Atmospheric Fuzzy Risk Assessment of Confined Space Entry at Mine Reclamation Sites

Ladan Mohammadi
Mining Engineering, University of British Columbia, Vancouver, Canada

John A. Meech
Mining Engineering, University of British Columbia, Vancouver, Canada

Abstract

A confined space accident that occurred in 2006 at the Sullivan Mine in Kimberley, British Columbia has brought to light that certain reclamation activities can lead to an atmospheric hazard that is difficult to recognize. In this paper, application of a fuzzy logic-based expert system to assess the risk of an atmospheric hazard at a waste dump site is described. AFRA is a rule-based system that estimates fuzzy values of four major elements (gas generation, gas emission, gas confinement, and human exposure) that affect the risk of creating a confined space hazard within an enclosed structure such as a sampling shed located at the toe of a sulfide waste dump. The system is able to generate realistic advice about a site even when data are imprecise estimates. Should discrete measurements be available, these are transformed into linguistic expressions with respective Degrees of Belief (DoBs) that combine with other inputs to generate a Degree of Belief in each element value through the use of heuristic weighted-average equations. The assessment depends on different conditions at a site. The system has been validated for a total of nine dump sites around the world (6 reference and 3 test sites). It is recommended that atmospheric risk assessments should be carried out for sulfide waste dumps and tailings dams on a regular basis especially when a change in climatic conditions, site design, or site operation takes place.

Introduction

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

Mine waste piles may create a number of dangers for different nearby environments (the hydrosphere, the lithosphere, and the atmosphere). Risk assessment in a waste dump reclamation program is generally done to protect the environment and develop protocols to handle issues such as acidic water drainage, erosion, slope-stability, and liquefaction. With the exception of spontaneous combustion, dangerous atmospheric releases from a waste dump are not regularly assessed or even recognized as a realistic need. It is now apparent that a risk assessment should be extended to identify human occupational-health dangers at a reclamation site especially from atmospheric emissions. It seems prudent that future permitting processes should include such an approach. Currently, there is no risk assessment tool to use with a reclamation site or, for that matter, to apply a standardized procedure to other types of confined spaces with an atmospheric hazard. Neither is there a requirement for operators to conduct such an analysis. Recognizing the presence of a hazard and evaluating the development of dangerous conditions at a site are essential first steps in preventing future accidents of this type.
Part of the reason for a confined space accident is due to a lack of knowledge transfer from experts on a variety of inter-related and inter-connected topics into the workplace. One way to transfer knowledge is to create a software system to educate and train people about the key issues surrounding confined space hazards at reclamation sites. Such a system can be used routinely to perform a risk assessment to discover hazards early and to mitigate the problem. The consequence of an exposure to a confined space with an atmospheric hazard is the death of any person entering the space in an unauthorized or unsafe manner. The degree of danger varies on an hourly, seasonal, and decadal basis, so recognition of the hazard is difficult to establish in situations where changes in risk take place dynamically. Someone may occupy the space one evening without any problem while the next day, conditions change and the space has become deadly.

This paper describes an Atmospheric Fuzzy Risk Assessment (AFRA) tool to transfer knowledge from specialists to industry to the workplace. Requiring managers and workers to use this tool when designing mine closure plans may prevent "blind" reliance on "past safe performance" of their industry (or site) – which is a major reason for failing to identify a confined space situation.

Atmospheric risk assessment is perhaps as important as environmental risk assessment of ARD impact on an aquatic environment. Such analyses should be carried out on a regular basis after mine closure. It is emphasized that both environmental and atmospheric risk analysis should occur in parallel to derive site specific solutions that address the needs of both aspects.

Regular atmospheric risk assessment is important because unknown future activities may be carried out that can change the risk level. Certain provisions and rehabilitation activities at a closed mine may increase atmospheric risk. Over time, changes occur within the dump as sulfide minerals continue to oxidize consuming oxygen from pore gas, generating acid, and producing carbon dioxide from reaction of the acid with carbonate-type minerals. More importantly, temperature changes within the dump due to these reactions lead to periods of danger followed by dormant behaviour and then followed again by danger over decades of time.

Software Overview

The decisions required to operate a reclamation site effectively and safely with respect to atmospheric danger requires identification (or perception) of a potential "high" atmospheric risk. 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 a computer using linguistic terminology with the findings reported 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. An additional three dumps not used to create the system were applied to validate the system's ability to predict behaviour of previously unseen dumps. AFRA was designed to conduct a detailed site assessment to provide this perception if a "high" risk is identified through a logical process. The risk assessment consists of four major elements:

1. Gas generation,
2. Gas emission,
3. Gas confinement, and
4. Human exposure
In this paper, the key variables that affect these four elements are identified. Each of these elements can be described by measurements or in a fuzzy way that derives from linguistic or measured values of other variables. AFRA follows a step-by-step entry of relevant data that determines a Degree of Belief (DoB) that each of these four issues is "high", "medium", or "low". These elements are collected together to assign a linguistic risk in entering an identified confined space or enclosed structure.

AFRA assesses risk given the properties of a particular enclosed structure together with possible pathways that may connect the waste dump to that structure. Some elements of risk are specific for each structure (e.g., pathways and confinement), while other properties such as dump permeability, reactivity, internal temperature, and cover properties are specific for the dump and so, are common for all structures depending on the degree of homogeneity of the dump. AFRA conducts its diagnosis in four steps using the structure shown in Figure 1. A final confined space risk is determined for each structure. The output is given numerically and linguistically accompanied by recommendations and suggestions about future risk.

**Figure 1: Structural architecture of AFRA.**

The calculated risk is adapted to a final value using an adaptation factor \((\alpha)\) as in **Equation. 1** (Veiga, 1994):

\[
Risk_{final} = 100 \times \left(\frac{Risk_{initial}}{100}\right)^{\alpha}
\]  

(1)

Adaptation depends on input parameters such as observations of dead wild life around the enclosed structure, people entering the space showing signs of sickness, or people possessing a confined space entry permit, and future plans for worker protection. The adaptation factor is applied as an exponent to the initial estimated risk value which gives considerable elasticity to the risk prediction. As shown in **Figure 2**, the adaptation factor \((\alpha)\) varies logarithmically from 100 to a value approaching 0, with 1.0 representing no adaptation. When \(\alpha\) approaches 0, even a small initial Degree of Belief is amplified significantly while when \(\alpha\) approaches 100, even a small amount of uncertainty moves the final Degree of Belief close to 0. In AFRA, the value of \(\alpha\) is restricted to a range from 0.1 to 10. If the system is
satisfied that future plans and site observations show that a confined space is recognized and mitigation step implemented, the risk estimate is reduced. However, should AFRA believe that recognition of the problem is unclear, the final degree of belief in a "high" risk level is elevated.

![Diagram showing different adaptation factors.](image)

**Figure 2: Diagram showing different adaptation factors.**

The system can use site climate type (Köppen’s climatic classification) to estimate extreme conditions (highest risk). If gas emission at this extreme is "low", there is minimal or no concern about site results for the remainder of the year. The results and input values are stored in an Excel spreadsheet as well as an ASCII file for future analysis or modification.

**Waste Dump Properties and Gas Generation and Emission**

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

To predict the extent of generation, a number of factors have been examined from observations at different reference waste dumps around the world. The following factors are combined to predict the extent of gas generation:


The evidence is collected to give the DoB for "high" gas generation. The higher the Degree of Belief in "high" generation, the higher our belief that "high" oxygen depletion is occurring. As the number of variables describing a particular system increases, the number of fuzzy rules to deal with all combinations expands exponentially. To avoid this problem, neural equations based on the Perceptron neural network methodology developed by Rosenblatt in 1957 (Minsky & Papert, 1969; Meech & Kumar, 1992) are used to handle multiple variables within a single rule (Veiga & Meech, 1995). In this method, all inputs are summed after multiplying by a subjective weight. Input value for many of these
variables are shown to the user in the form of fuzzy values or linguistic expressions such as: "high", "low", or "very low". As such, calculation can be done even when measurements are not available.

"High" permeability dumps with a low-permeability cover are likely more hazardous regarding oxygen-deficient air. Although the fuzzy value of hazardous gas generation in some "high" permeability dumps may be "low", when gas blows out through a specific pathway, the danger may be "high". When the sulfide content is "low" (0.015-0.02), and the waste dump has a "high" permeability, oxidation is inhibited by lack of sulphide, despite oxygen being widely available. In this situation, gas generation is "low". If the site is located in an area of high winds, advection may be high for high elevation dumps (Wels et al., 2003) so more oxygen can enter to give a level that is "enough" to sustain oxidation in the central core. The free energy difference between the inside and outside of the dump determined from temperature and pressure measurements controls the direction of gas movement which affects the Degree of Belief in a "high" gas generation. Intermediate factors such as mineral reactivity and dump permeability are estimated from other factors in the dump.

Fuzzy values of direction of the gas movement and properties of the pathway connecting the air inside an enclosed structure to pore gas inside the waste dump define the value for gas emission. Air may be drawn in at the top of the dump and toxic gas emitted through the toe (usually quickly diluted and dispersed) when the dump’s internal temperature is below that of the atmosphere. This direction is reversed when the atmosphere is cooler than the dump (i.e., at night perhaps, and in the winter months). On these occasions, air is drawn in at the toe and emitted from the top of the dump. Differences in free energy inside and outside the dump are correlated with the direction of air/gas movement. A direct connection is needed to cause the oxygen-depleted air or carbon dioxide to collect within an enclosed structure. For example in the case of the Sullivan Mine tragedy, the sampling shed was safe before the toe-drain was covered which created a direct connection between air in the shed and gas in the dump. Variables that determine the Degree of Belief in a "high" gas emission are:

1- Material reactivity, 2- Direction of gas movement, 3- Dump configuration, 4- Age of the dump, 5- Design of each pathway to the enclosed structure.

Similar weighted inference equations are used to combine these variables.

**Internal Temperature**

Since the internal and atmospheric temperatures are the most important factors that drive pore gas out of a dump, it is necessary that AFRA be given such data. At least one internal measurement is needed, although the position (height) in the dump is important since a temperature gradient will exist. If internal temperature measurements are not available, AFRA can still provide an estimate of risk by offering a prediction of the internal temperature.

Factors used by AFRA to calculate the internal temperature are

1- Position in the dump where average temperature conditions are considered to exist,
2- Reactivity of dump material, 3- Permeability at edges of the dump, 4- Dump height,
5- Height:width ratio, 6- Presence of benches, 7- Presence of fumeroles, 8- Slope of sidewalls,
9- Cover age and effectiveness, 10- Effluent pH, 11- Dump age.

Some factors increase temperature while others decrease it. The output for internal temperature is given as a fuzzy value varying from "extremely high" to "extremely low" with each term covering a range of about 5°C. The weights were derived initially by common sense judgement and were adjusted to match reported measurements for the six reference dumps used to create AFRA. While exceptions
may exist, it is considered that the chosen weights describe all cases. The validation and verification results are given in Table 1.

Table 1: Comparison of internal temperature prediction (°C) with observations at 9 mine sites.

<table>
<thead>
<tr>
<th>Dump Site</th>
<th>Prediction</th>
<th>Observation</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nordhalde</td>
<td>10-15</td>
<td>14</td>
<td>Lefebvre et al., 2001(a); Wels et al., 2003; Smolensky et al., 1999</td>
</tr>
<tr>
<td>Doyon</td>
<td>&gt;40</td>
<td>45</td>
<td>Lefebvre et al., 2001(a); Wels et al., 2003</td>
</tr>
<tr>
<td>Sugar Shack South</td>
<td>&gt;40</td>
<td>40</td>
<td>Wels et al., 2003 and 2001; Lefebvre et al., 2001(b) and 2002; Shaw et al., 2002; Robertson GeoConsultants Inc., 2001</td>
</tr>
<tr>
<td>Aitik Mine</td>
<td>2-6</td>
<td>0-3</td>
<td>Stromberg &amp; Bawart, 1999/1994; Ritchie, 2003; Takala et al., 2001</td>
</tr>
<tr>
<td>Number One Shaft</td>
<td>10-15</td>
<td>12&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Lahmira et al., 2009</td>
</tr>
<tr>
<td>Equity Silver Main</td>
<td>&gt;40</td>
<td>52&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Aziz &amp; Ferguson, 1997; Lin, 2010</td>
</tr>
<tr>
<td>West Lyell</td>
<td>35-40</td>
<td>38</td>
<td>Garvie et al., 1997</td>
</tr>
<tr>
<td>Sullivan North</td>
<td>30-35</td>
<td>33&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Lahmira et al., 2009; Dawson et al., 2009</td>
</tr>
</tbody>
</table>

For each denoted dump, the temperature was measured a) one, b) two, c) four, d) eight year(s) after cover installation.

Grey shading denotes verification dumps.

An example of the factors and weights that affect the internal temperature for the Nordhalde Dump is shown in Table 2. The DoB in "high" internal temperature is 33% which results in an internal temperature estimate of 10-15 °C for a position at 0.23 x dump height at its edges. This estimation agrees with a temperature measurement of 12 °C at the same location in the dump.
The factors in Table 2 are directly or inversely related to a "high" internal temperature. For example, the presence of benches causes more gas to flow into a dump and provides more oxygen for sulfide reactions (Wels et al. 2003). If the waste dump has benches, this increases the Degree of Belief in a "high" internal temperature proportional to the certainty about their presence.

The weights were chosen based on the relative importance of each value. A dump with a gentle slope (<20 degrees) receives less convective flow than one with a high slope (>43 degrees) (Wels et al., 2003). As well, high dumps with a long slope will achieve very high convective flow. As a result, such dumps maintain a high internal temperature even when the sulfide content is moderate (>0.01 and <0.02) (Lefebvre, 2001(b)). Therefore the weight for height in a short dump such as the Nordhalde dump will be less than if the dump is extremely high (>450m).

The age of the cover is important in estimating internal temperature. When the cover has just been placed (<1 yr), it has not yet affected the internal temperature, therefore its weight is low (0.2). The effect increases when the cover is young (1-5 yrs) (weight = 2.0). But when the cover is >7 years, it loses its effectiveness due to erosion (weight = 1.5). This effect is shown through a factor called adjustment for cover age that is multiplied by the weight of the cover effectiveness. The weight of the cover effectiveness for a cover with "very high" effectiveness is -2, while this value for a cover with "very low" effectiveness it is 0.07.

Apart from the effect of age on gas emission and generation, age also has an indirect effect in estimating internal temperature through reactivity. A waste dump must be old enough to have elevated temperatures at depth, so that not only does convection start, but the generated heat is retained as well since the reaction front moves towards the center as the waste dumps ages.

### Other Elements of Confined Space Risk

Gas confinement can take place in an enclosed structure near to the point of emission which might be a pipe or a surface depression. If the accumulation remains undiluted, a confined space hazard exists that must be permit-required for entry. Similarly, oxygen-depleted water may enter through a buried conduit and acts to deplete oxygen from the air within the structure.
The initial Degree of Belief in whether an enclosed structure will confine a gas is set by default using a value within the range 40 to 100. Gas confinement is also affected by artificial ventilation or other devices used for gas control such as a U-tube on the effluent flow pathway. If there is no confined structure or the structure is not large enough for a human to enter, the degree of gas emission from the surface is estimated. Surface emissions can pose a hazard to a person bending down or lying on the ground. Gasses emitted from a waste pile are quickly dispersed or vented at the surface over a short distance under most circumstances. Wind velocity, surface topography and geometry as well as temperature inversions can play important roles in dissipating or intensifying the danger however. Other factors, such as snow covering a structure and the presence of a door or window also affect the degree of belief in gas confinement. A number of rules are used to calculate the effectiveness of ventilating a confined space. One of these rules is as follows:

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

These rules together with others are combined to formulate an "alpha" factor similar to that shown in Equation 1 to adjust the initial Degree of Belief in confinement.

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. Sampling had been done in this shed for over five years 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.

People can be exposed to the atmosphere inside an enclosed structure either by entering the structure, by extending their head into the structure; or by bending down, lying, or falling on the ground. If a structure (j) is large enough to enter, then the Degree of Belief in human exposure is calculated by AFRA using Equation. 2. If the structure is not large enough to enter, then the DoB of human exposure is only due to head exposure:

\[
\text{DoB HumanExposure}(j) = \max(\text{DoB exposure by entering } (j), \text{DoB exposure by entering in the future } (j), \text{DoB head exposure } (j), 0)
\]

Fuzzy Characterization of Confined Space Risk

Assessing a confined space risk involves recognizing conditions that may convert an enclosed structure (potential confined space) into a confined space. These include changes in configuration, environment, or operation of the structure or its surroundings. The transition can be slow and steady or can be sudden and dramatic depending on the presence of elements that increase the possibility of an atmospheric hazard. For example, when gas blows or flows into an enclosed structure used by people, this completes the necessary elements in the accident chain of events. Depending on the magnitude of gas emission, the level of risk will differ. This characteristic of a confined space shows that risk varies in a fuzzy and perhaps, unexpected way rather than in a crisp fashion. Many terms to describe a hazard (e.g. Hazardous, Marginal Hazardous, Safe) can be defined to describe each stage of risk as more elements/factors are added to the chain of event. A number of fuzzy if-then rules conclude about each term depending on the combinations of the Degrees of Belief in each of the four elements. For example the following rule defines the confined space risk as being a "Marginal Problem":

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"

To define the fuzzy risk for other types of hazards in other industries, the problem can be broken down into the elements of risk that define that hazard.

As an example, an atmospheric risk diagnosis of the Number One Shaft Waste Dump is presented below. Inputs for the risk assessment are as follows:

In this dump, a low sulfide content (0.018), a relatively young age (56 yrs), an effective cover (89% "high"), a low to-moderate water saturation (0.24), and the presence of few fine-grained particles result in a moderately reactive (76% "high") situation. This low reactivity results in a low internal temperature (10-15°C) in the centre. The outside temperature at Kimberley can reach as high as 32°C which causes colder heavy gasses to sink from the top to the bottom of the dump and be emitted. High permeability of the dump (1E-11) resulting from end-dumping helps gas to flow out of the dump. If a buried pipe is present, connecting the dump pore gas to the atmosphere inside an enclosed ARD collection sump, then Gas Emission to the structure is 100% "high".


Gas blowing out of the bottom of the dump (low oxygen inflow) along with moderate reactivity and other minor factors such as light winds, relatively "high" cover effectiveness, "high" dump permeability, and dump being mixed with other materials (garbage or wood) result in a 100% belief in a "high" toxic gas generation level. This agrees with the "low" oxygen content of 0-5% measured at edges of the dump in August 2006, 2007, and 2008 (Sullivan Mine Incident Technical Panel, 2010).

The cover acts as a seal leading to oxygen-deficiency ("high" belief in toxic gas generation in the dump) although the internal temperature may not rise as much as when there is no cover which may create a more hazardous atmosphere. The cover effectiveness was estimated to be 89% "high" – a value inferred by AFRA from the type of the cover and its properties, i.e., a cover that is relatively young (<2 years old); a conventional cover (till); a thickness <1.5 m; which stays saturated most of the time and contains active clay. There are no defects in the cover and its permeability is low (5E-13), although it does have some hot spots which reduces its effectiveness to some extent.

Assuming the sump is in regular use, gas confinement and human exposure beliefs are both 100% "high". The confined space risk is assessed as HAZARDOUS (0.900).

After the hazard is assessed, it can be mitigated by redesigning reclamation practices or by adhering to proper entry procedures (permit-required, proper signage, oxygen-meters, and use of proper respirators.

### Cyclic Variation in Waste Dumps

No atmospheric accident similar to the Sullivan Mine tragedy has ever occurred elsewhere in the world. The industry has been fortunate not to have seen a similar incident at another dump site. The following analysis describes why we believe other waste dumps have not shown an atmospheric hazard in the past. The reason lies in the fact that several cyclic behaviours are exhibited by a waste dump with respect to oxygen-depleted gas being released into an associated confined space. These include:

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

   Each day as the temperature cycles from hot in the daytime to cool at night, the dump may transition from blowing to sucking - this will occur if the maximum internal dump temperature lies between the daytime maximum and night time minimum temperature;
2. **Seasonal:** Safe in winter / Dangerous in summer

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

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

Initially, there is a low reaction rate of sulfides with oxygen so the pore gas is not depleted of oxygen and high convective flow is not yet established. But as the dump temperature rises due to internal heat generation from the oxidation reactions, more air is sucked in through convection and the rate of reaction intensifies (especially as sulfiferous and ferriferous bacteria begin to accelerate the surface reactions) – the pore gas now becomes depleted of oxygen and dangerous. As years pass, the maximum internal dump temperature continues to rise, perhaps climbing to a level above the maximum diurnal temperature in the summer. When this occurs, the dump will suck in air at the bottom all the time and no danger will exist in a confined space connected to the bottom of the dump. As the mineral surfaces continue oxidizing, eventually the sulfides approach the point of depletion and the maximum internal dump temperature will begin to fall. As it passes below the maximum diurnal temperature in summer, the dump will begin to exhale toxic gas at the bottom of the dump once again thus recreating the hazard. Eventually the reactions will stop altogether and the pore gas will no longer be depleted of oxygen, hence the danger will be gone forever.

**Figure 3** shows an idealized long-term risk variation and internal temperature change over time for Number One Shaft dump (a typical waste dump). In this assessment, the internal temperature changes as the dump ages. The maximum outside temperature is assumed to be 32 °C each year to ensure the evaluation detects the maximum likelihood of risk in that year (although warmer conditions could prove more hazardous). In this assessment, the internal temperature was estimated by varying the age of the dump and considering all the real dump properties of the dump. The Number One Shaft waste dump was about 66 years old when the accident took place in 2006, although this is really an estimate since the dump is heterogeneous and was used for waste disposal off and on over its life to closure; reaction rates may not have varied uniformly over the years as AFRA assumes.
Figure 3: Conceptual long-term risk variation of No. 1 Shaft dump in a temperate climate.

In the early years (<5 years) 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 only one being "low", the risk level would be "very safe". Here, a "low" Gas Emission in combination with "high" values for Gas 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 oxygen level in the pore gas declines to a very low value. The internal temperature increases and convective air flow is established with internal temperatures below the outside temperature. As such, risk increases to "Hazardous". Between 50 to 80 years, the internal temperature continues rising until it exceeds the maximum reported outside temperature of $32^\circ C$ causing the risk to decline to a "Significant Problem". From 80 to 150 years the internal temperature reaches its maximum (about $32^\circ C$) and flow reversal occurs year round – at this point, the risk is judged to be "A Problem". At 150 to 170 years, the internal temperature begins to drop due to a decrease in dump reactivity as the sulfides become depleted causing the risk to increase to "Hazardous" once again. From 170 to 190 years, the danger starts to decline as the sulfides become depleted. At a very old age (>200 years) the sulfides in the dump are completely depleted and so, the pore gas is no longer oxygen-depleted, i.e., "No" toxic gas is generated. Although the internal temperature is lower than the maximum atmospheric temperature which may continue to induce air emission from the toe, the risk is a "Marginal Problem" since the pore gas oxygen level will have increased to that of normal air. It must be understood that spatial differences in these transitions may occur at different times due to dump heterogeneities.

Recognize that the temporal boundaries between these projected risk levels are fuzzy concepts which vary significantly by changes in the site setting and waste dump properties. Currently some of the
dumps listed in Table 1 appear to be at the stage of reduced danger due to their extremely high internal temperature, and so, these dumps do not show an atmospheric risk. Of course, this stage is followed by rapid increase in atmospheric risk if confinement and exposure exists. Dumps with high sulfide content may reach this stage as early as 20 years old.

Conclusion

In this paper it was shown that confined space problems at reclamation sites involve exposure of humans to oxygen-depleted air usually accompanied by high levels of carbon dioxide. This toxic gas danger results from a chain of mechanisms that occur in sequence leading to the death of any exposed human. 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.

An atmospheric fuzzy risk assessment tool (AFRA) has been introduced to assist in recognizing atmospheric hazards of confined spaces at a mine reclamation site before the danger can cause death. Verification and validation of AFRA shows excellent agreement with actual measurements in terms of internal temperature estimates at the chosen dumps. It is recommended that AFRA or other risk assessment tools be used in designing a waste dump reclamation program.

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