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Risk management related to long-term mine gas emissions: feedback from a French experience

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Abstract

Mine closure activities in underground mines lead to stopping water pumping and ventilation systems. Unflooded voids form reservoirs where dangerous air or toxic gas can appear. Adits, shafts or boreholes shape potential migration pathways for gas transfer to the surface but also fresh air entrances. Gas can also migrate through overburden if it is fractured by former underground mining activities. Eventually gas migration between mining voids and the surface is mostly driven by temperature and pressure gradients that cyclically change with seasons.

Gases constituting the atmospheres within underground old mines have several possible origins: surface 'fresh' air entrance, degassing from rock formations (e.g. coal seams), deep gas seepage (e.g. mantle gas), redox or acid-base reactions, biological processes, etc. Any underground mining context may be affected by risks related to mine gas. Usual components of mine gas are nitrogen, oxygen, carbon dioxide, methane, carbon monoxide and hydrogen sulphide.

Once emitted to the surface, mine gas may lead to hazardous situations for people. Related hazards are explosion, suffocation and poisoning. Underground mine gas reserves, migration pathways, the composition of the emitted gas, the dynamics of the emission (flow, duration) and the potential of accumulation in dwellings, confined or semi-confined premises (i.e. poorly ventilated spaces such as cellars, basements, underground networks and inspection hatches) must be considered when managing the risks.

In two case studies of populated areas we illustrate how risks related to mine gas emissions to the surface are managed in France: the first in a former coal basin and the second in a former iron ore mining area. Authors detail how mine gas monitoring helps to understand underground gas production processes and gas migration transfers to the surface. They also describe mitigation measures implemented and provide feedback based on French experiences.

Keywords: *mine gas, emission, surface, monitoring, risk management, mitigation, France*

1 Introduction

Emission of mine gas to the surface is one risk that must be considered when closing an underground mine because it may lead to hazardous situations for people, goods and the environment.

We discuss risk management related to long-term mine gas emissions to the surface from the French experience. After detailing the considered risk scenario, we expose the classic constituents of mine gas and the related hazards. The phenomena governing the migration of mine gas between underground workings and the surface are then presented and we also illustrate the migration pathways for mine gas rising to the surface. We conclude by providing examples of how risks related to mine gas emission to the surface are managed in France, illustrated by a few case studies in populated areas.

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The French National Institute for Industrial Environment and Risks (Ineris) has proposed a methodology for assessing risks associated with mine gas emissions to the surface in the context of French mines (Ineris 2016).

2 Considered risk scenario

The risk scenario we consider is the surface emission of mine gas that may present a danger to people, goods and the environment. As closing underground mines leads to the cessation of water pumping and ventilation systems, it may emphasise issues regarding uncontrolled migration and emission of mine gas to the surface, especially in urban areas.

Here we focus on former underground mines as:

- The residual voids and underground formations impacted by mining form more or less confined volumes from the surface. The more intensive the mining operations, the larger the underground residual volumes (up to several hundreds of Mm^3 for former coal and iron mines in France). The residual volumes that are not flooded form underground reservoirs may contain a gas phase (mine gas) with a different composition to that of the surface atmosphere. During mining operations, mechanical ventilation is used to dilute and pump out mine gas from the underground workings. But after mining operations have ceased, the unflooded residual volumes are usually very poorly ventilated by natural exchanges and may thus accumulate gas.
- Mined underground rock formations are sources of gas: they may degas, constitute migration pathways or be the site of (bio)(geo)chemical reactions consuming or producing gas. This may induce the formation of atmospheres containing dangerous gases or being oxygen-depleted within the underground reservoirs formed by the residual voids.
- Former mine openings (adits or shafts) but also boreholes shape potential migration pathways for gas exchange between underground reservoirs and the surface. Filling and abandonment operations undertaken after mining operations have ceased define the predisposition for gas migration through the former openings, which may act as drains. Furthermore, the mechanical relaxation and fracturing of the overlying formations induced by mining operations may enhance their porosity and permeability, thereby easing the migration of gas. Thus, both former mine openings and impacted overlying formations may play a key role in controlling gas exchanges between the underground reservoirs and the surface.

Because the addition of these three characteristics makes it possible to accumulate significant volumes of underground mine gas at dangerous concentrations likely to migrate towards the surface, the risk of the surface emission of mine gas must be assessed when closing mining activities. If mine gas emissions present a risk to people, goods and the environment, mitigation measures must be implemented.

3 Mine gas composition

The composition of mine gas varies from one mine to another. Due to gas exchanges between underground reservoirs and the surface, mine gas is generally a mixture of an underground contribution and a surface atmospheric contribution (i.e. fresh air inlet). The proportion of each contribution varies according to the underground sources of gas, and to the nature and condition of the aeraulic connections between the underground reservoirs and the surface.

Mine gas is composed of:

- gas compounds initially present underground before mining. They may have been produced within the mined formations, or were deeper down and migrated upwards (e.g. magmatism). Their emission within the underground workings during mining operations can be a source of danger for miners (e.g. firedamp) and usually continues when operations cease

- gas compounds produced by (bio)(geo)chemical reactions within the underground reservoirs. Because mining disturbs the underground strata it may lead to a change in the initial (bio)(geo)chemical equilibrium. This can result in gas consumption and production, which continues as long as the reactions are sustained
- gas compounds from the surface atmosphere that enter the underground reservoirs via the aeraulic connections with the surface are created by mining operations (mine openings, boreholes and impacted overlying formations). The supply of oxygen from an atmospheric air inlet can trigger and supply redox reactions (such as combustion or sulphur reduction).

Table 1 lists the usual mine gas compounds and their possible origins. Only main origins are listed. Origins not related to mining refer to initial underground sources of gas that existed before mining operations began. Mining-related origins are the consequence of mining operations.

Table 1 The main origins of mine gas compounds

Mine gas compound	Origin not related to mining	Mining-related origin
Argon (Ar)	–	Surface air inlet
Carbon monoxide (CO)	–	Combustion
Carbon dioxide (CO_2)	Organic matter decomposition Magmatism	Acid-base reactions Combustion
Hydrogen sulphide (H_2S)	–	Redox reactions
Methane (CH_4)	Organic matter decomposition	–
Nitrogen (N_2)	–	Surface air inlet
Oxygen (O_2)	–	Surface air inlet
Radon (Rn)	Thorium and uranium radioactive decay chains	–

4 Mine gas-related hazards at the surface

Hazards related to mine gas emission to the surface are ignition or explosion, suffocation, poisoning and radiation.

- The hazard of ignition or explosion is associated to flammable gas such as methane or heavier gaseous hydrocarbons. Ignition and explosion may only happen when the gas concentration is in a flammability range delineated by the lower and upper flammability limits (LFL and UFL). LFL and UFL are usually given in percent by volume (vol%) in air. Outside the flammability range, a flammable gas or mixture cannot be ignited. For instance, the flammability range for methane is 5–15 vol% in air. These concentrations are not unusual for a mine gas mixture. Carbon monoxide and hydrogen sulphide are also flammable gas but their LFL (12 vol% and 4 vol% in air, respectively) are far above the concentrations observed in mine gas mixtures (usually in ppm by volume).
- Suffocation is caused by a lack of oxygen. Oxygen in a gas mixture can be consumed by redox reactions or diluted by an oxygen-free gas. Normal concentration of oxygen in fresh surface air is 20.9 vol%. First impacts on human health are documented for oxygen concentrations below 18 vol%. At the surface, oxygen depletion is frequently measured at around 1–2% by volume in weakly or non-ventilated cellars or basements (i.e. O_2 concentration ≈ 19 vol%) because these spaces are confined or semi-confined. It can reach a few percent in buried piping or soil gas. Since underground environments are mostly reductive, the concentration in free oxygen is (close to) zero.

Mine gas can thus be completely oxygen-free. The oxygen measured in mine gas comes from mixing with surface atmospheric air entering the mine reservoir.

- The presence of carbon monoxide or excess carbon dioxide in the human blood limits oxygen transport. These gas compounds have a toxicity effect that impedes the blood's ability to carry oxygen to body tissues and vital organs. Hydrogen sulphide is also a toxic gas compound as it inhibits cellular respiration. Those toxicity effects occur at low concentrations (ppm range for CO and H_2S, a few % for CO_2) likely to be measured in mine gas. They occur even if there is sufficient oxygen.
- Radon is a naturally occurring radioactive gas. It is an intermediate product of the decay chains of uranium-238 (as radon-222 with a half-life of 3.8235 days) and thorium-232 (as radon-220 with a half-life of 55.2 seconds). The decay of radon produces other short-lived solid radionuclides that may be carried by airborne dust particles, i.e. they can be inhaled. As uranium and thorium are ubiquitous elements, radon is found in all lithological contexts. The higher the uranium or thorium content, the higher the radon concentration. Inhalation of radon and its daughters contained in mine gas poses a radiation hazard.

5 Mine gas migration to the surface

5.1 Transport mechanisms

Mine gas is transported to the surface by several mechanisms:

- Mine gas is transported according to the pressure gradient between the mine reservoir and the surface. Mine gas migrates from higher pressure to lower pressure (advective transport). The stronger the gradient, the more important the mechanism. Various surface phenomena control the pressure gradient and so the direction of gas flow (e.g. via a mine gas outlet from the mine reservoir or surface air inlet in the mine reservoir).
  - Fluctuations of surface barometric pressure induce gradient value changes. Thus, the direction of gas flow is subject to inversion between low and high barometric pressure episodes. Figure 1 shows how barometric pressure changes impact CO_2 concentration in a surface fracture induced by underground mining. The CO_2 concentration is high when the barometric pressure decreases (depression episode) as underground gas is emitted to the surface. And the CO_2 concentration decreases when the barometric pressure increases (anticyclone episode) as surface air enters the fracture.

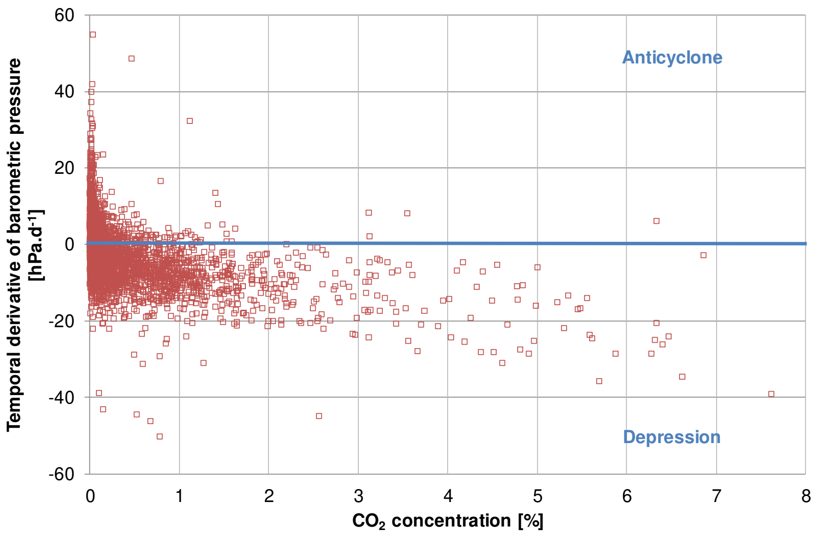

Figure 1 Influence of barometric pressure changes on CO_2 concentration in a surface fracture induced by underground mining (Lafortune et al. 2019)

- Fluctuations of outside air temperature induce gas density changes impacting the pressure gradient value. Indeed, as air gets warmer its density decreases. The direction of gas flow may thus be subject to inversion depending on the temperature difference between the mine reservoir and the outside air (thermal draught). Seasonal inversions (winter/summer) are sometimes observed at the outlets of abandoned adits (Lagny 2014). Figure 2 shows the influence of the natural thermal draught on CO_2 concentration in a surface fracture induced by underground mining and located at a high topographic point: the CO_2 concentration increases during winter as underground gas is emitted to the surface and decreases in summer as surface air enters the fracture.

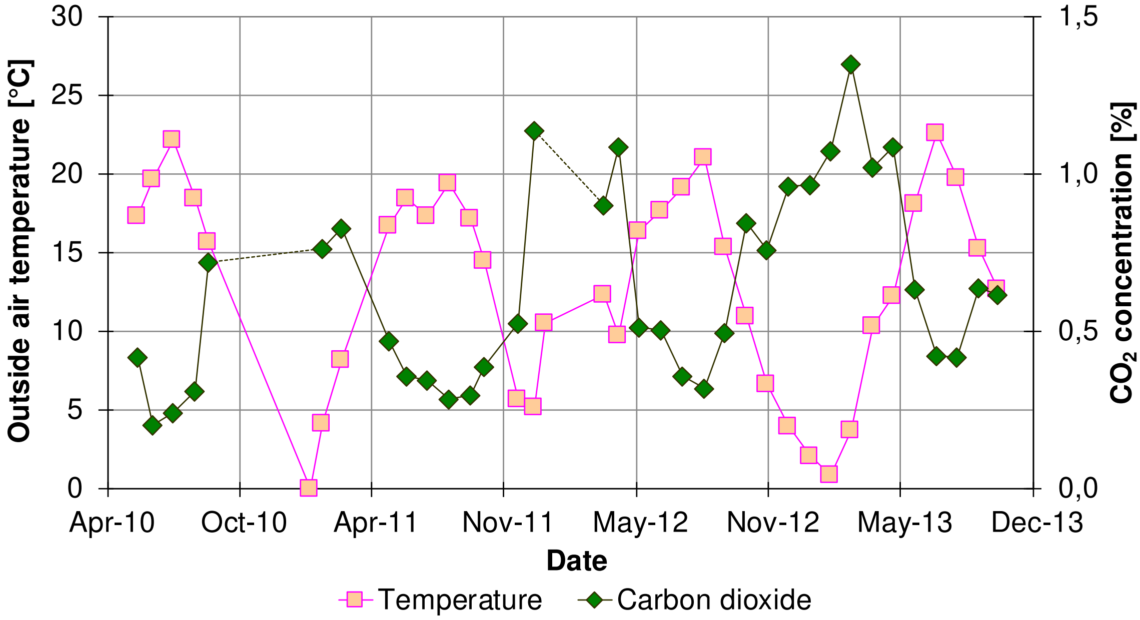

Figure 2 Influence of the natural thermal draught on CO_2 concentration in a surface fracture induced by underground mining and located at a high topographic point (Lafortune et al. 2019)

- Wind induces local overpressure effects that can disrupt mine gas flows to the surface. The disturbances are local and generally last a short time (several minutes or hours). The effects of wind are particularly noticeable when the effects of fluctuations of surface barometric pressure and outside air temperature are low (Lafortune et al. 2019).

There are also underground phenomena that control the pressure gradient by modifying the gas pressure in the mine reservoir (such as the flooding of mine workings), but they are not detailed here.

- Mine gas may be transported with mine water in the dissolved phase. Mine gas is thus transported by the water flow. The gas solubility limits the amount of gas that can be transported in the dissolved phase. Gas solubility increases with pressure. At the surface, dissolved gas may degas where mine water is discharged if there is no equilibrium of pressures or concentrations with surface atmosphere (i.e. dissolved gas oversaturation). Degassing may be enhanced by the water stirring at the point of discharge.
- Diffusion may also be a transport mechanism for mine gas. Gaseous compounds are transported according to their respective concentration gradient: from higher to lower concentrations until concentration equilibrium is reached. Diffusion occurs both in dissolved and gaseous phases. It is a very slow mode of transport that is usually neglected.

As all these mechanisms are processes with no time limit, mine gas transport can be maintained over long periods of time as long as the source of gas and migration pathways exist. Understanding mine gas transport mechanisms is a first step in designing adequate mitigation measures, and usually involves measuring or monitoring surface gas emissions.

5.2 Migration pathways

Mine gas can migrate to the surface through the overburden or via the shafts, adits and boreholes that link the mine workings to the surface.

Figure 3 shows possible migration pathways for mine gas between the underground reservoir and the surface. These migration pathways include:

- Man-made pathways — If they have not been treated to prevent gas circulation (e.g. capping with a concrete plug), adits and shafts ease gas exchanges between a mine reservoir and the surface. Gas can flow in the two directions: inwards (surface air entrance within the reservoir) or outwards (outlet of mine gas to the surface). Gas can also be transported in a dissolved phase to the mine water discharge points. Boreholes reaching the mine workings from the surface (piezometer or pressure-relief borehole; see below) are also man-made pathways that ease gas exchanges.
- Pathways induced by mining — Mining impacts surrounding formations by increasing their permeability through rock deformation and induced fracturing. Dewatered aquifer formations are permeable formations impacted by mining and through which mine gas can migrate. All those pathways induced by mining can facilitate the transport of mine gas to the surface, particularly at shallow depths.
- Pre-existing pathways — Open faults or permeable rock formations are pre-existing pathways through which mine gas can migrate and may reach the surface.

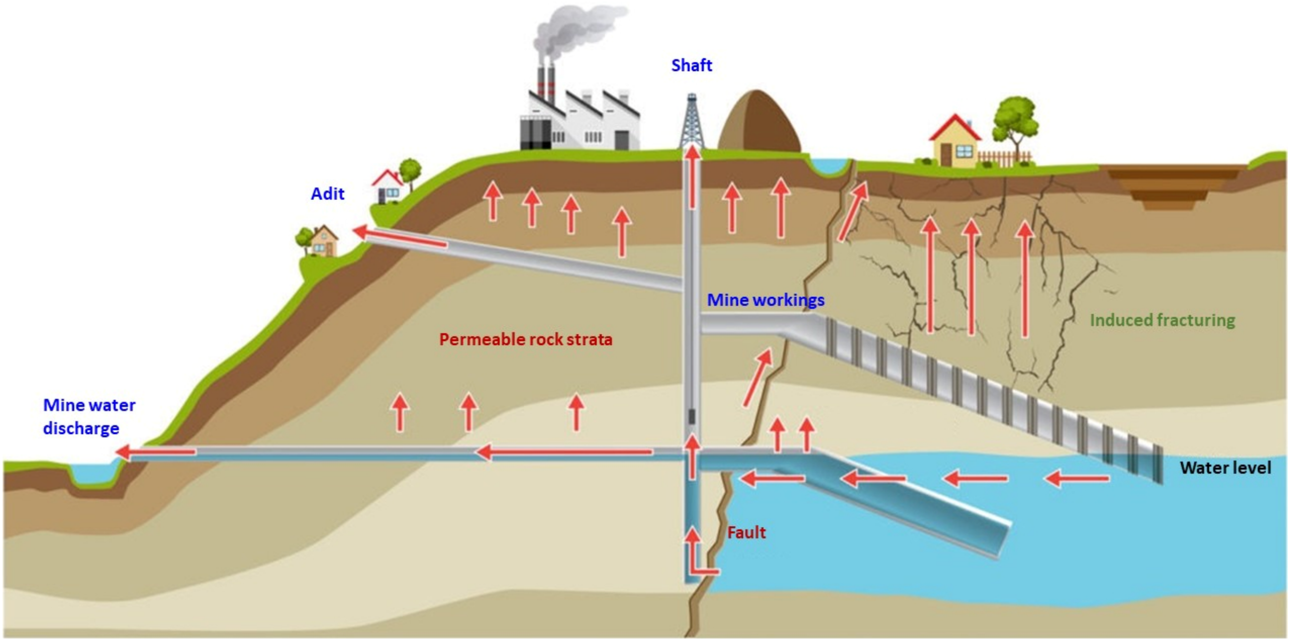

Figure 3 Possible migration pathways for mine gas between an underground mine reservoir and the surface: man-made pathways in blue, pathways induced by mining operations in green, and pre-existing pathways in brown. Mine gas may migrate following the red arrows (GEODERIS 2020)

Pathways of different nature may interact. For instance, a borehole that is not directly connected to mining voids may have an indirect connection through an aquifer formation dewatered by mining operations or an open fault. This can explain why mine gas is detected in a borehole with no direct connection to the mine reservoir.

Controlling migration pathways is a way to mitigate mine gas emissions to the surface. Man-made pathways can be treated to prevent gas circulation or specifically designed to safely release mine gas to prevent significant and uncontrolled emissions to the surface. For instance, pressure-relief boreholes can be drilled after mine closure to ensure a natural drainage (purging) of mine gas from mining voids to the surface (Figure 4). These boreholes are drilled from the surface to reach the shallower mining voids; their heads are usually located far from surface stakes (e.g. dwellings) and designed considering the risk of formation of explosive atmospheres if relevant. At release points, gas monitoring, equipment servicing and maintenance must be carried out for as long as required.

(a) (b)

Figure 4 Schematic diagram and photography of a pressure-relief borehole: (a) Schematic diagram showing the connection between a mine gas reservoir and the surface atmosphere, and all safety equipment on a pressure-relief borehole head (modified from a document by the French Department for Mine Safety and Risk Prevention); (b) Photography of a pressure-relief borehole head (the vent, the metal box and the concrete slab are visible in the picture)

6 Case studies

Mine gas emission to the surface is a risk that must be assessed when mines are closing as it may lead to hazardous situations for people, goods and the environment. France has solid experience in dealing with risk management related to long-term mine gas emissions to the surface. Two case studies are detailed here as examples of how risks related to mine gas emission to the surface in populated areas are managed in France: the Nord-Pas-de-Calais (NPdC) coal basin and the Lorraine iron ore basin (LIB). Figure 5 shows where these two basins are located in mainland France.

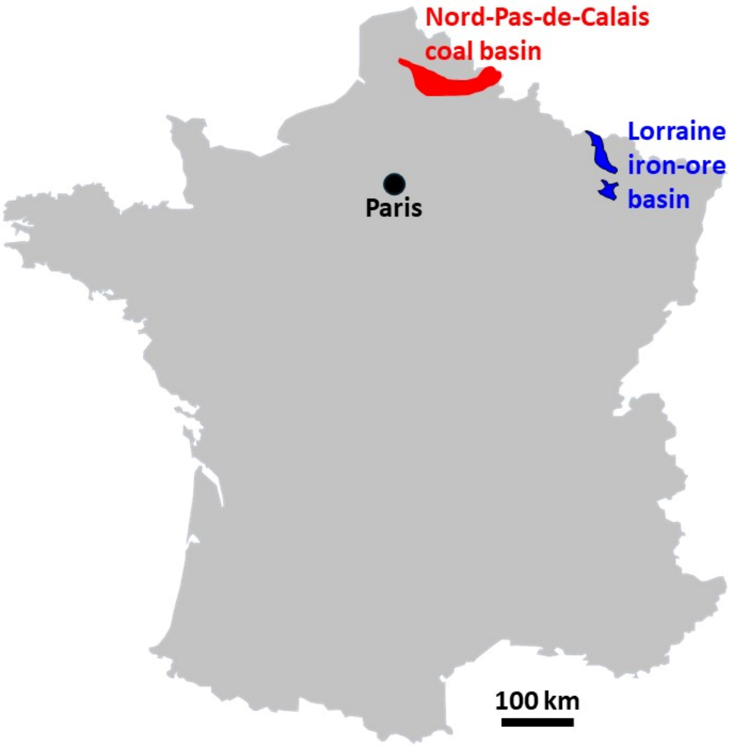

Figure 5 Location of the Nord-Pas-de-Calais coal basin (red) and of the Lorraine iron ore basin (blue) in mainland France

6.1 Mine gas emission management in the Nord-Pas-de-Calais coal basin

The NPdC basin is located in northern France and is the largest coal basin ever exploited in France. A total of 2,400 Mt of coal have been produced over 270 years (from 1720 to 1990). Mining was completed underground over an area of about 900 km^2. Coal mining was extensive, with an exploitation of several superimposed coal seams. When mining stopped, the residual voids had an estimated volume of approximately 700 Mm^3.

During mining operations the entire coal deposit was known to be 'gassy'. In several sectors, one tonne of coal in place could contain up to 20 m^3 of methane. After coal mining stopped, gas continued to be released from unmined seams of the coal deposit. Methane can thus accumulate in residual mining voids (reservoirs) and migrate in an uncontrolled manner to the surface. This can lead to hazardous situations. The observed mean mine gas composition is the following: 40 to 65 vol% of methane, 10 to 15 vol% of carbon dioxide and about 1 vol% of oxygen.

The drainage and exploitation of mine gas from the surface were implemented by the mining company Charbonnages de France (CdF) in the 1970s, in parallel with the gradual end of the mining operations, as a solution for managing surface mine gas emissions. Today, mine gas is still naturally drained to the surface or exploited for abandoned mine methane (AMM). Dedicated boreholes were drilled for AMM production, which gradually led to the depletion of a large part of the residual voids. The pressure in depleted mining voids is continuously below barometric pressure, so that surface atmospheric gas may enter the former mine workings. But some residual voids are not depleted, leading to possible migration of mine gas to the surface.

Flooding is ongoing in the NPdC basin but it is slow and the hydrological equilibrium is not expected to be reached before 2150. The risk of flooding must be carefully considered as it may lead to the closure of aeraulic connections and to the isolation of sectors of residual voids to which drainage and exploitation boreholes are connected. In isolated residual voids, mine gas pressure may increase due to the rise of the water level (piston effect) and to the desorption of methane from the unmined seams of the coal deposit. This situation causes a risk of mine gas migration towards the surface.

This is why a mine gas management and monitoring plan was setup by CdF between the end of the 1980s and 2006. CdF oversaw the monitoring until 2006, when the French Department for Mine Safety and Risk Prevention (BRGM-DPSM) took over. Today, mine gas monitoring is performed on a total of more than 540 locations including former mine shaft heads, pressure-relief boreholes connecting mine gas reservoirs to the surface atmosphere (Figure 4) and deep piezometers drilled to monitor the flooding dynamics (evolution of the water level within the mining voids). Monitoring includes measurements of the barometric and wellhead pressure, methane, oxygen, carbon dioxide and trace gas (carbon monoxide and hydrogen sulphide) concentrations, and of the water level. Additional measurements can be carried out if needed. Figure 6 shows the measuring equipment installed by BRGM-DPSM at the head of a pressure-relief borehole to continuously monitor the barometric pressure, the pressure within the mine reservoir and the methane content of the mine gas. The interpretation of the measurements helps to identify eventual technical problems or changes in the behaviour of reservoirs which may require action or remediation (such as additional investigations or safety improvement works, for instance).

Figure 6 Measuring apparatus installed at the head of a pressure-relief borehole to continuously monitor the barometric pressure, the wellhead pressure (i.e. mine reservoir pressure) and the methane content of the mine gas (photography by French Department for Mine Safety and Risk Prevention)

Since 2019, GEODERIS has been coordinating a study regarding the gas monitoring plan of the NPdC basin. The purpose is to determine if the monitoring plan requires improvement to control mine gas emissions to the surface. Special consideration is given to pressure-relief boreholes as they are important mitigation measures that prevent pressurisation of the unflooded sectors of the mine gas reservoir located outside the drainage area related to AMM production. This study is based on the use of a 3D geometric model inherited from the mine operator and since then regularly updated by BRGM-DPSM and Ineris. The model includes all the mined coal seams and a simplified representation of the main skeleton of the underground works, as well as gas and water monitoring and mitigation equipment such as the pressure-relief boreholes and deep piezometers. This model is still maintained and updated as it is a useful tool for the management of mine gas emissions in the NPdC basin (Lafortune et al. 2023).

6.2 Mine gas emission management in the Lorraine iron ore basin

The LIB is located in northeastern France. It extends over about 1,700 km² in densely urbanised areas. The mines were closed in 1997 after more than a century of exploitation. 40,000 km of galleries were excavated. When mining stopped, adits were closed and the residual voids had an estimated volume of about 1 Gm^3 (Vuidart 2014).

The stabilisation of the water level within the former mine workings results in the creation of significant unflooded residual volumes. In these unflooded volumes, gaseous atmospheres can evolve and become noxious. Indeed, some mineral phases can react with the oxygen supplied by atmospheric air inlets within the unflooded mining voids. This is the case with sulphides, for example. Oxidation of sulphides (e.g. iron pyrite, FeS_2) coupled with dissolution of carbonates (e.g. calcite, $CaCO_3$) leads to the consumption of oxygen and the production of carbon dioxide. Oxidation of sulphides is a well-known process in mining contexts (Banks et al. 1997; Mayo et al. 2000). In France it is observed in closed mines in the LIB, where it causes noxious gas emissions to the surface (Pokryszka & Grabowski 2003; Lagny 2015) and induces acid mine drainage. Acidification of mine outflow water can be buffered through carbonate dissolution according to Equation 1, where 15 moles of oxygen are consumed and eight moles of CO_2 are produced:

$$4\ FeS_2 + 15\ O_2 + 8\ CaCO_3 + 6\ H_2O = 4\ Fe(OH)_3 + 8\ CO_2 + 8\ SO_4^{2-} + 8\ Ca^{2+} \quad (1)$$

Equation 1 induces the formation of O_2-depleted and CO_2-enriched atmospheres within the unflooded mining voids that may migrate to the surface. In some parts of the LIB, former mine workings are very shallow and located in city centres. In the event that mine gas is released to the surface it is likely to penetrate dwellings and accumulate to create hazardous situations for inhabitants (suffocation or toxic effect). Concentrations of up to 6 vol% for CO_2 and down to 12 %vol for O_2 have been measured by Ineris in mine gas emitted in a densely urbanised city centre in the LIB.

At the request of GEODERIS, Ineris has been carrying out studies since 2017 to precisely delimit the area of a town centre affected by mine gas emissions and to design remediation solutions. The chosen remediation solution is to reopen former adits that were closed after mining operations ceased. This is a solution that should ease natural drainage of the mine gas by creating preferential flow pathways between the underground mine reservoir and the surface. It should also prevent diffuse migration of mine gas through surrounding strata to dwellings. A first adit was reopened in 2000 and gas flow has since been monitored at its outlet. Monitoring reveals that the gas flow dynamic is seasonal: the mine gas is emitted to the city centre in summer and fresh air enters the unflooded mining voids in winter. In early 2024 BRGM-DPSM reopened two other adits with the aim of improving natural drainage and further reducing the diffuse migration of mine gas through surrounding strata (Figure 7). A measurement campaign is already planned for the summer of 2024 to assess the impact of reopening the two adits on mine gas emissions in the city centre. The results will make it possible to quantify the impact and plan for further works to be carried out to limit mine gas accumulation in dwellings.

(a) (b)

Figure 7 Reopening of an adit closed after mining operations ceased to ease natural drainage of the mine gas: (a) Before reopening in July 2020; (b) After reopening in April 2024, with safety devices (inclined deflectors and fences) to prevent people from being exposed to mine gas emissions (photography by BRGM-DPSM)

7 Conclusion

Mine gas emission to the surface is a risk that must be assessed when mines are closing as it may lead to hazardous situations for people, goods and the environment. France has solid experience dealing with risk management related to long-term mine gas emissions to the surface. Two French case studies were described as examples to document situations likely to cause dangerous situations and to detail the chosen mitigation methods: one in the NPdC coal basin and the other in the LIB.

In the NPdC basin the residual voids have a significant volume. Flooding is very slow. Mine gas emissions to the surface are controlled by natural drainage through pressure-relief boreholes and AMM production which should both prevent pressure build-up in the mine reservoir as long as aeraulic connections between the boreholes and the mining voids are unflooded. The mine gas management and monitoring plan set up by the mining operator in the late 1980s is currently under revision. A 3D geometric model is used to understand and interpret monitoring measurements but also to propose new mitigation solutions.

In the LIB, the residual voids also have a significant volume. In unflooded underground mine workings the atmosphere may evolve due to chemical reactions consuming oxygen and producing carbon dioxide. Because the mine workings are sometimes very shallow, the O_2-depleted and CO_2-enriched mine gas may be emitted to the surface and into dwellings, exposing inhabitants to hazardous situations. To ease the natural drainage of mine gas it has been decided to reopen former adits that were closed after mining operations ceased. This should prevent diffuse migration of mine gas through surrounding strata to dwellings by creating preferential pathways for the mine gas flow.

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