Gases emission monitoring in a post-mining context

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ABSTRACT: Closed mines are often sources of dangerous gas emission. Flammable and/or toxic gases or deoxygenated air can be transmitted to the surface through existing aerodynamic links like abandoned shaft or galleries and fissures in rock. The gases issued from closed mines may generate public health and safety concerns and these problems are encountered for nearly all mine types. For the last 10 years, INERIS has developed in situ gas monitoring methods whose objectives are (i) to characterise gas emissions and to improve our knowledge of the processes governing their migration; (ii) to allow their risk evaluation and, eventually, to enable gas detection and alarm triggering. After briefly presenting each method, we will focus on some typical examples of monitoring by continuous automatic in-situ measurements that we have set up.

KEYWORDS: gas emission; abandoned mines; monitoring; in-situ measurements.

RESUME : Les mines abandonnées sont fréquemment le lieu de dangereuses émissions de gaz. Des gaz inflammables, toxiques et/ou de l'air désoxygéné peuvent migrer vers la surface à travers les anciennes infrastructures minières (puits, galeries…) ou des fissures dans le recouvrement. Les émanations de gaz à partir des mines abandonnées peuvent poser des problèmes de sécurité et de santé publique. Au cours de la dernière décennie, l'INERIS a développé des méthodes de monitoring in situ dont les objectifs sont (i) de caractériser les émissions de gaz et approfondir notre connaissance des processus gouvernant leur migration et (ii) d'aider à l'évaluation des risques et, le cas échéant, de permettre la détection des gaz et le déclenchement d'alarmes. Après avoir brièvement présenté chaque méthode, nous nous attarderons sur quelques exemples de surveillance par des mesures in situ en continu que nous avons mis en place.

MOTS-CLEFS : émission de gaz; mines abandonnées; surveillance; mesures in-situ.

1. Introduction

Problems of mine gas issuing at the surface have been encountered all over the world in all types of active or closed mines.

Mine gas develops in underground reservoirs formed by residual voids left by the mining activity. It can migrate to surface under the effect of several mechanisms and thereby presenting considerable hazards for individuals and property (explosions, intoxication, asphyxia, etc). Therefore it is crucial to have technical means to monitor gas emissions characteristics.

The intent of this paper is to briefly present the various methods that we have at our disposal. We then focus on three sites in a post-minig context in which we have set up gas monitoring systems.

2. Mine gas hazards on surface

2.1. Mine gas

In underground closed mines, they are often residual cavities resulting from the mining activity: abandoned rooms and pillars sectors, partial filling in, caving, galleries… or voids due to the increase in the porosity of surrounding strata resulting from their distressing and fracturing. This forms a true underground reservoir in which gases can build up. The composition of the gas mixtures in this volume considerably varies from one mine to another.

The gases most commonly found in mining contexts are oxygen, nitrogen, carbon dioxide and methane, and less often, hydrogen sulphide and carbon monoxide. In a simplified way, one can distinguish two origins for these gases: they can be geological gases, contained in rock before mining or the result of (bio)geochemical reactions in the deposit or in surrounding rocks, during or after mining. Thus the coal spontaneous combustion in abandoned mines causes frequently toxic gas emissions to the surface.

The major noxious gases are the very poisonous carbon monoxide and carbon dioxide. Hydrogen sulphide is extremely poisonous, but rarely occurs in dangerous quantity. Moreover mine gas is generally accompanied by a variable degree of oxygen depletion. Mine gas consequently presents several hazards including asphyxia, due to the oxygen concentration being too low, intoxication, due to the presence of carbon monoxide and hydrogen sulphide and, to a lesser extent, carbon dioxide, and finally ignition or explosion, due to the presence of hydrocarbons. These hazards are, of course, increased when the mine gas rising to the surface accumulates in locations accessible to the public.

2.2. Factors governing the migration of mine gas to the surface

Noxious gases or deoxygenated air can be transmitted on the surface through existing aerodynamic links like abandoned shaft or galleries and fissures in rock.

The gaseous mixtures build up in the reservoir formed by residuals voids can be transmitted to the surface when the pressure within the reservoir is higher than the atmospheric pressure. The different reasons for such a positive pressure differential between the reservoir and the surface are mostly:

- A dilatation of the atmosphere in the mine, due to a decrease of the atmospheric pressure at the surface;
- An increase of the pressure inside the reservoir due to :
    - The hydrostatic pressure imposed by rising water levels. The displacement of gas and reduction in storage volume add to the effect ;
    - The release of gas initially trapped;
- The production of gas by geological gas desorption and/or (bio)geochemical reactions that can lead to local overpressures within residual voids.

Any thermal gradient between the underground reservoir and the surface will also lead to gaseous migration. In this case, the air flow may reverse direction from one season to another.

These causes of surface gas emissions may occur simultaneously.

Therefore the gases issued from closed mines may generate public health and safety concerns and these problems are encountered for nearly all mine types.

2.3. Incidents caused by gas from closed mines

In France, few accidents or incidents associated with emissions or accumulations of coal mine gas after mine closures have fortunately been reported. Some cases have, however, been reported and looked into (Pokryszka and al, 2000). In the United Kingdom, on the other hand, ten or more incidents of this type have occurred over the last 50 years (Robinson, 2000). Other incidents or accidents have been reported in some countries with coal mining industries (Kral and al, 1998; Novotny and al, 2001).

Some residential areas of the iron basin of Lorraine (in the Northeast of France) are affected by noxious gas emissions (under-oxygenated and noxious gas loaded mixtures). The most spectacular phenomenon occurred in the built-up area of Moyeuvre-Grande in Moselle, especially in the district of the town located very close to the former underground mine workings in which some inhabitants observed faulty working gas cookers and boilers (Grabowski and Pokryszka, 2003).

The occurrence of gas in salt and potash mines and caverns has often been mentioned in the literature and in the historical reports of mine operations. Numerous mines in operation have experienced sudden, usually unexpected, expulsions of gas or continuous gas emissions. Incidents or accidents, sometimes very spectacular, occurred in mines due to gas emissions. At the beginning of the century, several potash mines of northern Europe were abandoned because of problems caused by gas outbursts (Gimm, 1968). In the early history of salt mining (prior to the current practice of evacuating the mine prior to blasting), many fatalities resulted from gas outbursts. A large portion were due to secondary factors, such as a methane explosion, suffocation, and poisoning (Dorfelt, 1966). Even with the practice of mine evacuation, outburst gases have in some cases filled the mine, blown out of the mine shafts, and caused fatalities at the surface. In one case, the heavier-than-air gas (CO2) gas blew out of the mine shafts for 25 minutes, flowed down a hill into a populated area, and killed 3 people. Several potash mines were abandoned due to a high number of casualties (Baar, 1977). These types of incidents can also occur after mine closures.

3. Gas monitoring methods

3.1. In-situ direct gas measurements or/and gas sampling and laboratory analysis

The gas composition can be determined by in situ direct measurements with portable gas sensors. The sensors have to be frequently calibrated with several gas standards covering the range of interest. Relative uncertainties in the readings are generally <5%. Portable gas detectors can either monitor :

• a single specific gas, e.g. methane, carbon dioxide, etc ;

• all volatile organic carbon (VOC) gases, or total hydrocarbons ;

• all flammable gases as a total ;

• oxygen ;

• a combination of flammable gas(es), oxygen, carbon dioxide and other gases such as hydrogen sulphide or nitrous oxide. Separate sensors being used for each gas/ group of gases and the values being reported separately.

Portable gas detectors are point source detectors. They measure the concentration of the gas at the sampling point of the instrument. The unit of measurement is % volume ratio, % lower explosive limit (LEL) for flammable gas, ppm for low-level concentrations (and toxic gases) or mg/m^3. There are a number of techniques used for gas detection.

Those detectors give a first idea of gas composition in an area. They allow the measurement of numerous points and numerous gases but there are just periodic and limited measurements.

Gas samples may conjointly be collected in order to be analysed in laboratory. Such analyses are more precise concerning gas concentrations.

3.2. Continuous automated monitoring of old mining sites

Gas monitoring can be accomplished by an automatic continuously operating station located on site. Continuous gas emission monitoring systems refer to a package of gas sampling system, gas analysers and other sensors of aerodynamics or meteorological parameters that are integrated with a data acquisition and data logging system. Continuous automated gas measurements can be performed in former mine workings, in soil, in air and at particular gas emissions points on surface (old shafts, fumaroles, faults…).

In a continuous emission monitoring system, a sample of gas is continuously withdrawn from the chosen source point and presented to various gases or other parameters sensors. Gas concentrations and other parameters are measured, recorded and stored as data. The data is used to generate reports, alarms... This system offers the advantages of choosing the most appropriate analysis technique for the desired components and concentration ranges.

3.3. Gas flux measurements on surface.

The measurement of the gas flow out of soil is probably the best method to detect and estimate the importance of gas emissions at the surface. It can be measured by placing accumulation chambers at discrete locations on surface and monitoring the rate of gas that accumulates in the chamber. INERIS has been developing and validating such methods since 1992 (Pokryszka et al., 1995). These methods, which were originally intended for landfills and contaminated ground, quickly found an application in mines (Pokryszka et Tauziède., 1999).

The method uses a chamber that avoids perturbing too much the environment (cf. Figure 1). The gas escapes from the covered area then accumulates in the chamber. In this way it is possible to monitor how the atmosphere becomes enriched in a studied gas. A sample of the mixture is fed to an analyser and then returned to the chamber. By monitoring the rate at which the recirculated mixture is enriched in the gas, it is possible to deduce the local gas flow at the given point. The dimensions of the chamber and the operating parameters of the method were optimised at the design stage on a test rig using known gas flows. The measurement system used is relatively simple to operate. The total time necessary for an individual measurement is of the order of 5 to 10 minutes, so that a large number can be made daily (from 40 to over 60 points according to the difficulties of the site).

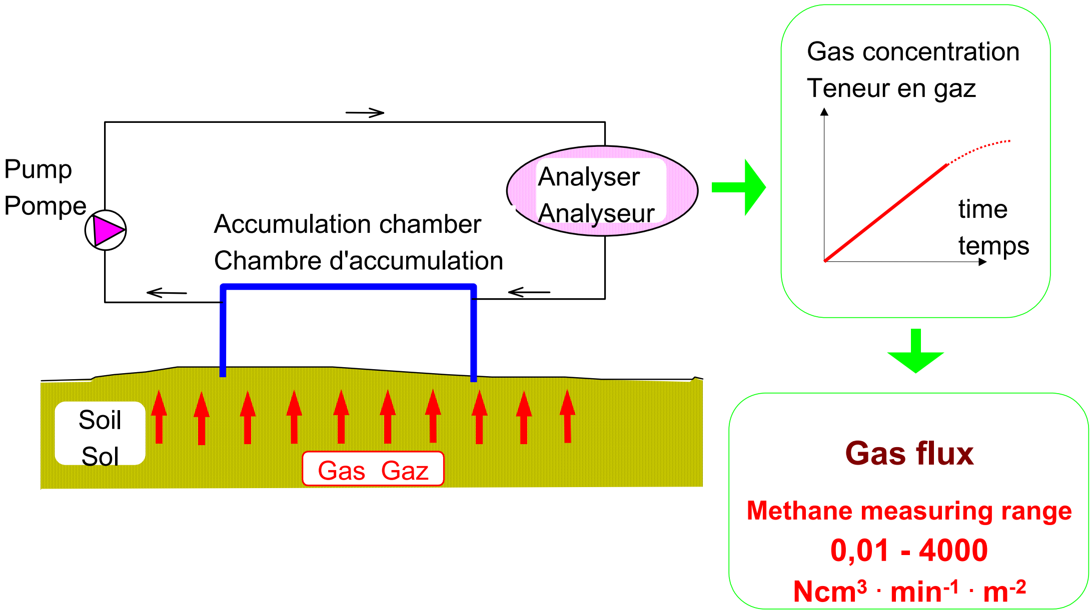

Figure 1. INERIS method of gas flow measurement on the soil surface

The method has already been applied in an operational manner for methane on the surface emissions diagnostics and appraisal on number of old mines sites in France, Czech Republic and Spain. The procedures involved in this method are protected by a European patent No. 96-05996.

The research work is now in progress at INERIS to adapt this method for CO_2 and radon emissions measurement on the surface of closed mines.

4. Examples of gas monitoring

4.1. Gases concentrations and aerodynamics parameters measurements in a closed iron mine

An automatic continuously operating station has been set up at the entrance of a former gallery connected to a closed iron mine in Lorraine, in Moyeuvre-Grande area. This area is affected by noxious gas emissions (under-oxygenated and noxious gas loaded mixtures).

In order to estimate the importance of these possible gas emissions, we have studied the influence of the aeraulic conditions within the underground voids on the gas flow from the old workings to the surface. We thus measured some aeraulic parameters in a former gallery, and interpret them in terms of process.

The monitoring device measures some aerodynamics parameters and gases concentrations. It is constituted by:

- A temperature sensor, that measures the air temperature old mining workings ;
- A barometric pressure sensor;
- A differential gas pressure sensor that measures the pressure difference between the old workings and external atmosphere;
- An O_2 and a radon gas sensors that measure the air composition in the gallery ;
- A data acquisition and data logging system.

Table 1 summarises the monitored parameters, their measure range and the sensors' characteristics. Figure 2. shows the monitoring station.

Table 1. Monitored parameters and the sensors' characteristics

Parameter	Sensor's measure range	Sensor	Sensor's accuracy	Acquisition frequency
O_2	0 to 25 (%vol.)	Polytron 2, Dräger	1% (± 0,1% O_2)	30 min
temperature in the gallery	-20 to +40 (°C)	PT 385, Prosensor	± 0,3°C	30 min
Atmospheric pressure	600 to 1060 (hPa)	Analogic barometer, PTB 101B, Vaisala	± 0,15 hPa	30 min
Differential pressure	-1 to 10 (Pa)	FCO 332, Furness Control	1%	30 min
radon	0 to 10 000 (Bq/m^3)	Barasol probe, Algade	65 $Bq/m^3\ h^{-1}$ (±0,8 imp.)	50 min

We also have at our disposal a measure of the outer atmospheric temperature.

The continuous monitoring of aeraulic parameters in the former gallery shows us that:

- The differential pressure between the outer atmosphere and the measured point in old workings, which is relatively close to the entrance (400 m), is low, in a range of -1 to 7 Pa. It is positive in summer and fluctuates around zero in winter;
- Theoretically the possible gas flow to the surface is low and goes preferentially through the fractures. This flow is higher in summer than in winter when it tends to zero and can even reverse.

These results give us data about the gas emissions from the former workings to the surface through the overburden. However, we need to perform other measurements in order to assess the importance of the flux through the fractured rocks.

Figure 2. Automatic continuously operating station at Moyeuvre-Grande

4.2. Monitoring of gas emission in deep boreholes in an operational salt mine

We have set-up an automatic continuously operating station in the context of an active salt mine in Lorraine. There, the salt is mined by the method of solution mining. Fresh water is injected through wells drilled into the salt bed, around 200m deep, to dissolve the salt and the resultant brine is then pumped to the surface. Dissolution of the salt forms a cavern in the salt deposit.

The objective of the experiment are (i) to identify the presence of gas within the salt deposit and (ii) to qualify and quantify the gas emission during the salt dissolution until the cavern collapses.

A continuous monitoring of the gaseous composition above the salt roof is allowed by the mean of an equipped drilling that emerges near the salt cavern. The gas mixture is measured by a withdrawal of the gas at the bottom of the drilling and its analysis by a specific device. The withdrawal and analysis of the gas are done continuously in a closed cycle (the gases are injected back in the drilling). This drilling is closed and allows the build up of the gases that can potentially be emitted at the salt roof.

The device is constituted by:

- Two flexible pipes: one channels the gas from the bottom of the drilling to the measure system and the other injects back the analysed gas at the bottom of the drilling;
- An automatic continuously operating station with :
  - Gas sensors;
  - A pump;
  - A data acquisition and data logging system.

The methods of analysis are non-destructive; therefore the gases can be injected back in the drilling in order to modify the composition of the gas and the pressure in the drilling.

Since the drilling has been equipped, in 2004, the system works under in-situ conditions. However, the salt exploitation is stopped and until now the composition of the air above the salt is the same as the atmosphere.

Moreover in situ direct measurements with portable gas sensors have been realised several times in the neighbour drillings above the future collapsed area. For that we insert a flexible pipe in the drilling. The CO_2, CH_4, H_2S, CO and O_2 concentrations are measured for each drilling. We noticed a spatial heterogeneity of the composition of the air in the drillings. The air is sometimes similar to the atmosphere and is sometimes enriched by methane or hydrogen sulphur.

4.3. Underground fire monitoring in an old mine of brown coal

On the site of the former lignite mine of Bois d'Asson, in Provence-Alpes-Côte d'Azur (SE of France), a spontaneous combustion has been noticed in 1999 through an old adit located close to the surface. Since the gas emissions on the site have been monitored by periodic in situ direct measurements with portable gas sensors.

We have set up a monitoring system in order to monitor the evolution of the combustion by measuring the underground temperature at various locations. This system also allows data logging and acquisition and transmission of these data by GSM.

The system consists of:

- Four temperature sensors placed in particular points of the site (Figures 3 to 5):
    - In the affected gallery;
    - In a fumarole at the surface above the gallery;
    - In the soil, 0,5m depth in a location where there is no influence of the coal heating;
    - In the atmosphere in a sun-protected location;

    The two least points are references in order to take the meteorological and climatic conditions into account.
- A station for data acquisition, data logging and data transmission by GSM (cf. Figure 6);
- An autonomous electric supply with two batteries, a loader and a solar panel (cf. Figure 7).

After one year, the experience has shown that the system works well. Thanks to the temperature measurements and the data teletransmission, it is possible to better follow the evolution of underground fire on this old mining site.

Figure 3. Temperature sensor at the entrance of the gallery

Figure 4. Outer temperature sensor

Figure 5. Sensor in a fumarole

Figure 6. Sensor in the soil

Figure 7. Box that protects electrical and electronic elements.

Figure 8. Whole view of the station

5. Conclusion

After mine closures gas emission risks may persist. Gases accumulated in post-mining voids can migrate to the surface through aerodynamic links. This may lead to risks of accidents on surface like explosions, asphyxia or intoxications.

Methods have been set up to monitor the sites where there are risks. Continuous automated systems associated with data teletransmission appear to be the best method to monitor old mine sites.

INERIS has developed efficient methods that have been validated in several post mining sites. These methods can now be used in the case of gas hazards in other closed mines sites.

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