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Confined Space Atmospheric Risk Assessment

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RS2009-DG05

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Title of the project:
Confined Space Atmospheric Risk Assessment

Investigators: John A. Meech and Ladan Mohammadi

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Main Research Outcomes and Policy Implications

Research Outcomes

- A detailed analysis of the Sullivan Mine confined space accident that occurred in May 2006 at the Number One Shaft Waste Dump in Kimberley, B.C. 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.

- Confined space problems at reclamation sites involve exposure of humans to O_2-depleted air usually accompanied by high levels of CO_2. 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.

- 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.

- Gas Generation (O_2-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. Water needs to percolate through the dump at only 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.

- 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, O_2-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.

- An atmospheric fuzzy risk assessment tool (AFRA) has been devised to assist in recognizing such hazards 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 entry control (permit-required, proper signage, O_2-meterage, 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.

Policy Implications

- The terminology of confined spaces is extremely confusing, varying by jurisdiction and agency. This report 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 be 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. 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.

- AFRA is available free-of-charge through a UBC web site. (www.ubc.mining.ca/AFRA) It can be downloaded for use by engineers and inspectors for regular evaluation of a reclamation site. 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 or design of the site.

- First Responders (paramedics, fire-fighters, and police officers) should be encouraged to download the associated education 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.

Executive Summary

In May 2006, four people lost their lives in a sampling shed located at a waste dump reclamation site at the Sullivan Mine in Kimberly, British Columbia. The direct reason for these fatalities was the collection of O_2-depleted gas emissions from a waste dump through a buried pipe into a sump at the bottom of the sampling shed. Following this tragedy, the Chief Mines Inspector of British Columbia issued a warning to all mines in the province about the dangers of sampling sheds connected to mine waste dumps. He stated that this accident was "unprecedented in the history of mining".

While that statement is true, the circumstances of this accident parallel those of virtually all atmospheric related confined space accidents. These include, but are not limited to:

- The hazard is unrecognized by operators and by the victims;
- The hazard (in this case O_2-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.

As a result of this accident, the Norman B. Keevil Institute for Mining Engineering at the University of British Columbia decided to undertake a study to assist reclamation practice designers to recognize these dangers before a human is exposed to the hazard and to develop a tool for first-responders to help prevent harm to themselves. It was considered that knowledge transfer is at the heart of the issue and that communication about this type of accident needs to be broadcast widely throughout the Mining Industry and beyond.

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, particularly at mine reclamation sites. In addition, such a system can be used routinely to perform risk assessments at a site to discover the hazard early and introduce mitigation practices.

The Sullivan Mine accident demonstrates that mine waste dump reclamation sites are associated with atmospheric environmental problems and risks. The accident shows that regular and consistent atmospheric risk assessment is needed at all closed sites. The project goal was to understand the nature of different atmospheric-related dangers at a waste dump to support a tool that could prevent future accidents. This methodology can be applied to other industrial sites however the focus is on the specific issues of mine reclamation.

This report 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 such systems rely on mimicking the direct dialog with humans to achieve successful transfer of information. It can be tuned to be cautious or to allow risk behaviour – in this case the former is clearly preferred. Linguistic terminology is used rather than numbers 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 gasses 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. This unpredictable nature limits mathematical approaches to situations where dumps are heavily instrumented with input data being collected on an hourly basis over months and years. This is both impractical and infeasible in most cases. Fuzzy logic rule-bases on the other hand, use approximation arithmetic of the 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, 1999).

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 O_2-depleted gas within the dump;
2. Minimize, eliminate, or control the emission of toxic gas from the dump;
3. Identify structures or surface anomalies that might 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 these 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 risk is high. AFRA has been designed to provide a logical process to understand and conduct a detailed assessment of a site to provide this perception.

The research has identified the key variables that affect gas generation, gas emission, gas confinement, and human exposure. 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 risk probability in a linguistic fashion. Atmospheric risk (O_2-depletion and/or CO_2) is assigned one of the following terms: "Not a Problem", "Very Safe", "Safe", Marginally Safe", Marginal Problem", "Problem", Significant Problem, Marginal Hazard", and “Hazardous". This diagnosis is modified by three additional issues:

- what precautions have been implemented to control entry to the confined space?
- what types of people might enter the confined space?; and
- what future procedures are being considered?

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 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 estimates.

There are three main policy implications for mining companies and government regulatory agencies to consider. The first deals with the current terminology about confined spaces which is considered confusing. This report suggests only two terms be used to simplify the characterization of an enclosed place: “enclosed structure” and “confined space”, where the latter term designates those spaces that require an entry permit.

The second recommendation involves updating the B.C. Mines Act (2008) to include a section on confined space issues at reclamation sites. The Act should require all closed sites to conduct an atmospheric risk assessment before commencing reclamation work. Furthermore risk assessments should be redone whenever a significant change in the environment or design of the reclamation practices takes place at the site.

Finally, AFRA has been placed on a UBC web site (www.mining.ubc.ca/AFRA) for downloading without charge by users at mining companies, government agencies, and/or safety professionals. All potential users are encouraged to acquire a copy of AFRA and to use it to conduct risk assessments of reclamation sites, especially prior to preparing an inventory of confined space issues at their site.

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1. Research Problem/Context

Over the period May 15-17, 2006, four people were asphyxiated in an Acid Rock Drainage (ARD) sampling shed at a waste dump located on the Sullivan Mine property in Kimberley, British Columbia. (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;).

The accident occurred as a result of O_2-depleted gas collecting within an ARD sampling station (Mohammadi and Meech, 2008). To understand how this happened, it is necessary to break down the reclamation activities into their specific contributions that increased the risk of a confined space accident. Reclamation activities in the summer of 2005 included extension of the toe of the dump by about 70 m which covered over an effluent collection ditch along the toe thus converting it to 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 O_2-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 be problematic 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 O_2-depleted gas to flow from the dump into the shed (Philips et al. 2008) – see Appendix A for details. Some confined space protocols, but not all, mention the hazard of sudden changes in atmospheric temperature and pressure affecting the influx of toxic gas into a confined space. NIOSH discusses the danger of manholes located within a swampy area (Michaelsen and Park, 1954; Pettit, 1994) in which a sudden barometric pressure drop caused methane to diffuse into the manhole through its walls. At other times, these spaces had been entered without problem. When a confined space is connected to an outside environment, atmospheric pressure and temperature changes affect gas flow into and out of the space. Some typical examples are breathing water wells (Hill, 2004); breathing coal mines (Wang et al, 2003), and manholes located in oil-contaminated soils (Michaelsen and Park, 1954). Knowledge about these diurnal and seasonal changes is essential in assessing the atmosphere within a confined space.

In the case of the Sullivan Mine accident, had an atmospheric risk assessment been done as the work proceeded, contractors and mine employees might have realized that the shed had become a "permit-required confined space”. Currently there is no risk assessment tool available for use with such 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 a risk analysis. Recognizing the presence of a hazard and evaluating the development of dangerous conditions at a site is an essential first step in future prevention of such accidents.

Atmospheric risk assessment is perhaps as important a reclamation task as is the environmental risk assessment of Acid Rock Drainage (ARD) impacting on the aquatic environment and should be carried out on a regular basis after closure of a mine. Both environmental and human health risk analyses should be done in parallel to find specific solutions that may address both issues at the same time. A regular atmospheric risk assessment is necessary because unknown future activities might take place at the site. 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 day to night. Seasonal changes take place as the near-surface internal temperature increases or decreases. Reclamation design factors (covers, slope changes, etc.) and dump properties (e.g., sulfide content, water content, particle size, etc.) also play important roles. 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, about one year after rehabilitation commenced, the internal temperature at 10 m depth dropped from 49 ºC to 44 ºC, and the O_2-level in the pore gas declined to <1% (Harries and Ritchie, 1983). It will be demonstrated in Section 3 that decreases in internal temperature create an unobvious and dangerous situation with respect to atmospheric risk. 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. Table 1 in Appendix E shows the variables that affect cover effectiveness. 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; with White’s Dump, at the end of the wet season the internal temperature dropped 2 to 3 ^{0}C because of an increase in cover effectiveness due to saturation.

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. Continuous and regular measurement of O_2 levels is necessary or else a “false perception” of safe may result. This may be impractical and as an alternative, a risk assessment tool can prove helpful. Such a system should give designers and operators the knowledge of possible danger in the first 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 can help predict that uncertain risk.

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 connecting a shed to bad air in the dump, the shed will likely always be safe. Regulations are encouraged to require reclamation designers and operators to conduct an atmospheric risk assessment and determine if a hazard is present at the beginning of the reclamation work and on a regular basis thereafter. The system reported here can suggest ways to overcome a hazard and remove it from the site.

2. Methodology

A hazard is recognized by AFRA using a general and a detailed assessment of numerous variables observed and measured at a site. The main focus of AFRA is a detailed assessment of a sulfide waste dump with the aim to estimate risk due to O_2-depleted gas emission. The general risk assessment in AFRA can extend to other possible gas problems such as nitrogen monoxide/dioxide and carbon monoxide/dioxide or methane in which conditions for occurrence of such gases may exist at a site. As such, AFRA can warn about atmospheric hazards from coal waste dumps or from blasting agents. APPENDIX B presents an overview of how fuzzy logic-based expert systems work while APPENDIX C describes the general assessment process. 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 base could be done in the future.

Help files in the tool account for possible atmospheric hazards at any particular site to provide a classification of hazardous gas generation and emission 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. Development of the help file is based on a review of confined space regulations and previous accidents. This knowledge has been gathered and coding is still under development.

AFRA is written within a Visual Basic .Net 2008 environment allowing customized design of the fuzzy system and making the software extremely portable. Features can be added by creating different and/or new membership functions, applying different fuzzy mathematical techniques, and 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 and LPA VisiRule); there are few limitations on progression or transfer of the software since there is no need for a proprietary software product. Visual Basic is one of the most commonly-used programming languages. It is user-friendly and robust and compatible with PC technology.

The system is easy to use, and a user is not forced to enter all the data. There are only two pages of questions - further questions may be asked if some factors are undetermined. If measurements are available they can be entered directly, but if unavailable, then ranges or linguistic terms can be chosen by the user instead. Selection of a range is associated with entering a degree of belief, which represents the user's certainty about the entry.

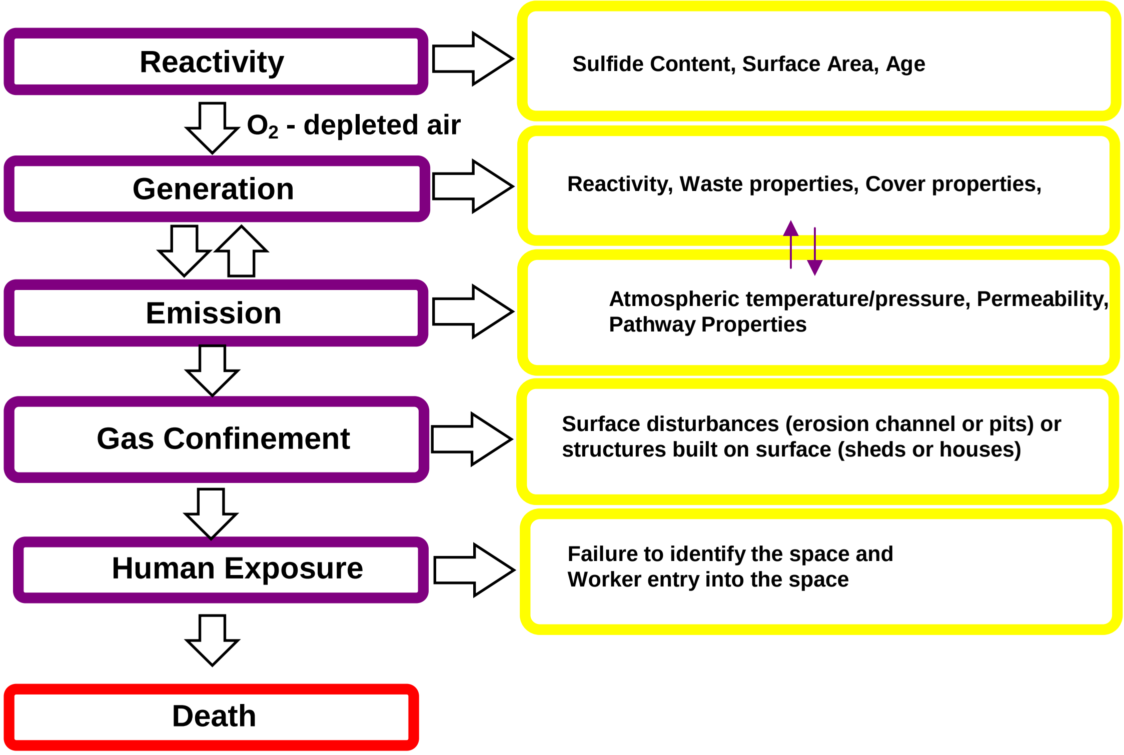


Figure 1. Stages for the Atmospheric Risk Assessment

In a detailed assessment, AFRA synthesizes confined space risk into four major elements: gas generation, gas emission, gas confinement, and human exposure (see Figure 1). A heuristic method is used to model Unsafe and Safe situations at a sulfide waste dump. Most of the assessment focuses on the first two elements, generation and emission, but clearly the latter two are central in creating the final conditions for an accident. The first two elements of danger relate to when O_2-depleted air or carbon dioxide (gas generation) develops within a waste dump and then transfers to the outside (gas emission). Environmental risk assessment of a waste dump deals with ARD in which there is a balance in NP (neutralization potential) and AP (acid potential) in the solid material which ultimately impacts water effluent quality. What is examined in AFRA is the process of O_2-depletion of air (the first element of risk) and the process of oxygen displacement coupled with processes of O_2-depleted gas emission (the second element of risk). Rather than AP and NP, AFRA is interested in dump permeability and the driving forces of thermal convection and advection that places O_2 within the dump. O_2 consumption is characterized by the oxidation rate of sulfides which depends on many factors (e.g., sulfide content, water content, pore gas O_2 levels, particle size, etc.). Many of these mechanisms also control 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 influences convective transport. The degree of oxygen depletion depends on a balance between O_2-consumption and O_2-replenishment by convective air. The set of variables that characterize these processes are identified by AFRA for each site.

In AFRA, general rules created from knowledge of waste dump behaviour (specifically Number One Shaft Waste Dump) are used to conduct the atmospheric risk assessment. The rules also derive from comprehensive studies of waste dumps 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 D. The software was validated on three waste dumps that were withheld from system development (test dumps) and was verified for five other waste dumps in the literature (reference dumps) used to help build the system. Designing the system based on rules from reference dumps alone does not guarantee that the system will model all dumps correctly. The model should be tested and weights updated as more dumps are tested. Testing with reference dumps provides verification that the model works correctly. Working with test dumps provides validation that the model can correctly assess a new dump previously unseen. As more dumps become tested the full spectrum of possible combinations of important variables that control an atmospheric hazard will be supported. Note that the previous work on test and reference dumps (except for Number One Shaft Dump) focused on issues related to liquid emissions to the aquatic environment.

Lefebvre et al. (2001a) is one of the few studies to deal with gas transport processes. They describe a general conceptual model for multiple gas transfer processes within a waste dump based on physiochemical conditions of two dumps (Nordhalde and Doyon) which exhibited widely different conditions and responses. AFRA has been based on these two dumps as well as three others. The multi-dimensional graph in Figure 16 in Appendix F shows the levels of variation defined by the reference dumps. Since these represent a diverse range of conditions, if a heuristic function (fuzzy model) is fitted to them, the model can be said to properly predict the risk at all dumps.

The reference waste dumps and their sources are:

1. White's Dump at the Rum Jungle mine (U) in Australia
   (Harries and Ritchie, 1980, 1983, 1986, 1987; Ritchie, 2003),
2. Sugar Shack South Dump at Questa Mine (Mo) in New Mexico
   (Wels et al. 2003; Lefebvre et al., 2001a,b and 2002; Shaw et al., 2002;
   Robertson GeoConsultants Inc., 2001)
3. South Waste Dump at the Doyon Mine (Au) in Quebec
   (Wels et al. 2003),
4. Nordhalde Dump at the Ronnenburg Mine (U) in Germany
   (Wels et al. 2003; Smolensky et al. 1999),
5. Aitik Mine dump (Cu) in Sweden
   (Stromberg and Bawart, 1999; Stromberg and Bawart, 1994;
   Ritchie, 2003; Takala et al., 2001)
6. Number One Shaft Waste Dump at the Sullivan mine (Pb/Zn)
   (Lahmira et al., 2009)

The test dumps are:

1. Main Waste Dump at Equity Silver Mine (Au/Cu/Ag) in British Columbia
   (Aziz and Ferguson, 1997; Lin, 2010)
2. West Lyell Dump at Mt. Lyell Mine (Cu) in Tasmania
   (Garvie et al. 1997)
3. North Dump at the Sullivan mine (Pb/Zn)
   (Lahmira et al., 2009; Dawson et al., 2009)

. These dumps are located in different environments allowing comparison of atmospheric hazard predictions under different climates.

2.1. Characterizing Enclosed Structures and Confined Spaces

In 1993, OSHA coined the terms "confined space" and "permit-required confined space" and defined their general entry requirements (Franseen, 1995). OSHA defines a "confined space" based on its size, configuration and use (OSHA, 2004). A confined space is a place that:

(1) Is large enough and so configured that an employee can enter and perform assigned work;

(2) Has limited or restricted means for entry or exit;

(3) Is not designed for continuous employee occupancy (OSHA, 2004, Pettit and Linn, 1987).

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 (atmospheric or physical), requiring a permit for entry. A "*non-permit confined space*" does not contain any hazard or hazardous atmosphere able to cause death or serious physical harm. When a change occurs in their use or configuration, they should be re-evaluated and may be reclassified as permit-required confined spaces (OSHA, 2004). The U.S. National Institute for Occupational Safety and Health (NIOSH), Canada’s National Occupational Health and Safety (CCOHS) and WorkSafeBC regulations emphasis the main characteristics of confined spaces similar to OSHA, but the definition of each characteristic differs from one to another.

In a confined space, the contained atmosphere can become dangerous to health mainly because air cannot move freely due to the design of the space and/or because there is no natural ventilation. OSHA’s definition led us to consider the term “**confined space**” instead of permit-required confined space, and “**enclosed structure**” instead of the many differing terms used by OSHA. The term “confined space” means a confined or enclosed structure with a physical, chemical, radiation, inhalation, and/or poisoning hazard. We prefer this definition since an enclosed structure does not require a restricted entry permit unless an assessment of it leads to the need to convert it to a permit-required confined space. According to our definition, a room in a house with a closed door and/or window is an example of an enclosed structure (a potentially-safe confined space) while a trench or ditch in the ground is an example of a potentially-unsafe confined space (permit-required confined space) in which not only a cave-in hazard exists, but toxic, flammable, explosive, or O_2-deficient gas may migrate through soil and become confined therein.

2.2. Atmospheric Confined Space Fuzzy Risk Assessment

Although an enclosed structure is not dangerous by itself, all such structures can potentially become dangerous confined spaces when gas generation and/or emission are high. A confined space risk logarithmic scale was introduced with linguistic fuzzy sets ranging from 10^{-4} (not a problem) to 1.0 (hazardous) – see Figure 2. The transition from an enclosed structure to a hazardous confined space depends on the assessed risk as shown in Figure 2. Different types of people respond differently to different risks, meaning that a space called Marginal Problem by AFRA may actually 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 an acceptable threshold is requested of each individual system user. Figure 2 gives the default setting of the linguistic risk threshold for entry of the public (Marginally Safe); for a paramedic (Problem); while places with higher risk (Significant Problem or greater) should be entered only if the person is wearing an appropriate respirator.

Gases generated within a waste 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 dangers, i.e., the presence or absence of gas generation and/or gas emission, AFRA will likely convert an “enclosed structure” to a “confined space” or vice versa respectively. As a result, the atmospheric risk level will decrease or increase when these elements are eliminated from or added to an enclosed structure respectively.

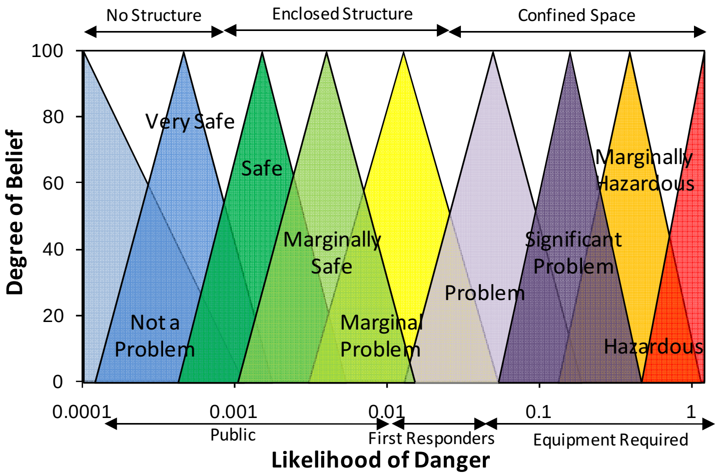


Figure 2. Fuzzy sets defining levels of risk for a confined space.

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, and erosion channels which may confine the emitted gas. A waste dump site is considered safe when there is no concentration of gas emission. Although a gas emission may exist, if it is quickly dispersed or diluted with ambient air, no significant atmospheric 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 gas emission rate. A site audit and review of past events is necessary to identify pathways that develop over time.

Assessing risk using heuristic formulas (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). The tool 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 3 shows the rules that link the four elements of risk to the final assessed value.

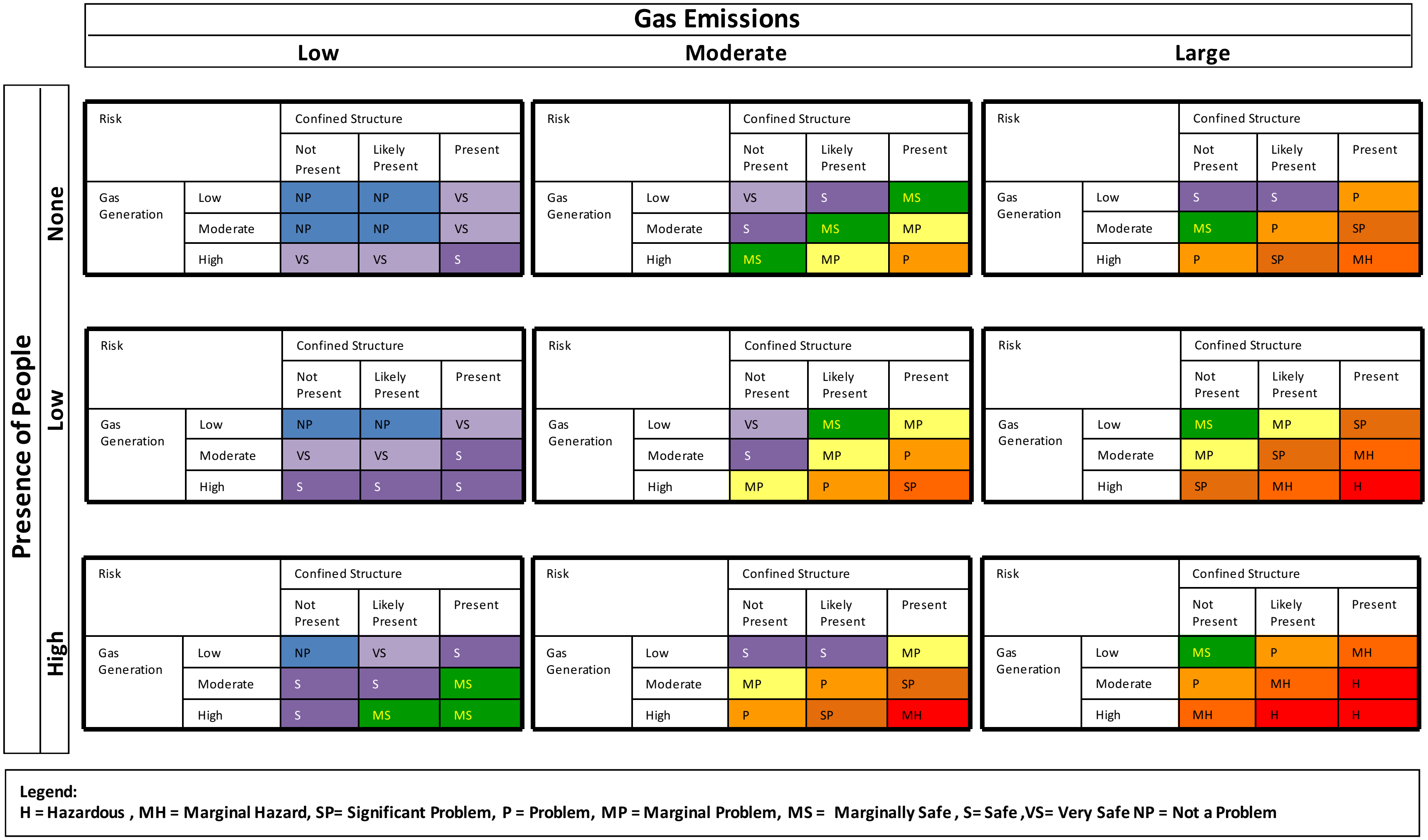
For example:

> 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 updated based on information gleaned from the literature and discussions with experts. The knowledge gained was used to decide on what level of risk should match a dump with a high degree of gas emission and a moderate level of gas generation. The assessment will follow a similar pattern at other dumps. Results change in a smooth logical fashion and try to predict the risk at a particular dump at a certain time of day and year as changes occur. In calculating risk, a fuzzy risk value for each element is calculated. The degrees of belief (DoBs) of these elements are combined to determine the overall risk. (See APPENDICES D, E, and F for a detailed description of how the system operates.)

Figure 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. Each variable was described by a number of fuzzy sets to characterize different ranges (i.e., low, medium, and high). The Degrees of Belief (DoBs) of the fuzzy value of “high” is used to characterize the major elements of risk. APPENDIX E summarizes the weights of the effect of minor/major variables and the heuristic formulae used to assess each risk element. For example, Table 6 in APPENDIX E indicates that the DoB of “High” gas generation depends on cover, permeability, and reactivity – all of which affect reactions leading to O_2-depleted air. Similarly, the DoB of “High” gas emission depends on climatic changes, dump configuration, and the design of each pathway to the enclosed structure – see Table 5 in APPENDIX E. While gas emission is generally higher in the summer, it is more accurate to say that gas emission can range from low to high in the summer depending on the internal temperature and, in some cases, the internal dump pressure. Prediction of the effect of each variable is done either directly or by estimating intermediate variables that link the inputs and outputs. This forms a hierarchy of inter-connected fuzzy rules. Each variable has a different weight in terms of affecting intermediate factors or elements. The effects of these weights are projected through the rule-base by specific rules or by applying the weights within a heuristic equation. The weights were selected subjectively and then modified to match the reference and test waste dump data. APPENDIX F shows the verification and validation results.

In conventional risk assessment, risk is generally defined as the probability of a hazard together with the severity of the consequence. In assessing the atmospheric hazard of a confined space, the presence of the hazard and an exposed human leads to death in seconds or minutes. As such, the severity of the hazard is constant at the highest possible level and is an unnecessary complication to include as an element. In our system, risk represents the probable occurrence of the hazard. In our judgment, use of standard risk assessment approaches that include an assessment of the severity of the consequences in the matter of a confined space analysis is redundant and can lead to failure in applying the system especially when no history of a similar problem exists. A similar argument can be made for any activity in which exposure to the hazard results in immediate death.



		Gas Emissions								
		Low			Moderate			Large		
Presence of People	Risk	Confined Structure			Confined Structure			Confined Structure		
	Gas Generation	Not Present	Likely Present	Present	Not Present	Likely Present	Present	Not Present	Likely Present	Present
None	Low	NP	NP	VS	VS	S	MS	S	S	P
	Moderate	NP	NP	VS	S	MS	MP	MS	P	SP
	High	VS	VS	S	MS	MP	P	P	SP	MH
Low	Low	NP	NP	VS	VS	MS	MP	MS	MP	SP
	Moderate	VS	VS	S	S	MP	P	MP	SP	MH
	High	S	S	S	MP	P	SP	SP	MH	H
High	Low	NP	VS	S	S	S	MP	MS	P	MH
	Moderate	S	S	MS	MP	P	SP	P	MH	H
	High	S	MS	MS	P	SP	MH	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 3. Fuzzy Associated Memory Map for Confined Space Risk as a function of gas generation, gas emission, gas confinement, and exposure of humans.

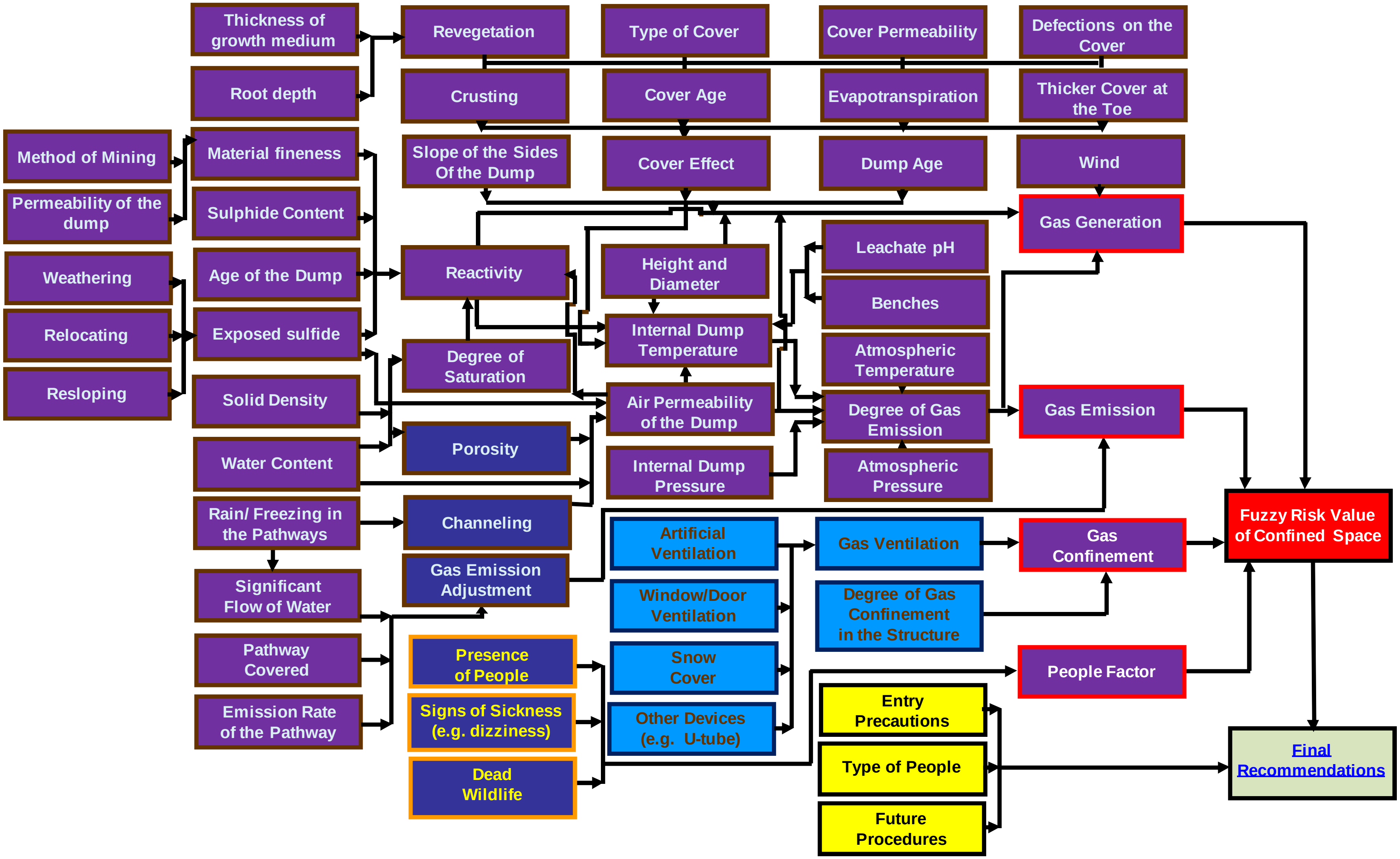


Figure 4. Overall Flowchart of AFRA.

3. Software Architecture

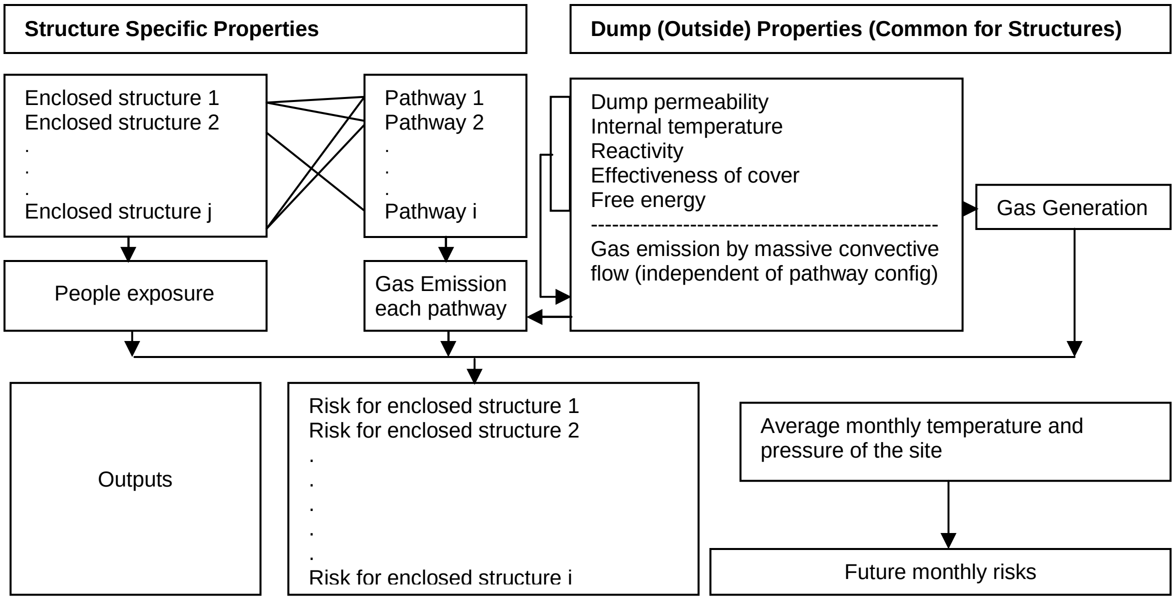


Figure 5. Structural architecture of AFRA.

In AFRA, a list of possible enclosed structures at a reclamation site is presented to the user to choose one or many. Next the possible pathways that may connect the waste dump to each structure are entered. Some risk elements 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 waste dump and so, are common for all structures depending on the degree of homogeneity of the dump (see Figure 5). A final confined space risk is determined for each selected enclosed structure. The output value is given numerically and linguistically accompanied by recommendations and suggestions about future risks. The calculated risk is adapted to a final risk level according to factors such as observation of dead wild life around the enclosed structure, people entering the space showing signs of sickness, or people possessing a confined space entry permit. 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 pressure at that time throughout the year allows the system to calculate the atmospheric risk of the dump on a temporal basis over the year. When the outside temperature rises above the internal temperature of the dump (at its centre), gas emission from the dump will be judged high. This statement is based on an analysis of data from Number One Shaft Waste Dump where it was found that whenever the outside temperature rose above the internal dump temperature, pore gas is emitted and whenever the outside temperature lies below the internal dump temperature, air is transported into the dump - see Figure 9 in APPENDIX A which shows gas velocity in a connected pipe depends on outside temperature.

Since the Number One Shaft dump is very heterogeneous, its 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 measured value is likely the most practical way to assess the direction of gas flow at this time.

The user is warned if the outside temperature lies above the central internal temperature. If the outside temperature for all months of the year is not provided or available, the system can use site climate type (Köppen's climatic classification) to estimate the maximum outside temperature (climate type can also be used to predict rainfall to estimate changes in cover effectiveness). Given the maximum outside temperature on an annual basis will predict the extreme condition (highest risk) at the site. If gas emission at this extreme is "LOW", there is little or no concern about the site 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 later uploading to AFRA for future analysis or modification.

4. Simplified Representation of the Rules in AFRA

The following examples show pertinent rules within the general structure of 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 at 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 temperature → 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 → risk is low (safe) at this time because oxygen-depleted gas does not find a way out of the dump to flow into the shed.

2. High sulfide content → High reactivity → High internal temperature → but Lower internal temperature than outside temperature → gas sinks from the top to the centre and flows out of the bottom edges (gas emission is high) → oxygen content inside the 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 → risk is very high because highly-oxygen depleted gas is blowing into an unventilated confined space.

3. Very young age >2 years or Old age >60 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 temperature → gas sinks from the top to the centre and flows out the bottom edges (gas emission is high) → Oxygen content inside the dump is moderately low because of a balance between low reactivity that consumes less oxygen and low diffusive and convective gas inflow because of the effective cover → a buried pathway connects the atmosphere in the dump to a shed → the shed has no open window or artificial ventilation → risk is high because oxygen-depleted gas is blowing into an unventilated confined space.

4. Low sulfide content → Low reactivity → Low internal temperature → but Higher internal temperature than outside temperature → gas rises to the top from the centre and air flows into the dump from the bottom (gas emission is low) → Oxygen content inside the dump will be moderately high because of the low reactivity of the dump material and gas inflow to the dump → a buried pathway connects the atmosphere in the dump to a shed → the shed has no open window or artificial ventilation →risk is very low at this time since oxygen-depleted gas is not blowing into an unventilated confined space and oxygen-depleted gas generation is not high.

5. Research Outcomes

The research outcomes from this project involve the creation of a fuzzy methodology to perform an atmospheric risk assessment at mine waste dump reclamation sites. The design of this “expert system” is a significant research achievement that should help prevent another accident similar to the Sullivan tragedy. An effectiveness evaluation was done to verify that the system meets the requirements of risk assessment at sites used as input to the development process. The system was validated against three sites that were not used as input. The results in APPENDIX F give both a verification and validation of AFRA for these dumps. APPENDIX E contains the weights derived to estimate the relative importance of the fuzzy values of each variable in affecting the respective fuzzy values of each risk element. Applying these weights to user inputs gives an estimate of the probability (Degree of Belief or DoB) of O_2-depletion gas generation and emission at any waste dump around the world. The confined space risk for an enclosed structure was determined for the summer season for all dumps examined assuming a confined structure exists at the toe of these dumps and that the probability of human exposure is high. For further details on gas convective flow and knowledge behind the interpretation of the weights in each table in APPENDIX E, refer to APPENDIX D.

To estimate the fuzzy values for hazardous gas generation and emission, the effect of atmospheric pressure and temperature on gas movement is considered in keeping with the conditions and findings at the Sullivan Mine site. Table 4 in APPENDIX E predicts gas velocity direction at the toe of the waste dump from calculated free energy changes measured from July 2006 to December 2008. The free energy boundaries that classify gas direction were determined from temperature and pressure data at the Number One Shaft dump measured hourly - details about this thermodynamic model can be found in the final PhD thesis. Although there is no other method to estimate gas flow direction in the literature, results of this thermodynamic model with respect to convective flow are similar to those from the conceptual numerical gas transfer model developed by Lefebvre et al. (2001).

For this approach the central problem faced by mine and reclamation practice designers is to obtain internal temperature and pressure profiles. These are rarely available without drilling a number of boreholes throughout the dump. If the top pressure (P_{atmT}) and bottom pressure (P_{atmB}) are available, then pressure inside 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. It is considered that pressure changes reach thermodynamic equilibrium between the dump and the atmosphere relatively quickly – perhaps within about 20 minutes – while the thermodynamic equilibrium of temperature takes considerably longer, if ever, to be established – mainly because of the cyclical nature (diurnal and seasonal) of atmospheric temperature and the need for convection into the dump. For a proper risk assessment, internal temperature measurements are preferred, but if not available, other factors can be used to infer the value. If the rate of oxidation has been studied, this 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., 2001a) and so, field measurements are needed to provide valid data. AFRA can use inference equations to interpret an approximate value of reactivity to estimate the internal temperature range. Internal temperature depends on the degree of saturation (or water content), reactivity, permeability, cover effectiveness and cover age, dump age, dump geometry and pH – as in Table 7 in Appendix E. The following intermediate variables can be input in order to estimate internal temperature which then leads to gas emission and gas generation estimates:

1. **Reactivity:** Reactivity is a function of dump age, sulfide content, particle size, water saturation, and extent of weathering – Table 3 in APPENDIX E. Based on these data, reactivities of the test and reference dumps are predicted in Table 10 in APPENDIX F.
2. **Water content or saturation:** The value for water content or water saturation is important in determining reactivity and is also used to estimate permeability. If water saturation is undetermined it can be estimated given water content, solid density, and

porosity similar to that done by Lefebvre et al., (2001a). In Table 8 in APPENDIX F, undetermined water saturation was estimated for the reference and test dumps. If porosity is unknown, water saturation and porosity can be estimated by bulk density, solid density and water content. An undetermined permeability can be estimated based on the weights given in Table 2 in APPENDIX E.

3. **Permeability:** Table 8 in APPENDIX F shows the estimates of Degrees of Belief (DoBs) in “high” permeability for reference and test dumps. The calculated DoBs for permeability values are projected onto a fuzzy set for “High” permeability (1E-8 to 1E-12) to arrive at an estimated discrete value for permeability.
4. **Cover Effectiveness:** A value for cover effectiveness can be estimated from the weights presented in Table 1 in APPENDIX E. Estimates of the value for cover effectiveness for test and reference dumps are shown in Table 9 in APPENDIX F.
5. **Various topographical features:** Geometrical or topographical properties such as the presence of benches, dump height, height/diameter ratio, and slope should be known and entered into AFRA.

Table 15 in APPENDIX F shows the estimation of an undetermined internal temperature for each of the test and reference dumps. The results indicate that the heuristic estimates based on the weights in Table 7 in APPENDIX E give reasonably accurate representations of the range of internal temperatures in all reported results for each dump. The yearly trend of the internal temperature for the reference dumps is shown in Table 11 in APPENDIX F. This information can help in future risk analysis. A cooling dump initially becomes more hazardous while a heating one will likely become safe(r) for some considerable time.

Once the internal temperature is known or estimated, the direction of gas velocity (at the bottom of the dump) can be determined. Table 11 in APPENDIX F gives the estimates of gas flow in the reference and test dumps. Gas velocities in an ARD collection pipe were only measured at the Number One Shaft dump and at the North dump at the Sullivan mine. So the estimates of gas velocity direction during the warmest time of the summer for both dumps at Sullivan mine show results comparable to the measurements. As shown in Figure 9 in APPENDIX A when the outside temperature is 32^0C (highest reported value at Kimberley), the gas velocity shows the highest negative value that occurred at Number One Shaft dump (~ -1 $m \cdot s^{-1}$). This agrees with AFRA's estimation of gas velocity of "Negative Big" for an outside air temperature of 32 ^{0}C – see Table 11 in APPENDIX F. According to Dawson et al. (2009), monitoring of the North dump seepage collection system has not shown any significant O_2-depletion or CO_2-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 ^{0}C – see Table 11 in APPENDIX F.

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. One may wonder if O_2 content in the dump might also verify the direction of gas flow, but a "High" or "Low" oxygen content alone is indicative of a gas flow out or an air flow into the dump respectively when the dump reactivity is extremely high. Comparison of seasonal changes in oxygen content can be used to infer if gas or air is flowing into or out of the dump. Such a comparison was reported by Smolensky et al. (1999) which allows conclusions about the direction of convective gas/air flow in the Nordhalde dump. According to these results, during the late autumn and early winter when the temperature in the upper near-surface portions of the dump (affected by outside temperature) falls below the internal temperature, the profiles show an increase in oxygen content, suggesting the onset of air convective inflow. The effect was more evident for boreholes near the edges of the dump. In all boreholes, the pattern of low oxygen concentration at depth reestablished itself during the late spring and summer when the temperature within the upper near–surface portions of the dump rose above the internal temperature – see Figure 13 in APPENDIX D. At this dump, AFRA estimated a gas velocity value at the bottom of the dump of “Negative Very Small” during the summer resulting in a gas emission belief of 100%. During the winter, the gas velocity was estimated as “Positive Big”, resulting in a maximum gas emission belief of only 18% - Table in APPENDIX F. These results compare well with oxygen levels in summer (0%) and winter (8%) in this dump. Therefore, seasonal cyclic changes in O_2 levels within a waste dump (related to outside temperature changes) appear to be useful in verifying the model.

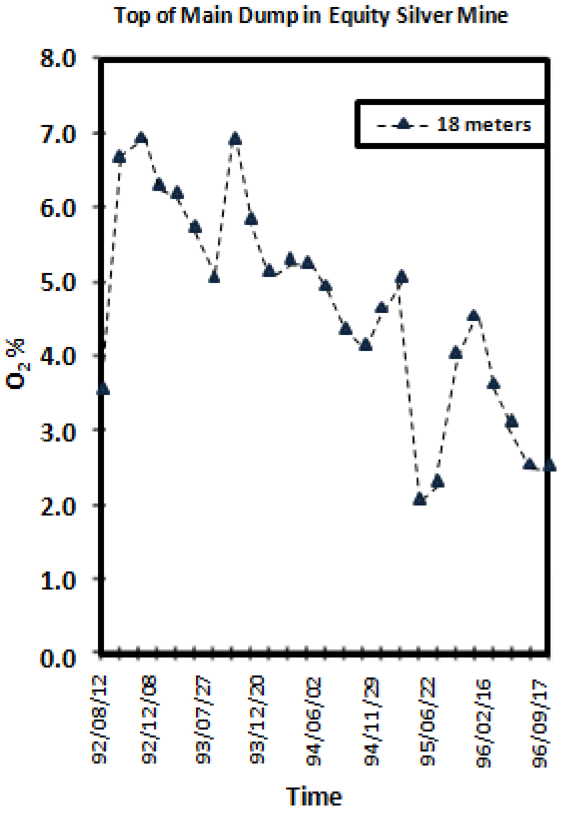


Figure 6. Oxygen profile at top of Equity Silver’s main dump (from Aziz and Ferguson, 1997).

At Equity Silver’s main dump (one of the test dumps in this work), the O_2 concentration in the dump varies seasonally at 18 m inside the dump – see Figure 6 above. The data show that the internal O_2 content increases during colder months and drops during the warmer months. An increase in O_2 content indicates that air flows into the dump in winter at the bottom, while the decrease in internal O_2 content shows that pore gas flows out the bottom during summer. As shown in Table 11 in APPENDIX F, the gas velocity directions for Equity Silver's Main Dump during summer and winter are estimated by AFRA to be "Positive Big" and "Positive Very Big" respectively. So AFRA is in agreement with the information that this dump is apparently never completely O_2-depleted. During the colder periods in time when the gas velocity is "Positive Very Big", the O_2 content increases relative to that measured in the warmer months when the gas velocity is "Positive Big". These two examples demonstrate that the rules determining gas and air flow in the reference dumps matches AFRA predictions for flow and hence, the gas emission values are likely valid.

Furthermore, the change in O_2 levels year over year within Equity Silver's Main Dump, suggests that the magnitude of air flow into the dump may be dropping over time for the period in which measurements are reported - see Figure 6. This may be due to a decline in internal dump temperature because of age or cover placement (causing a decrease in reactivity). When the internal temperature reaches a value close to that of the outside temperature (even during the colder months of the year), a lower inflow of air will result. This causes a lower internal O_2 content than in the previous year. According to Aziz and Ferguson, (1997) the dump internal temperature is slowly decreasing which supports AFRA's prediction.

Given gas/air velocity and factors such as pathway properties, type of cover, permeability, channeling, percent fine materials, and water saturation, the value of gas generation and emission can be estimated by applying the weights in Tables 6 and 5 in APPENDIX E respectively. Tables 12 and 13 in APPENDIX F show the results of gas generation and emission estimates respectively for the reference and test dumps. The gas generation estimates have been compared with O_2 levels measured at the dump edges (mid-height) and good agreement is shown for each of the studied dumps. For example, the gas generation value for the Nordhalde dump was estimated as 100% in summer and 86% in winter. Although it is not possible to calculate the exact O_2 concentration with this low level of knowledge, the software was able to estimate fuzzy values close to reality showing that gas generation is lower during the winter – Table 12 in Appendix F.

Given the value for gas generation and gas emission, the atmospheric risk of a confined space hazard was estimated for the reference and test dumps – Table 14 in Appendix F. For this analysis it was assumed that each dump was connected to a sampling shed through a buried pipe that delivers ARD effluent to a enclosed structure (similar to the situation at the Number One Shaft dump). Gas confinement was estimated as 90% by AFRA for the purposes of this analysis. It was also assumed that the structure is in regular use by mine employees and therefore the Degree of Belief in human exposure was taken to be 100%. The risk assessed for Number One Shaft Waste Dump during the hottest time in the summer was calculated as 0.90 (Hazardous). Risk was also determined for the period May 13-17, 2006 (the time of the Sullivan Mine accident) when the outside temperature reached 20 ^{0}C because of a sharp increase in temperature based on data from the Cranbrook airport (about 20 km away). This also gave a risk level of 0.90 (Hazardous). It is obvious that the estimated risk is close to reality despite the many factors set to undetermined due to a lack of measurements. The confined space risk at the Nordhalde Dump was estimated as 0.21 which is a “Significant Problem” in winter, and was estimated as 0.89 which is “Hazardous” in summer.

O_2 measurements at a structure located at the bottom of the North dump connected to the dump was equal to that of fresh air and therefore, the Sullivan Mine Accident Technical Committee has indicated North dump to be safe. For the North dump, AFRA assessed the risk as 0.25 (Significant Problem) during the hottest time of the summer at Kimberley which is about 32 ^{0}C. This temperature is close to the internal temperature of the dump (33 ^{0}C). Since the structure at the bottom of the dump was categorized by AFRA as being a high risk, this suggests that a few degrees decrease in internal temperature or increase in outside temperature may cause such a structure to collect a deadly atmosphere in the future. In this dump, the presence of an enclosed structure with complete confinement connected to the internal dump pore gas dump taken together with the high gas generation ability within the dump gives a high final risk despite the low gas emission value of 18%.

Risk was calculated for two other waste dumps in the literature – Equity Silver's Main dump and the West Lyell dump at Mt Lyell mine - see Table 14 in APPENDIX F. The risk at Main Dump was estimated to be 0.19 which is "A Problem" while that for West Lyell Dump was estimated as 0.16 (also "A Problem"). The "Extremely High" Internal temperature of 52^0C at Equity Sliver and the "High" internal temperature 34^0C within the West Lyell Dump of leads to low gas emission estimates for both dumps. Oxygen levels were measured at 0% for some points and 20% at most points along the edges of the West Lyell Dump throughout the year. These dramatic differences are claimed to be due to pods of high oxidation rate materials (5% sulfide content) in the dump which is typical of most heterogeneous coarse waste rock dumps. Although a "Very High" sulfide content in some parts of the dump consumes oxygen completely, the "High" oxygen content in other zones suggests that air flows into to the dump along the toe. Estimates of a "Low" gas generation degree of belief of 66% and a "Low" gas emission degree of belief of 82% at this dump match this observation. For Equity Silver's Main dump, the seasonal cycling in O_2 content levels mentioned above agrees with AFRA's gas velocity estimates for summer and winter.

The reference waste dumps (Sugar Shack South and Doyon) that produce a lower atmospheric risk assessment ("A Problem") do not have covers on their surface. These lower risk outputs occur in AFRA since without a cover, oxygen is not inhibited from moving freely into the dump and so, a higher oxidation rate exists leading to higher internal temperatures (>40 ^{0}C). 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 95%., 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. If these two effects are not present, then the atmospheric risk at these dumps would be judged “Very Safe” and “Not a Problem” respectively.

No similar atmospheric accident to that of the Sullivan mine has ever happened at any other reclamation site. As such, the results of this project cannot be compared directly with other studies. Atmospheric investigation of waste dumps is a relatively young field of research. Further studies of other waste dumps should be done to provide more evidence about atmospheric risk. The industry seems to have been fortunate not to have seen a similar incident at another dump site. The following analysis describes our belief as to why most waste dumps have not shown an atmospheric hazard in the past and at present. It must be recognized that there are a number of cyclic behaviours exhibited by a waste dump with respect to O_2-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 outside temperature cycles from hot in the daytime to cool in the night, the dump may transition from blowing to sucking - this will occur when 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 pulled in 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. In this case the dump will suck air at the bottom all the time and no danger will exist in the confined space. As the surfaces continue to oxidize, eventually the sulfides are depleted 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 stop altogether and the pore gas is no longer depleted of oxygen, hence the danger is now gone forever. Exactly when each of these transitions occur 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 based on the age of the dump (estimated for the Number One Shaft 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. atmospheric temp
150 - 170 years	Rapid increase in risk - internal temp falls below max. atmospheric 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 now safe - no O_2-depleted gasses are generated or emitted

Recognize that the temporal boundaries between these projected risk levels are fuzzy concepts which vary significantly by changes at the site setting and waste dump properties. Currently many of the dumps that were studied are 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 a 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 7 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. A maximum outside temperature of 32 ^{0}C each year is assumed to ensure the evaluation detects the maximum likelihood of risk for each year (although warmer conditions will be more hazardous). – The dump was about 56 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 ~16 ^{0}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 ^{0}C per year. If this rate of increase continues, by 2030, the maximum internal dump temperature may reach ~36 ^{0}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 ^{0}C per year until a final equilibrium temperature of 10 ^{0}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 degree of belief 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 O_2 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 to rises until it exceeds the maximum reported outside temperature of 32 ^{0}C causing the risk to decline to a “Significant Problem”. From 80 to 150 years the internal temperature reaches its maximum (~32 ^{0}C) and flow reversal occurs year round – at this point, risk is “A Problem”. At 150 to 170 years, the internal temperature begins to drop due to a decrease in dump reactivity as the sulfides are depleted causing the risk to increase to “Hazardous” once again. From 170 to 190 yrs the danger declines as the sulfides become depleted. At a very old age (>200 yrs) the sulfides in the dump are completely depleted and so, pore gas is no longer O_2-depleted, i.e., “No” toxic gas is generated. Although the internal temperature is lower than the maximum atmospheric temperature which may continue to induce emission from the toe, the risk is a “Marginal Problem” since the pore gas O_2 level will have increased to that of normal air. It must be understood that spatial differences in these transitions may occur at different times due to the dump heterogeneity.

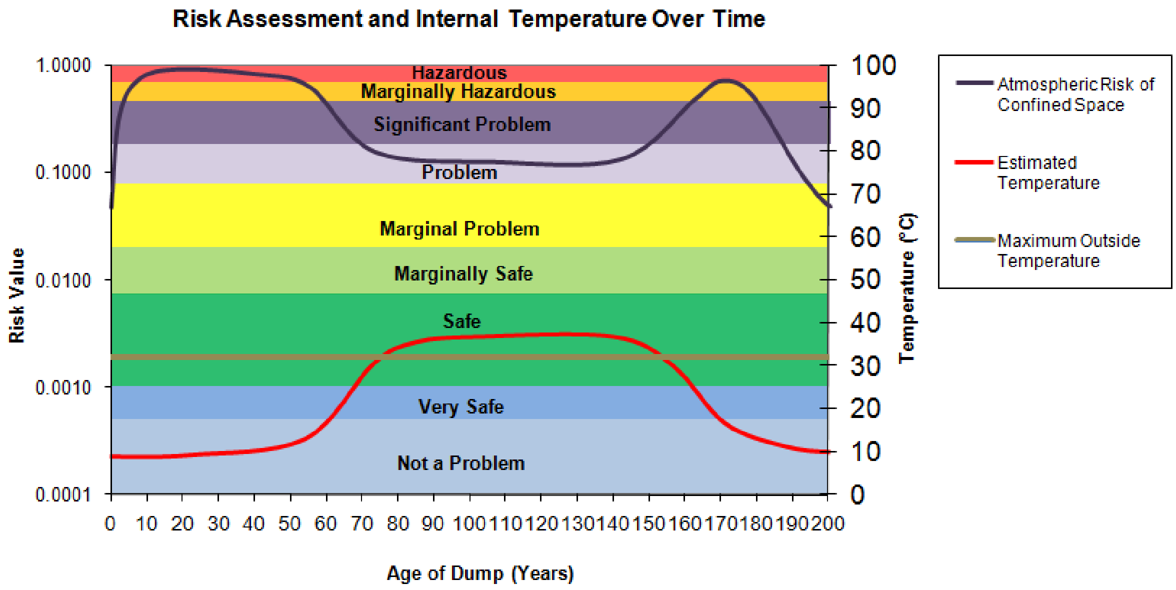


Figure 7. Decadal variations in internal temperature and confined space risk.

A sensitivity analysis was done for Number One Shaft dump to show how the confined space risk value varies when the values for gas emission, gas generation, gas confinement and human exposure each change from “Low” to “High” - the results are presented in Figure 17 in APPENDIX G. 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 (~32 ^{0}C). In this table, gas emission varies for different internal temperatures: for T = 28 ^{0}C, Emission belief = 100%, for T = 30 ^{0}C, Emission belief = 89%, while for T = 32 ^{0}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”.

6. Implications for Future Research on Occupational Health

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-O_2 levels from displacement by N_2 and CO_2. Deoxygenation of air in the well occurs from contact with O_2-depleted well-water from underground. Denitrification of commercial nitrate fertilizers in a perched zone above the aquifer can generate N_2 that is picked-up by ground water. Sulfide mineral surfaces and/or organic matter in a semi-saturated, permeable zone consume dissolved-oxygen and emit CO_2 to ground water flowing into the well. Gas emission is influenced in this case by barometric pressure changes much more than by temperature changes. Air moves into the well when the 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, this oxygen-depleted air rises up the well and into the an enclosed structure such as a surface pit, well head, or sump. Eventually fresh air bleeds into the confined space, but until then the space is highly dangerous. When air pressure rises, the restored fresh air in the space is forced back into the well and the cycle continues (Hill, 2004). 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 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. Many companies have policies that require regular assessment (for example once a year). It is proposed here that assessments should be repeated whenever any change takes place at a site. Although this concept may seem simplistic, it can, and will prevent other accidents from happening.

7. Policy and Prevention

7.1 Identification of Policy and Prevention Implications Arising from the Research

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. 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 dump site, e.g., placement of a cover to seal the O_2-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. Controlling worker access to the workplace as well as proper and efficient emergency response can also help to stop additional fatalities or prevent the first one.

This analysis has focused on structures linked to a dump at the toe. Danger also exists in a reverse manner with structures built on the 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. There is insufficient definition and regulations about confined spaces in the BC Mines Act. There is no specification of possible O_2-deficiency at sulfide mine reclamation sites in any mining-related regulation throughout the world. Outside temperature and pressure effects that convert a safe enclosed structure to a dangerous confined space in a few hours is discussed in some U.S. regulations (NIOSH) but these are unrelated to mine reclamation. Section 3.4.4 of the 2008 version of the B.C. Mines Act and the WorkSafeBC Confined Space Entry Program – A Reference Manual both recommend testing air inside a confined space at intervals during work progress to ensure air quality does not deteriorate. While the regulations emphasize monitoring during work, an atmospheric risk assessment should also be required when changes in climate occur. As a result, suspicious non-permit required 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.

The Sullivan mine tragedy should focus our attention on the fact that insufficient time is spent studying hazards at reclamation sites, especially when these dangers are associated with new techniques designed to protect the environment. Continued risk assessment is needed to investigate atmospheric hazards in industry. For example, there is an atmospheric hazard associated with blasting gases (NO_2, CO) in which these may migrate through the ground into a nearby confined area potentially exposing workers to such gasses while working in a pit or trench. Current mine regulations do not warn about such hazards. 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.

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. Relying on a single reading of a multi-gas meter will not help this understanding. 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 O_2 level in the air within the space. AFRA is able to predict an O_2-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.

An additional goal of the project has been to develop an application for hand-held pocket PCs or "smart" phones to provide first-responders with immediate answers about a particular confined space situation. Such a mobile application can help train paramedics, fire-fighters, or police officers to be vigilant about confined spaces so when responding to an accident site, they understand the need for multi-gas meters and appropriate respirators.

7.2. Identification of Relevant User Groups for the Research Results

Most engineers at reclamation sites are unaware of the danger inherent in the atmosphere within a dump. Mining companies should be required to use this tool when designing waste dump reclamation activities. Companies can be provided with AFRA through the B.C. Ministry of Energy, Mines, and Petroleum Resources, to assess confined spaces at the site.

AFRA should be used before developing an inventory of confined spaces at a site. In this way, engineers can add structures suggested by the system (ones where risk exceeds the threshold of "Marginal Safe") to their confined space inventory and test them further (tests should be comprehensive and done for dangerous times or for different times of the day, week, month or year). In this way, any mistake made in data entry can be reevaluated during further investigations at the site. An expert system tool is only as accurate as the experts who contributed to its construction and to the reliability of the data entered – as such it may underestimate or overestimate risk in certain boundary condition situations. Users can write comments about flaws and shortcomings or common mistakes within AFRA on our websites. They can also suggest changes in the definitions of fuzzy sets and the linguistic terminology.

The Sullivan Mine accident would not have happened if the site has been routinely assessed with a tool such as AFRA. If using such a tool was required and enforced in the workplace, engineers would have to perform the assessment regardless of whether anyone recognized that the space could become hazardous. Such an assessment should be done whenever a change is made in site design, site activities, or site environment. The risk assessment results are valid for the time when the data are collected. For example, outside temperature changes on daily/monthly/yearly basis will significantly affect the risk. Other parameters such as internal temperature vary on a yearly basis and so require less frequent measurement. AFRA can project the results into future situations in time or space.

7.3. Description of Policy-Related Interactions Undertaken by the Applicant

A review of confined space hazards was shared with BHP-Billiton, Nickel West Division. This review was basically a summary of the important points in other confined space manuals (WorkSafeBC, NIOSH and OSHA). To enhance this work further, a review of different types of confined space (or atmospheric-related risks) was done for a variety of mine sites. This analysis looked at previous accidents and also considered other atmospheric-related accidents that have occurred in industries such as construction (which has received more attention than the mining industry in this regard).

During the project, knowledge about the short-comings of the confined space section of the Mines Act was shared with the B.C. Ministry of Mines and Petroleum Resources as well as a review of confined spaces accidents and assessment methods. Unfortunately such concerns have yet to be addressed despite the fact that the Mines Act was updated after the Sullivan mine accident. The new version is still deficient with respect to the Confined Space Manual issued by WorkSafeBC. Although the definition of a confined space and confined space entry procedures were updated in 2008, there are no examples given of potential confined spaces at a reclamation site. There is no review of potential materials or activities that can develop a hazardous atmosphere for operating or closed mines. This information is embedded in AFRA and the hand-held version as a Help file. Other atmospheric related hazards at reclamation sites are addressed in the general risk assessment portion of AFRA.

Knowledge transfer has also been done through poster presentations and talks at a variety of conferences and workshops. Describing this accident and suggesting ways to prevent it from happening again will bring more attention to confined space issues at mine sites.

8. Dissemination/Knowledge Transfer

The help file in AFRA will be shared with others and made available through our website. The files on the website are offered to BC-MEMPR for application at mine sites and to WorkSafeBC for dissemination to others. AFRA can be updated based on feedback and as a result, the tool will become stronger (or smarter) as it is used. After completion, maintenance of an expert system is very important. AFRA methodology during early stages of development has been presented to MEMPR for consideration of policy changes. Representatives of the Ministry have asked to share in the research findings. The hand-held tool will be disseminated to paramedics to help educate them about confined space hazards and prevent rescuer fatalities.

Publications

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

L. Mohammadi, J.A. Meech, 2010, Effect of Atmospheric Temperature and Pressure on Confined Space Risks at Mine Reclamation Sites, submitted to J. of Loss Prevention; pp.28.

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Posters

L. Mohammadi, J.A. Meech, 2008, Risk Assessment of O_2-Depletion and Hazardous Gas Emissions at Mine Reclamation Sites, BC Environmental and Occupational Health Research Network (BCEOHRN) AGM & Scientific Exchange, Vancouver, B.C., November.

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

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

A manual on confined space hazards written for the BHP-Billiton, Nickel West Division and BC Ministry of Energy, Mines, and Petroleum Resources. The confined space manual considered important points in other similar manuals (WorkSafeBC, NIOSH and OSHA). To enhance the manual further, a review of different types of confined spaces was done for mine sites.

Presentations

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

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

9. Conclusion

Recognizing a potential confined space atmospheric hazard is essential in preventing accidents. 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. Climatic temperature and pressure changes control gas emission into an enclosed area at different times of the day and year. As such, a confined space can switch from being safe in one instance to being unsafe in another. A confined space may be measured as being safe when later on it is not. Most confined space regulations do not warn about this transformation. Current B.C. mining regulations do not address atmospheric problems with mine waste dumps undergoing reclamation. There is no mention of the possibility of an O_2-deficient environment at a mine reclamation site in any mining-related regulation around the world.

An Atmospheric Fuzzy Risk Assessment (AFRA) tool has been created that can be used by mining personnel to identify atmospheric hazards when developing a confined space inventory at a reclamation site, whether these spaces involve a sump, a well, a pipe, a sampling shed, or a topographical anomaly. AFRA has been tested on data from a number of waste dumps which have been instrumented and studied previously for ARD control. Verification and validation of AFRA shows excellent agreement with these measurements and helps us understand why other sites have never shown the potential for such an accident. AFRA warns about future risks (especially from daily and seasonal changes in climate conditions), and will ask a user to run the software for different times of the year, and to redo the assessment if any changes occur in design, operation, and environmental or climatic conditions at the site. The results show that AFRA can identify gas hazards and provide a means to recognize a confined space that may exist or develop over time.

Although, reclamation activities are beneficial for ARD management certain aspects can increase the risk of atmospheric hazard. Placement of a cover will inhibit abundant O_2 and water inflow into the dump. When O_2 is not prevalent for sulfide reactions, the oxidation rate will decline resulting in a lower internal temperature. As this temperature decreases or stays low, it may remain below the annual maximum outside temperature. This will result in a higher atmospheric risk. Other reclamation activities that may lead to increased atmospheric risk include covering the effluent collection ditch and building an ARD collection sump and shed. These actions may result in direct connection between the dump air and the shed atmosphere, increasing gas emission and gas confinement values leading to a higher atmospheric risk.

10. Acknowledgment

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APPENDIX A:
Description of the Sullivan Mine Accident and Contributing Factors

Sullivan Mine Accident

Four people died in a sampling shed because of an oxygen-depleted atmosphere within this structure at the Number One Shaft Waste Dump at the Sullivan Mine in Kimberley, B.C. in May 2006 (http://thetyee.ca/News/2007/07/09/MineDeaths/; Phillip et al. 2008; Mohammadi and Meech, 2008). The accident occurred when oxygen-depleted air (and water) caused by sulfide oxidation flowed out from the dump through an underground drainage channel and buried pipe connected directly to the sampling shed – see Figure 8. Seasonal temperature changes have been found to cause pore gas to flow from the dump into the shed (Philip et al., 2008). Before the ditch was covered, there was no direct connection between pore gas in the dump and air in the shed. The ditch was open to the atmosphere allowing the ARD effluent to become re-oxygenated as it flowed along the channel. So, water entering the shed was not O_2-depleted prior to the ditch being covered. After covering the ditch, a well-sealed, underground drain was created, isolated from the atmosphere, creating an unrecognized hydraulic conduit for pore gas and O_2-depleted waters to flow from the dump to the shed.

Figure 8. Number One Shaft waste dump at the Sullivan Mine prior to covering with glacial till.

Reclamation began at the site prior to closure and is still on-going today to manage activities aimed at restoring the site to a form compatible with the local environment. In 1995, a V-notch weir was installed to measure flowrate. In 1997 to overcome winter ice build-up on the weir, concrete blocks were placed around it and a shed was erected to protect the weir from the elements. In 2004, the open ditch was partially covered as the toe of the dump was extended forward to reduce the profile in preparation for revegetation and erosion control. In 2005, 1m of glacial till was placed over the waste rock and drainage ditch. This seal reduces water percolation and, when saturated with water, prevents air infiltration slowing oxidation as the pore air remains depleted of O_2 rather than being replenished by fresh air. The drainage ditch running along the toe was engineered into a sealed drain and then covered by the toe extension to prevent seepage. The sump collected effluent and diverted it through a buried pipeline to a water-treatment facility. The sampling shed was used in the fall of 2005 and winter and spring of 2006 on a regular basis up to one week before the tragedy – without any incident or indication of a problem.

From May 15 to May 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 a lack of oxygen. Following a preliminary investigation, the Chief Inspector of Mines for B.C. issued an immediate warning to all mines in B.C. 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."

Contributing Factors

During the summer of 2005, the dump was covered with 1m of glacial till and the slope re-contoured. In this way a 12m long, 400mm diameter pipe that directed acidic water to the shed became isolated from the atmosphere. The oxygen-depleted effluent flowed into the bottom of the sump over a weir. What previously was oxygenated surface water was now de-oxygenated groundwater creating an unrecognized and dangerous situation. Even more hazardous, the covering of the ditch meant air in the shed became directly connected to "bad" air in the dump.

In August 2006, the dump was instrumented to monitor respiration and data was collected on an hourly basis until the summer of 2008. Data collected included air velocity and gas composition in the pipe, at the end of the pipe, and about waist height within the shed. Site meteorology, cover moisture content, internal temperature, gas composition, and pressure at 16 locations were also monitored.

Oxygen concentrations of air in the dump range from normal air (about 21%) to near zero. Carbon dioxide concentration range from near zero to about 5% in most locations, but were as high as 21% in one drillhole. The instruments within the dump show an internal temperature range from 5℃ to 16℃ (at various locations and from top to bottom of the dump) indicative of sulfide reactions within the dump. During this same period, the outside air temperature ranged from -17℃ to +32℃. Data collected using instruments installed by Teck Resource's Technical Advisory Committee show clearly that the flow direction and quantity of gas in the underground pipe varies in accord with atmospheric temperature. As can be seen in Figure 9, for temperatures below ~12℃, the direction of flow is into the dump (the dump is "inhaling"), and when the temperature rises above ~12℃, the dump begins to "exhale" resulting in O_2-depleted air flowing through the pipe with the water and into the bottom of the sump. Figure 10 shows gas composition measurements at 2.4 m up the pipe from the ARD collection sump. Gas composition changes with flow direction so when the gas velocity is negative for a short amount of time, the O_2 concentration in the sump falls below 21%. Taking into account the measured leakage flow of oxygen-depleted air from the pipe into the shed (from 11th to 13th of May 2007), the time for the sump's oxygen level to drop below 17% was calculated to be less than 10 hours.

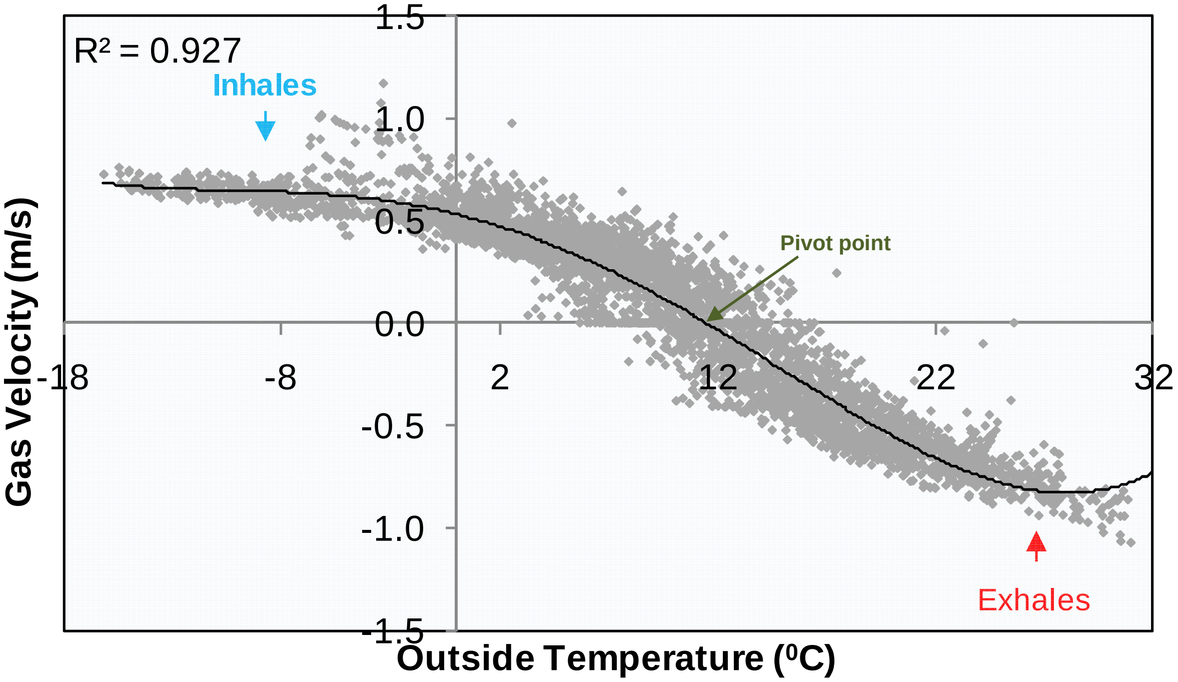


Figure 9. Relationship between air velocity in the sampling shed feed pipe and atmospheric temperatures at the Sullivan Mine Number One Shaft Waste Dump (adapted from Philip et al. 2008).

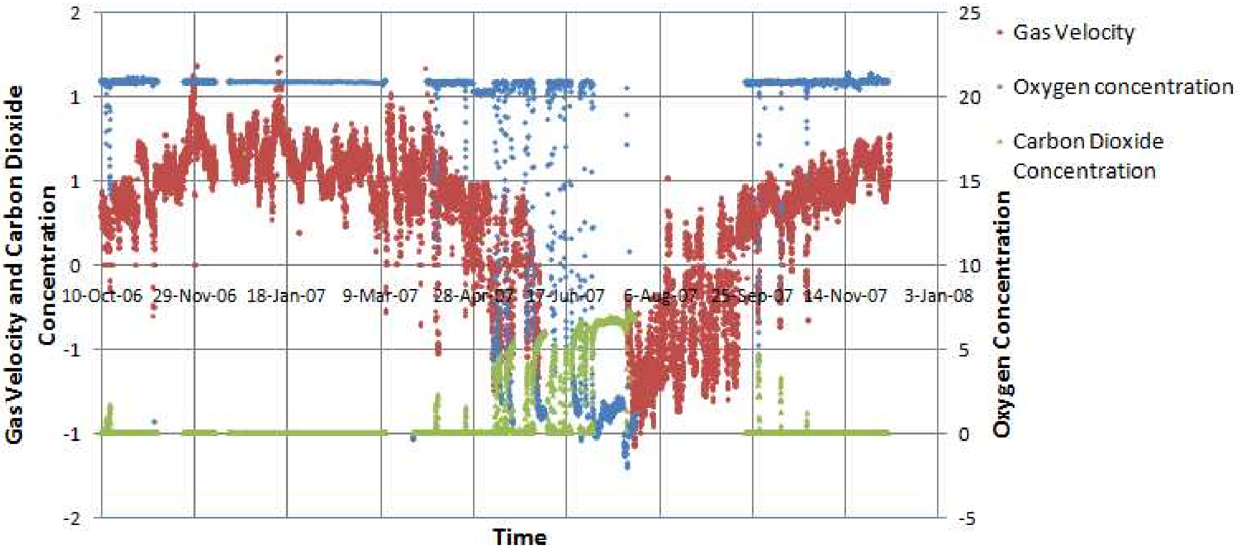


Figure 10. Gas velocity, oxygen and carbon dioxide concentration in Number One Shaft Waste Dump.

APPENDIX B: Description of a Fuzzy Rule-based System

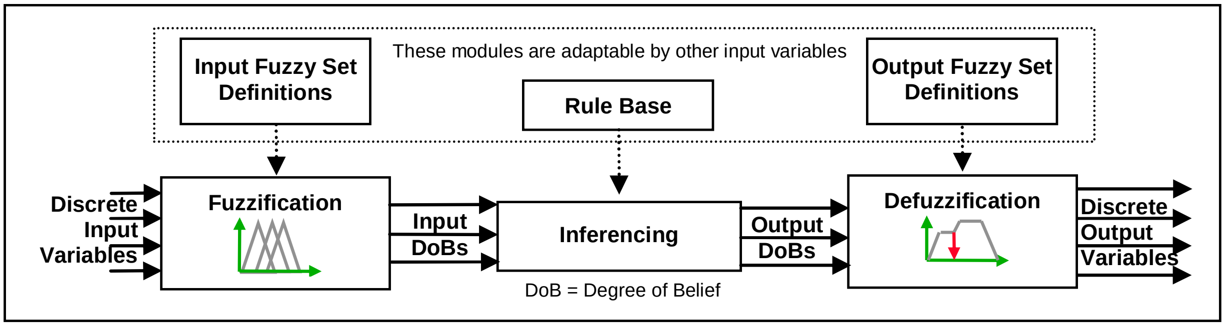


Figure 11. Structure of a fuzzy expert system.

Figure 11 represents the major parts of a fuzzy rule-based expert system. The first unit is called Fuzzification wherein membership functions which are local descriptions of variables are assigned Degrees of Belief. A membership function gives the degree of belief in 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 characterized by membership functions. The premise part of each rule partitions the input space into a fuzzy region that overlap with other rule-defined regions, while the conclusion or output part describes how the system might behave in each region. In the Inferencing unit, depending on the input values some of the fuzzy rules stored in the rule-base will fire. Note that fuzzy rules are descriptions of the undetermined problem under all determined circumstances. They form a decision-making unit using expert knowledge and understanding of the problem.

An example is given of two rules that model dump reactivity based on two inputs (dump age and sulfide content) – see Figure 12. Each of the inputs is divided into a number of different fuzzy linguistic sets: age is Very Young (<2yrs); age is Young (2-7 yrs); and sulfide content is Low (0.015-0.02); sulfide content is Moderate (0.02-0.025). Note that the fuzzy sets overlap and the boundary between adjacent sets are not crisp. A fuzzy set is assigned to each linguistic term to determine its degree of belief. The shape of the fuzzy set shows how the linguistic term is defined. For example, to what extent is the dump young? In Figure 12, a 3 yrs old dump is about 80% young.

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 100. If the rule premise has more than one part (in this example, 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 or for an AND conjunction the minimum DoB is chosen. In this example, similar to AFRA, the AND (minimum) conjunction is applied to calculate the net degree of truth - e.g. for the first rule this value is 20%. 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 using the maximum method which truncates the output (or conclusion) fuzzy set at the value of the corresponding Degree of Belief value in the premise multiplied by the variable weight. For implication, every rule has a weight (between 0 and 1). In the example in Figure 12, the AND operator is used and the weight for each rule is 1. The conclusion fuzzy set in this example is a Gaussian set - although AFRA uses fuzzy singletons without any loss in accuracy. A Fuzzy Singleton is a fuzzy set whose support is a single point with a pulse membership function of 1. This membership function gives results almost identical to a Gaussian membership function over much of the entire hyper-space.

If more than one rule with similar fuzzy set conclusions fire together, 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.

In many process control fuzzy systems, the output is a single crisp value. This is achieved by the Defuzzification unit converting the fuzzy set into a crisp output that represents the Possibility Distribution of an inferred fuzzy control action. Although different defuzzification methods are available (over 99 different methods are reported in the literature), AFRA uses the Weighted Average approach shown in Figure 12. This method is not computationally intensive and produces results only slightly different from techniques such as “area-centroid” or “mean of maximum” which many practitioners prefer.

If data is unavailable for certain variables (such as wind velocity) fuzzy linguistic sets are chosen by a user 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.

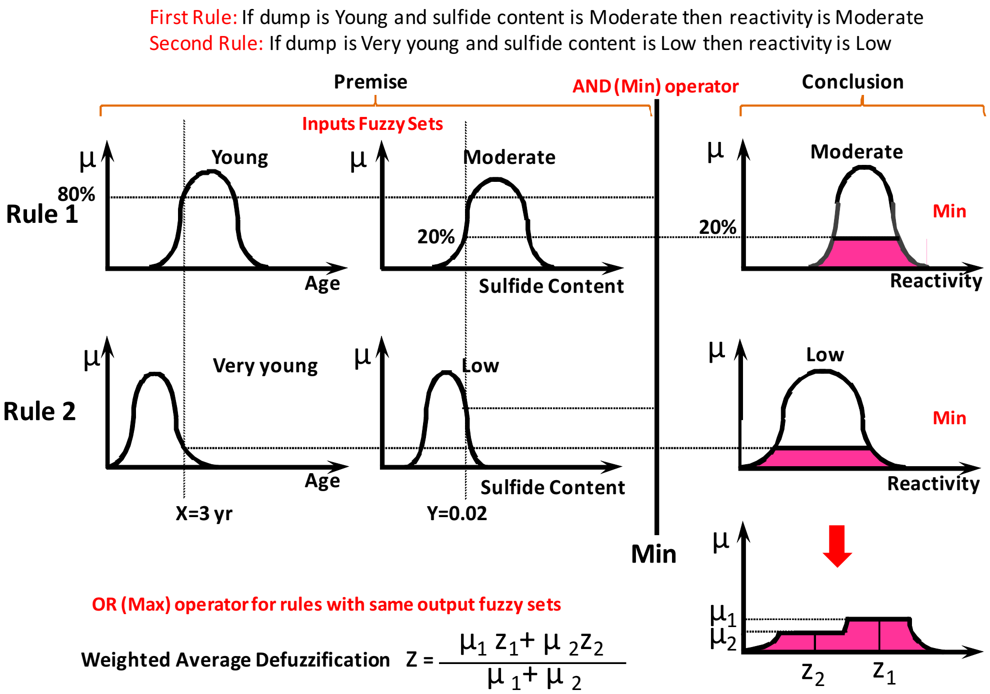

First Rule: If dump is Young and sulfide content is Moderate then reactivity is Moderate
Second Rule: If dump is Very young and sulfide content is Low then reactivity is Low

Figure 12. Representation of fuzzy expert system with two rules to show Inferencing and Defuzzification.

APPENDIX C: General Risk Assessment

For a general assessment regarding the nature of the waste material, the presence of confined structures at the site, and human activities at the site, AFRA simply decides if there is a confined space risk to human health from exposure to a dangerous gas. The risk at this stage is assessed based on the degree of certainty that a confined structure exists; that a source of hazardous gas exists; and the probable exposure of humans. A number of waste materials may be present that can create an atmospheric hazard. These are listed so a user can choose those that are known or considered to be present. 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 and emission from soils and mined materials was reviewed. Some of the possible hazards are as follow: Sump or well head or drill holes, Erosion channels, ditches, and/or drains, tailing pond/waste dump water (O_2-deficient), blasting agents or residues, maintenance facilities after closure, tree falls forming a pit or hole, etc.

After recognizing the types of hazardous gas, some details about how each may accumulate or concentrate gas are provided as well as how and why the gas is generated. The appropriate respirator(s) are recommended. A further detailed risk assessment is advised when uncertainty exists, when an unacceptable level of risk in the general assessment is determined, or when the site setting is very sensitive.

APPENDIX D:

Literature Knowledge Acquisition for Gas Generation and Emission

Convective and Diffusive Gas Flow in Waste Dumps

The hazard of a confined space at a waste dump reclamation site is largely determined by the potential flow of pore gas between the dump and any structures located in the vicinity. 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.

Oxygen transport is a major rate-limiting factor in sulfide mineral oxidation and so, air and pore gas flow mechanisms are extremely important. Sulfide oxidation within the dump generates heat that accelerates oxygen (air) transfer into dumps with high permeability by a process called thermal convection (Lefebvre, 2001a). In the early years of the dump, air diffusion is the main transport mode. As time passes, heat accumulating from oxidation by this diffusive air establishes convective flow conditions in high-permeability dumps (Ritchie, 1994). Convection leads to increased air flow into the dump (depending on the sulfide content more O_2 than needed for oxidation may be self-supplied), but this inflow may be limited to small areas or hot-spots on the slopes of the dump (Sracek et al., 2006). Generally, best practice reclamation activities aim to minimize gas and water flow into the dump. Hence covers are often placed on the surface of a dump to reduce air and water infiltration.

Ritchie (1994) claims that gas diffusion dominates in waste rock piles with a permeability value below 10^{-10} m^{-2}, while convective flow plays a minor role. The permeability of the Nordhalde dump among all dumps examined was lower than that which Ritchie (1994) believed prevented the onset of thermal convective gas flow. However the oxygen profile for the Nordhalde mine shows seasonal changes that are caused by convective oxygen-flux changes according to Lefebvre et al. (2001a) – see Figure 13. 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.

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. To effectively reduce convective air movement, covers with permeabilities of 10^{-13} m^{-2} are often used. 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., 2001b, 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.

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., 2001b, 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 14) (Smolensky et al, 1999). The difference in O_2 concentration at the slopes of the dump and its centre is due to high reactivity that causes the air to become O_2-deficient when it reaches the centre of the dump. 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 O_2 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 O_2 level in the pore gas. This effect is apparent at the South Doyon waste dump (BH4 located at its centre) which had “Low” oxygen concentration and hot conditions (Lefebvre et al, 2001a). At the Sugar Shack South dump which has a considerably lower reactivity than that of Doyon (Lefebvre et al, 2002), when air reaches the centre, it still has O_2 concentration greater than 0%. Oxygen levels at BH5 located at the center of this dump show ~ 6% during winter when air flows into the dump at the toe. The internal temperature at Doyon is as high as 40 ^{0}C, yet lower than the edges which approaches 65 ^{0}C. This shows that reactions at the centre are still significant even when the oxygen is almost completely consumed (Lefebvre et al, 2001a).

Although sulfide reactions can continue without oxygen from pore gas, 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. When convection is established, a higher quantity of oxygen becomes available for oxidation. As a result, the temperature within such regions of a dump increases 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, (2001a). The optimum temperature range for bacterial activities which are very important in catalyzing the reactions (especially at the centre where O_2 may not be available) is from 20-42 ^{0}C. Above this range these reactions may slow appreciably.

Temperature and oxygen profiles show more variability when convection is the dominant mechanism. In this case, the temperature peaks at a shallow depth which is often accompanied by a peak in oxygen level in the pore gas. 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 (e.g., site 7 and site TBT at the Doyon dump) (Wels et al. 2003). This observation further supports the conclusion that all dumps are sufficiently permeable for mass transport of air/gas by convective flow. Depending on flow direction, convection can either bring more O_2 into the dump or can create more O_2-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. 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 O_2 content and heat generation within the dump. The increased heat will move even more fresh air (hence O_2) into the bottom of the dump by convective flow as the hot gasses rise through the dump to the upper surface (Lefebvre et al., 2001a).

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. 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 complete the chain of risk than when no risk factors 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 is observed for an enclosed structure located on the top of the dump.

Seasonal changes in atmospheric temperature determine the gas flow direction (Philip et al. 2008). Seasonal effects on gas flow can be seen in the Nordhalde dump (Figure 13) 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 no hazardous gas emission and generation (“None”). 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.

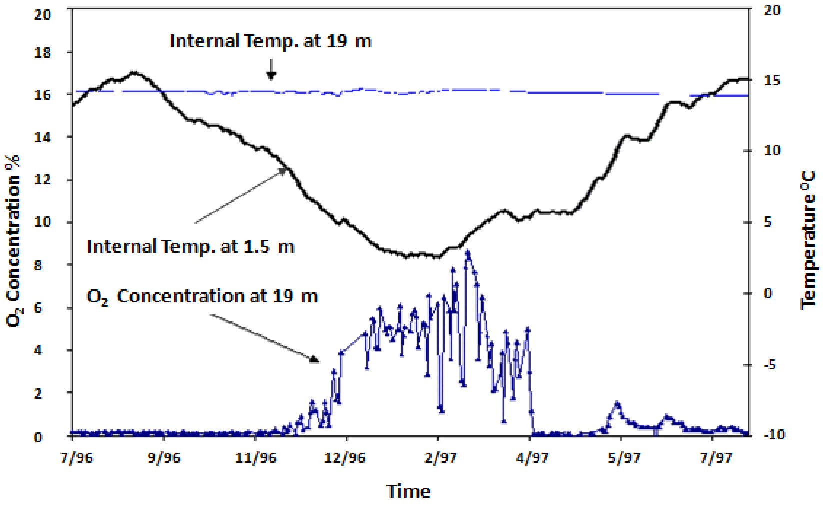


Figure 13. O_2 levels and temperatures at BH36 (near the edge) in Nordhalde dump (Smolensky et al, 1999).

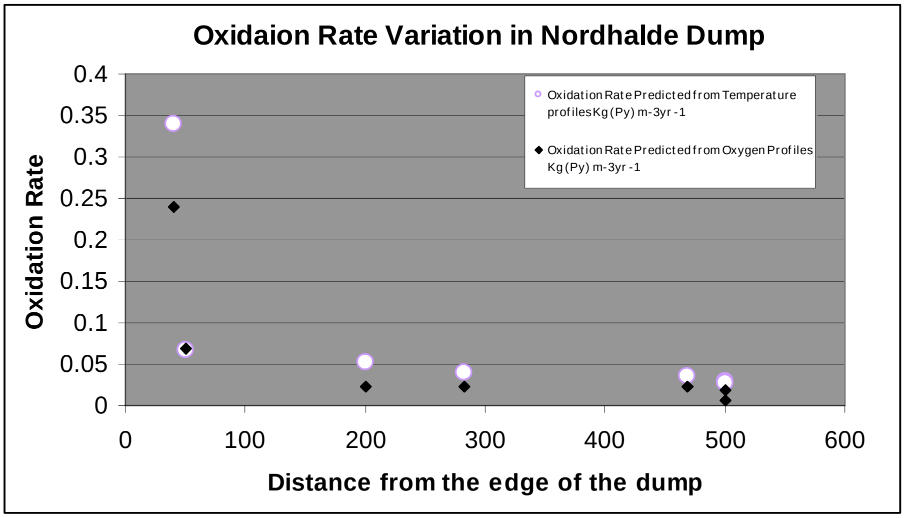


Figure 14. Oxidation rate declines when moving from the edges of the waste dump (Smolensky et al, 1999).

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 the presence of fine materials (Low permeability) – the effects of these factors on reactivity are given in Table 3 in APPENDIX E.

Many of the factors affecting gas generation and emission depend on the method of dump construction and the method of mining. For example, underground mining generates finer, more uniform waste rock with higher exposed sulfides which in turn lead to higher internal temperatures. This effect is seen in the North waste dump at the Sullivan Mine where higher internal temperatures (~36 ^{0}C) are attributed to finer and more homogeneous material in the dump as compared to that of the Number One Shaft Dump.

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 1 Shaft 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). When the dump was constructed, most oxidation occurred near the sides of the dump and over time the main oxidizing zone has moved into the centre. White’s Dump at Rum Jungle also exhibits this phenomenon (Cathles and Schlitt 1980). In the early stages (<2 years) the dump had not yet established convective flow and internal temperatures was not yet elevated due to non-availability of oxygen for sulfide oxidation.

More important than infiltration, there must be enough water to meet the reaction requirement of 2% water saturation - below this level, oxidation is observed to cease. 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 ~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). Stone (1987) studied the moisture content in unsaturated spoils at the Utah Navajo Mine in New Mexico. His results show that for seven undisturbed and reclaimed sites, moisture and solute profiles terminate after 6-10 years of mining. So, in areas such as New Mexico where annual precipitation (14.5 cm) is ~10 times lower than evaporation (142 cm), there is no chance for recharge (Morin, 1991). This suggests water content at the Sugar Shack dump is close to zero. The cumulative potential evaporation is ~1.5 to 2 times more than cumulative precipitation, and the average water saturation for the bulk of this dump is 0.38 which is only moderate (Wels et al, 2001) .

Water saturation is needed for oxidation, but if higher than required, the oxidation rate does not necessarily increase. When the degree of saturation is insufficient, the reaction will not take place and no heat is generated. So when the fuzzy value of degree of saturation is “None”, this has a very high weight in lowering the estimate of the internal temperature. When the degree of saturation is well above the critical level of 2%, the Degree of Belief in a “high” internal temperature is unaffected - see Table 7 in APPENDIX E.

Dumps with long slopes and low thickness (<100 m) will achieve very high convective flow. As a result such dumps are actively heating and they 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 ~100 m. Convective air flow has caused a very high internal temperature (40 ^{0}C) while the sulfide content is only about 0.019 (Lefebvre, 2001b).

Gas Emission

Regarding the configuration and design of each pathway, the amount of effluent running in a pathway together with the degree to which the pathway is covered generates a value for gas emission – the Degree of Belief (DoB) in a fuzzy gas emission of “High” where DoB can range from 0 to 100. This term describes the extent to which gas emission belongs to different fuzzy sets defined as “Low”, “Moderate” or “High”. Depending on the effectiveness of each pathway to transfer a hazardous gas from within the dump to the outside, a value from 0 to 100 is assigned to each possible pathway called PathDOB(i) - where i represents each pathway. If the dump gas is O_2-depleted, then effluents coming from the covered pathway are also O_2-depleted with respect to dissolved oxygen. These effluents will pick up O_2 when they come into contact with the outside atmosphere and if this occurs within an enclosed structure, it may also contribute to O_2-depletion if the flowrate to structure volume ratio is high enough and the influx of fresh air is low. Therefore the DoB for toxic gas emission may increase if a considerable amount of effluent water is running through the pathway. The DoB for the presence of significant effluent in the dump is represented by PathEffluentDoB(i). The DoB for this effect is derived from data entry of effluent flows by the user who should have knowledge of effluent in the pathway as these data are generally collected monthly for ARD risk assessment purposes. The extent to which the pathway is covered is important in isolating water and air from picking up oxygen from the atmosphere before reaching the enclosed structure. This effect is represented by PathCoverDoB(i). These effects are combined through Eq. 1 to calculate the effect of pathway properties on gas emission – PathwayEmissDOB(i). 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 Degree of Belief in “High” gas emission to each enclosed structure, The variable is MaxPathwayEmissDOB(j) (as in Eq. 2), where j represents different enclosed structures at the site:

PathwayEmissDOB(i) = Min(100, (PathDOB(i) + 0.2*(PathCoverDoB(i) + PathEffeluentDoB(i)))) Eq. 1

MaxPathwayEmissDOB (j) = Max (PathwayEmissDOB (i)), where i =0,…,n Eq. 2

The effect of pathway properties on gas emission together with other physical factors such as the difference in outside and inside temperature and pressure will determine the final value of gas emission. Considering these effects, the overall gas emission to each enclosed structure (j) is determined by Eq. 3, in which gas emission is affected by other factors such as permeability and dump age. In Eq. 3, "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 in APPENDIX E.

DoBforGasEmissionn(j) = Max(0, Min(100, (DoBperm * PermWeight + DoB GasVelocityWeightforEmiss * GasVelocityWeightforEmiss + DoBAge * AgeWeightforEmiss + MaxPathwayEmissDOB (j) * Weightfor MaxPathwayEmissDOB))) Eq. 3

Note that the weight for dump age is set to -0.8 for new dumps (<2 years) since convective flow is not yet established (Ritchie, 1994). As a result although internal temperature may be below the outside temperature, no toxic gas emission occurs. The effect of permeability is much lower than other factors such as gas velocity direction.

The emitted gas may become trapped in one place without being vented. Any structure existing on the surface of the dump or in a working place that can accumulate O_2-depleted air can create a dangerous condition. Items such as a sump, a manhole, a large pipe, a space with internal baffles, a surface depression, a tank, a shed, a tunnel, a well house, a pump house, a basement, a storage room, a steep surface, a trench, and an erosion channel - all are possible sites to concentrate and accumulate gas at a mine reclamation site. Regarding the degree to which any of these structures confine the gas, the DoB for Gas Confinement is determined.

Gas Confinement is affected by artificial ventilation or other devices used for gas control such as a U-tube on the effluent flow pathway. Other factors, such as snow covering the structure and the presence of a door or window, also affect the initial Gas Confinement value.

Gas Generation (O_2-depletion)

At the Number One Shaft Waste Dump, the O_2 concentration varies from 0% in BH3A to 13% in borehole 3B to 20% in BH2A which shows a variation from “Marginal Low” to “Oxygen Deficient” depending on depth in boreholes located at the edge of the dump. Figure 15 shows the O_2 ranges and their corresponding fuzzy values. Although any oxygen value below 19% is unacceptable for permanent human occupancy, it is highly possible that air blowing out of an effluent pipe at other dumps like this one will have an oxygen concentration below this level. The purpose of this section is to fuzzify the gas generation value in order to understand the extent of the danger in different situations. When O_2 is blowing out of the pipe at Number One Shaft dump, it was below 8% all the time (Figure 10) which is definitely “oxygen deficient”. This happens despite the fact that many boreholes show “Marginal Low” oxygen concentrations at the dump edges which is related to a higher permeability at the bottom because of end-dumping. Although a 1 m deep impermeable cover was placed over this dump, this did not stop convective gas flow especially at the toe of the dump where because of topography, the cover may fail to serve its purpose. “High” permeability waste dumps that have a low permeability cover are likely to be more hazardous regarding oxygen-deficient air. Although the fuzzy value of hazardous gas generation in some “High” permeability dumps due to gas convection can be “Low”, when the gas is blowing out of the dump through different pathways, it is very likely that the danger may be “High”.

When sulfide content is “Low” (0.015-0.02), and the waste dump has a “High” permeability, oxidation is less (inhibited by lack of sulfide) despite oxygen being widely available throughout the rest of dump. 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). This is important because more oxygen can enter the dump by advection and as a result the oxygen concentration within the dump will be “enough" for oxidation in the central core. Table 6 in APPENDIX E shows weights used to calculate the DoB for “High” gas generation.

Waste dumps are also sources of carbon dioxide which create another hazard by displacing oxygen. In the Number One Shaft Waste Dump when the pore gas blows out of the pipe, the CO_2 concentration was as high as 5% which is an additional hazard in its own right. Carbon dioxide emission occurs because acid generated by the sulfide oxidation reactions will contact carbonate materials in the dump and release CO_2. Carbonate rock in this dump varies from 0.1 to 0.7 %. 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. The range of carbonate at this dump is “Enough” to generate a “High” carbon dioxide gas emission. Obviously, the amount of sulfide is also a factor as the acid generated by the sulfide oxidation is what generates CO_2. In some fully-neutralized waste dumps, CO_2 can vary from 20-60% according to Hockley et al., 2000. The CO_2 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).

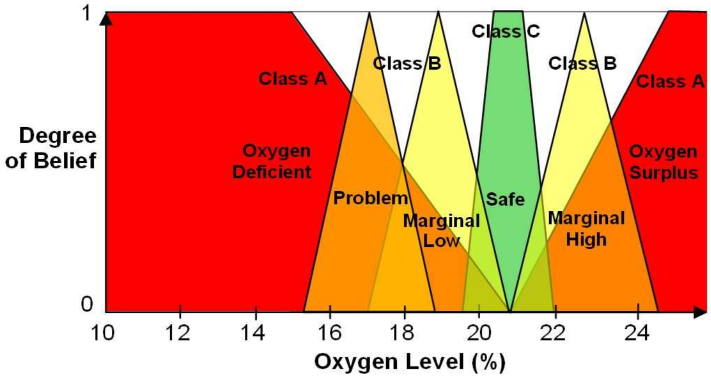


Figure 15. Fuzzy representation of O_2 levels.

APPENDIX E: Weight Tables for Factors affecting Dump Behaviours

Table 1. Factors affecting Cover Effectiveness to control O_2 transfer (adapted from O'Kane and Wels, 2003)

Inputs	*Range*	*Characteristics*		*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	< 2 yr				Young	0.2
	< 5 yr				Middle Age	-0.1
	>10 yr				Old	-0.2
Evaporation /Precipitation	> 10%				-	-0.03
	> 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	<1E-12				Low	0.6
	1E-10 to 1E-12				Moderate	0.2
	>1E-10				High	0.1
Hydraulic conductivity of the compacted layer (m/s)	<1E-9				Low	0.6
	1E-9 to 1E-5				Moderate	0.2
	>1E-5				High	0.1

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
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)		

Table 2. Estimation of the Degree of Belief 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 r bucket excavator		0.1
Percentage of coarse material at the base of the dump	None	0%	0
	Low	0-20%	-0.5
	Moderate	20-50%	-0.2
	High	50-80%	-0.08
	Very High	>80%	0.25
Water saturation	High	>0.75	-0.1
	Moderate	0.4-0.75	-0.2
	Low	0.2-0.4	-0.22
	None	0-0.2	0.1
If saturation level is unavailable then use Water content	High	>10%	0.1
	Moderate	5-10%	-0.3
	Low	<5%	-0.2
	None	<2%	-0.1
Channeling	Present		0.08
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)		

Table 3. 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 in Table 2	0.05
Age		> 180 yrs	-0.8
		150-180 yrs	-0.15
		130-150 yrs	-0.1
		110-130 yrs	-0.05
		85-110 yrs	0.05
		60- 85 yrs	0.1
		30-60 yrs	0.03
		15-30 yrs	0.03
		6-15 yrs	-0.1
		2–6 yrs	-0.15
		0–2 yrs	-0.9
Underground mining (resulting in finer grained materials and more uniform particles)			0.08
Open Pit mining			-0.02
Resloping	Was done		0.04
Relocation	Was done		0.05
Mining with blasting (because these affect particle exposed surface)			-0.02
Waste material from processing plant (resulting in fine grained materials)			0.08
DoB for “High” reactivity	Min((DoB Sulfide content * W Sulfide content + ...+ DoB Waste material from processing plant * W Waste material from processing plant), 100)		

Table 4. Fuzzy Rules to predict direction of gas velocity at the bottom of the dump

Free energy difference between outside and inside of dump (J/g)	*Direction of Gas Velocity at bottom of the waste dump*
dh>32	Extremely Negative Big
10<dh<32	Negative Big
7<dh<10	Small negative
0<dh<7	Very Small Negative
-7<dh<0	Very Small Positive
-10<dh<-7	Small Positive
-32<dh <-10	Positive Big
dh<-32	Extremely Positive Big

Table 5. Weights to calculate Degree of Belief in “High” gas emission at the bottom of the waste dump

Inputs	*Fuzzy Values*	*Range*	*Weight*
Gas Velocity at the bottom of the waste dump	Extremely Negative Big		0.6
	Negative Big		0.8
	Small negative		1.0
	Very Small Negative		1.5
	Very Small Positive		-0.2
	Small Positive		-0.8
	Positive Big		-1.0
	Extremely Positive Big		-1.5
Permeability at edges at the bottom	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 inTable 2	0.25
Maxpathway			0.3
DoB for Gas Emission at the Bottom of the Dump	Min ((DoB Gas Velocity Direction * W Gas Velocity Direction + …+ MaxPathway * W MaxPathway), 100)		

Table 6. Factors affecting “High” gas generation (oxygen depletion within the dump)

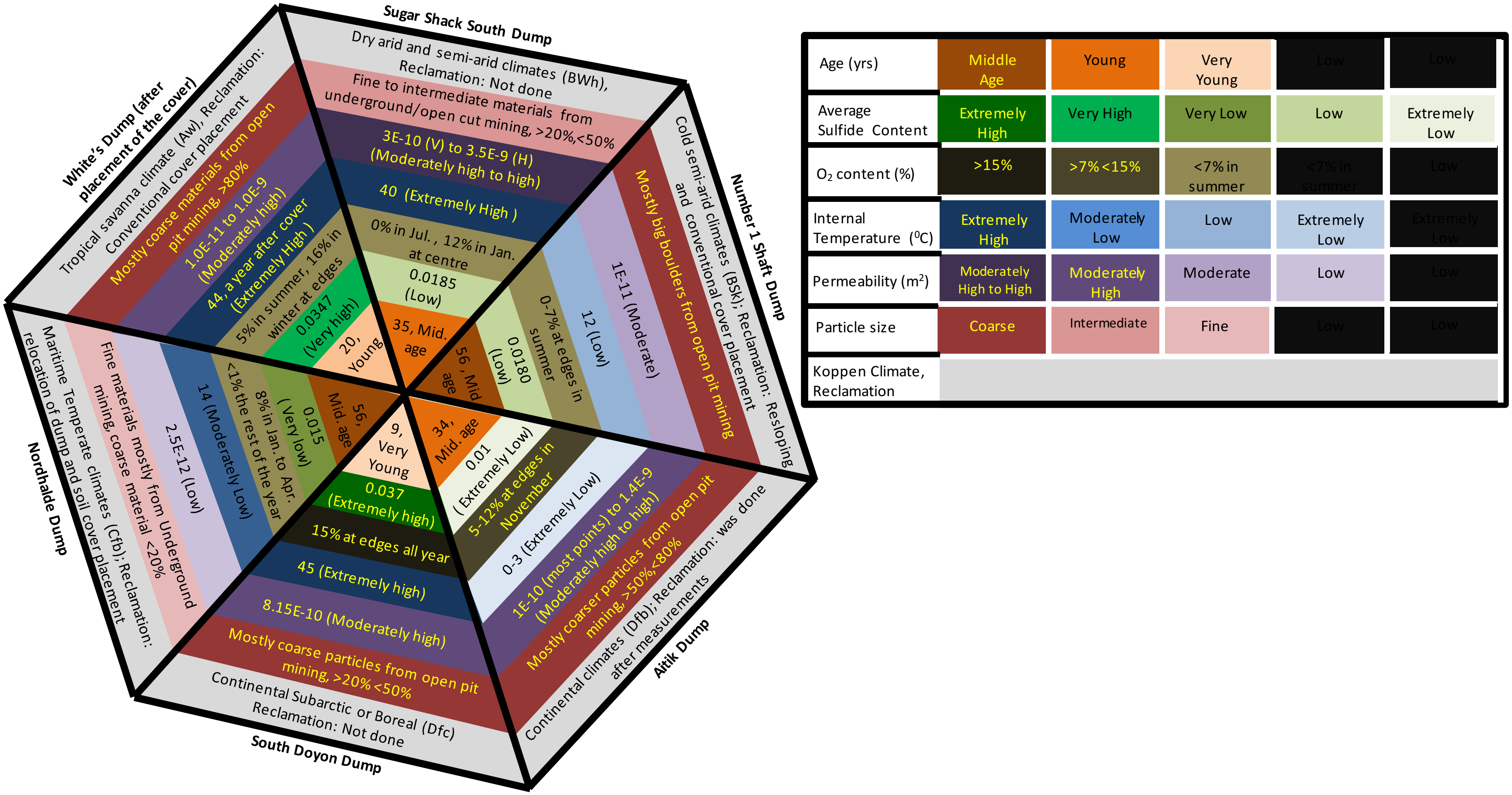
Inputs	*Fuzzy value*	*Ranges*	*Weight*
Gas Velocity at the bottom of the waste dump	Extremely Negative Big		0.2
	Negative Big		0.3
	Small negative		0.5
	Very Small Negative		0.8
	Very Small Positive		-0.08
	Small Positive		-0.1
	Positive Big		-0.15
	Extremely Positive Big		-0.3
Permeability at Edges	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 2	-0.25
Cover effectiveness	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
Reactivity (to place more importance on Reactivity when its DoB is low, lower Reactivities have higher weights)	High	<60	1
	Moderate	<40	1.4
	Low	<20	1.6
Height	Short	<50 m	0
	Moderately High	50-100 m	-0.025
	High	100-400 m	-0.05
	Very High	>400 m	-0.08
Wind	Not Windy		0
	Light Winds		-0.03
	Heavy Winds		-0.05
	Frequent Heavy Storms		-0.08
DoB for “High” O_2- depleted gas generation	Min(DoB Direction of gas velocity * W Direction of gas velocity + ... + DoB Wind* W Wind), 100)		

Table 7. 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 2)	Positive		80-100	0.8
			70-80	0.6
			60-70	0.4
			50-60	0.2
			40-50	0.1
			30-40	0.05
			20-30	-0.1
			10-20	-0.2
			0-10	-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 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 / Diameter (h/x)	Negative	x>>h	(>7)	0.01
		h=x	~1	0.0
		X<h	(<7)	-0.01
Dump slope	Positive	Steep	> 40 ^{0}	0.10
		Moderately Steep	20-40 ^{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=1.50
			5-7 yrs	A=0.30
			7-10 yrs	A=0.17
			>10yrs	A=0.09
Cover and Crusting DoB for "High" effectiveness - Table 1	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 ^{0}C
	Very High		90-95	35-40 ^{0}C
	High		80-90	30-35 ^{0}C
	Moderately High		70-80	25-30 ^{0}C
	Moderate		60-70	20-25 ^{0}C
	Moderately Low		50-60	15-20 ^{0}C
	Low		30-50	10-15 ^{0}C
	Very Low		15-30	5-10 ^{0}C
	Extremely Low		<15	2-5 ^{0}C

APPENDIX F: Reference and Test Dump Properties and Outputs.

Note - Variables in gray color are assumed values.



Age (yrs)	Middle Age	Young	Very Young	Low	Low
Average Sulfide Content	Extremely High	Very High	Very Low	Low	Extremely Low
O_2 content (%)	>15%	>7% <15%	<7% in summer	<7% in summer	Low
Internal Temperature (^{0}C)	Extremely High	Moderately Low	Low	Extremely Low	Extremely Low
Permeability (m^2)	Moderately High to High	Moderately High	Moderate	Low	Low
Particle size	Coarse	Intermediate	Fine	Low	Low
Koppen Climate, Reclamation					

Figure 16. Input data for reference waste dumps.

Table 8. 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 >70mm 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 end dumping 100	<20%, 100	UN	0.63	2751	0.30	UN	UN
		1.0E-12					0.63	0.10				
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
		2.6E-10					0.42	0.07				
Sugar Shack South	3.5E-9 (H) to 3.0E-10 (V)	>20% 100	30	Blasting 100	open pit and Underground end dumping 100	20-50%,80	UN	0.35	2740	0.33	UN	UN
		2.8E-10					0.35	0.075				
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
		1.0E-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% 100	0.11	Est. 0.46	(2800)	0.40	1862	0.110
		6.4E-10					0.46	UN				
Number One Shaft	1E-11	2-7% 50	100	Blasting 100	open pit100 end dumping 100	>80% 100	0.08	0.24	(2800)	0.33	UN	0.080
		7.1E-10					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
		1.0E-12					UN	UN				
Main dump at Equity Silver Mine	Undetermined	UN	30	Blasting 100	underground 50 end dumping 100	UN	UN	UN	UN	UN	UN	UN
		1.9E-10					UN	UN				
West Lyell waste dump	Undetermined	UN	30	Blasting 100	open pit 100 end dumping 100	UN	UN	UN			UN	UN
		4.8E-10					UN	UN				

Table 9. Estimation of Cover Effectiveness

Dump Site	Cover type			Thicker at the toe	Cover defects	Revegetation		Permeability, Infiltration rate, or Hydraulic conductivity	Cover Age **	Crusting	Time of Cover Installation start to end	Effectiveness Estimate Input by User	Climate Type [a]	E:P [++] Ratio	Season	Humid /Dry	Hot Spots	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	Low	Summer	H	30%	84%
	-	-	-			UN	UN											
Doyon Dump	UN (assumed no cover was installed)												Dfc	Low	Summer	H	-	0%
Sugar Shack South Dump	No cover												BWh	High	Summer	D	-	0%
Aitik mine Dump	Simple soil cover (half dump)			No	Yes	None		Moderate, UN, 2E-7 ms-1	0[†]	30%	1997 - UN	Low	Dfb	Low	Summer	H	30%	0%
	>1m	-	-			Shallow	0.2-0.3											
White's Dump	Conventional cover			Yes	Yes	Done		Low	~ 1 yr	100%	Sept. 1983 - UN	High	Aw	5 – 10	Summer	H	100%	100%
	100% <1.5	saturated	stable			Interm.	UN											
Number One Shaft Dump	Conventional cover (till)			No	Yes	Not done		5E-13	2 yr	30%	2005	60% High	BSk	5 – 10	Summer	D	100%	85%
	100% <1.5	saturated	active			-	-											
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	-	0%
North Dump	Conventional cover			No	20%	Present		Low	~9 yr	100%	cover 1997, vegetate1998	High	BSk	5 – 10	Summer	D	30%	100%
	100% =1.0	Saturated	active			Interm.	UN											

[++] 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 10. 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	UN	Done	UN	>20%, 100	56	June1997	Underground	UN	56%
Doyon Dump	0.037	8.15E-10 [†]	0.42	Not done	Not done	UN	<2%, 100	9	July1993	Blasting	UN	100%
Sugar Shack South Dump	0.0185	3.5E-9 (Hor) to 3.0E-10 (Ver)	0.35	Not done	Not done	UN	>20%, 100	35	July 2000	Blasting	High, 100%	83%
Aitik Mine Dump	0.01	1.0E-10 to 1.4E-9	Very low	UN	UN	UN	2-7%, 100	34	Nov. 1991 ***	Blasting	UN	12%
White's Dump	0.0347	1E-11 to 1E-9	UN	Done	UN	UN	2 -7%,100	20	Nov. 1984	Blasting	Low, 100%	100%
Number One Shaft Dump	0.018	1E-11	0.24	Done	Not done	UN	2-7%. 100	56	July 2007	Blasting	UN	81%
Main Dump at Equity Silver Mine	0.0185	UN	UN	Done	Not done	UN	UN	13	June 1994	Blasting	UN	82%
West Lyell Waste Dump	0.027	UN	UN	Not done	Not done	UN	UN	58	July 1994	Blasting	UN	100%
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 11. Estimation of gas velocity

Dump site	Outside Temperature (℃) **	Central Internal Temperature of the dump	ΔF caused by ΔT	ΔF caused by ΔP	Total ΔF (J/g)	Gas Velocity at base of dump †	Internal Temperature Trend
	Outside Pressure at top of the dump at time of Max T (Pa)	Central Internal Pressure at same time					
Nordhalde Dump	18	14	7.700	0.017	7.740	Negative Very Small	Pseudo steady state
	97,000	97,020					
Nordhalde Dump (January)	-8	14	-22.08	0.017	-22.097	Big positive value	Pseudo steady state
	97,000	97,020					
Doyon Dump	20	45	-25.120	0.017	-25.140	Positive Big	Pseudo steady state
	97,020	97,000					
Sugar Shack South Dump	24	40	-16.080	0.017	-16.050	Positive Big	Cooling
	97,020	97,000					
Aitik Mine Dump	15	3	23.270	0.017	23.310	Negative Big	Undetermined
	97,020	97,000					
Aitik Mine Dump (November)	3	3	0.016	0.017	0.033	Negative Very Small	Undetermined
	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
	97,020	97,000					
Number One Shaft Waste Dump	32	12	39.025	-0.005	39.020	Negative Big	Heating 2^0C / year (2 years after cover)
	86,210	86,215					
Number One Shaft Dump (May 2006 - time of the accident)	20	12	15.458	-0.008	15.450	Small negative	Heating 2^0C / year (2 years after cover)
	86,344	86,352					
Main Dump at Equity Silver Mine	22	52	-30.150	0.017	-30.120	Positive Big	Cooling
	97,020	97,000					
Main dump at Equity Silver Mine (January)	-4	52	-56.267	0.017	-56.25	Extremely Positive Big	Cooling
	97,020	97,000					
West Lyell Waste dump	22	34	-12.060	0.017	-12.030	Positive Big	Undetermined
	97,020	97,000					
North Dump	32	33	-1.005	-0.005	-1.010	Positive Very Small	Undetermined
	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 12. Estimation of gas generation

Dump Site	**Gas Velocity**	**Wind Conditions**	**Dump Height (m)**	**Climate type [a]**	**Material in dump**	**Dump mixed with garbage**	**Reactivity**	**Dump Permeability**	**Cover Effectiveness**	**Gas Generation in summer**	**Oxygen measurements**
Nordhalde Dump	Negative Small	Frequent Heavy winds	80	Cfb	Underground	No	56%	2.50E-12 [†]	84%	100%	8% in Jan. to Apr. 1997 at edges, <1% the rest of the year
Doyon Dump	Positive Big	Frequent Heavy winds	35	Dfc	Blasting	No	100%	8.15E-10 [†]	0%	38%	15% at edges all year
Sugar Shack South Dump	Positive Big	Not windy	450	BWh	Blasting	No	83%	3.5E-9 (Hor) to 3.0E-10 (Ver)	0%	27%	0% in July 2000, 2% in Sept. 1999 , 12% in Jan 2000 at centre
Aitik Mine Dump	Negative Big	Not windy	20	Dfb	Blasting	No	13%	1.0E-10 to 1.4E-9	0%	69%	UN
Aitik Mine Dump (November)	Negative Very Small	Not windy	20	Dfb	Blasting	No	13%	1.0E-10 to 1.4E-9	0%	39%	5-12% at edges in November
White's Dump (1 year after cover)	Positive Very Small	Heavy winds	18	Aw	Blasting	No	100%	1.0E-11 to 1.0E-9	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 Big	Light winds, 50%	50	BSk	Blasting	Yes	81%	1E-11	85%	100%	0-7% at edges in summer
Main Dump at Equity Silver (4 years after cover)	Positive Big	Less frequent Heavy winds	~80	Cfb	Blasting	No	82%	UN	100%	66%	5% at edges and 10% at the center in summer
West Lyell Waste Dump	Positive Big	Frequent Heavy winds	90	Cfb	Blasting	No	100%	UN	0%	34%	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)	Negative Very Small	Light winds, 50%	50	BSk	Uniform <2.5 cm	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 ℃ 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 13. 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			2.50E-12 [†]	Negative Small	100%
	bottom	Yes	100%			
Doyon Dump	Pipe			8.15E-10 [†]	Positive Big	15%
	bottom	Yes	100%			
Sugar Shack South	Pipe			3.5E-9 (Hor) to 3.0E-10 (Ver)	Positive Big	18%
	bottom	Yes	100%			
Aitik Mine Dump	Pipe			1.0E-10 to 1.4E-9	Negative Big	100%
	bottom	Yes	100%			
White’s Dump	Pipe			1E-11 to 1E-9	Positive Very Small	22%
	bottom	Yes	100%			
Number One Shaft Dump	Pipe			1E-11	Negative Big	100%
	bottom	Yes	100%			
Main Dump at Equity Silver Mine	Pipe			UN	Positive Big	18%
	bottom	Yes	100%			
West Lyell Waste Dump	Pipe			UN	Positive Big	18%
	bottom	Yes	100%			
North Dump	Pipe			Low	Negative Very Small	18%
	bottom	Yes	100%			

[†] effective air permeability

Table 14. 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	100	90	100	0.896	Hazardous
Nordhalde Dump (winter)	86	18 (82% low)	90	100	0.206	Significant Problem
Doyon Dump	38 (76% medium)	15 (85% low)	90	100	0.146	Problem Exists
Sugar Shack South Dump	27 (92% medium-low)	18 (82% low)	90	100	0.131	Problem Exists
Aitik Mine Dump	69 (31% medium-high)	100	90	100	0.755	Hazardous
Aitik Mine Dump (November)	39 (61% medium-high)	60 (40% medium-high)	90	100	0.416	Significant Problem
White's Dump	100	22 (88% medium-low)	90	100	0.253	Significant Problem
Number One Shaft Waste Dump (summer)	100	100	90	100	0.896	Hazardous
Number One Shaft Waste Dump (during the accident period – May 2006)	100	100	90	100	0.896	Hazardous
Main Dump at Equity Silver Mine (summer)	66 (67% medium-high)	18 (82% low)	90	100	0.185	Problem Exists
Main Dump at Equity Silver Mine (winter)	66 (67% medium-high)	18 (82% low)	90	100	0.185	Problem Exists
West Lyell Waste Dump	34 68% medium)	18 (82% low)	90	100	0.156	Problem Exists
North Dump	100	18[b] (82% low)	90	100	0.253	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)

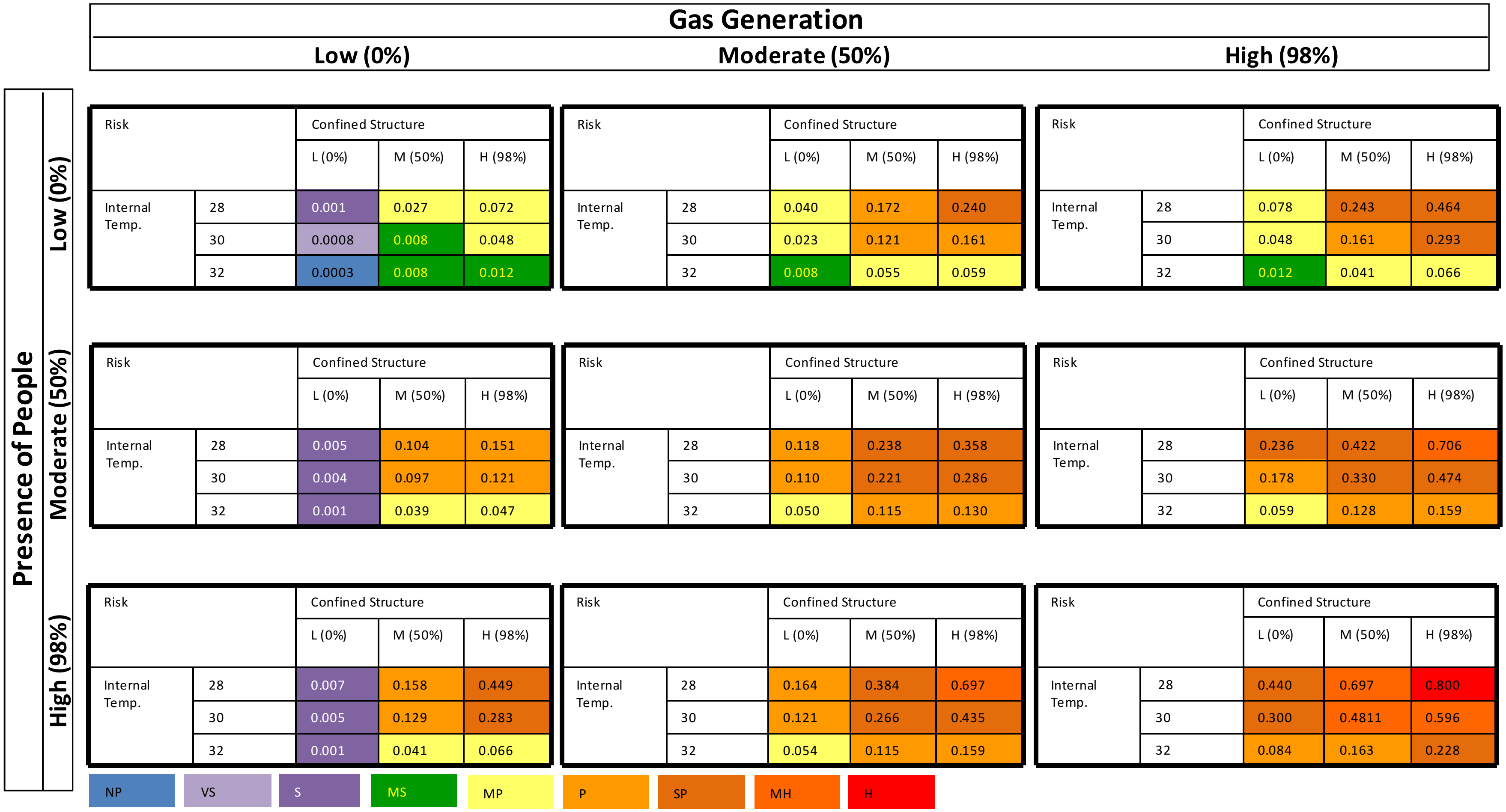
[b] Gas velocity is not a positive-big value because the low permeability of the dump decreases gas emission

Table 15. 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	56%	80	30	Gentle	2.50E-12 [†]	Yes	0.100	2.7	84%	0.23 Height	Edges	10-15	14
Doyon Dump	100%	35	0	Steep	8.15E-10 [†]	Yes	0.070	<2	0%	0.50 Height	Center	>40	45
Sugar Shack South Dump	83%	450	100	26	3.5E-9 (Hor) to 3.0E-10 (Ver)	Yes	4.090	UN	0%	0.50 Height	Center	>40	40
Aitik Mine Dump	13%	20	30	33	1.0E-10 to 1.4E-9	Yes	0.100	4.1	54%	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	81%	50	30	21	1E-11	Yes	0.143	~3.0	85%	0.50 Height	Center	10 -15	12
Main dump at Equity Silver Mine	82%	~80	30	20	UN	Yes	~0.160	2.6	100%	0.20 Height	Center	>40	52
West Lyell Waste dump	87%	90	30	UN	UN	Yes	0.191	UN	0%	0.33 Height	Center	35-40	38 (Max Temperature)
North Dump	100%	50	30	21	Low	Yes	0.10	~2.8	100%	0.50 Height	Center	30-35	33

[†] Effective Air Permeability

APPENDIX G: Sensitivity Analysis



Presence of People Low (0%) – Gas Generation Low (0%)

Risk		Confined Structure		
		L (0%)	M (50%)	H (98%)
Internal Temp.	28	0.001	0.027	0.072
	30	0.0008	0.008	0.048
	32	0.0003	0.008	0.012

Presence of People Low (0%) – Gas Generation Moderate (50%)

Risk		Confined Structure		
		L (0%)	M (50%)	H (98%)
Internal Temp.	28	0.040	0.172	0.240
	30	0.023	0.121	0.161
	32	0.008	0.055	0.059

Presence of People Low (0%) – Gas Generation High (98%)

Risk		Confined Structure		
		L (0%)	M (50%)	H (98%)
Internal Temp.	28	0.078	0.243	0.464
	30	0.048	0.161	0.293
	32	0.012	0.041	0.066

Presence of People Moderate (50%) – Gas Generation Low (0%)

Risk		Confined Structure		
		L (0%)	M (50%)	H (98%)
Internal Temp.	28	0.005	0.104	0.151
	30	0.004	0.097	0.121
	32	0.001	0.039	0.047

Presence of People Moderate (50%) – Gas Generation Moderate (50%)

Risk		Confined Structure		
		L (0%)	M (50%)	H (98%)
Internal Temp.	28	0.118	0.238	0.358
	30	0.110	0.221	0.286
	32	0.050	0.115	0.130

Presence of People Moderate (50%) – Gas Generation High (98%)

Risk		Confined Structure		
		L (0%)	M (50%)	H (98%)
Internal Temp.	28	0.236	0.422	0.706
	30	0.178	0.330	0.474
	32	0.059	0.128	0.159

Presence of People High (98%) – Gas Generation Low (0%)

Risk		Confined Structure		
		L (0%)	M (50%)	H (98%)
Internal Temp.	28	0.007	0.158	0.449
	30	0.005	0.129	0.283
	32	0.001	0.041	0.066

Presence of People High (98%) – Gas Generation Moderate (50%)

Risk		Confined Structure		
		L (0%)	M (50%)	H (98%)
Internal Temp.	28	0.164	0.384	0.697
	30	0.121	0.266	0.435
	32	0.054	0.115	0.159

Presence of People High (98%) – Gas Generation High (98%)

Risk		Confined Structure		
		L (0%)	M (50%)	H (98%)
Internal Temp.	28	0.440	0.697	0.800
	30	0.300	0.4811	0.596
	32	0.084	0.163	0.228

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 17. Sensitivity analysis for various internal temperatures at the Number One Shaft Waste Dump assuming maximum atmospheric temperature of 32 ℃. 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.