

GAS MIGRATION FROM CLOSED COAL MINES TO THE SURFACE. RISK ASSESSMENT METHODOLOGY AND PREVENTION MEANS

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ABSTRACT: French law as regards renunciation to mining concessions calls for the mining operator to first undertake analyses of the risks represented by their underground mining works. The problem of gas migration to the surface is especially significant in the context of coal mines. This is because mine gas can migrate to the earth's surface, then present significant risks: explosion, suffocation or gas poisoning risks. As part of the scheduled closure of all coal mining operations in France, INERIS has drawn up, at the request of national mining operator Charbonnages de France, a general methodology for assessing the risk linked to gas in the context of closed coal mines. This article presents the principles of this methodology. An application example based on a true case study is then described. This is completed by a presentation of the preventive and monitoring resources recommended and usually applied in order to manage the risk linked to gaseous emissions.

KEYWORDS: gas, coal, mine, closure, risk.

RESUME : La réglementation française en matière de renonciation aux concessions minières prévoit que l'exploitant minier réalise au préalable des analyses des risques présentés par ses travaux miniers souterrains. La problématique de remontée de gaz en surface est particulièrement importante dans le contexte des mines de charbon. En effet, le gaz de mine peut migrer vers la surface du sol et présenter alors des risques importants : risques d'explosion, d'asphyxie ou d'intoxication. Dans le cadre de l'arrêt programmé de l'ensemble des exploitations de charbon en France, l'INERIS a établi, à la demande de Charbonnages de France, une méthodologie générale d'évaluation du risque lié aux gaz dans le contexte des mines de charbon arrêtées. L'article présente les principes de cette méthodologie. Un exemple d'application sur un cas concret est ensuite exposé. Il est complété par la présentation des moyens de prévention et de surveillance préconisés et appliqués habituellement pour gérer le risque lié aux émissions gazeuses.

MOTS-CLEFS : gaz, mine, charbon, fermeture, risque.

1. Introduction

French law as regards renunciation to mining concessions calls for the mining operator to first undertake assessment of the risks represented by their underground mining works in terms of people, property and the infrastructure present on the surface. In cases where significant levels of risk are identified, the operator must furthermore define and implement the appropriate preventive measures.

The problem of gas migration to the surface represents one of the major aspects of this risk assessment, especially in the context of coal mines, for these works very often combine the

three components needed to trigger the appearance of the feared phenomena:

- the presence of residual mining voids which, together with the natural porosity of the strata, forms underground reservoirs. Taken together, given the conditions of French coal seams, these reservoirs could represent 25 to 35% of the total volume of coal extracted (Degas and Wojtkowiak, 2003),
- the presence of dangerous gases,
- the possibility that these gases could accumulate and migrate, in significant concentrations, to the surface.

2. Mine Gas and the Dangers Linked to its Presence

Coal seams very often contain significant amounts of endogenous gas (firedamp), whose main component is typically methane and sometimes carbon dioxide. Firedamp can be released from unmined parts of the seam for a relatively long time after the end of mining operations.

It accumulates in residual mine spaces at the same time as other gases from the transformation of materials present in the old workings and/or in the air that may still be able to circulate through the old workings (nitrogen, carbon dioxide, carbon monoxide, hydrogen sulphide...). The combinations of these gases form a mixture called "mine gas". Very often, this mixture is severely lacking in oxygen or even virtually oxygen free.

Mine gas can migrate to the surface where its presence can then induce significant risks: risks of explosion, suffocation or poisoning. In France and in other coal mining countries affected by mine closures, a number of accidents and incidents linked to releases or build ups of mine gas have been reported in the literature (Sizer *et al*, 1996; Burrell and Friel, 1996; Kral *et al*, 1998; Jackson, 2000; Łukowicz and Walter, 2000; Pokryszka and Tauziède, 2000; Robinson, 2000; Novotny *et al*, 2001).

The most common situations that have caused these incidents or accidents are:

- Local, concentrated, releases of mine gas through a direct path between the old workings and the surface (mining opening, faults, crack...);
- A build up of gas in confined or semi-confined spaces (basements or underground locations, or in buildings themselves as well as in underground networks, etc.);
- The unintentionally connection of a post-mining voids to the atmosphere (e.g. due to drilling or excavating work conducted close to old workings...).

3. Mine Gas Migration to the Surface

The transfer of gas from post-mining voids to the surface may be driven by a number of mechanisms:

- the rising water level within the old workings;
- feeding the reservoir with gas by its release from the coal left in place;
- variations in barometric pressure;
- natural draft.

These different possible causes of gas releases on the surface may occur simultaneously. Nevertheless, the period during which the water level rises once pumping stops represents the most critical phase.

The possible appearance and intensity of gas emissions on the surface from old workings will essentially depend on three main factors:

- the gaseous (firedamp) nature of the post mining reservoir present, especially represented by the type of gas that is present, the importance of its "production" in the reservoir and the volume of the voids;
- the degree of differential pressure between the reservoir and the surface generated in combination by the various mechanisms mentioned above;
- the resistance of the environment to gas migration, simultaneously represented by former mine-surface links and by the covering strata, including water bearing horizon within it.

This shows the importance of knowing the underground mining reservoir (the structure and distribution of any residual voids, their position in relation to the surface...), their geological environment and their hydro-geological behaviour, so as to best appreciate the problem posed by the migration of mine gas to the surface.

Gas may rise to the surface:

- preferably through former works linking the mine and the surface (shafts, adits, access galleries) which constitute individual gas emissions points, if they have remained open or are not sufficiently tightly sealed off;
- through the covering ground itself, especially in areas of only slight thickness and/or where permeability is greatest. This is because a slight thickness in the covering ground, when naturally permeable (with high built-in permeability, the presence of cracks...) or made permeable as a direct consequence of mining operations (induced fracturing), is the situation that is most likely to favour gas releases;
- to a lesser extent, through water release or with the water from mine drainage (dissolved gas).

Figure 1 illustrates the various possible paths used by mine gas when migrating towards the surface.

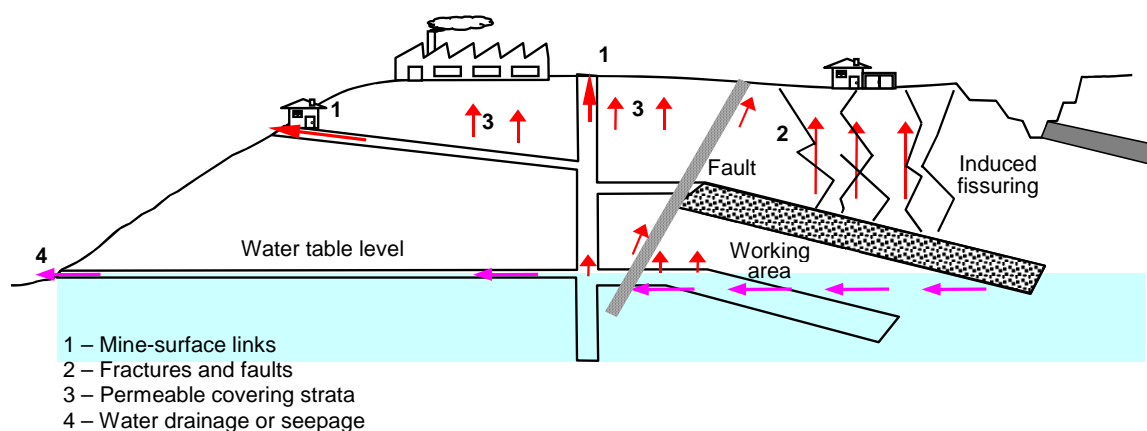


Figure 1 Mine gas migration paths towards the surface

4. Risk Assessment Methodology

Considering the shutdown of all coal mining operations in France, INERIS at the request of Charbonnages de France, drew up a general methodology for assessing gas related risks. This methodology, drawn up in its initial version around 1995 for the specific context of coal mines closure has since been improved and expanded to take into account the experience gained from handling a larger number of real life cases.

The methodology is based on taking into account and analysing various types of information and data:

- Data relating to the underground reservoir: the firedamp characteristics of the seams, the volume and extent of the residual mining voids, their position in relation to the surface...;
- Data relating to covering strata: type, structure and overall thickness of the covering strata, thickness of the various specific bedrocks and their permeability. The latter parameter may be strongly dependent on the fissuring induced by the workings;
- Information relating to hydrogeology: type, thickness, shape of the water bearing horizons, their position in relation to the mine workings and their evolution over time;
- Elements relating to seam structure: here the aim is especially to identify any possible presence of formations likely to encourage the accumulation and migration of mine gas;
- Data relating to ground occupation: geographic position and density of built up areas for rising gases result in a risk that is all the more significant if there is a human presence in the area and a possibility that gas will accumulate on the surface.

The superimposition and mapping of the various data and information is carried out on a map background using a scale chosen to obtain a result that provides enough overall coverage while being sufficiently precise.

This work is performed in line with the following major steps:

- collecting the knowledge available on the firedamp nature of the mining concession studied, from archive documents completed by any reconnaissance and measurements taken on field;
- information on the mine workings and the geological and hydro-geological context;
- identification of areas that may potentially release gas, based on geological and hydro-geological data and on working characteristics that are specific to the mining area;
- identification of risky areas, based on surface occupation;
- definition of the means of prevention and/or monitoring applied to manage the risk.

In cases where the hydrodynamic situation of the studied area has not yet stabilised (the water table is rising and the former workings are progressively flooded), the analysis of the problem of gas migration to the surface is performed separately for the two consecutive hydro-geological configurations:

- for the rising water level phase, and
- for the phase that follows the stabilisation of the hydrodynamic situation.

This general approach is presented in graphic format in Figure 2.

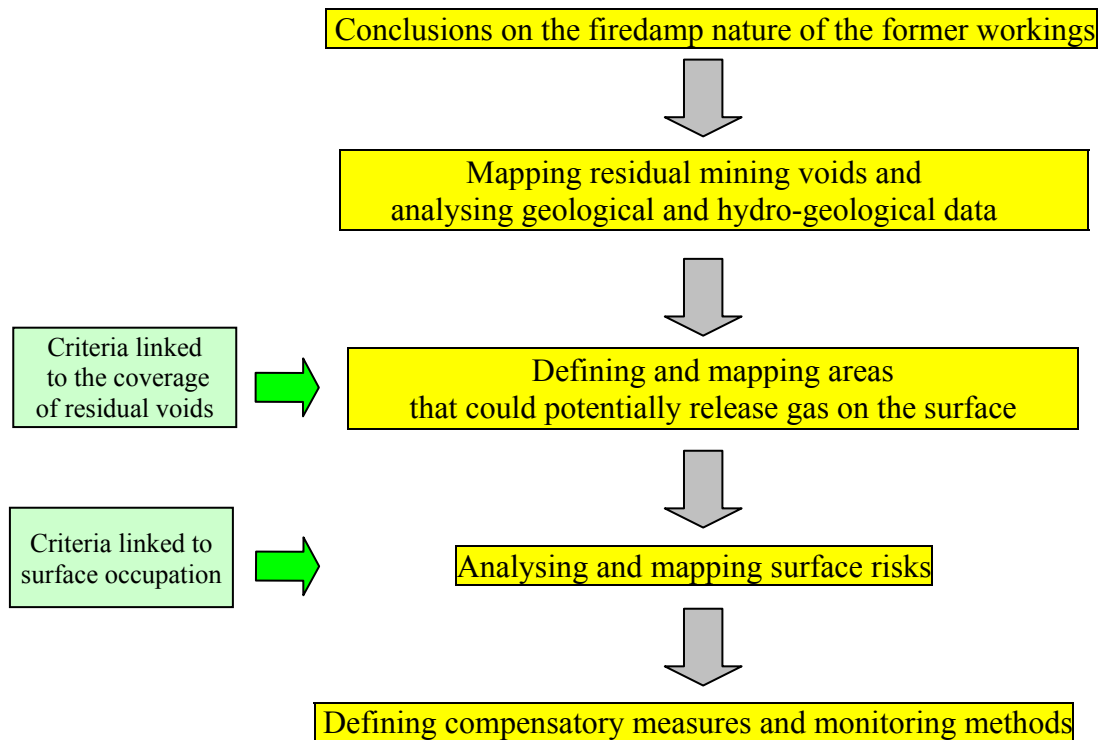


Figure 2. General approach applied to the analysis of the problem of mine gas rising to the surface

4.1. Conclusions on the Firedamp Nature of the Former Workings

This step aims to define the potential for former mine workings to release and to accumulate mine gas as well as to identify the type of gas likely in time to transit to the surface.

The analysis is performed through the search for numerous quantitative or simply qualitative data. The following especially should be retained:

- reports of the appearance of firedamp in the underground workings as stated in the reports filed by the operators or the authorities in charge of supervising the mines, or even various works describing the history of the mining operations.
- administrative ranking of workings in relation to firedamp that appeared in France towards the end of the 19th. Century.
- implementation during mining operations of firedamp prevention measures: safe explosive, safe lamps, mechanical ventilation, firedamp meters...
- reports on firedamp related accidents.
- results of the various measurements taken of firedamp releases during mining operations.

This data can be collected, more or less exhaustively, from the various archives available, those kept by mining operators, the mining administration or national or local public archives. This approach can be completed by reconnaissance on field and especially taking gas release measurements from mining openings where this is still possible.

The data collected is then compared and summarised so as to determine to what extent the workings being studied and their various sectors are affected by the presence of mine gas.

4.2. Mapping Residual Mining Voids and Analysing Geological and Hydro-geological Data

This work comprises analysing and summarising the various elements relating to the workings considered and are necessary to evaluate the sensitivity of the old mine being studied to gas accumulation and its transfer towards the surface, namely:

- a cartographic presentation of the main working areas and any underground links that may exist between these areas,
- identifying the upper mined out areas in the former mine workings that form "potential mine gas traps" and their position in space,
- the thickness of the overlying covering strata in the upper mined out areas,
- information relating to the structure, type and aeraulic characteristics of this covering strata as well as the degree of fissuring affecting it (both natural and that induced by the workings),
- information relating to overlying water tables above the upper mined out areas,
- current hydrological situation and the way it changes over time and in space, for the rising water phase as well as the future stabilised phase,
- the presence of any geological structures that favour the accumulation and/or migration of gas.

4.3. Defining and Mapping Areas that could potentially release Gas on the Surface

This step serves to locate and to set out a hierarchy, where possible, those areas that may contain mine gas and release it to the surface. This work is performed using the data acquired during the previous step.

The analysis requires setting out a number of criteria, the two main ones being:

- thickness and type of soil covering the upper mined out areas in the post-mining reservoir.
From a general point of view, a covering thickness of more than 200 meters is sufficient to obstruct the rise of gas in any way other than in a diffuse way. This limit thickness has been adopted on the basis of models developed in Europe for predicting the release of firedamp from a coal exploitation by caving longwalls, one that is the most penalising in terms of weakening the overlying strata.

These models consider that there is no significant influence by mine workings on the aeraulic properties of the covering strata in excess of a height of some 150 to 170 meters above the seam (Gunther, 1965; Coal Directorate, 1980; Pokryszka, 1992).

Depending on the refinement of the analysis, it is also possible to introduce intermediate limits in the covering thickness thereby ensuring partial protection in relation to gas migration.

At the same time, depending on the hydro-geological context of studied mining area, one takes into account when setting out the criteria, the existence in the covering strata of impervious beds (clay for example) or even water bearing beds, on condition that these are thick enough and continuous in order to form an efficient obstacle to rising gases.

- degree of flooding in the former workings still in contact with the unmined seam.

This aspect is especially relevant for the stabilised hydrodynamic phase, in cases where the workings or some of its parts remain insufficiently flooded. This is because, in this case, the gas contained in unmined seams may potentially continue to be released and transit to the surface.

For lack of studies or relevant past data, dedicated research work has been undertaken in order to be able to propose criteria relating to this aspect. This study covered the behaviour of the gas (methane) adsorbed in the coal in the presence of a hydraulic load created by the flooding water.

Experiments performed in the laboratory showed that finely split flooded coal, with no significant hydrostatic pressure may still, despite this, release gas. However desorption kinetics are very weak, some ten times less than with dry (not flooded) coal.

When the hydrostatic pressure caused by the flooding rises, the gas release kinetics falls. If the water pressure approaches that of the adsorbed gas, then the quantities of gas released become highly insignificant: they are in this case in the order of a few percent of the volume that can be desorbed. Figure 3 shows an example of the results obtained.

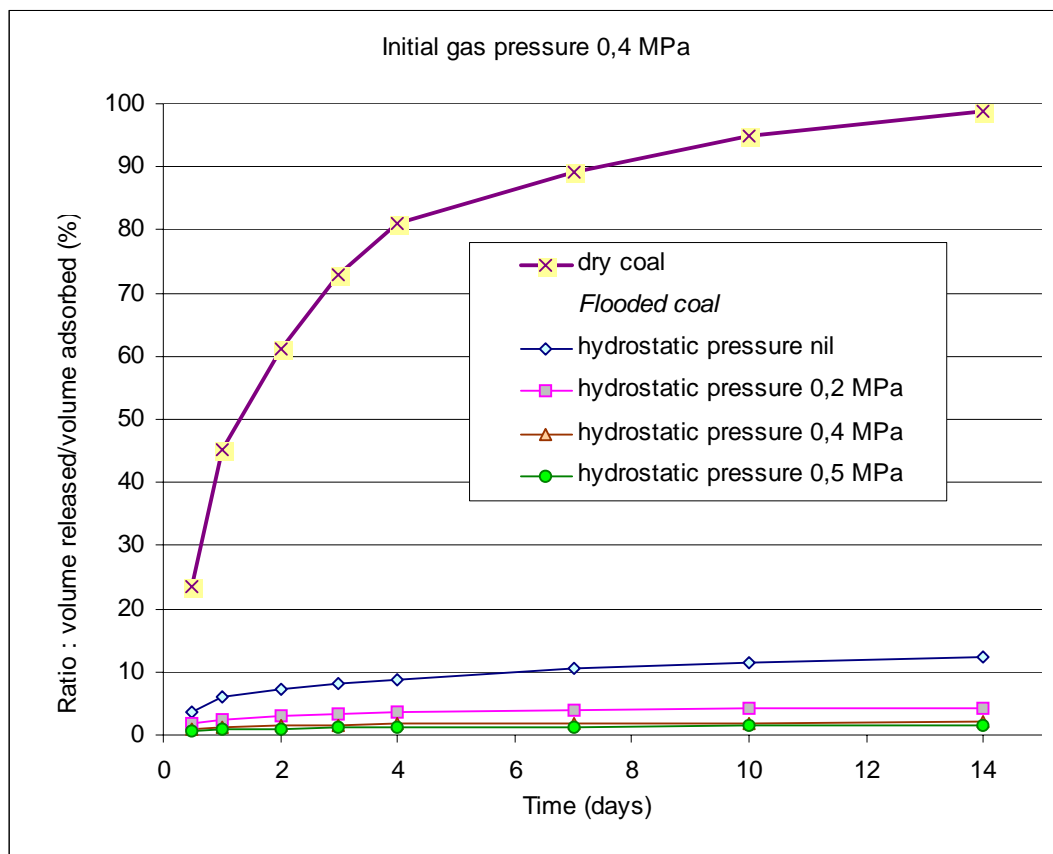


Figure 3. Example of the influence of water on coal gas desorption kinetics. Laboratory experiment using finely split coal.

All of these results have made it possible to detail the notions of "coal seam gas pressure" and the "minimum flooding level" as the basis for setting out criteria that correspond to the degree of flooding affecting former workings.

Applying these criteria makes it possible, for example, to eliminate from the rest of the risk assessment, those areas that are sufficiently flooded at a given time, by considering that in this configuration, the water present effectively inhibits any significant release of firedamp from the residual coal still in place.

In the analysis of areas that may potentially release gas, it is also considered, in parallel with the upper areas in former underground workings, those geological or tectonic structures that favour the accumulation or the migration of gas towards the surface (porous and permeable layers, anticlines, faults...).

This entire step leads to drawing a map of "areas likely to release mine gas". As an example, Figure 4 shows an excerpt of the mapping of such areas for a part of the French Nord-Pas-de-Calais coal mining area, representing some 13 square kilometres.

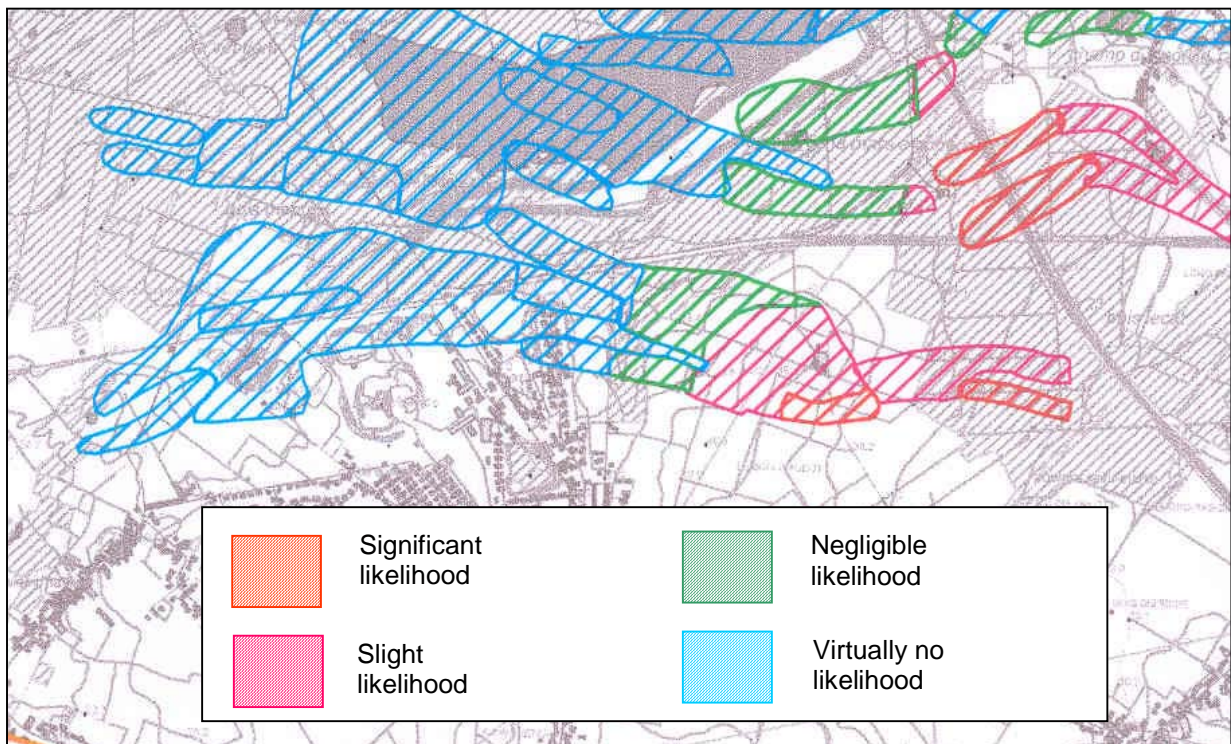


Figure 4. Excerpt from the mapping of areas potentially likely to release gas produced for the Eastern part of the Nord-Pas-de-Calais coal mining area

4.4. Analysing and Mapping Surface Risks

This step comprises identifying, from among those areas that could potentially release mine gas, those which are occupied on the surface by gas sensitive elements. This analysis is done by superimposing the aforementioned map of areas that could potentially release mine gas over a surface occupation map.

In this analysis, special consideration is of course given to built up areas occupied by buildings and industrial installations, for any release of gas can all the more frequently result in accidental events when there is a human presence and possibilities for mine gas to accumulate in buildings or in surface infrastructures. Built up areas therefore increase surface vulnerability and consequently, with the same likelihood of gas releases, the degree of risk.

Consequently, when enough information is available, the analysis is conducted so as to result in a hierarchy of risk, based on geographic location, the type and density of vulnerable areas. It should be noted that the risk mapping that is generated in this way is valid for the occupation of the surface in question, as it was when the study was conducted.

This step results in a so-called map of "mine gas emissions risk area". Figure 5 illustrates the result of this mapping effort drawn up for the same part of the French Nord-Pas-de-Calais coal mining area as presented in the preceding subsection.

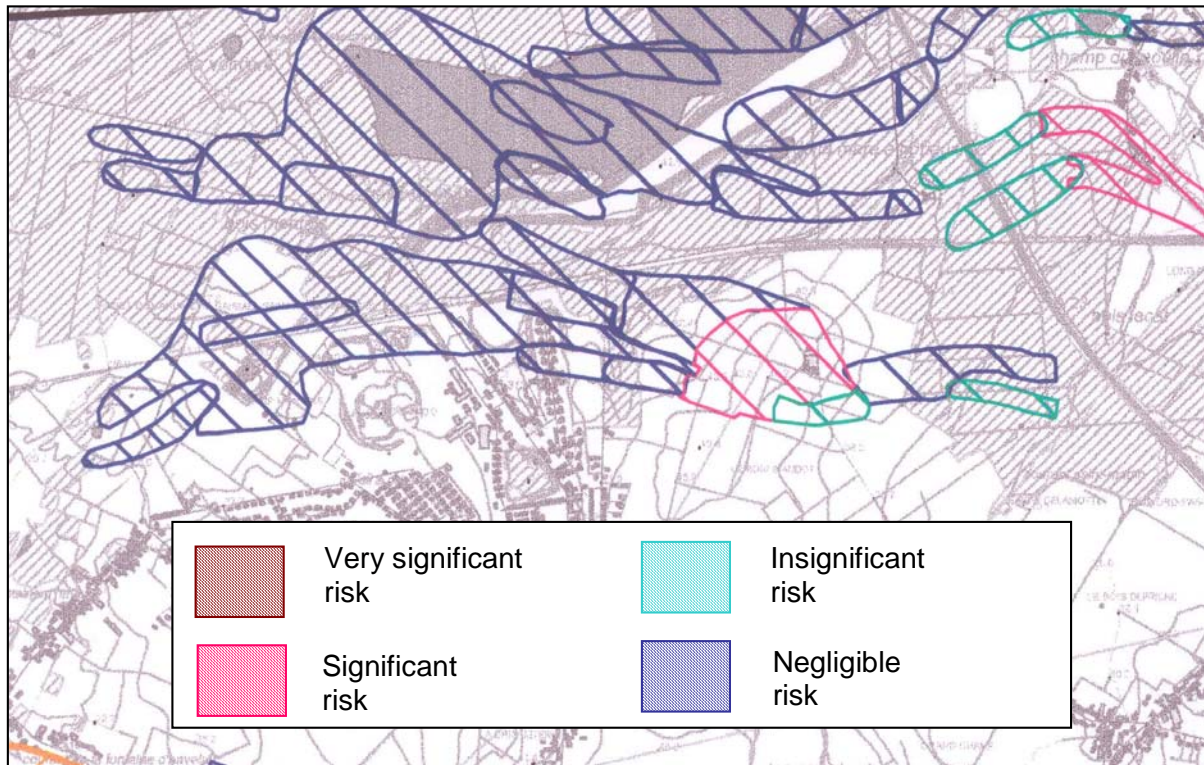


Figure 5. Excerpt from the mapping of areas with a mine gas emissions risk produced for the Eastern part of the Nord-Pas-de-Calais coal mining area

4.5. Defining Compensatory Measures and Monitoring Methods

4.5.1 Compensatory Measures

Once the risk linked to the rise of gas to the ground's surface is quantified and mapped, it is necessary to define the preventive or compensatory measures well suited to the context. These measures should make it possible to reduce the risk to a technically and financially acceptable minimum.

Two types of measures are possible to minimise the rise of gas to the surface: active treatment and passive treatment of the mine gas.

Capturing firedamp (drainage) from the surface represents an especially efficient active treatment of the problem. It usually creates a more or less significant vacuum in the mine reservoir compared with the surface level, but one that is sufficient to stop any uncontrolled release of gas on the surface. For example, large scale gas capture installations have been set up in the Nord-Pas-de-Calais mining area where a majority of the former mine workings are now under a vacuum of up to -500hPa .

This costly and complex method is most often practised in very gassy mining areas in order to industrially capture the gas and it is technically difficult to apply to low firedamp content seams. It is however possible, in some cases, to set up a local capture station intended to avoid any uncontrolled gas releases at local level (Robinson, 2000) or even a mobile installation that can be temporarily connected to capture points set up ahead of time in those areas where mine gas periodically appears on the surface (Novotny *et al.*, 2001).

In mines where firedamp collection systems have been set up in the past during mining operations, whether for safety reasons or gas exploitation, it may be interesting to keep such mechanisms in service even after coal mining stops, so as to control the water flooding phase for as long as possible. This is the case with the capture installations operating in the eastern and central parts of the Lorraine coal mining area.

Passive treatment comprises implementing, in areas of risk, priority escape routes for the gas, by building decompression installations (existing shafts suitably fitted out or drilling performed specially). This is because it is necessary for the gas contained in the reservoir to find a priority escape route to the outside atmosphere, i.e. one that considerably less resistant than the former mine-surface connections that are closed off or the covering strata.

The drilling required, which does not necessarily necessitate a very large diameter to be efficient, must aim for the high parts in the mining reservoir, in order to favour the decompression of the voids that are the closest to the surface and to allow the release of gas for as long as possible during the rising water phase.

Figure 6 illustrates the operating principle of a decompression borehole connected to a flooding post-mining reservoir. Given the normally very limited level of the unitary gas flows involved, one can easily assume that the releases from all of the system components (post-mining reservoir, covering, shafts and decompression works) are mainly laminar (Couillet *et al.*, 1998).

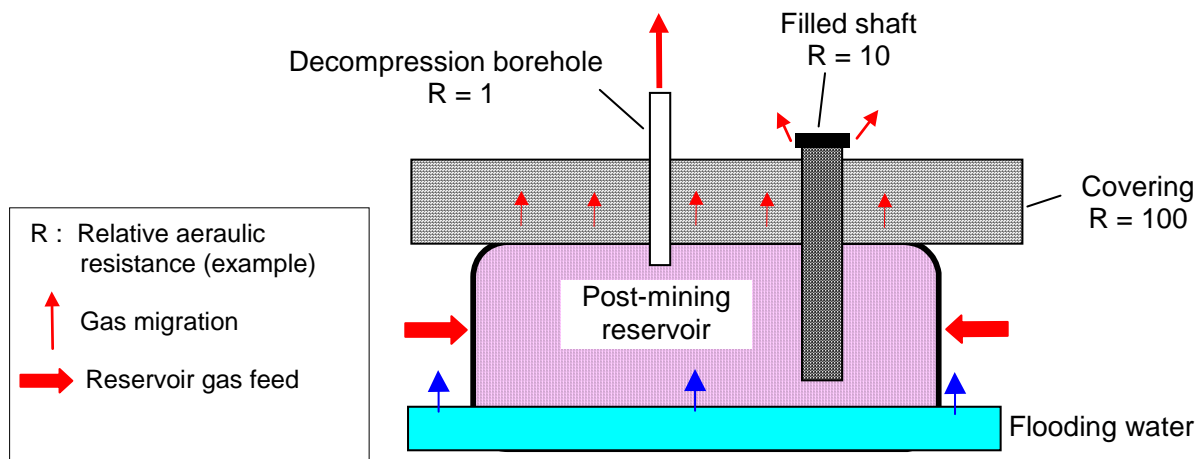


Figure 6. Operating principle of a decompression borehole linking a post-mining reservoir that is flooding

In this case, the distribution of the gas flow migrating to the surface spread among the three possible paths, i.e. the covering strata, the former adits or shafts and the decompression works will take place proportionally to the relative aeraulic resistance of each of these paths. The gas will therefore generally be released mainly by the one or more decompression devices as these offer the circuit with the least resistance.

It should be noted that prevention systems of this type have been proposed and/or implemented in a number of mining countries: in France, but also in Germany, Great Britain

(Jackson, 2000), in Poland (Łukowicz and Walter, 2000), in the Czech Republic (Novotny *et al.*, 2001; Prokop, 2001), etc.

Installing decompression works requires implementing specific safety measures in relation to the risks linked to the gas that can emerge from the post-mining voids (inflammation, suffocation, poisoning). In the same way, once completed, these works must be made safe in view of their often long term operation by fitting them with safety equipment such as cut off valves, flame arrestors..., and made inaccessible to the public.

For those drillings where it is assumed that they will become highly active, it is also necessary to establish a protection area that takes into account the above mentioned risks. An example of how to define this area in relation to the thermal effects caused by accidental gas (methane) inflammation conducted by INERIS on a drilling in the Lorraine coalfield, is presented in Figure 7.

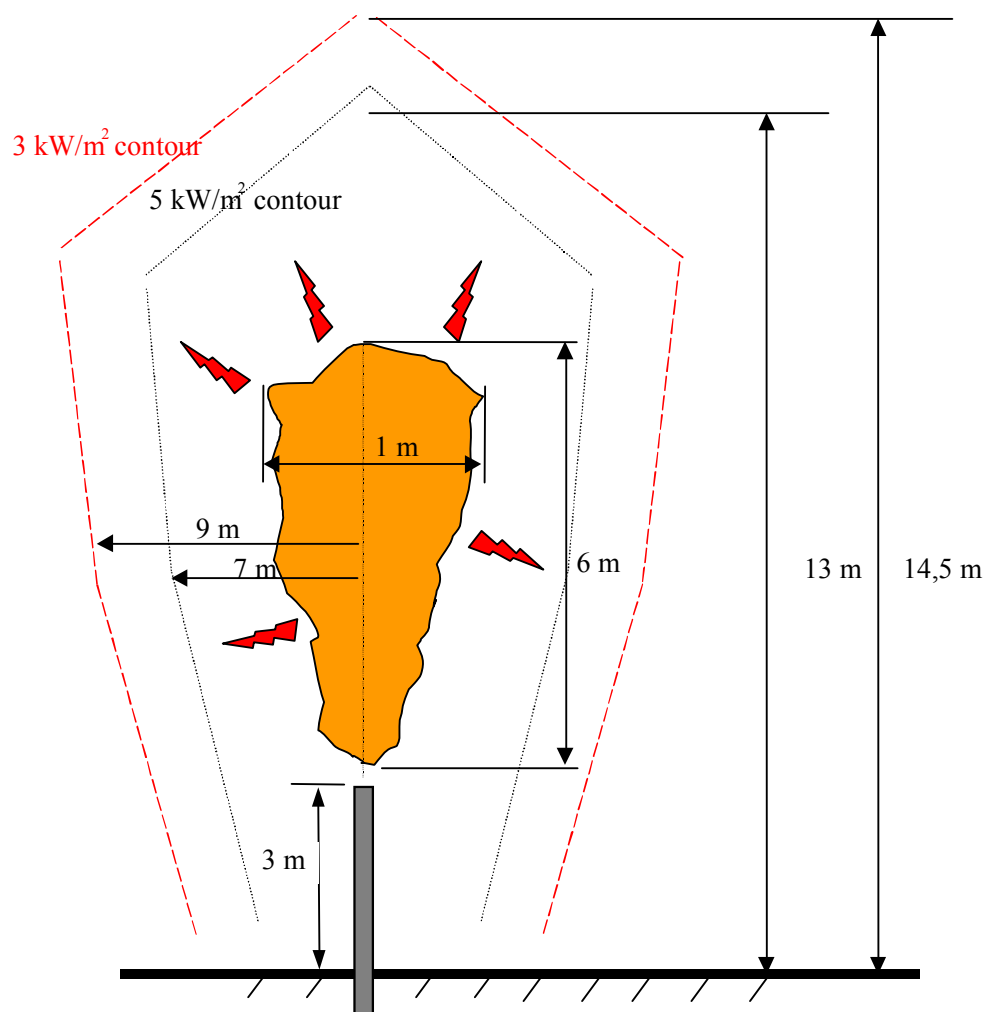


Figure 7. Example of the definition of the protection area around a highly active decompression drilling in relation to the thermal effects linked to accidental gas inflammation (methane outflow $0,3 \text{ m}^3/\text{s}$)

It should be noted that these decompression installations should play a part during the entire time taken to flood the underground works, the most critical phase, but that they may also need to be retained in situations where flooding of post-mining voids will never be complete.

As an example, Figure 8 presents the change, over a three-year period, to the activity of a decompression borehole placed into service in Cransac in France's Decazeville coalfield that is flooding.

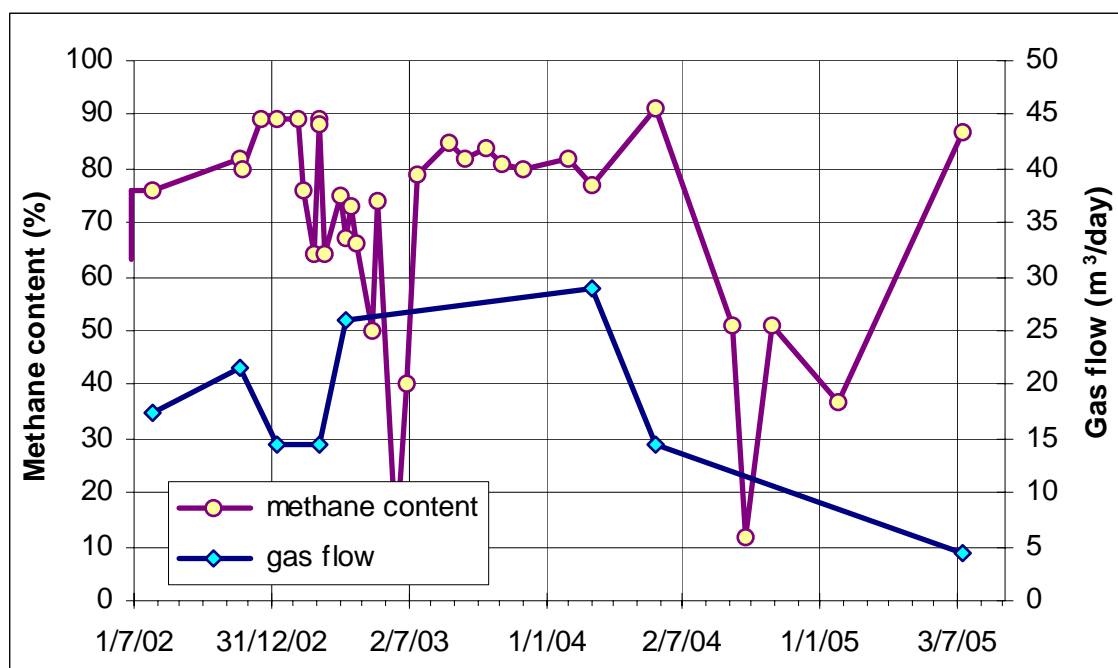


Figure 8. Example of the activity of a decompression borehole in the Decazeville coalfield

The intensity of the gaseous release from this borehole, as established from one-off measurements of the methane content and gas flow clearly show the beneficial effect that this kind of installation can have in terms of reducing the pressure level in the post-mining reservoir and in reducing the amount of gas likely to migrate uncontrollably to the surface.

4.5.2 Special Measures and Land Management

In those special cases where implementing efficient prevention methods is technically impossible or where the action of all of the means implemented turns out to be insufficient, the appropriate administrative approach must be undertaken as regards the urban development of those areas classified as being the most likely to release gas to the surface.

Depending on the local context, this may require:

- temporarily ruling out any urban development in the affected areas or the banning of new building projects without any additional preventive measures, at least during the rising flood water phase;
- the mandatory inclusion as part of any building permit, of technical and/or constructive measures that inhibit the penetration and accumulation of gas within the buildings envisaged.

These measures which have to be set out on a case by case basis, must come with the appropriate inspection and monitoring procedure.

4.5.3 Inspection and Monitoring Means

Whatever the treatment mode chosen and implemented, monitoring the operating parameters of the underground mining reservoir and the presence of any mine gas on the surface is necessary to ensure that the preventive measures taken are effective.

It is especially necessary to regularly check the correct operation of the decompression shafts or boreholes (or the gas drainage system) so as to be sure that the reservoir is not placed under pressure. This check must be carried out throughout the service life of the system.

Post-mining site monitoring can be performed by:

- manual checks and measurements (covering gas content, pressure, direction of release, flow...) performed periodically at strategic locations or those that are most exposed (decompression boreholes, former mine-surface links, locations where build-ups may occur such as in underground networks and basements...), using portable devices;
- implementing automated measurement or remote monitoring systems. A system of this kind has, for example, been installed by Charbonnages de France in the Nord-Pas-de-Calais coalfield, to monitor the overall behaviour of the post mining reservoir from some twenty observation points;
- direct measurements of gas flows on the surface. These measurements are especially effective in assessing the importance of the actual transfer of gas towards the surface (Pokryszka and Tauziède, 1999). This is recommended for sensitive built up areas, if the presence of gas is observed using the aforementioned monitoring measures.

The means available for use in checking and monitoring post-mining sites are described in greater detail in a communication dedicated to this problem (Besnard and Pokryszka, 2005).

5. Conclusions

The risks linked to the rise of mine gases to the surface represents a problem that is especially important in the context of closed coal mines. This aspect should be taken into consideration during regulatory investigations prior to a mining operator relinquishing their mining concessions.

A methodology for analysing and assessing this risk has been developed by INERIS in cooperation with Charbonnages de France. It is based on compiling and analysing multiple data relating to the studied mining area: historical data, the characteristics and the behaviour of the post-mining reservoir, the geological and hydro-geological characteristics of the seam... It results in a quantified mapping of risks and in defining those preventive measures that should possibly be implemented.

This method has been applied to all closed down mines belonging to Charbonnages de France in the various French coalfields where an analysis of the risk relating to migration to the surface of mine gas turned out to be relevant.

Furthermore, even if there remains a number of phenomena that are insufficiently understood¹, the development and research work undertaken in the context of establishing this methodology have made it possible to improve knowledge of gaseous phenomena in the

¹ For example: the evolution of gaseous properties of post-mining voids and their hydro-chemical behaviour over the long term, the durability of decompression works...

context of shutdown coal mines and to move along the understanding of the behaviour of post-mining reservoirs in a complex geological and hydrological environment.

The knowledge acquired and those elements of the methodological approach established can be used or derived to evaluate the risks linked to gases in other post-mining contexts other than closed coal mines. It can be also used in the context of setting out Mine Risk Prevention Plans (Plans de Prévention des Risks Miniers or PPRM) described in a communication dedicated to this regulatory tool (Didier and Leloup, 2005).

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