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Reassessment of long-term monitoring of underground heating: a 25-year case study at a former lignite mine

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Abstract

The former Bois d'Asson underground lignite mine, located in southeastern France, has been monitored since 1999 following the detection of a surface manifestation of underground heating characterised by the emission of fumes. Mitigation works were implemented in 2000 to confine the emission point and reduce air circulation feeding the heating source. Despite these measures, the underground combustion was not fully extinguished and a long-term monitoring has operated since then.

This paper presents a reassessment of the relevance and performance of the monitoring system based on more than 20 years of temperature measurements, gas composition analyses and flow rate observations. High-frequency monitoring data acquired between 2017 and 2023 are analysed using descriptive statistics and time-series decomposition to separate long-term trends from seasonal and short-term variability. The results indicate that the underground heating source remains active but has stabilised in recent years, with a gradual reduction in intensity observed since the mid-2000s.

The study highlights the influence of soil temperature on fumarole temperature measurements and demonstrates the limitations of absolute temperature thresholds established early in the monitoring history. A revised criterion based on the temperature difference between fumarole and soil measurements is proposed to improve robustness against weather-driven variability. Gas analyses confirm persistent combustion signatures while underlining the importance of representative sampling protocols.

The Bois d'Asson case provides a long-term reference for mine closure practitioners dealing with persistent low-intensity heating in abandoned coal mines and demonstrates how long-term monitoring objectives and thresholds should evolve once an underground combustion process has stabilised. It also provides a transferable framework for proportionate post-closure surveillance at abandoned coal mines.

Keywords: *gas emissions, lignite, long-term monitoring, mitigation, spontaneous combustion, telemonitoring, underground heating*

1 Introduction

Persistent underground heating and spontaneous combustion represent a well-known challenge for coal mining, both during active operations and long after mine closure. In contrast to rapid mine fires, low-intensity heating phenomena may continue for decades, generating gas emissions, thermal anomalies and odour nuisances that require long-term management but are difficult to extinguish once established.

The former Bois d'Asson lignite mine, located in southeastern France, offers a rare opportunity to analyse such a phenomenon over more than 2 decades. Surface manifestations of heating were first detected in 1999, long after the end of mining activities. Since then, the site has been the subject of successive

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investigations, mitigation works and long-term monitoring conducted by public institutions (BRGM, GEODERIS and Ineris) on behalf of the French ministry in charge of the environment.

In summer 2022 changes observed in monitoring data prompted the regional environmental authority (DREAL Provence-Alpes-Côte d'Azur) to request a reassessment of the risks associated with the site and, more specifically, of the continued relevance of the monitoring system (BRGM 2025). This paper presents the results of that reassessment performed by GEODERIS in 2024, with 3 main objectives:

1. to synthesise long-term monitoring data and analyse recent trends in temperatures and gas emissions
2. to evaluate the effectiveness and limitations of mitigation measures implemented in 2000
3. to propose adjustments to monitoring criteria and strategies in light of the stabilised behaviour of the phenomenon.

The key objective of this paper is not to demonstrate the extinction of the underground heating but to assess whether the existing monitoring system remains relevant, decision oriented and proportionate in the context of a stabilised post-closure hazard.

Beyond its site-specific context, the Bois d'Asson case provides transferable lessons for mine closure and post-closure management in coal-bearing formations with high susceptibility to spontaneous combustion.

2 Site location, geological setting and mining history

The location of the Bois d'Asson lignite mine is shown in Figure 1. The surface manifestation of heating occurs in a forested area ('bois' means woods in French). The nearest surrounding affected party is a seasonal campsite located 700 m to the southwest.

Figure 1 Location of the Bois d'Asson lignite mine in metropolitan France. Modified from a map by Twilight-Brawl. Licence: https://creativecommons.org/licenses/by-sa/3.0/

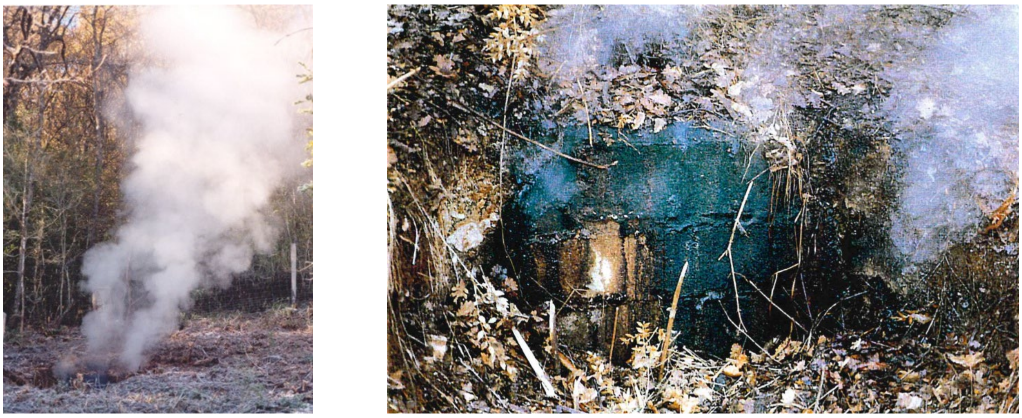
The lignite deposit is characterised by seams interbedded with oil shale layers and exhibits a steep structural dip of approximately 70°. The lignite has a high volatile-matter content (35–50 wt%) and elevated sulphur concentrations (5–10 wt%), largely associated with pyrite. These characteristics confer a strong intrinsic spontaneous combustion (self-heating) propensity (Beamish & Theiler 2019).

Mining of the Bois d'Asson lignite dates back at least to the 17th century, with more systematic underground exploitation documented from the 19th century onwards. The mining layout included a combination of hillside galleries and deeper workings. Documentation of these workings is incomplete, particularly for the oldest phases of exploitation (GEODERIS 2018). As a result, the precise geometry and connectivity of certain underground voids remain uncertain. This lack of detailed mine plans prevents the interpretation of underground airflow and gas-migration pathways in the post-closure context.

Furthermore, natural fracturing associated with stratification and historical mining activity has resulted in a highly permeable near-surface environment, facilitating gas migration between underground voids and the surface. The geological structure thus creates favourable conditions for both the initiation and long-term persistence of underground heating phenomena.

3 Detection and initial characterisation of the heating phenomenon

The underground heating phenomenon at the Bois d'Asson site was first formally identified in November 1999 following observations of warm gaseous emissions at the surface. These emissions were characterised by visible vapour plumes (as shown in Figure 2), strong tar-like odours and elevated temperatures relative to ambient conditions. In situ and laboratory analyses conducted at that time demonstrated that the emitted gases were almost entirely depleted in oxygen (O_2; measured at ~0.6% v/v) and enriched in combustion products, notably carbon dioxide (CO_2; ~16% v/v) and carbon monoxide (CO; ~0.4% v/v), together with smaller proportions of hydrogen (H_2; ~0.4% v/v) and gaseous hydrocarbons (e.g. CH_4; ~0,6% v/v).



(a) (b)

Figure 2 Surface manifestation of the heating observed by Ineris in November 1999: (a) Overall view of the emitted plume; (b) Close-up view of the emission point (behind a masonry wall)

Measured gas temperatures at the emission point were in the order of 60–65°C; significantly lower than temperatures typically observed close to active combustion fronts (up to 1,000°C) and suggesting that the heat source was located at some distance from the surface. Gas flow rates were estimated at several hundred litres per second, confirming the presence of a sustained underground convection pathway.

Based on available mine plans and field observations, the emission was interpreted as occurring within a sub-vertical structure connected to the surface; possibly corresponding to an inclined ventilation shaft or shallow gallery intersecting lignite outcrops. The limited number of available plans prevented precise reconstruction of underground connections and airflow pathways.

4 Mitigation works implemented after detection

Several surface-level risks associated with the heating phenomenon were considered, including inhalation of toxic fumes, formation of an explosive atmosphere and risk of vegetation fire through fire transfer to the surface. Thus, immediate prevention measures were taken in 1999, including:

- installation of a fence with a 10 m outer radius around the fume emission point, in order to protect people likely to be in the affected area from inhaling undiluted fumes
- installation of a warning sign about the risk of poisoning and death
- systematic brush clearing within the fenced area.

In February 2000 a mitigation strategy based on confinement of the surface emission point was also implemented. The primary objective was to confine the heating source by reducing air circulation feeding the combustion while acknowledging that full extinction might not be technically achievable, given uncertainties regarding underground geometry.

As shown in Figure 3, the emission point was sealed using a layered system comprising compacted clay barriers separated by a low permeable geomembrane and capped with a reinforced concrete slab. Two steel pipes equipped with valves were installed to allow controlled gas sampling and pressure relief if required (valves are normally kept closed.). This configuration provided operational flexibility while maintaining a high degree of confinement under normal conditions. Photographs of closure works are shown in Figure 4.

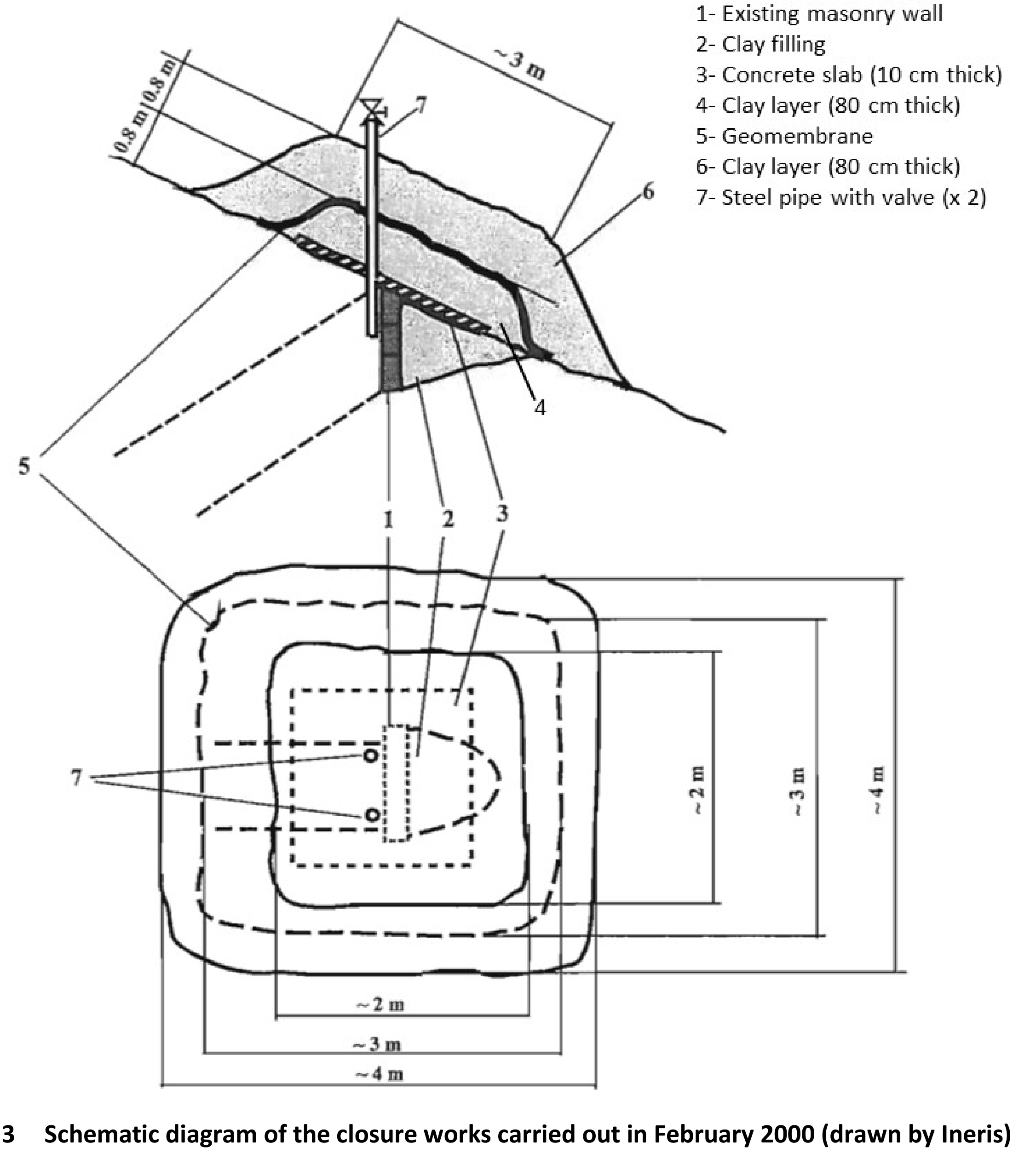


Figure 3 Schematic diagram of the closure works carried out in February 2000 (drawn by Ineris)

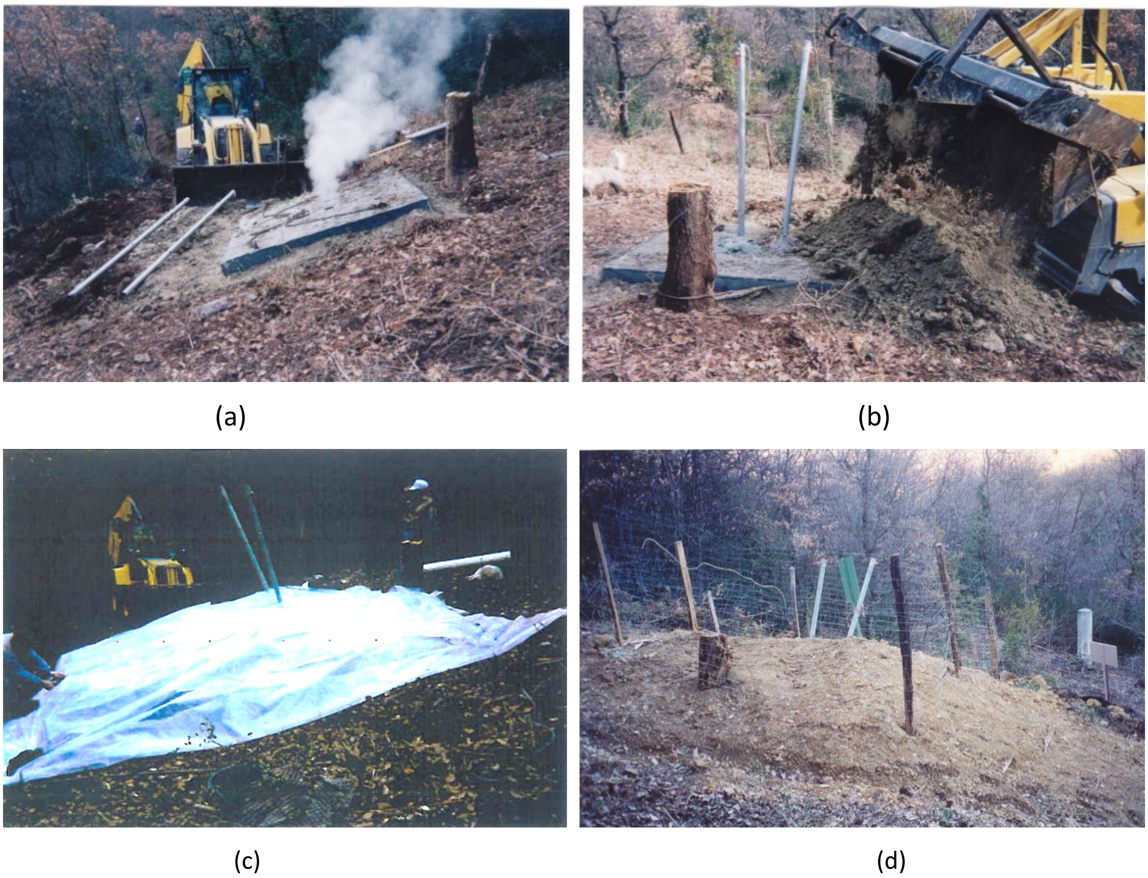


Figure 4 **Closure works carried out in February 2000 (photographs taken by Ineris): (a) Concrete slab in place; (b) Installation of the first clay layer, after the pipes were installed; (c) Installation of the geomembrane; (d) Overall view of the completed works**

Post treatment monitoring conducted throughout 2000 confirmed a significant reduction in gas fluxes and concentrations (including CO, H_2 and gaseous hydrocarbons). No abrupt reactivation or displacement of the combustion zone was observed following sealing. However, diffuse odours and low-temperature fumaroles appeared in the surrounding area, indicating a slight redistribution of gas migration through the ground rather than complete suppression. Fumaroles appeared within a radius of 30 to 40 m around the treated emission point.

5 Deployment of a telemonitoring system

5.1 Monitoring objectives and conceptual framework

After mitigation works, long-term monitoring at Bois d'Asson was designed to detect any unfavourable evolution of the underground heating that could lead to renewed surface emissions, while distinguishing such evolution from variations driven by meteorological conditions or equipment-related issues.

Given the persistence of the phenomenon and the impracticality of frequent field interventions, a dedicated autonomous telemonitoring system was deployed by Ineris in late 2004. The conceptual framework focuses on temperature measurements and assumes that surface measurements reflect both the dynamics of the underground heat source and transport processes along different pathways. Consequently, multiple temperature monitoring points were selected to capture complementary information.

5.2 Monitoring system design

The autonomous remote monitoring station was deployed to complement periodic site inspections carried out up to that point. The system operates on photovoltaic power with battery storage and transmits data via the mobile network.

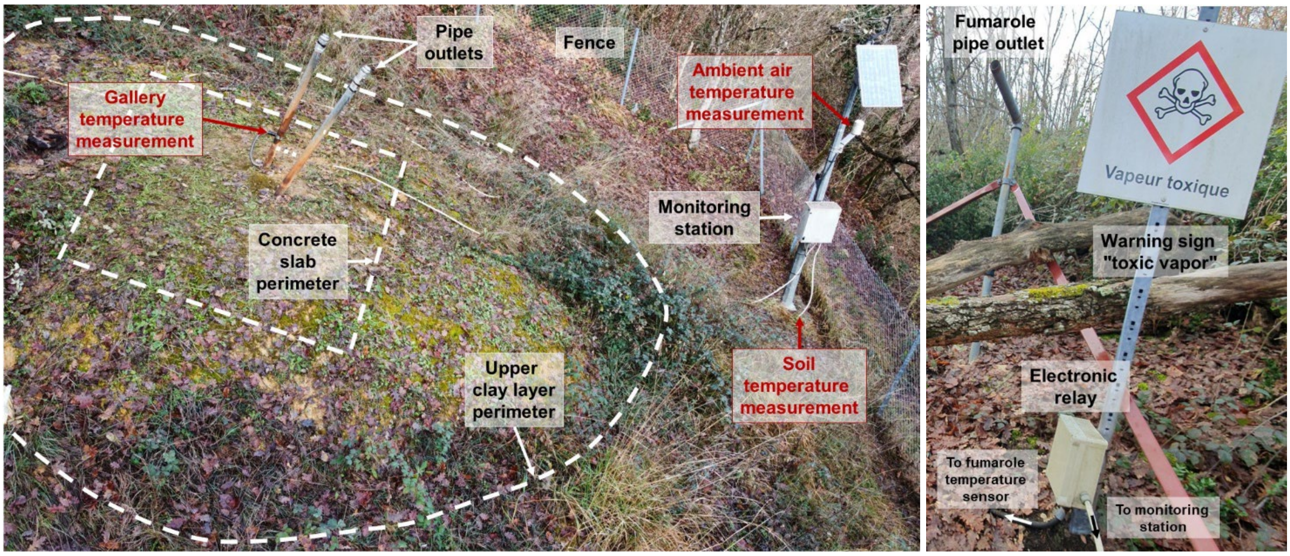
Continuous monitoring focuses on temperature measurements at 4 locations:

- within the sealed structure at the original emission point (location named 'Gallery')
- at one of the secondary fumaroles that appeared after closure works (location named 'Fumarole')
- within the soil at a 0.5 m depth, beyond any influence of the heating phenomenon
- in the ambient air under sheltered conditions.

The last 2 locations serve as references to account for the influence of meteorological conditions.

These measurements are complemented by periodic site visits involving gas composition analyses and flow rate estimations. Responsibility for system operation and maintenance was transferred successively from Ineris to GEODERIS and then to BRGM, which has overseen monitoring activities since 2007. To date, the monitoring system remains operational (BRGM 2025; République française 2025).

Figure 5 shows recent photographs of the site and the location of different temperature measurement points.



(a) (b)

Figure 5 Monitoring sites in 2024 (photographs taken by BRGM): (a) General drone view of the fenced area. The perimeters drawn in dotted lines are for illustrative purposes only and may not correspond to the actual footprints; (b) 'Fumarole' measurement point located outside the fenced area. The fumarole temperature measurement point is not visible in the photograph. The temperature sensor penetrates the ground at the base of the vertical pipe to reach the emission point

5.3 Monitoring thresholds

In 2006, based on the analysis of temperature and gas data acquired between December 2004 and October 2006, Ineris established a monitoring procedure relying on reference threshold values given in Table 1 and intended to identify unfavourable evolution of the underground heating.

Table 1 Normal behaviour ranges for temperature measurements defined by Ineris in 2006

Monitored parameter	Normal behaviour range
Temperature at Gallery	Nearly constant: remains within 58–60°C
Temperature at Fumarole	Range of variation: 10–23°C No daily fluctuations
Soil temperature	Range of variation: 15 ± 10°C No daily fluctuations
Ambient air temperature	Range of variation: 12 ± 25°C Daily fluctuations of ±10°C

Three main temperature-based criteria were defined:

- A critical threshold of 100°C, measured either at the treated Gallery or at the Fumarole, was considered indicative of a severe evolution requiring immediate specialist intervention.
- A first-level alert threshold was defined at 65°C for the gallery.
- A first-level alert threshold was defined at 28°C for the fumarole.

Exceedance of these first-level values was considered significant when observed either for at least one week with a rapid temperature increase (greater than 2°C per day) or for at least 2 consecutive weeks, in which case an expert assessment was required within a short time frame.

Thresholds associated with minimum temperatures and battery voltage were also defined to identify anomalies of an electrical or instrumental nature rather than changes in the heating phenomenon itself (they are not detailed here).

A monitoring procedure was formalised as a decision flow chart, distinguishing equipment-related malfunctions addressed through maintenance interventions from thermal anomalies potentially related to the underground combustion, which then triggered the involvement of a combustion specialist. Figure 6 shows the part of the decision flow chart relating to thermal anomalies. At the time of implementation, data were downloaded and analysed on a biweekly basis, and it was explicitly planned that the reference values and relationships between monitored parameters would be revised. However, no deadline was set for the revision.

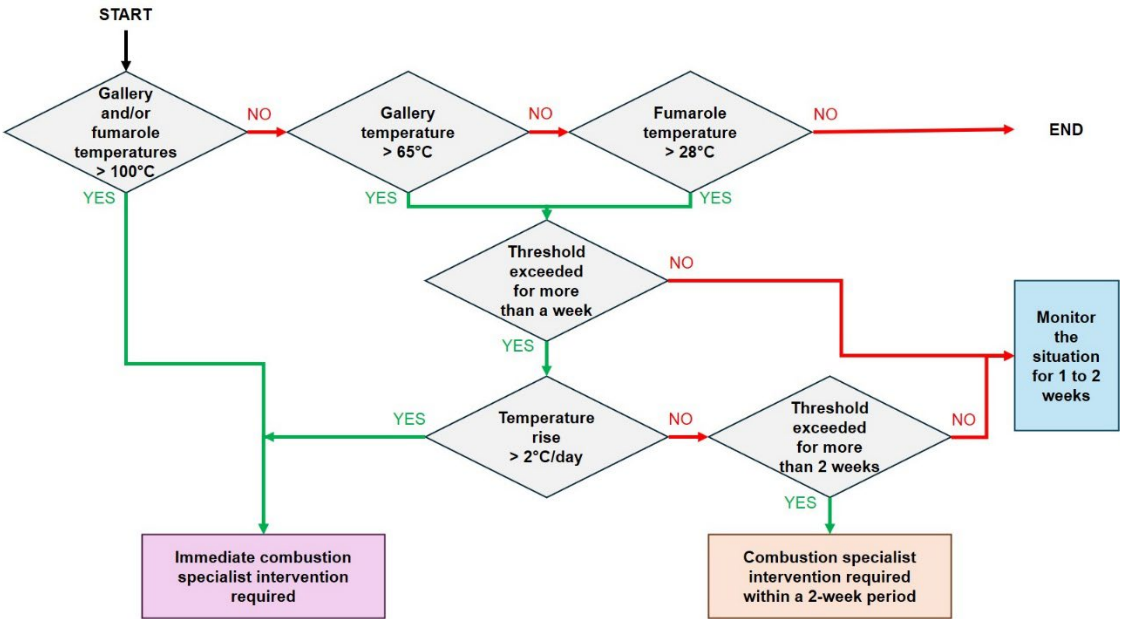


Figure 6 Decision flow chart related to thermal anomalies defined in 2006. Modified from Ineris

6 Long-term monitoring data synthesis and recent trends analysis

6.1 Temperature monitoring results

The reassessment performed in 2024 primarily used high-resolution temperature data acquired by BRGM between October 2017 and December 2023, when measurements were available at 30-minute or hourly intervals. Over this period, the monitoring system exhibited high operational reliability, with data availability exceeding 90% at all measurement points. Earlier data are available as annual averages but were considered insufficient for detailed temporal analysis.

Temperature data were analysed using descriptive statistics and Tukey's box plots to characterise variability and identify statistically anomalous values (Figure 7), and to compare them to normal behaviour ranges for temperature measurements defined in 2006 (Table 1). The time series were harmonised to an hourly timestep to enable consistent statistical processing, and then time-series decomposition was applied to separate long-term trends (not shown), seasonal components (Figure 8) and short-term residual variability (not shown).

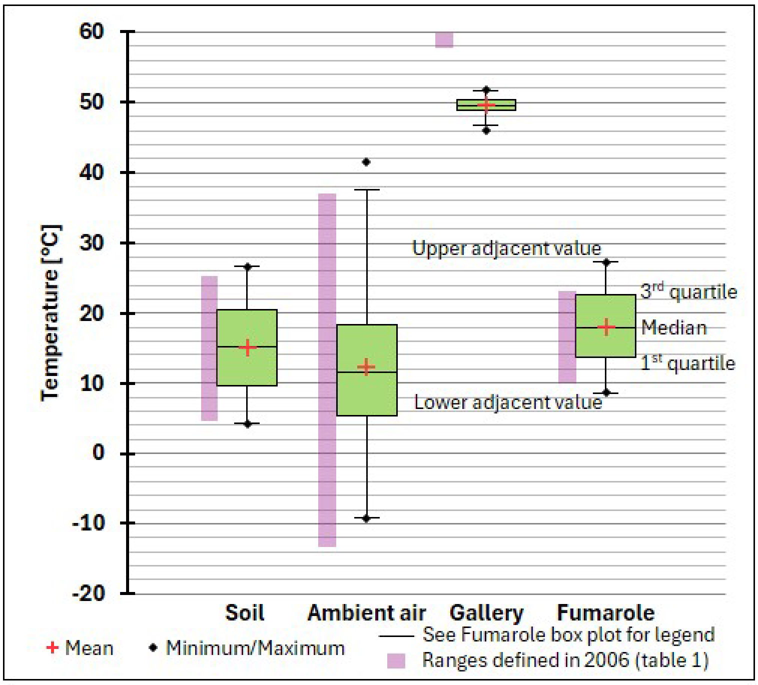


Figure 7 Tukey's box plots of temperature data acquired by BRGM between October 2017 and December 2023 compared to normal behaviour ranges for temperature measurements defined in 2006

Temperature values measured within the gallery remained consistently elevated, with a mean value close to 50°C and very limited variability. Seasonal and daily fluctuations were minimal, indicating that this measurement point remains primarily controlled by subsurface thermal processes rather than atmospheric conditions. From 2007 to 2017, BRGM observed a decrease in the average annual temperature at the gallery, from 58.6°C to 50°C (not shown). All these observations suggest a slow but persistent decrease in underground combustion intensity.

By contrast, temperatures measured at the fumarole and within the surrounding soil exhibited pronounced seasonal variations. Decomposition of the temperature time series demonstrated a strong correlation between soil temperature and fumarole temperature, with synchronous seasonal cycles and limited residual variability. This confirms that the temperature of gases emerging at the fumarole is primarily governed by heat exchange with near-surface soil during upward migration, rather than by direct coupling with ambient air temperature.

The external air temperature showed the greatest variability and strong diurnal cycles, but its influence on fumarole temperature was indirect and mediated by soil thermal inertia.

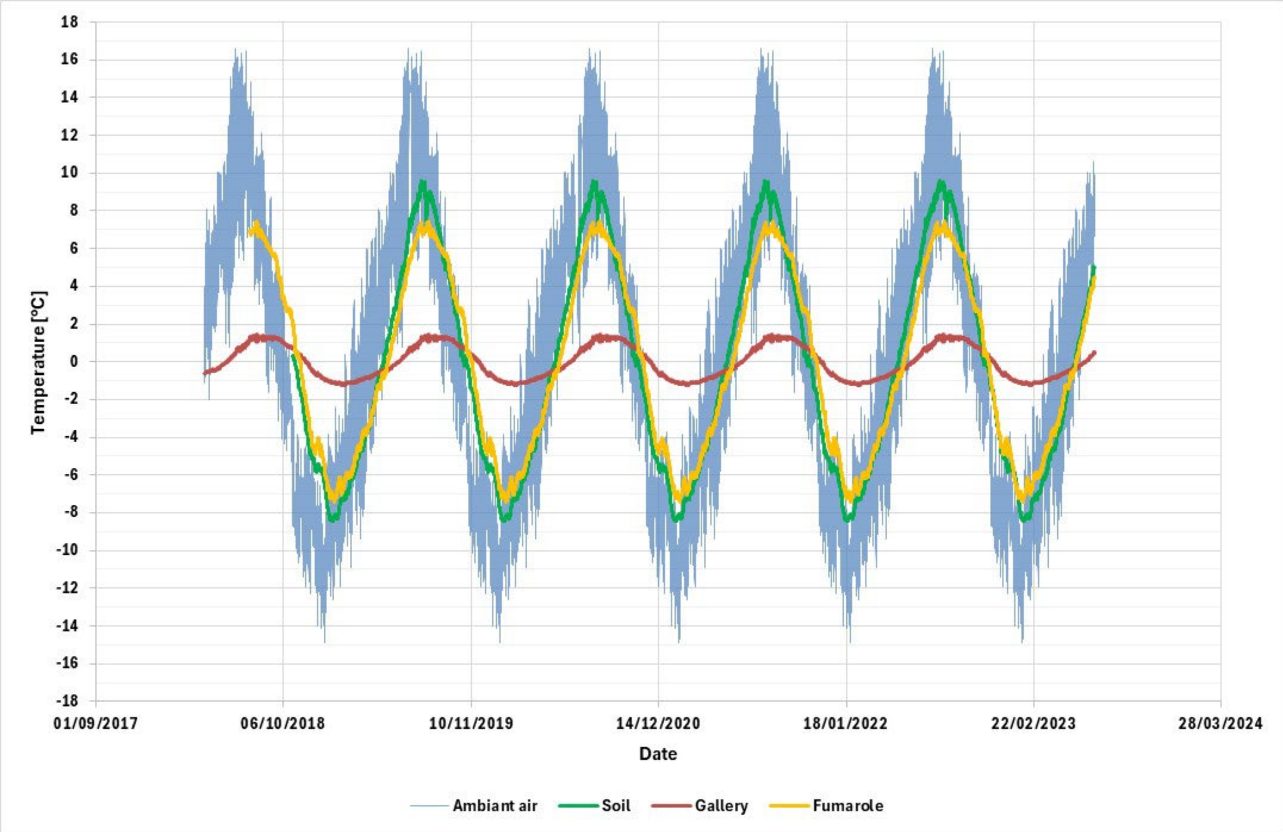


Figure 8 Seasonal components of the temperature time series acquired by BRGM between October 2017 and December 2023

6.2 Gas composition trends

Datasets of gas composition of fumes emitted at the gallery cover 1999–2006 and 2009–2023 and provide valuable insight into the evolution of the underground heating process. They were initially collected by Ineris (1999–2006), and subsequently by BRGM (2009–2023). Gas composition of the fumes emitted at the fumarole was measured in 2005 and 2016 (not shown) and was equivalent to that measured at the gallery.

Prior to analysis, datasets were reviewed to identify input errors, unit inconsistencies and potentially contaminated samples. Isolated anomalies in gas composition (i.e. high O_2 and low CO_2 contents) were attributed to atmospheric contamination during sampling and were excluded from interpretative analyses.

Gas compositions were interpreted using a process-based framework distinguishing major gases (i.e. N_2, O_2, CO_2) and marker gases for underground heating and mine fires (i.e. CO, H_2 and, to some extent, gaseous hydrocarbons and sulphur compounds such as H_2S and SO_2) (Barnerjee 1985; Ineris 2016; Mitchell 1996). As shown in Figure 9, O_2 concentration versus CO_2 concentration relationships were examined to identify combustion signatures and atmospheric dilution effects.

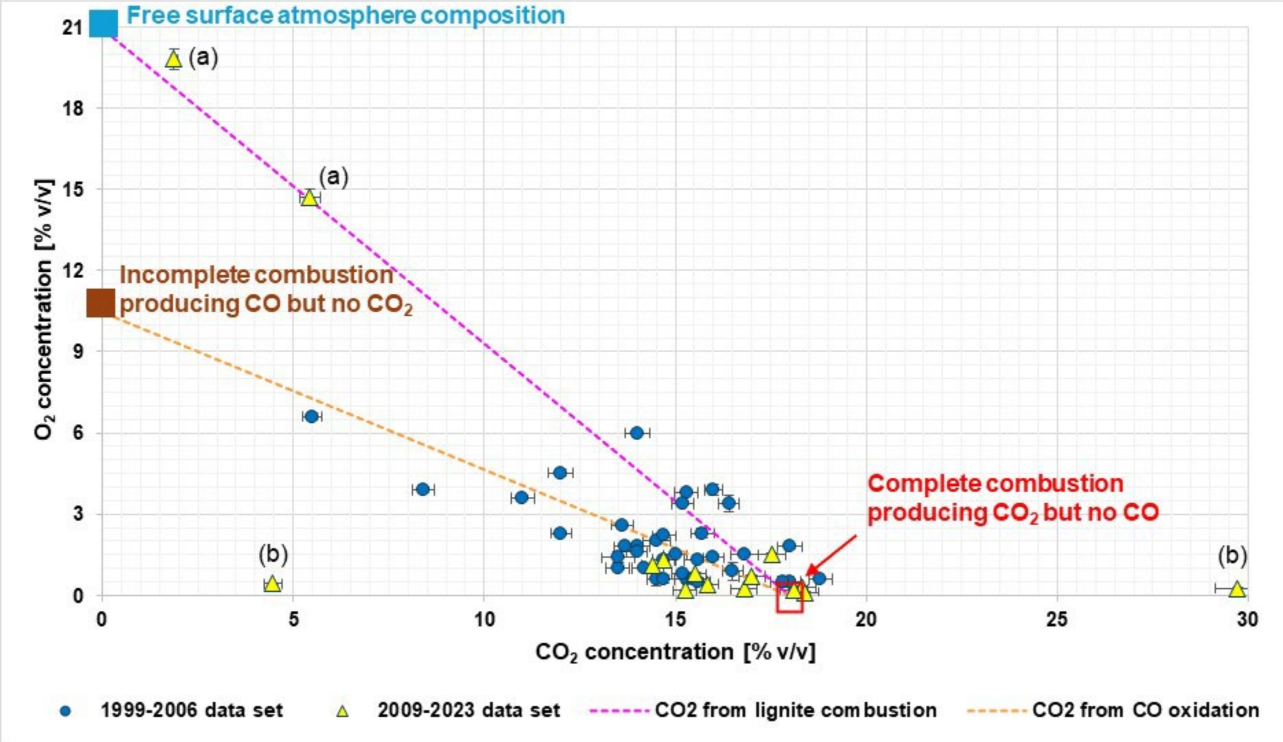


Figure 9 **O_2 concentrations versus CO_2 concentrations in fumes emitted at the gallery, measured by Ineris and BRGM between November 1999 and September 2023. Plot shows error bars and theoretical compositions of free surface atmosphere (blue square; O_2 = 20.9% v/v and CO_2 = 0.04% v/v), incomplete combustion (brown square; O_2 = 10.45% v/v and CO_2 = 0.04% v/v) and complete combustion (transparent red square; O_2 = 0% v/v and CO_2 = 18% v/v), considering a lignite with a volatile-matter content of 40% (Lassaux 1969). The purple dotted line highlights contamination of combustion fumes by atmospheric air. The orange dotted line highlights mixing of CO_2 origins (combustion or oxidation of CO): (a) Samples contaminated by surface air; (b) Outliers of undetermined origins**

Prior to the 2000 treatment, gas mixtures were rich in combustion and pyrolysis products, with negligible O_2 content; consistent with active oxidation of lignite. Following confinement of the emission point, concentrations of H_2, CO, saturated or unsaturated gaseous hydrocarbons decreased markedly (not shown), confirming the effectiveness of the treatment in limiting O_2 supply. However, O_2 was never fully eliminated from the emitted gases, and CO_2 concentrations remained high, indicating continued combustion. Recent analyses continue to show gas compositions dominated by CO_2 enrichment and O_2 depletion (see Figure 9), with occasional detection of combustion markers such as CH_4 or CO (see Figure 10).

These observations demonstrate that the underground heat source remains active but at reduced and stable intensity.

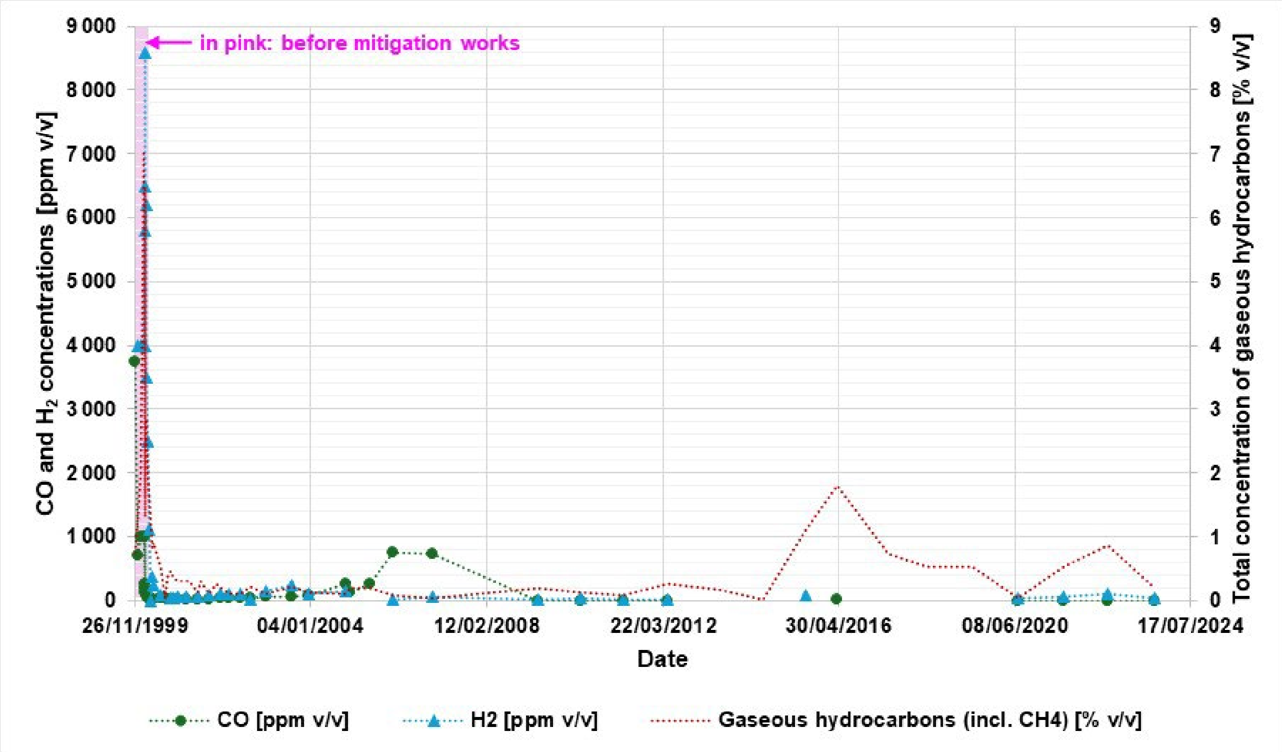


Figure 10 CO, H_2 and gaseous hydrocarbons (including CH_4) concentrations in fumes emitted at the gallery, measured by Ineris and BRGM between November 1999 and September 2023

6.3 Gas flow rates

Gas flow measurements conducted at the gallery pipes over the monitoring period were interpreted qualitatively, considering the disturbed nature of measurements and documented changes in outlet pipe geometry over time (not shown).

These measurements indicate a strong reduction in emission rates compared with pre-treatment conditions. Although measured flow rates are subject to uncertainty due to the transient nature of valve opening (the valves are normally kept closed) and system response time, the consistently low values confirm that the sealed structure continues to function effectively as a barrier to free gas migration.

Residual gas transport now occurs predominantly through diffuse pathways in the soil, resulting in limited and highly diluted surface emissions at secondary fumaroles.

7 Reassessment of the risks and of the monitoring strategy

7.1 Long-term effectiveness of confinement-based mitigation

The Bois d'Asson case study provides rare multidecadal evidence of the performance of confinement-based mitigation for residual underground combustion. The results demonstrate that sealing of a major fume outlet can significantly reduce combustion intensity and surface impacts, even when complete extinction is not achieved. The 2000 closure works remain effective in reducing surface emissions at the treated opening (gallery).

However, the persistence of stable combustion over more than 20 years highlights the intrinsic limitations of this approach when the heat source is deep, spatially constrained and fed by slow but continuous O_2 ingress through fractured or porous media. The continued O_2 supply sustains low-intensity combustion, illustrating a common limitation in poorly documented abandoned workings.

These findings are consistent with earlier predictions that extinction timescales following confinement may extend over several decades for lignite deposits with high volatile content and extensive historical workings.

7.2 Implications for post-closure risk management

From a mine closure perspective, the primary risks associated with the Bois d'Asson site relate to toxic gas exposure and, to a lesser extent, vegetation ignition. Current monitoring results indicate that these risks remain effectively controlled under present conditions, provided that the surface access restrictions and safety measures are maintained (see the immediate prevention measures listed in Section 4).

Nevertheless, the analysis also highlights the vulnerability of the system to potential reactivation scenarios. The formation of new air pathways (for example, due to subsidence, erosion or the degradation of unknown legacy structures) could increase O_2 supply and lead to renewed combustion intensification, even outside the currently monitored zone. Thus, the current monitoring system may not detect all potential reactivation scenarios.

This underscores the need for continued vigilance and for monitoring strategies capable not only of tracking known emission points but also of detecting deviations indicative of broader subsurface changes. In this context, the role of monitoring progressively shifts from tracking extinction to acting as a sentinel system, designed to detect significant deviations from an established stable regime rather than minor fluctuations.

7.3 Adaptation of monitoring thresholds

Fixed absolute temperature thresholds, while simple to implement, have proven increasingly sensitive to meteorological variability, particularly at the fumarole measurement point. Statistical analysis of recent data demonstrates that seasonal warming of soils can cause fumarole temperatures to approach intervention thresholds without any change in underground combustion behaviour. Therefore, and following the analysis done on temperature data, the reference threshold values applied at the Bois d'Asson site were adjusted to reflect the now-stabilised nature of the underground heating phenomenon.

The historical thresholds designed to detect an unfavourable evolution of the combustion process were largely retained (see Figure 6). However, the absolute threshold of 28°C previously applied to the fumarole temperature was abandoned as it no longer allowed reliable discrimination of abnormal behaviour under conditions of strong seasonal influence. It should be replaced by a differential criterion based on the temperature difference between the fumarole and the reference soil temperature measured at a depth of 0.5 m. Analysis of data acquired between 2017 and 2023 showed that this difference remains within a normal range of -2°C to +9°C, as shown in Figure 11, with an average value of approximately +3°C. Therefore, a new operational alert threshold is proposed to be set at +14°C (i.e. the upper bound of normal behaviour increased by 5°C), beyond which an unfavourable evolution of the heating is considered plausible and requires detailed assessment by a combustion expert. Implementation of this revised threshold represents a pragmatic and scientifically justified refinement of long-term post-closure monitoring practices.

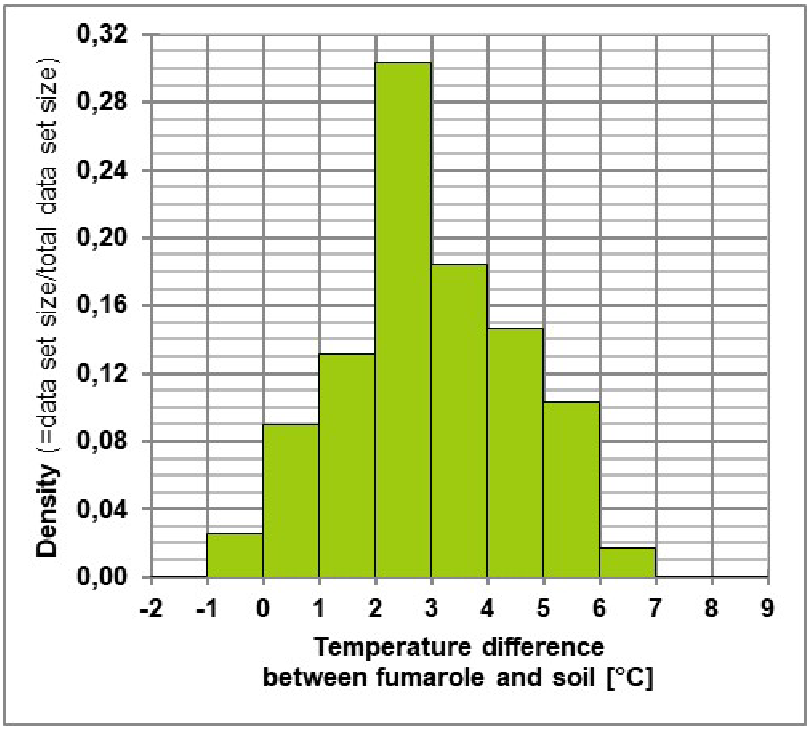


Figure 11 Histogram of differences between fumarole temperature and soil temperature acquired by BRGM between October 2017 and December 2023. Density values for extreme intervals: [-2°C; 1°C] = 3,65 × 10-5; [7°C; 8°C] = 2,06 × 10-4; [8°C; 9°C] = 3,65 × 10-5

This approach illustrates how monitoring thresholds originally developed for an evolving system must be revisited once the phenomenon reaches a stabilised regime to avoid weather-driven false alarms and maintain decision relevance.

7.4 Proportionate long-term strategy

Given the stabilised behaviour of the phenomenon and limited affected proximate parties, a reduction in the monitoring intensity is recommended. This includes validation of reduced acquisition frequency (time interval of 1 or 2 hours instead of 30 min) and, in the longer term, consideration of transitioning from continuous temperature monitoring to only periodic (annual) measurements, while maintaining the capacity to respond to new manifestations. Transition could take place at the end of the present equipment's service life. Thereafter, annual site visits will have to be maintained to check the condition of safety devices (fenced perimeter, effectiveness of the confinement, condition of the pipes and valves etc.) and to control the monitored parameters by means of manual measurements or sampling.

8 Conclusion

More than 25 years after its initial detection, the underground heating phenomenon at the former Bois d'Asson lignite mine remains active but has stabilised. The confinement measures implemented in 2000 have proven effective in minimising oxygen ingress and surface emissions, though not in fully extinguishing the underground heat source.

Comprehensive analysis of temperature and gas monitoring data confirms slow long-term cooling of the system after implementation of the confinement measures. The reassessment of the risks and of the continued relevance of the monitoring system highlights the importance of adapting monitoring thresholds and strategies as post-closure systems evolve.

The Bois d'Asson case offers valuable lessons for mine closure practitioners managing persistent low-intensity heating in abandoned coal mines. From a mine closure perspective, the Bois d'Asson case highlights the importance of periodically reassessing monitoring objectives, thresholds and acquisition frequency as post-closure hazards evolve. Long-term surveillance should remain technically robust while being proportionate to residual risks and site-specific stakes.

The lessons drawn from Bois d'Asson are directly applicable to other legacy coal sites where complete extinction of underground fires is impractical, and where long-term risk management must be integrated into mine closure planning.

Use of artificial intelligence disclosure statement

In the preparation of this work the authors used Microsoft 365 Copilot, based on the GPT-5 model, to facilitate the synthesis of all the work carried out and to improve English wording. The authors have reviewed the content and edited it where required, and take full responsibility for said content.

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