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How Does It Explode? Understanding Risk in European Mining Doctrine, 1803–1906

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Abstract

The historical risk and disaster scholarship has paid little attention to coal mining—an industry characterized by extreme risks and disasters—even though coal mine operators were concerned with the causes of explosions throughout the nineteenth and early twentieth centuries. This article goes beyond nationally oriented mining scholarship on coal mine safety and regulations to examine one particular form of industrial risk and analyze how European researchers understood the role of coal dust in mine explosions. It describes the complex factors involved in applying science and technology methodologies to solve industrial risk in this dangerous sector. It traces European countries shifting after 1882 to new types of mine experimentation sponsored by the state and mine owners to better mimic real-life situations, while French mining researchers continued to defend work in laboratory settings. They converged methodologically with their colleagues after the French Courrières mine catastrophe in 1906.

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On March 10, 1906, disaster struck at the Courrières colliery in Pas-de-Calais on the northern coast of France, at what was considered an extremely safe and productive mine. During the morning shift, surface workers heard a blast and saw flames shooting out of pit openings.

Below ground, an explosion coursed through several pits connected by many kilometers of galleries and shafts, killing eleven hundred miners. Much of the works was destroyed; the last bodies were only recovered eight months later. Within days, the catastrophe spurred some forty thousand miners to go on strike, soon spreading to include nearly all eighty thousand miners in the Nord–Pas-de-Calais region. To intimidate the strikers, on May Day the government surrounded Lens, the city nearest Courrières, with twenty thousand troops.[1] Investigators entered the mine to determine the cause of the disaster. Soon all parties accepted that the epicenter was a bord (underground space created to give miners access to coal seams) leased to the Lecoeuvre brothers.[2] Forensic engineers, however, could not immediately discern what had gone wrong in the heading (horizontal passage or roadway).

European scientists and engineers, closely studying the causes of coal mine explosions in the nineteenth century, drew different conclusions. Before 1882, researchers in France came to similar results about coal dust and the mine gas known as firedamp (*grisou* in French) to those in other European countries. Firedamp, primarily composed of methane, was considered a necessary component in both ignition and combustion—coal dust was thought to propagate the initial explosion. For nearly twenty-five years after 1882, however, mainstream French assessments dramatically dismissed the role of coal dust in explosions. Here the French perspective differed from a growing body of work in Britain, Belgium, Germany, and

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[1] Neville, "Courrières Colliery Disaster." Before the accident, Courrières produced well above the national average tons of coal per miner: Conus, "Une entreprise."

[2] Such subcontracting in mines was common. Zola, *Germinal*, describes the right to work a newly opened heading as leased by auction to the lowest bidder. On "butty gangs" in British mines: Jevons, *British Coal Trade*, 333.

Austria, where evidence supported the hypothesis: coal dust should be considered a major, not a secondary, concern. The hypothesis gained traction that coal dust, not only in combination with firedamp but also on its own, contributed to explosions of greater magnitude. Only after the Courrières explosion in 1906 did French investigators reconsider the danger of coal dust. The evolution of a scientific hypothesis rarely comes with such a clearly delineated timeline.

Our case shows how one particular event caused the divergence between French and other European coal producers' perceptions of coal dust, while another resolved that paradox, and we can precisely date both events. In 1882, France's *Annales des Mines* (Mining annals) published an article minimizing the role of coal dust in explosions.[3] The article persuaded most of the French mining community that coal dust was unimportant and marked a triumph for French researchers known as *antipoussièristes* (*poussière* = dust) for condemning the coal dust hypothesis. We can date the disappearance of *antipoussièrisme* to March 10, 1906.[4] Ultimately, forensic engineers proposed to reframe coal dust as the cause of the propagation and magnitude of the 1906 explosion. The shift in the French mining community's support for the coal dust hypothesis reunified European and transnational mining principles.

This article explains why research followed a certain path, even leading to conclusions that may have induced disaster. Many French scientists viewed technoscientific knowledge differently from the rest of the international scientific community. The shift occurred when research in other European coal-producing nations embraced new

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[3] F. Ernest Mallard and Henry L. Le Chatelier, "Du rôle des poussières de houille dans les accidents de mines," *Annales des Mines* 8, no. 1 (1882): 5–98.

[4] Neville, "Courrières Colliery Disaster;" Escudier, "Coup de poussières."

experimental installations, a hybrid of previous methods that had proved inadequate. The novel technology, allowing researchers to mimic real-life conditions more accurately, led to new conclusions. The story also unveils how the workings of authority downplayed criticism and built scientific consensus, also manifest in technical—in this case safety-oriented—procedures.[5] This study builds on the rich risk management scholarship that has somewhat overlooked coal mining—a hazardous industry that boosted nineteenth- and early twentieth-century economic growth in Europe and the United States.[6] It also builds on coal mine safety scholarship emphasizing national (government) safety regulations. It traces how scientists and engineers shifted to mine explosion research after pumping technology had solved water

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[5] A well-known example of abandoning established doctrine despite new evidence is Agassiz's rejection of Darwin: Lurie, "Louis Agassiz"; Winsor, "Louis Agassiz." On the slow acceptance of the germ theory: Richmond, "Some Variant Theories." On authority in science, perhaps more closely studied currently: Bijker, Bal, and Hendriks, *Paradox of Scientific Authority*; Shapin, "Way We Trust Now."

[6] On applying risk frameworks to historical issues: Fressoz, "Beck Back in the 19th Century"; Moses and Rosenhaft, "Moving Targets"; Crook and Esbester, *Governing Risks*; Itzen and Müller, "Risk as a Category of Analysis." There are many studies analyzing accidents: Figlio, "What Is an Accident?"; Cooter and Luckin, "Accidents in History"; Sellers and Melling, "Towards a Transnational Industrial-Hazard History"; Knowles, "Learning from Disaster?" On disasters in coal mining: Harvey, "Oaks Colliery Disaster"; Singleton, *Economic and Natural Disasters*, ch. 5. On the importance of coal mining: Mokyr, *Enlightened Economy*; Silvestre, "Productivity, Mortality, and Technology."

drainage issues.[7] The authors examine the affluence of creative technoscientific knowledge across major European coal-producing nations after 1803.

Toward a Shared European Hypothesis on Coal Dust's Role in Mine Explosions

Before 1882, European research on mine explosions ran along similar lines. It assumed that firedamp was the cause of mine explosions. Coal dust appeared in British studies in 1803, when an explosion at Wallsend, near Newcastle, killed thirteen miners. Surviving miners recalled being showered with "red-hot sparks of the ignited dust." Mining entrepreneur and colliery viewer (manager) John Buddle drew two conclusions: (1) contact between a pocket of firedamp ("bag of foulness") and an open-flame lamp ignited the explosion, and (2) coal dust propagated it.[8]

In 1844, an explosion at the Haswell collieries in Durham, northeast England, killed ninety-five miners. The British government asked scientific advisor Michael Faraday and geologist Charles Lyell to investigate. Because the mine "appears to have been most

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[7] British mining engineer and colliery manager Robert L. Galloway highlighted explosions in Galloway, "History of Coal Mining," 76. On coal mine safety: Bartrip and Burman, *Wounded Soldiers of Industry*; Leboutte, "Mortalité par accident"; Leboutte, *Vie et mort*; Fishback, *Soft Coal*; Aldrich, *Safety First*; Conus and Escudier, "Sécurité et transformations"; McIvor and Johnston, *Miners' Lung*; Mills, *Regulating Health and Safety*; Boal, "Work Intensity." On U.S. explosions research: Aldrich, "Preventing 'the Needless Peril.'"

[8] On the flammability of firedamp: Clayton, "Experiment Concerning the Spirit of Coals"; Davy, "On the Fire-Damp of Coal Mines"; Buddle, "On Making the Society," 331; Parliamentary Papers, *Accidents in Mines*, 30.

admirably ventilated," they eliminated ambient firedamp as the sole cause. They hypothesized that, as at Wallsend, the immediate cause was a dropped, broken safety lamp. The lamp's flame ignited a small quantity of firedamp. The resulting explosion stirred and set fire to coal dust from the floor, throwing "friable coked" crusts against timbers.[9] Faraday and Lyell concluded that firedamp had been necessary to trigger the explosion, and the coked crusts were evidence that coal dust had propagated the explosion. Yet the findings of these researchers—and others like John Buddle—were ignored in mine explosion research over the next few decades.[10] British researcher William Galloway, an experienced mine sub-inspector, first in Scotland and then Wales, wrote to the Royal Society of London in 1876 that British studies "hardly ever allude to the existence of coal-dust." He managed to insert a footnote to Faraday and Lyell's essay from three decades earlier, acknowledging that coal dust was a priority.[11] After years studying dust in explosions, Galloway became the most prominent advocate for his version of the "coal-dust hypothesis," that firedamp and coal dust interacted to make a more dangerous combination than either component alone.[12]

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[9] Faraday and Lyell, "Report to the Rt. Hon. Sir James Graham"; James and Ray, "Science in the Pits."

[10] Rice, *Explosibility of Coal Dust*, 12.

[11] Willam Galloway, "On the Influence of Coal-dust in Colliery Explosions," *Proceedings of the Royal Society of London* 24 (1875): 354–72, 354; Mills, *Regulating Health and Safety,* 184.

[12] William Galloway, "On the Influence of Coal-Dust in Colliery Explosions. No. V," *Proceedings of the Royal Society of London* 37 (1884): 42–46, 46.

To test the role of coal dust in explosions, Galloway first adapted a laboratory originally built to test the stability of flames in safety lamps subjected to air currents (figure 1). Constructed at a gassy Welsh mine, Llwynypia, an experimental chamber in his setup accessed a blower (a pressurized pocket of firedamp behind a coal wall) that provided actual firedamp for testing. Valves at either end of the apparatus controlled the airflow, and a hopper near the middle introduced coal dust. A window allowed observation. This was a step forward compared to the first forensic mine research, when investigators entered after an explosion and observed in situ: a scorched floor or coked crusts on timbers indicated burnt dust; burn marks on roofs likely came from gas flames, as firedamp was lighter than air and rose in passageways. However, observation alone could not determine causal relationships. This issue required several variables to be held constant: the temperature in the mine, the speed of air currents, the type of coal, the presence and qualities of dust (e.g., percentage of volatiles), the source of firedamp, and so on. Controlling these variables required a laboratory.[13] Galloway experimented with a variety of coal dusts and concluded ambivalently that "the mixture of air, firedamp, and coal-dust was found to be somewhat explosive."[14] He stated that coal dust had a ("somewhat") limited role. Firedamp remained a necessary component for flammability, but the exact density of that "small quantity" was unclear.

[Insert Figure 1 around here]

When investigating an accident that began with misfired (failed to detonate as planned) powder at a new gassy mine in Pontypridd, South Wales, Galloway suggested that a very small concentration of coal dust was enough to cause an explosion. On a Sunday when

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[13] Laboratory experiments by chemist Frazer, "Laboratory Investigations."

[14] Galloway, "On the Influence," 356.

the mine was closed, he persuaded the operator to bank the ventilating furnace and cover the top of the downcast shaft with canvas. Galloway reported, "although there was no accumulation of firedamp in any part of the workings, and no trace of it could be observed in the [moving] air, there could not be any doubt that a certain more or less constant quantity of it was being given off by the coal all along the course of the air-current." After adjusting for ordinary ventilation, he calculated that at the time of the accident the concentration of firedamp had been 0.5 to 0.75 percent. Galloway mused that coal dust might explode at concentrations of firedamp lower than anyone had suspected—perhaps even with no firedamp present at all.[15]

Gradually Galloway concluded that coal dust alone could produce catastrophic explosions. After a disaster at Penygraig colliery (1880), he proposed that only a coal dust explosion could explain the extent of damage throughout the dusty mine. However, Galloway's nascent theory still needed an ignition source. Evidence from Penygraig suggested a blown-out shot, whereby the explosive force of powder shot back into the gallery rather than forward into the coal face. The transmission through "pure air" (without firedamp) could occur owing to the combustion of coal dust. If a blown-out shot replaced burning firedamp as the source of ignition, and coal dust acted as means of transmission, Galloway concluded, "firedamp is altogether unnecessary."[16]

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[15] Galloway, "On Coal-Dust Explosions," 67.

[16] William Galloway, "On the Influence of Coal-Dust in Colliery Explosions. No. IV," *Proceedings of the Royal Society of London* 33 (1881): 437–45, 445; William Galloway, "On the Influence of Coal-Dust in Colliery Explosions. No. III," *Proceedings of the Royal Society of London* 33 (1881): 490–95; Galloway, *Course of Lectures on Mining,* 36.

Mine Inspectors Henry Hall and George Clark also initially hypothesized that a blown-out shot could ignite nearby coal dust. Their laboratory test gallery showed that without firedamp the presence of dust near a shot extended blast flames a greater distance and magnified their destructive power. However, the ambiguous effects of coal dust in experiments elsewhere in Britain led other researchers to believe that a small amount of firedamp must have been present in Hall and Clark's gallery.[17] In the mid-1870s, A. Freire-Marreco and D. P. Morison constructed a laboratory test chamber at Durham in the north of England to estimate the influence of air currents, dust types, and amount of powder on blasts that began with shots (figure 2). The air current only traveled about 25 feet, but the proportions of the chamber and direction of the airflow mimicked a typical room in a bord-and-pillar mine. They concluded that the location of the coal dust was a critical factor. If the dust was circulating in the air, shots easily ignited it. If the dust was only on the ground, many shots, even if quite close, failed to ignite it.[18]

Support for Galloway's coal dust hypothesis declined for a time. In September 1880, an explosion at Seaham Colliery, Durham, killed 164 miners. Frederick Abel, chemist and

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[17] Henry Hall and George Clark, "The Mechanical Effect of 'Blown-Out Shots' on Ventilation," *Transactions of the North of England Institute of Mining and Mechanical Engineers* 25 (1875–76): 239–48, 244; Rice, *Explosibility of Coal Dust*, 13.

[18] A. Freire-Marreco and D. P. Morison, "An Account of Some Recent Experiments with Coal Dust," *Transactions of the North of England Institute of Mining and Mechanical Engineers* 28 (1878–79): 85–104. In a bord-and-pillar (or room-and-pillar) mine, miners worked in the middle of the vein (the room), leaving large blocks of coal as pillars to hold up the roof.

authority on explosives, tested coal dust from this mine for explosiveness and found only marginal effects. He was broadly skeptical of the risk that coal dust presented. After all, he noted, "if coal dust alone would have exploded, every colliery would have been wrecked long ago."[19] Galloway realized that "a very large majority" of mine engineers believed firedamp caused every catastrophic explosion.[20] One U.S. engineer criticized Galloway's emphasis on coal dust: "How many practical mining engineers could be gotten to indorse [*sic*] this theory? I think very few."[21] Galloway defended his hypothesis so vigorously that some engineers found him a gadfly—"an enthusiast, if not a crank"—for claiming that coal dust alone could cause a catastrophic explosion.[22]

Until then, British mining researchers had found the effects of coal dust in explosions uncertain or implausible. Gradually, however, support for the coal dust hypothesis gained momentum. Several royal commissions reported between 1886 and 1894 that post hoc investigations provided "substantial support" for the notion that coal dust had played an important role in some accidents. In addition, experiments in Britain ("absolutely") and Germany ("still more completely") refuted most extreme antipoussièrisme, to which, the

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[19] Rice, *Explosibility of Coal Dust*, 13; Atkinson and Atkinson, *Explosions in Coal Mines*, 138.

[20] William Galloway, "On the Influence of Coal-Dust in Colliery Explosions. No. V." *Proceedings of the Royal Society of London* 37 (1884): 42–46, 44.

[21] McNeil, "Colliery Explosions," 4. These may have been typical of American mine engineers' opinions. Skepticism about coal dust explosibility persisted there well into the twentieth century. Aldrich, "Preventing 'the Needless Peril,'" 498.

[22] Buck, "Coal Dust and Mine Explosions," 179.

commission concluded, “no importance can be attached.”[23] An 1891 Royal Commission determined that “experiments conclusively prove that blasting with gunpowder in dry and dusty mines may cause serious disasters *in the entire absence of firedamp*.”[24] The 1894 report did not, however, fully endorse the coal dust hypothesis. The rare convergence of sufficient dust and absence of firedamp suggested skepticism about the extent of the problem. The commission conservativgiely proposed that in day-to-day mining the conditions leading to a coal dust explosion “must be exceptional, and are only likely to be produced on rare occasions.”[25]

Galloway continued to examine mine disasters with an eye to his coal dust hypothesis. At Altofts in Yorkshire, workers had carried open flames for twenty years without incidents. In February 1886, the last of three successive gunpowder shots, none of which blew out, caused an enormous explosion, killing twenty-two miners. Because the flames stopped just where the irrigation of dusty in-mine roads began, Galloway proposed that dry coal dust had fueled the explosion.[26] Galloway slowly gained more recognition. By 1890, Frederick Abel

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[23] Parliamentary Papers, *Accidents in Mines*, 46.

[24] Rice, *Explosibility of Coal Dust*, 18; quoting First Report of the Royal Commission on Explosions from Coal-dust in Mines, 1891, 153; emphasis in the original.

[25] Rice, *Explosibility of Coal Dust*, 19; quoting Second Report of the Royal Commission on Explosions from Coal-dust in Mines, 1894, 24.

[26] William Galloway, “A Coal-Dust Explosion,” *Proceedings of the Royal Society of London* 42 (1887): 174–76.

(now Sir Frederick), ten years earlier a skeptic, now agreed with Galloway on "the serious danger arising from the existence of dust-accumulations in galleries."[27]

Concerns about dust grew as mining conditions and technology evolved. Mining methods across Europe were similar—taking into account differences in geological conditions such as seam depth, thickness, and inclination. Over time, deeper mine shafts led to the replacement of bord-and-pillar mining with the generally safer longwall mining, first in Britain and then spreading across Europe after the 1880s.[28] However, deeper mines were often gassier. Highly respected French state engineer Jacques Taffanel—later in charge of the Liévin experimental station (introduced below)—summarized that the very same methods to control firedamp, such as improved ventilation, had unforeseen consequences, as did roadways carrying tubs on rails and coal-cutting machines. These innovations produced clouds of dust that settled throughout dry mines, thus raising the probability of an explosion.[29]

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[27] Abel, *Mining Accidents*, 211.

[28] Lupton, *Elementary Treatise*, 168–76; Murray and Silvestre, "Small-Scale Technologies," 892; Aldrich, "Preventing 'the Needless Peril,'" 488. In longwall mining, miners working on a long face removed the stone, slate, or other scrap materials packed afterward to form the "gob" or "goaf" that held up the roof.

[29] Jacques Taffanel, "French Coal-Dust Experiments," *Proceedings of the South Wales Institute of Engineers* 26, no. 2 (1908–9): 775–809, 776. Also Harger, *Prevention of Explosions and Fires*, 97–100; McTrusty, *Mine Gases and Gas Testing*, 96–99. Electrical sparks could produce explosions, but the electrification of European coal mines really materialized in the twentieth century. Milward and Saul, *Economic Development*, 187;

Support for the coal dust hypothesis gathered elsewhere in Europe. Like in Britain, coal-producing countries appointed commissions to study explosions. A remarkable research feature emerged in the late 1800s: a hybrid of the two previous mine inspection and laboratory observation approaches, the experimental mine. In the most developed version, a mine owners' association or the state supplied an entire gallery to researchers for testing. One consequence of these new test mines was a reduction in false negatives. Earlier experiments had failed to obtain a greater number of coal dust explosions because a laboratory could not mimic a mine environment regarding the type of dust and its location, as well as the weight of the explosive charge. Furthermore, in relation to the waves caused by explosions, test sensitivity also depended on scale, as well as the distribution of roadways and crossroads.[30] Thus, experimental mines resembled more closely the causes and effects of coal dust explosions and the conditions miners faced.

Between 1889 and 1891, Austrian firedamp commission experiments at the Segen Gottes and Polnisch-Ostrau pits in Moravia tested different types of coal dust from dozens of mines, with various ignition sources and firedamp concentrations. Austrian experimental mines could test quantities of explosives that would have destroyed older experimental

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Wautelet, "Accumulation et Rentabilité du Capital," 281; Lamb, "Coal Mining in France," 161; Greasley, "Diffusion of Machine Cutting"; Hickey, *Workers in Imperial Germany*, 112.

[30] Galloway, "Question of Priority"; Galloway, "Some Phases," 570; Harger, *Prevention of Explosions and Fires*, 78; George S. Rice, "Investigations of Coal-Dust Explosions," *Transactions of the American Institute of Mining Engineers* 50 (1914): 552–85, 553–56; Greenwald, *What Do We Know*. On how closely a test resembles practice: Collins and Pinch, *Golem at Large*, 38.

chambers. These tests implicated coal dust as flammable during any type of firing activity. The usual procedure was to fire a charge, large enough to cause ignition, and then reduce this gradually. A large amount, 300 grams, ignited every type of dust. Even a small amount, such as 100 grams of new safety explosive (such as dynamite), ignited most dusts. Those that proved difficult to ignite in pure air could cause a disastrous explosion if a small amount of firedamp was present. This combination, the commission wrote, was not uncommon and potentially catastrophic.[31]

In 1884, Prussia's firedamp commission issued a preliminary report. In an experimental gallery, the length of flames in a test blast increased as researchers ran additional coal dust along the floor. German engineers interpreted these figures to show a positive and direct relationship (figure 3). The blast flame would travel the length of the dust, no matter how far. The Prussian final report in 1887 again implicated coal dust as a risk factor. At Neunkirchen, Saarland, German engineers Hilt and Margraf built an experimental gallery that combined the conditions in an active mine with the control of the air current and coal dust (figure 4*A*). Researchers drew firedamp from naturally occurring blowers. Hilt and Margraf tested dust with and without firedamp from all the major German coal fields in Silesia, Schaumburg, the Ruhr valley, Aachen, and Saarland. The König mine proved critical

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[31] W. N. Atkinson, "The Report of the Austrian Fire-damp Commission," *Transactions of the Federated Institution of Mining Engineers* 3 (1891–92): 531–50; René Grey, "Résumé des conclusions du rapport final de la commission autrichienne du grisou," *Bulletin de la Société de l'Industrie Minérale* 3, no. 5 (1891): 663–709; G. Chesneau, "Note sur les résultats des travaux de la commission autrichienne du grisou," *Annales des Mines* 9, no. 1 (1892): 239–64.

in persuading observers that experimental mines were superior to earlier detonation chambers in testing explosions; the methods applied there became one of the models to emulate.[32] (The French emulated them only later [figure 4B].)

In Belgium, researchers worked on an initial experimental pit at Seraing (1882), established by the commission to revise safety regulations, and then at Frameries (1902), promoted by the inspector general of mines, Victor Watteyne. The earliest experiments resembled those by Galloway and Abel. Expecting that they could identify flammable concentrations of firedamp as low as 0.1 percent of mine air, engineers carefully measured air current speed with a custom-built anemometer. Their results showed a continuum of dust flammability, with sufficient danger from most dusts to support *poussièrisme*. Indeed, engineers Victor Watteyne and Adolphe Demeure concluded in 1890 that the danger of dust was as least as great as from firedamp, and preventive measures against both deserved equal attention.[33] Notably, Belgian work complemented Austrian and British research on testing

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[32] Hasslacher, *Haupt-Bericht*. The report on coal dust is in vol. 1, pt. 1, sec. 6, 114–28, and results are in vol. 4, pt. 1 of the appendix. Rice, "Investigations of Coal-Dust Explosions," 554; Marshall, *Explosives*, 34; Escudier, "Coup de poussières," 34.

[33] "Expériences sur l'Inflammabilité des poussières de charbon," *Annales des travaux publics de Belgique* 47 (1890): 265–78; Victor Watteyne and Adolphe Demeure, "Notice sur les moyens employés pour combattre le danger des poussières charbonneuses dans les mines," *Annales des travaux publics de Belgique* 47 (1890): 565–627.

explosives in the presence of firedamp and coal dust by better determining the maximum charge (*charge limite*) that can be fired without causing ignition.[34]

The evidence collected by the national commissions helped to delineate revisions of existing safety regulations regarding explosion risks. These revisions included provisions for coal dust, first recognized in Britain as a cause of explosions in the 1887 Coal Mines Regulation Act. In addition to common classifications of gassy and non-gassy mines and the correct use of safety lamps, new regulations referred to recent ventilation methods, safety explosives and their maintenance, and blasting.[35] People objected to the term "safety explosive," since an explosive cannot always be safe. However, under certain precautions and having been officially tested, listed safety explosives proved to be safer than, for example, gunpowder or even dynamite.[36]

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[34] Watteyne, *Office of Accidents in Mines*. On British research: the 1894 Royal Commission's long quote in Rice, *Explosibility of Coal Dust*, 18; Galloway, "Coal-Dust Explosion," 176. On Austrian research: Atkinson, "Austrian Fire-damp Commission"; Grey, "Résumé des conclusions"; Chesneau, "Note sur les résultats."

[35] Wright, *Coal Mine Labor*, 100, 103–8, 176–78, 374, 380–88, 522, 527–29, includes summaries of the British act of 1887, Austrian decrees of 1876 and 1879 and an 1895 ordinance, the 1865 Prussian mining code and supplemental act of 1892, and Belgian 1884 and 1895 regulations. On Belgian legislation dates: Delattre, *Lutte contre le grisou*, 111, 169; Leboutte, "Mortalité par accident." Also McQuaid, "Safety's Debt," 125.

[36] Atkinson, "Austrian Fire-damp Commission," 540; Rice, *Explosibility of Coal Dust*, 16; Rice, "Investigations of Coal-Dust Explosions," 555; Marshall, *Explosives*, 451; Leboutte, "Mortalité par accident," 709, 723.

French Coal Dust Consensus prior to 1882

Before 1882, French research found potential causal roles for both firedamp and coal dust.[37] The first French investigator to report coked crusts was Charles du Souich, chief engineer in the Saint-Étienne district. His report on an 1855 explosion at Firminy described "a crust made of light coke, gathered in mounds." He concluded that the crust was burnt coal dust "carried off by the extreme violence of the explosion." Du Souich again found crusts during post-explosion observations at Treuil (1861) and Villars (1867).[38]

Coked crusts on timbering suggested to self-taught engineer and inventor Claude Verpilleux, after reviewing evidence from the Villars accident, that coal dust propagated explosions. He also argued that "strong explosions are almost always caused by dust burning." Foreshadowing the official Courrières disaster report, Verpilleux compared an explosion in a mine gallery to a shot fired through a gun barrel: firedamp acts as the primer, and the coal dust acts as the powder.[39] Verpilleux played an important role in moving research into the laboratory. Although Galloway may have gained credit as one of the first to study mine explosions in a controlled setting, a decade earlier Verpilleux had already made a

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[37] Faraday and Lyell's article was translated and summarized in *Bibliothèque Universelle de Genève* 55, February 1845, 321, so its findings were soon available in French.

[38] Daniel, *Explosifs Industriels*, 221; Abel, "Dangerous Properties of Dusts," 199.

[39] C. Verpilleux, "Note adressée aux exploitants de mines de houille ou il se dégage du grisou," *Annales des Mines* 6, no. 12 (1867): 561–65.

model to study explosive forces. After experiments at Saint-Étienne, Verpilleux concluded that coal dust was a critical element in explosions.[40]

French engineer and Corp des Mines member Pierre Vital examined an 1874 accident at Campagnac in Aveyron. This explosion occurred in a part of the mine where, Vital reported, "workers had never found a trace of firedamp." A blown-out shot ignited a blast that traveled 150 meters from the charge, again covering timbers in coked crusts. In hospital interviews, surviving miners reported seeing red flames of dust, not the blue flame of firedamp. To further investigate the potential role of coal dust, Vital tested the flammability of dust samples from the worksite in a device he had designed (figure 5). He dismissed any role for firedamp, instead blaming "the exclusive influence of instantaneous combustion of coal dust, under the impact of a blown-out shot (*coup de feu*)." He boldly concluded that, even in the absence of firedamp, coal dust could explode with catastrophic effects. The combination of dust and firedamp, Vital proposed, was even more dangerous. It increased both the probability of an explosion and the destructive power of an explosion once initiated.[41]

The *Société de l'Industrie Minérale*, founded in 1855 and associated with the mining college at Saint-Étienne, commissioned a series of experiments on coal dust in 1872, using an ordinary instrument for testing safety lamps. Coal dust was thrown into the blades of a fan placed at the end of a wooden pipe. Ignition occurred using a steadily reduced amount of

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[40] C. Verpilleux, "Verpilleux, C. to Combes, 25 December 1867," *Annales des Mines* 6, no. 12 (1867): 565–66; Lupton, *Elementary Treatise*, 260.

[41] Pierre Vital, "Recherches sur l'inflammabilité des poussières de charbon," *Annales des Mines* 7, no. 7 (1875): 180–98, 197; Abel, "Dangerous Properties of Dusts," 199.

powder. The experiments were replicated in 1875, now using a purpose-built artificial gallery made of a wooden triangle with 1.50-meter sides, supported against a wall and the ground. A movable panel in the middle enabled different sizes of galleries; dust was placed in the galleries or thrown into the fan blades. The *Société* remained unconvinced about coal dust, describing its results as inconclusive.[42]

By the time of the 1882 article, many researchers had produced substantial evidence indicating special caution with coal dust in gassy mines. An 1875 *Annales des Mines* article argued that coal dust could explode in pure air.[43] Other experiments failed to confirm that dust was potentially dangerous in pure air. Research in Britain and France similarly concluded that the risk of coal dust interacting with firedamp was acute, but the risk of dust alone remained ambiguous.

French Mine Engineering on Coal Dust Diverge after "Du rôle" (1882)

The man who led French antipoussièrisme was Henry Louis Le Chatelier, a chemist who specialized in many fields and trained at the Êcole Polytechnique and the École des Mines in Paris—where he also taught. In 1878, Le Chatelier was appointed to the national firedamp commission, *Commission du grisou*, established the year before to study effective methods of

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[42] Desbief and Chansselle, "De l'influence des poussières charbonneuses dans les explosions de grisou," *Bulletin de la Société de l'Industrie Minérale* 2, no. 4 (1875): 205–28; Mallard and Le Chatelier, "Du rôle," 46.

[43] "Note sur les dangers que paraît présenter la poussière de houille dans les mines, même en l'absence de grisou," *Annales des Mines* 7, no. 7 (1875): 176–79.

explosion prevention.[44] The commission included mineralogist Ernest Mallard, Le Chatelier's senior colleague at École des Mines.

Between 1877 and 1882, one of the reports published on behalf of the *Commission du grisou* was Mallard and Le Chatelier's article of 1882. It summarized five years of investigations into mine explosions. The authors considered three sorts of evidence: thirty-nine published reports of French and British accidents attributed to coal dust, nine published reports of experiments in laboratories, and their own laboratory work. They concluded without reserve, "No accident of any importance can be attributed to coal dust in any plausible manner."[45]

Mallard and Le Chatelier dismissed abundant evidence implicating coal dust as the cause of explosions. Half of their case studies cited coked crusts on timbering. In many cases, no firedamp had been detected near the explosion site for days or weeks beforehand—in some cases, never. Several accident sites reported no sign of firedamp before the explosion or coked crusts afterward. The evidence in the source documents shows that researchers suggested that coal dust was the cause. Mallard and Le Chatelier rejected this implication. In their opinion, previous investigators let the trivial factor of remaining evidence (coal dust) mislead them and ignored the critical factor wholly consumed in the explosion (firedamp).[46]

To win the poussièrisme debate, Mallard and Le Chatelier staked everything on the difficulty of detecting small concentrations of firedamp. Safety lamps enabled the detection

[44] G. Chesneau, "Note sur les travaux de la Commission du Grisou de 1887 à 1900," *Annales des Mines* 9, no. 17 (1900): 621–59, 621; Letté, *Henry Le Chatelier*.

[45] Mallard and Le Chatelier, "Du rôle," 36.

[46] Mallard and Le Chatelier, "Du rôle," 37.

of firedamp because it made flames blue and elongated, but the lamps could not detect firedamp at less than 2 percent concentration in the air. The inability to detect lower concentrations was not a widespread concern, as air carrying no coal dust required a minimum of 3 percent firedamp to ignite. In the absence of coal dust, the 2 percent criterion sufficed for safety.[47] In Mallard and Le Chatelier's framework, safety lamps' inability to detect less than 2 percent firedamp could account for any observational anomaly. Explosions, they argued, were caused by firedamp that was dense enough to explode in an atmosphere with coal dust but too diffuse to test positive with a safety lamp. With this logic, any explosion could be blamed on firedamp, but its absence could never be established with certainty. As there was no explanation for coal dust's role, Mallard and Le Chatelier opposed Du Souich's, Galloway's, and Vital's interpretations of explosions.[48]

One way to make lamps more sensitive was new fuel. In 1881, Mallard and Le Chatelier had recognized the hydrogen lamp's potential for firedamp detection, but they dismissed its practicality, predicting that hydrogen lamps would exhaust their fuel long before the end of a workday.[49] However, "hybrid" oil-hydrogen lamps turned out to be

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[47] Abel, *Mining Accidents*, 21; McQuaid, "Safety's Debt."

[48] Mallard and Le Chatelier, "Du rôle," 6, 10–12, 15; Louis Aguillon, "Note sur les explosions survenues dans les houillères de Seaham et de Penygraig." *Annales des Mines* 7, no. 20 (1881): 209–47, 242. Mallard and Le Chatelier's source for their 1882 essay was Aguillon's article, not Galloway's report. Daniel, *Explosifs Industriels*, 221, citing Le Chatelier, *Le Grisou*, 71.

[49] Ernest Mallard and Henry L. Le Chatelier, "Sur les procédés propres à déceler la présence du grisou dans l'atmosphère des mines," *Annales des Mines* 7, no. 19 (1881): 186–211, 205.

eminently feasible. In 1893, according to inventor Frank Clowes, when burning hydrogen, his new lamp could detect firedamp at proportions as low as 0.2 percent (figure 6). In practice, the reduction in detectable levels of gas enabled researchers to test the explosibility of coal dust with almost no firedamp present.[50]

In several cases in their article, Mallard and Le Chatelier accepted that other factors implicated coal dust: a historical absence of gas, ample amounts of dust, negative firefighter reports, and a blown-out shot as ignition source. But in every case, the crux of their argument was that the current technology could not exclude the possibility of firedamp, leading them to conclude that firedamp was the causal factor.[51]

Their own experiments determined that "coal dust, at least when it is isolated, is not very dangerous" and was by far a secondary concern, as the primary danger was firedamp. They experimented with two devices, allegedly similar to those used by British researchers. To test the explosibility of coal dust, Mallard and Le Chatelier analyzed the impact of the flame's length, the speed of the airflow, the size of the dust, the type of coal, the relative proportion of dust and air, and the flame propagation speed. The results contradicted many of the Prussian commissions' findings about the major risk of coal dust. Consequently, Mallard and Le Chatelier championed antipoussièrisme in the European mining press, defending their own claims and attacking *poussièristes*. For example, they reinterpreted the Prussian national firedamp commission's findings, as shown in figure 3, and these confirmed their own antipoussièrisme. They suggested that the German results indicated diminishing returns,

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[50] Clowes, "On the Detection and Estimation," 311. On improved technologies to measure combustion under turbulence in the 1940s: Gökalp, "Turbulent Reactions."

[51] Mallard and Le Chatelier, "Du rôle," 10–17.

whereby an asymptotic maximum flame length of just over 58 meters was the limit of danger from a shot that ignited coal dust.[52]

However, the claim that the Prussian commission actually confirmed Mallard and Le Chatelier's earlier theories convinced few European mining scientists. Compared to German experiments, the conditions for Mallard and Le Chatelier's experiments came under criticism in the 1886 British Royal Commission report: they represented "some slight approaches to actual practice, do not even compare favourably with those of Galloway, Abel, and others whose results they were designed to combat, in substantiation of adverse criticisms."[53]

Mallard and Le Chatalier's antipoussièriste hypothesis was also based on an inadequate coal dust research strategy for explosives. A new French commission founded in 1887 aimed to study the use of explosives in gassy mines. Here, Mallard and Le Chatelier's work on detonation temperatures in gassy atmospheres led to a new generation of safety explosives based on ammonium nitrate.[54] However, research in other countries (discussed

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[52] F. Ernest Mallard and Henry L. Le Chatelier, "Sur les travaux de la Commission Prussienne du Grisou," *Annales des Mines* 8, no. 9 (1886): 638–64, 645. Also Commission des Substances Explosives, "Emploi des explosifs," 367, describing coal dust tests apparently designed, *pro forma*, to verify Mallard and Le Chatelier's criticism of the Prussian Firedamp Commission methods. The authors thank Patrice Bret for this observation. Mallard and Le Chatelier describe their experiments in "Du rôle," 56–65, 95–97.

[53] Parliamentary Papers, *Accidents in Mines*, 39–48, 46; Galloway, "On the Influence. No. III," 490; Abel, *Mining Accidents*, 64.

[54] Commission des Substances Explosives, "Emploi des explosifs." Also Guttmann, *Manufacture of Explosives*, 232.

above), particularly at experimental mines, suggested that the focus on detonation temperatures missed the point that the size of the charge was a key factor in explosions at both gassy and non-gassy mines (see below).

The Impact of Antipoussiérisme

Mallard and Le Chatelier's 1882 article had a huge impact. Belgian engineers Watteyne and Demeure divided the history of coal dust research into two periods: before and after this article.[55] Anglophone engineers traced misleading French safety claims back to the *Annales* article. Harvard professor of mining engineering Henry Lloyd Smyth wrote, "Since the famous report of Mallard and Le Chatelier in 1882, French engineers have been disposed to doubt whether the inflammation of coal dust alone, without firedamp, was capable of propagating a severe and far-reaching explosion."[56] Mallard and Le Chatelier's antipoussièrisme had set French mining research and policy on a different path from the rest of Europe.

The general acceptance of antipoussièrisme in France from 1882 onward may be due to the centralized nature of the national research structure and administrative zeal. At the top of the hierarchy was the firedamp commission, a common type of French joint research at the time. *Commission du grisou* included scientific notables from Parisian scholarly circles such as professors of the École des Mines—the "school of application" founded in 1873 and main center for mining research, teaching and supplying state mining inspectors—and sitting

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[55] Watteyne and Demeure, "Danger des poussières," 573.

[56] Henry Lloyd Smyth, "Notes on the Practice in Mining," *Mineral Industry* 17 (1908): 879–83, 879; Rice, *Explosibility of Coal Dust*, 12.

members of the Academy of Sciences.[57] The commission issued deliberations and reports that the French mining community followed closely.[58] Despite several members' lack of mining experience, the commission set regulations for coal mines. The considerable influence of the 1882 article was probably thanks to the fact that one of its authors—Mallard—was a member of the firedamp commission, rather than Le Chatelier's personal reputation, as formidable as that later became.[59]

French engineers were mostly antipoussièrisme followers. A key example was Louis Aguillon, who, on behalf of the *Commission du grisou*, had inspected firedamp management systems in British, Belgian, and Prussian mines.[60] The École des Mines taught the superfluity of coal dust, and Julien Haton de la Goupillière's mining text minimized the importance of coal dust explosions.[61] The author of a text in 1893 reported his surprise at explosions in controlled tests with coal dust but not firedamp.[62] Mallard and Le Chatelier used all their persuasive powers to gain support for their theory from the entire French mining

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[57] On relations between École des Mines and the Academy of Sciences: Artz, *Development of Technical Education*, 245; Crosland, *Science under Control*, 402.

[58] Crosland, *Science under Control*, 402; Bret, *L'Etat, l'armée, la science*, 371, 390; Reid, "Industrial Paternalism." Also Varaschin, "Risques au travail," 119; Caron, *Dynamics of Innovation*, 79.

[59] Letté, *Henry Le Chatelier*, 36–49; Escudier, "Ingénieurs du corps des Mines."

[60] Pernolet and Aguillon, *Exploitation et Réglementation des Mines*.

[61] Escudier, "Coup de poussières," 41; Haton de la Goupillière, *Cours d'exploitation des mines*. On de la Goupillère's text: Parker, *Europe, America, and the Wider World*, 65.

[62] Dorion, *Exploitation des mines*, 269.

community.[63] The 1870s *Annales des Mines* had published about the same number of articles on firedamp as on coal dust. But the 1880s were the decade of Mallard and Le Chatelier's most active time in the firedamp commission, and the contents of *Annales des Mines* reflected this leadership. From 1882 to 1901, *Annales* published thirty-eight articles on firedamp compared to four on coal dust. The number of British articles in translation declined sharply, and those by Mallard and Le Chatelier rose. In contrast, *Colliery Guardian* (Britain) and *Colliery Engineer* (United States) published twenty-one and twenty-five articles, respectively, on coal dust from 1881 to 1901.[64]

There was no consensus, though, and a few poussièristes persisted within the French mining establishment. However, some distinguished early poussièristes died before they could press mine regulators to act on their findings: Verpilleux in 1875 and Du Souich in 1888 (also Édouard Estaunié in 1862). Edmond Lorieux, secretary of the General Council of Mines (1879–88)—in charge of Corp des Mines—supported the coal dust thesis but did not propose any concrete measures; in 1894, main evening newspaper *Le Temps* echoed the coal

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[63] Daniel, *Explosifs Industriels*, 223; Galloway, "Some Phases"; S. Dardalhon, "Le grisou et les poussières au XIXe siècle dans les mines françaises," *Annales des Mines* 168, no. 10 (1962): 652–66 ; S. Dardalhon, "Le grisou et les poussières au XIXe siècle dans les mines françaises (Suite et fin)," *Annales des Mines* 168, no. 11 (1962): 721–44, 739; Rice, *Explosibility of Coal Dust*, 105; Farrenkopf, *Schlagwetter und Kohlenstaub*, 81.

[64] *Table alphabétique et analytique des matières des Annales des Mines* 1872–81, 1882–91, 1892–1901. Articles in Anglophone journals from Rice, *Explosibility of Coal Dust*, 168–82. On the extensive coverage of coal dust in British mining: McTrusty, *Mine Gases and Gas Testing*, 94.

dust debate and called for the type of experiments conducted in other countries, but to no avail.[65] École des Mines engineer Félix Colomer's later popular mining book (which ran to three editions) eventually recognized the coal dust hypothesis.[66] In practical terms, the advocacy of poussièrisme proved impotent, and the antipoussièrisme claim would remain the predominant French view into the twentieth century.

On this topic, an accident in 1890 at La Machine, near Decize in the French region Bourgogne, drew special attention.[67] At this non-gassy mine, two near-simultaneous blown-out shots killed forty-four miners and destroyed many galleries. Some miners were fatally burned 150 meters from the shot site. The works were abandoned, leading to a severe reduction in production; the accident also transformed working methods.[68] Investigating engineer Laurent Le Meur asserted directly that the cause of the explosion was coal dust, rejecting the possibility of the presence of even a small amount of firedamp. Once more eager to respond in print, Le Chatelier claimed, "Authentic accidents due exclusively to coal dust are very rare; dust never causes explosions by itself."[69]

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[65] Escudier, "Coup de poussières," 36; Varaschin, "Risques au travail," 118.

[66] Colomer, *Exploitation des mines*, 236.

[67] It stood out among other dust explosions with fewer casualties at Noeux (1893), Dourges (1895), and Aniche (1898).

[68] Sougy, *Charbons de la Nièvre*, 257.

[69] Laurent Le Meur, "Sur l'accident de La Machine (Nievre)," *Annales des Mines* 8, no. 19 (1891): 396–430; Henry Louis Le Chatelier, "Le grisou et ses accidents," *Revue Génerale des Sciences Pures & Appliquees* 1, no. 1 (1890): 630–35, 633; Passaqui, "Catastrophe du puits Marguerite."

A further explanation of Le Chatelier's widespread antipoussièrisme, thus endorsing firedamp as the main or single factor in causing explosions, may be that he was not only a chemist but at the same time a regulator, inventor, and businessman. Official antipoussièrisme led to discoveries and innovations in the prevention of firedamp explosions that would probably not have emerged without a thorough commitment to the doctrine. Between 1882 and 1906, French mining researchers studied nearly every possible risk from grisou. Mallard and Le Chatelier nearly discovered wave emission in the process of gas detonation.[70] Following their work on detonation temperatures and testing new safety explosives, state regulations in 1890—in line with the 1887 commission's doctrine on temperature limit as the most important characteristic of a permissive explosive—made it mandatory to use mixtures of high (fast-detonating), ammonium-nitrate-based explosives in gassy mines. The choice of other high explosives was left to operators, and low (slow-detonating) explosives and gunpowder were restricted or prohibited.[71] However, the 1887 Commission des Substances Explosives' focus on detonation temperatures instead of a charge limit was proved wrong, as ammonium-nitrate-based explosives could ignite coal dust

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[70] On related work by physicist Louis Crussard: Maurice Roy, "Sur la contribution de Louis Crussard à la théorie de la propagation des combustions et à ses applications," LAdM; Georges Schneider, "Louis Crussard et les problèmes de sécurité minière (grisou, poussières)," LAdM.

[71] Chesneau, "Note sur les travaux," 632–34; Guttmann, *Manufacture of Explosives*, 233; Davis, *Chemistry of Powder and Explosives*, 348; Escudier, "Ingénieurs du corps des Mines," 57; Bret, *L'Etat, l'armée, la science*, 389.

at low charges. Besides, the detonation temperature of ammonium-nitrate-based explosives proved to be closer to the limit than previously thought.[72]

Together with Mallard, and after Mallard's death in 1894, Le Chatelier introduced modified safety lamps and a gas detection device, or *grisoumeter*, that had become mandatory in 1893. Both reduced the risk of accidental ignition of firedamp. For example, Mallard and Le Chatelier adapted a Mueseler lamp, equipping it with a special screen that distinguished flames more easily. They also improved a gas metering device made by American engineer M. Shaw. They modified Coquillion's device to make it safer and more convenient. This device determined the proportion of gas, based on the combustion of firedamp in contact with a spiral of palladium heated bright red by an electric current and the reduced volume of air measured at constant pressure before and after combustion.[73] Through

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[72] James M. Comey, "Safety Blasting Explosives: Classes and Properties of Different Explosives; Apparatus and Methods Used in Testing," *Mines and Minerals* 29 (1908): 145–48, 148; Marshall, *Explosives*, 451–53; McTrusty, *Mine Gases and Gas Testing*, 97; Escudier, "Coup de poussières," 38. Also Saint Raymond, "Catastrophe de Courrières," 130; Varaschin, "Risques au travail," 121.

[73] F. Ernest Mallard and Henry L. Le Chatelier, "Recherches expérimentales et théoriques sur la combustion des mélanges gazeux explosifs," *Annales des Mines* 8, no. 4 (1883): 274–568; Chesneau, "Note sur les travaux," 649–52; G. Chesneau, "The Detection and Measurement of Fire-damp in Mines," *Transactions of the American Institute of Mining Engineers* 22 (1894): 120–70, 122–25, 144–45; Mallard and Le Chatelier, "Sur les procédés propres."'

the term “science industrielle,” Le Chatelier advocated and represented a paradigm of the connection between research and its industrial application in public and private arenas.[74]

The fact that fatal accidents from explosion were relatively rare in France from 1892 to 1905, reinforced by the impact of safety methods such as ventilation and explosives that actually worked, may have added to the Gallic confidence in antipoussièrisme. Particularly in the Nord and Pas-de-Calais coal basins, at the start of their expansion and with their abundant recently opened and shallow pits, most accidents were due to falling roofs and walls.[75] The downside was that low mortality made Le Chatelier’s antipoussièrisme appear efficacious. French engineers proclaimed that the risk of a firedamp accident in their mines had become “altogether improbable.” The primary reason was the development of “truly French” mine safety methods.[76] Mine owners supported these methods, as reflected in *Le Génie civil* (*Revue générale des industries françaises et étrangères*), French industry’s weekly journal. It sympathetically covered Mallard and Le Chatelier’s research and its technical applications.[77]

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[74] Paul, *From Knowledge to Power*, 134, 168; Caron, *Dynamics of Innovation*, 81; Letté, *Henry Le Chatelier,* 41, 57–66, 101–35. Le Meur, “Écoles des mines,” 381–82. On scientists and private enterprises: Lucier, “Professional and the Scientist.”

[75] Escudier, “Coup de poussières,” 42; Rice, *Explosibility of Coal Dust,* 20. On ventilation regulations: the 1895 reform in Wright, *Coal Mine Labor*, 264–66.

[76] Taffanel, “French Coal-Dust Experiments,” 776.

[77] On explosives research: *Le Génie civil,* December 8, 1888 (90), February 2, 1889 (217), August 14, 1897 (244). On the 1887 commission’s works: *Le Génie civil*, November 11, 1899 (32). On *Commission du grisou*: *Le Génie civil*, August 9, 1890 (238). On the poussièristes vs. antipoussièristes debate: *Le Génie civil*, November 4, 1893 (6). On safety lamps: *Le Génie*

Claims that the firedamp problem was solved and that coal dust had not been an issue in the first place led French mining research to ignore certain aspects of mines that by 1906 were seen as dangerous.

European Mining Principles Converge after Courrières

Referring to French antipoussiériste engineers, Belgian engineer Watteyne mourned, "It took the awful disaster of March 10 1906, at Courrières, to open their eyes."[78] An initial inquest commission headed by Le Chatelier proposed that the likely cause was an open flame igniting unexpected firedamp blowing near the Lecoeuvre pit head. Under district regulations, some miners at Courrières used Wolf safety lamps, fueled by benzene and able to detect sparse concentrations of firedamp, below 0.75 percent. Negative test results with these lamps, however, meant that miners were accustomed to using lamps with open flames.[79] The

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civil, November 30, 1895 (71). On experiments: *Le Génie civil*, January 4, 1896 (160). On gas detection: *Le Génie civil*, February 23, 1901 (296). On *grisou*: *Le Génie civil*, September 20, 1902 (339). On safety explosives: *Le Génie civil*, April 18 1903 (406). Company directors delegated such matters to mining engineers: Lamb, "Coal Mining in France," 107–9; Reid, "Industrial Paternalism," 594.

[78] Victor Watteyne, "Belgian Coal Dust Precautions," *Colliery Engineer* 34, no. 10 (1914): 599–601.

[79] G. Chesneau, "Sur une Nouvelle Lampe de Sûreté à Essence," *Annales des Mines* 9, no. 20 (1901): 493–520.

centrality of firedamp, then, was consistent with standard French thinking on mining safety, especially explosions.[80]

No other engineers, French or otherwise, accepted the explanation given by Le Chatelier, in part because they asked a different question: not how the disaster started, but what accounted for its magnitude. No evidence appeared of widespread gas that could have burned the entire works so rapidly, nor had miners reported stray blowers in recent weeks. Absence of this evidence, in a mine with extensive dust deposits, made consultant engineers suspect a coal dust explosion.[81]

The mine's firedamp-oriented regulations and the weight of the explosive charge were uncharacteristic. Ultimately the most widely accepted theory of ignition did not require a blown-out shot. The remains of the Lecoeuvre brothers' bodies were found near the site of a shot, far from where they would be for an intentional shot firing. Apparently their first shot had failed completely, and so they approached the borehole to try again. While removing the explosive materials, one man struck the detonator, and this exploded the charge.[82] Everyone

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[80] "Courrières Explosion: Report to and Opinion of the General Council of Mines. L. L. Belinfante, translator," *Transactions of the Institution of Mining Engineers* 34 (1907–8): 468–83, 475; Martin Walton Brown, "Discussion of Messrs. Atkinson and Henshaw's Paper on 'The Courrières Explosion,'" *Transactions of the Institution of Mining Engineers* 33 (1906–7): 303–11, 310.

[81] Ch.-E. Heurteau, "La Catastrophe de Courrières (10 mars 1906)," *Annales des Mines* 10, no. 12 (1907): 317–492, 429.

[82] A similar incident nearly cost Welsh miner-memoirist Bert Coombes his life: Coombes, *These Poor Hands*, 109.

agreed there were naked flames at the Lecoeuvre heading, that it was a dusty part of the mine, and that miners there used a particularly high explosive, Favier (ammonium-nitrate-based) powder no. 1, to blast coal from the mine wall. In the absence of firedamp, mine managers deemed the use of this type of explosive an acceptable risk in exchange for its blasting power.[83] The French government approved Favier powder no. 1, consequently considered a safe explosive, but based on inadequate tests and focusing on detonation temperatures—to avoid igniting firedamp—rather than a charge limit.[84]

A further divergent factor was the large scale of the mine. In Courrières, against prevailing doctrine in other countries, pits were connected below ground for convenient transport and ventilation.[85] As the explosion spread, nothing could prevent it from bursting out of the Lecoeuvre area and propagating through the entire mine. The explosion destroyed

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[83] Heurteau, "Catastrophe de Courrières."

[84] James M. Comey, "Safety Blasting Explosives: Classes and Properties of Different Explosives; Apparatus and Methods Used in Testing," *Mines and Minerals* 29 (1908): 145–48, 148; Marshall, *Explosives*, 451–53; McTrusty, *Mine Gases and Gas Testing*, 97; Escudier, "Coup de poussières," 38. Also Saint Raymond, "Catastrophe de Courrières," 130; Varaschin, "Risques au travail," 121.

[85] Heurteau, "Catastrophe de Courrières," 443. On doctrine: Atkinson, "Austrian Fire-damp Commission," 547; Prussian Fire-Damp Commission, "Report. Second Part," translated in *Transactions of the Federated Institution of Mining Engineers* 4 (1892–93): 631–80, 656–59; Rice, *Explosibility of Coal Dust*, 18; Galloway, "On the Influence. No. V," 43. Le Chatelier himself had drawn attention to this matter, with respect to other mine. Escudier, "Coup de poussières," 42.

110 kilometers of galleries and roadways. Two British veteran investigators, W. N. Atkinson and A. M. Henshaw, wrote, "Through the agency of coal-dust, the explosion was carried through the mine." They concluded, "the fact of supreme importance remains, namely, that, however originated, an explosion may traverse the whole extent of the largest mines by means of coal dust alone. The writers have no doubt that this was the case at Courrières."[86]

The government report on the disaster contained the first official French acknowledgment of catastrophic risk from coal dust. The key question was to what extent coal dust, even in the absence of firedamp, posed a risk. Previously, French engineers had argued that firedamp was the only credible danger in coal mines, and they made considerable efforts to mitigate its potential risks. Everywhere along the within-mine Courrières roadways, coked crusts from burning coal dust covered timbers. The report described "moss-like encrustations of coke" that "mantled the walls from end to end." Recalling Verpilleux from four decades ago, the report stated, "the coal-dust had been the priming powder . . . which had been ignited at the Lecoeuvre heading." Sparse firedamp could not burn so rapidly across such distances, but abundant coal dust could. In conclusion, "it is undeniable that the extent of the explosion was due to the propagation . . . of burning coal-dust over the entire area of the workings."[87] The greatest disaster in European mining history, then, was due to coal dust.

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[86] W. N. Atkinson and A. M. Henshaw, "The Courrières Explosion," *Transactions of the Institution of Mining Engineers* 32 (1906–7): 439–92, 478.

[87] Heurteau, "Catastrophe de Courrières," 394–95, 398. George Rice's claim, that no official French report attributed the catastrophe to coal dust, was thus incorrect. Rice, *Explosibility of Coal Dust*, 20.

The Courrières disaster reinvigorated research on the prevention of explosions in mines, mainly related to coal dust, in other coal-producing countries. The British Coal Operators Association opened research galleries at Altofts the following year; a new royal commission was also appointed.[88] In France, the reaction to Courrières suggests that the earlier commitment to antipoussièrisme was so deep that only a disaster on a huge scale would convince its followers that coal dust was indeed explosive under relatively common conditions.[89] A week after the accident, condemnation of antipoussièrisme appeared in the French mining press, squarely directed at Le Chatelier. Quoting the 1882 article at length, one writer summarized bitterly, "Need we add that not all engineers agree with the ideas of M. Le Chatelier on the role of dust in mines?"[90] The next-but-one issue (April 1, 1906) of *La Nouvelle Revue* demanded that coal dust finally be taken seriously.[91] Now aware of their

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[88] Rice, *Stone Dusting or Rock Dusting*; Rice, "Investigations of Coal-Dust Explosions"; Singleton, *Economic and Natural Disasters*, 112. On learning from failure: Petroski, *To Engineer Is Human*, 53–62, 82–84, 121.

[89] A parallel occurred in the "battle of the laboratories." Debates over adding amyl alcohol or diphenylamine to ammunition "Poudre B" ended in 1907 when armament magazines with amyl alcohol exploded aboard the French battleship *Iéna*, destroying her. Bret, "Guerre des laboratoires."

[90] Quote from *L'Écho des Mines*, March 19, 1906, 325; summary in Francis Laur, "La vraie cause del l'accident de Courrières." *Bulletin de la Societe Belge de Geologie de Paleontologie et d'Hydrologie* 20, no. 10 (1906): 70–72, 72. Also Watteyne, "Belgian Coal Dust Precautions," 599; Tauziède, "Creation des stations."

[91] Mikhaël Suni, "La Houille Homicide," *La Nouvelle Revue* 39, April 1, 1906, 341–48.

misunderstanding of coal dust, mine owners raced to catch up with poussièriste research abroad. Within months, the Comité Central des Houillères de France expanded one member's sleepy test pit at Liévin, about 15 kilometers from Courrières, into a fully kitted-out research mine (figure 4*B*). The very first investigation tested the explosivity of coal dust samples from mines throughout France, and coal dust remained its central research focus for some time.[92] Safety regulations were also updated.[93]

The shock of the Courrières catastrophe rippled through every level of French mining society, even to Le Chatelier. The final 1906 issue of *Revue de Metallurgie*, Le Chatelier's longest-lasting contribution to science, which he also edited, included a summary of a profoundly poussièriste British report on Courrières. It blamed the disaster on "an extensive and very formidable dust explosion." Even so, perhaps manifesting Kuhn's hypothesis of resistance to paradigm change by those who have committed their careers to it, Le Chatelier's introduction to the British report emphasized "the uncertainty that still exists today over the precise causes of the disaster." Le Chatelier dutifully noted the authors' observations that French engineers found it difficult to accept the importance British and German engineers attached to coal dust, and that in France they were convinced that dust was incapable of propagating an explosion very far in the absence of firedamp. But, Le Chatelier concluded, seemingly more in hope than in cool dispassion, "the primary cause of the accident remains

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92 Tony Callot, "Experimenting Station at Liévin"; Comité Central des Houillères de France, *Premiers Essais*.

93 Heurteau, "Catastrophe de Courrières," 443.

as shrouded in darkness as on the day of the event."[94] He must have been the only scientist left in Europe who thought so.[95]

Conclusion

The history of the coal dust hypothesis in Europe exemplifies the evolution of different approaches. Before 1882, neither the supporters (poussièristes) nor the opposers (antipoussièristes) of the theory were destined to produce accurate conclusions. As technology stood at the time of Mallard and Le Chatelier's "Du rôle" in 1882, both approaches presented reasonable explanations of mine explosions. However, between 1882 and 1906, the year of the Courrières disaster, research in both firedamp detection and coal dust combustibility in Britain, Belgium, Germany, and Austria diverged from new research and previous interpretations of firedamp as a causal factor in most of the French mining community. True, the presence of firedamp explained many mine explosions, and therefore the French approach was, to a certain extent, sensible.[96] However, considering the destructive

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[94] Henry Louis Le Chatelier, "L'accident des mines de Courrières: D'après le rapport de M. Cunynghame, sous-secrétaire d'État au ministère de l'Intérieur et M. Atkinson, inspecteur des Mines en Angleterre," *Revue de Metallurgie* 3, no. 12 (1906): 709–16; Kuhn, *Structure of Scientific Revolutions*, 151.

[95] In 2006, *Annales des Mines* published an article on Courrières: Saint Raymond, "Catastrophe de Courrières," showing how the explosion led to new safety regulations. There is no reference to Le Chatelier.

[96] On claims by British royal commissions: footnote 25; Parliamentary Papers, *Accidents in Mines*, 23.

capacity of coal dust, its underestimation as a risk factor shifted the attention from critical comprehension of the propagation and extent of explosions.

As for the Courrières explosion, working in a non-gassy mine—relatively safe from explosions—may have led to overconfidence compared to the greater care taken in gassy mines, as evidenced by research in other countries.[97] Nevertheless, because French mining doctrine underestimated the risk from coal dust, mines with extensive dust deposits such as Courrières, but without firedamp, omitted some otherwise standard safety precautions regarding the use of explosives and mine layout. When it was accepted that coal dust accounted for the propagation and magnitude of the explosion at Courrières, divergent understandings resolved rapidly after 1906.

This article underlines that applying science and technology methodologies to industrial risk, especially in dangerous sectors like mining, is never a straightforward process. The nature, structure, and governance of research hindered the understanding of a key explosion risk factor. The examination of coal dust promoted certain approaches but not others that seemed to be good enough or work better.

Bio/Acknowledgments

John E. Murray was the Joseph R. Hyde III Professor of Political Economy and professor of economics at Rhodes College. Javier Silvestre is professor of economic history at the University of Zaragoza and member of the Instituto Agroalimentario de Aragón and the Grupo de Estudios Población y Sociedad.

[97] Rice and Jones, *Methods of Preventing and Limiting Explosions*, 5.

John Murray died on March 27, 2018, in Memphis, at the age of fifty-eight. He was the prime mover of this article and our project on technological change in European and U.S. coal mining. John was first and foremost a friend, as well as a mentor and respected colleague. I (Javier Silvestre) have revised this article, and it is dedicated to John's memory and family.

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CAPTIONS

FIG. 1. In the late 1800s, experienced British mine inspector William Galloway spent years researching the causes of coal mine explosions. He designed this device (over 18 feet long) to test the explosiveness of coal dust in an experimental chamber at Llwynypia Colliery, Wales. (Source: Galloway, "On the Influence," 356; and Galloway, "On the Influence. No. II," 415.)

FIG. 2. In Durham, north England, A. Freire-Marreco and D. P. Morison designed this equipment (8 feet by 8 feet) in a chamber that mimicked a mine, to test the impact of factors like air currents on coal dust. (Source: Freire-Marreco and Morison, "Some Recent Experiments," 87.)

Figure 3. German engineers used these data from an 1884 Prussian Firedamp Commission experiment to highlight the risk of coal dust. The length of coal dust trail in relation to the length of flame in a test blast in an experimental mine: the König mine, near Neunkirchen (Saarbrücken). (Sources: Hilt and Margraf, "Bericht über die auf der Steinkohlengrube König"; Mallard and Le Chatelier, "Travaux de la Commission Prussienne," 642; Parliamentary Papers, *Accidents in Mines*, 39–41.)

FIG.4. Experimental mines were a new way of studying explosions, a hybrid of two previous strategies: mine inspection and laboratory observation. They resembled the real environments more closely and therefore produced more reliable results. *A*, German engineers Hilt and

Margraf's 51-meter-long test gallery at the König mine in Neunkirchen, Saarland, proved that for testing explosions experimental mines were superior to earlier detonation chambers. (Source: Hasslacher, *Haupt-Bericht*, 4:8.) *B*, Shocked by the Courrières disaster, mine owners in France quickly set up experimental galleries like this 400-meter-long one at Liévin in 1907, to test the explosivity of coal dust and catch up with international mining research. (Source: Callot, "Experimenting Station at Liévin," 1.)

FIG. 5. After designing this equipment to test the flammability of coal dust, French engineer Pierre Vital warned that the combination of dust and firedamp not only posed a greater risk of mine explosions but also wreaked more destruction. (Air flow is from right to left. For scale, arrow is pointing at tube (a) 12 cm long. The glass bottle on the right is 30 cm high and 15 cm in diameter.) (Source: Vital, "Recherches sur l'inflammabilité des poussières," 189.)

FIG. 6. In 1893, Frank Clowes invented this hybrid safety lamp, to help miners detect firedamp more effectively and safely (the metal container in the bottom of the lamp held a liquid fuel, and the smaller cylinder to the right held compressed hydrogen gas). (Source: Frank Clowes, "A New Portable Miner's Safety-Lamp," *Proceedings of the Royal Society of London* 52 (1892–93): 484–503, 488.)