90 – 100 , Do not enter

Figure G-5. AFRA CE Output for an Initial DoB in an atmospheric hazard of 99% as expressed by the User.