New process technologies in European coal production, 1850-1900:

The case of mine ventilation

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Coal was the major source of energy that powered the Industrial Revolution. Britain's endowment of the mineral, combined with innovations in coking, led to leadership in iron production. On the Continent, Belgium's coal deposits enabled its industrialization. In most retellings of the Industrial Revolution, the great process technologies in coal mining were the Savery and Newcomen pumps. These machines, which later gave way to separate pumps that were connected to steam engines with Watt condensers, allowed the search for coal to run ever deeper by removing ambient water. After mining engineers solved the problem of flooding, written histories shift their attention elsewhere, as if coal extraction proceeded evenly and without interruption—and without interest. But of course this was not the case. Eighteenth century pumping technology addressed only one of many bottlenecks in the coal production process, leaving other constraints to be solved later in the nineteenth century. One of those constraints was ambient explosive gas. In this paper we consider a particular kind of new process technology in coal mining, ventilation, that aimed to solve this problem.

As mines descended deeper and into previously unexploited basins, miners encountered an odorless, colorless gas in certain seams of coal. This was firedamp: in French, *grisou*, in German, *Schlagwetter*. Firedamp consists mostly of methane, and so presented two problems. First, it displaced oxygen in the mine atmosphere, creating a risk of asphyxiation. Second, it was flammable and explosive in the presence of open flames. To light their way and their work, miners initially brought candles to the coal face, which caused fatal accidents in the presence of firedamp. Engineers and tinkerers set to mitigating this problem in many ingenious ways. Sir Humphrey Davy invented the best known safety lamp (1816), which shielded the flame from the gas with wire gauze. Use of safety lamps did not solve the problem as mine fires and explosions continued. Attention focused on methods of removing firedamp from the mines, a continuous process that would allow miners to continue working amidst a reasonable amount of fresh air. Ventilation of mines began with the simplest of observations of the effect of heat on rising air, and then moved toward use of machines to create air currents, removing methane and replacing it with air from the surface.

The present paper considers the development of mechanical ventilation from several angles. First, mechanical ventilation was the subject of intense interest in European mining circles throughout the nineteenth century. Research into ventilation and ventilators proceeded at active mines, in mining colleges, and in experimental mines. Inventors created a variety of machines with varying degrees of effectiveness, and the mining press private and public reported in detail on field trials and tests in functioning mines. Governments created firedamp commissions, and charged them with studying mines foreign and domestic and recommending best ventilation practices. Clearly, nineteenth century Europeans believed that mine ventilation was an urgent issue, attention to which was necessary to maintain the flow of energy from the continent's mines. Given the written descriptions of many different ventilation technologies, we approach mine ventilation as a problem not solved by a single invention, but managed through a process of invention of several different kinds of mechanical ventilators. This way we can address questions of induced innovation as well as the incentives and costs facing mines in different geological situations. Further, we rely on surveys and reports from across Europe, so as to gain a broad view of approaches to continent-wide problems of energy extraction.

The process of research and development of this particular process technology addresses several outstanding questions in the historical literature. First, it considers extraction of the Industrial Revolution's primary fuel source into the decades after that event's traditional endpoints in the second quarter of the nineteenth century. Whereas Wrigley showed the necessity of coal to the Industrial Revolution proper, the present work shows how that necessary condition was fulfilled in the decades thereafter, when the Continental economies grew rapidly.[1] Further, the importance of coal was central to the Great Divergence analysis of Pomeranz, who proposed that European economic leadership followed from its "geographic good luck" of coal deposits. But the most fortunate natural resource endowments never sufficed for economic growth. As Wright showed in the American case, the complementarity of human capital and mineral deposits was necessary for their exploitation.[2] Huang criticized the conflation in the *Great Divergence* of natural resource *endowments* with natural resource *exploitation*.[3] China, like Europe, had coal deposits all along, but failed to learn how to exploit them until late in the nineteenth century. Europeans continued to improve methods of coal mining long after the cutting edge of new products, final and intermediate, had moved on from coal to chemicals, electric, and engineering. China seems simply not to have addressed these issues. Pomeranz noted that Chinese mines also suffered from ventilation problems and "spontaneous combustion" (presumably from coal dust or methane), the very problems Europeans eventually solved.[4] Chinese mines of the eighteenth and nineteenth centuries never did overcome those constraints, but European mines did. The European method was to tinker and test on a broad scale, in several different countries, addressing both general conditions and local peculiarities simultaneously, to publicize the results, and to adapt efficient methods of production without regard to their origins. This is the story we tell in this essay.

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[1] Wrigley, *Energy and the English Industrial Revolution*.
[2] Wright, "Origins of American Industrial Success."
[3] Huang, "Development or Involution".
[4] Pomeranz, *Great Divergence*.

A short history of mine ventilation

Descriptions of mine ventilation appear as early as the sixteenth century *De Re Metallica*. Metal mines simply did not encounter problem gasses as densely as coal mines did, and so the methods described by Agricola did not translate into the carbonaceous setting.[5] By the beginning of the nineteenth century two methods were commonly used to ventilate coal mines, natural ventilation and furnaces. Natural ventilation was limited to adit (walk-in) mines driven into hillsides. With a higher and a lower entrance into the same mine, connected in a C-shape, natural variation in temperature outside and inside the mine enabled a steady flow of air from the upper to the lower entrance in summer and vice versa in winter. Natural ventilation, however, worked in only the simplest of mines.

Vertical-entrance mines required a stronger method of ventilation. Here mine engineers used their knowledge that warm air rises to sink two shafts, the downcast shaft that carried air into the mine from above, and the upcast to carry stale air and firedamp to the surface. At the bottom of the upcast was the furnace, protected from the flowing air by a triangular dumb drift that separated the lighter firedamp from ambient air (Figure 1). The furnace heated the air in the upcast, thereby pushing it upwards. Furnaces worked best in metal mines and non-gassy coal mines, but because they were so cheap they also appeared in gassy (also called fiery) coal mines as well. The only real cost was building a dumb drift to direct firedamp-laden air away from the furnace flame. For safety purposes a second shaft was typically needed, and even for single-shaft mines a brattice (a portable divider made of wooden frame covered by canvas) could split the one shaft into upcast and downcast sections running side-by-side. To fuel the furnace required only small coal that had been dug from nearby galleries. Furnaces had no moving parts and were

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[5] Agricola, *De Re Metallica*, 203-207.

known to be reliable, which proved persuasive to many when mechanical ventilation first was tried and found to be of unpredictable reliability.

In the middle of the nineteenth century, Parliament convened a Select Committee on Coal Mines in Britain to assess the state of mining technologies, including those used for ventilation.[6] Field experiments and pithead investigations in Britain, France, and Belgium revealed a variety of ventilation methods in use. Table 1 shows the costs and a measure of productivity for furnaces and several mechanical methods around mid-century. Furnaces proved to be relatively inexpensive to build and operate, at least underground. Above ground furnaces were scarcely more cost-effective than the exotic new mechanical technologies. Allan Tetlow, a former miner and Lancashire miners' union official, reported that miners in general had no preference between furnaces and steam jets, but did prefer either to natural ventilation that was weak and untrustworthy.[7] Regarding the open flame in a potentially gassy mine, Herbert Mackworth, a government mine inspector, considered a furnace with a dumb drift "perfectly safe."[8] As so often in the history of technology, furnaces continued as a durable technology even after mechanical ventilators had become common. As late as 1901 a manager estimated that installing a furnace cost a tenth of the installation cost of a current model mechanical ventilator, while the annual operating costs favored the fan, but not by much.[9]

At mid-century, it appeared that the only alternative to furnace ventilation was steam. Steam had its advantages. It was a flexible power source. A boiler could be built on the surface, to force steam downwards through a pipe that heated air in the upcast shaft. Alternatively, a

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[6] First, Second, and Third Reports from the Select Committee on Accidents in Coal Mines, in Parliamentary Papers, Reports from Committees: 1852-53, Thirteenth Volume.
[7] Select Committee on Accidents in Coal Mines, Second Report, 69.
[8] *Reports from Committees: Accidents in Coal Mines*, 36.
[9] Kerr, *Practical Coal Mining*, 334.

boiler at the bottom of the shaft might either release steam or force it upwards through a pipe. In either case, similar to furnaces, boilers compensated for their inefficiency with the ability to burn small or otherwise unsalable coal at very low cost. Experiments with steam in Belgium dated from 1841, but with little success. Throughout English mines engineering trials found steam technologies far less powerful than furnaces. Then in 1871 the brothers Körting in Hannover produced their steam injector, which made steam more viable than furnaces and put it on a competitive footing with mechanical fans and turbines. Although much less fuel efficient than its nearest mechanical competitor, the Körting injector was cheap to set up and sufficiently reliable to serve as a popular reserve ventilator, as at Mährisch-Ostrau in Moravia.[10]

During this time a few inventors, nearly all of them Belgian or with Belgian connections, persisted with attempts to build mechanical ventilators,. Some of the early prototypes aimed to mimic the motions of the water pumps that had drained water from mines successfully. A plunger worked like a piston and a so-called bell like a cylinder in a conventional steam engine. Plunger and bell machines enjoyed some popularity in Belgium, where three were custom-made for particular mines. These included the horizontal Mahaut ventilator in Charleroi, and a vertical plunger at the Bonne Esperance mine in Seraing. The vertical plunger at Grand Buisson is pictured in Figure 2. Similarly in England one of the first mechanical ventilators was a Struvé pump erected at Eaglebush Colliery, South Wales, in 1849. This machine was reported to resemble that described by Agricola in *De Re Metallica*.[11] Another approach hearkened back to

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[10] Wabner, *Bewetterung*, 124-128.
[11] Wabner, *Bewetterung*, 125-145; Atkinson, *Key*, 65.

the Archimedean screw. In 1839 Maximilien Motte, of Hainaut, received a 15 year patent for his pneumatic screw (Figure 3), which was eventually installed in a few mines.[12]

The earliest successful technology was a lobe pump. Auguste Fabry, a mine engineer at Charleroi, introduced this ventilator (Figure 4) in 1845. The Fabry used two interlocking sets of blades rotated in opposite directions to expel air. It met with some early success, first appearing at the Grand Buisson mine, Belgium, in 1850. This ventilator did not scale up successfully as it vibrated too violently at high speeds, and the tolerances to prevent this were beyond machinists' skills at the time. As a result it remained in service where only moderate ventilation was required. As late as 1873, 82 Fabry ventilators remained in mines in Hainaut, some in reserve. It seems never to have gained a foothold in Britain.[13]

At mid-century on the Continent, centrifugal fans were one of many available mechanical ventilators. Having already developed his own condenser for a steam engine, Charles Letoret patented his centrifugal ventilator in November 1841, just after introducing it into the L'Agrappe colliery, Couchant de Mons, Belgium (Figure 4). Here was the first machine powerful enough to ventilate an entire mine. Within two years he had installed machines of his design at another pit at L'Agrappe and at Grand-Piquery. Another unusual shape was patented by the Belgian Theodore Lemielle in 1854 (Figure 6). Essentially an eccentric rotary engine with an interior rotor of hexagonal cross-section, the Lemielle continued to be installed in newly sunk pits as late as 1870. The final mid-century machine that had a limited impact was developed by Adolphe Lesoinne, a professor of metallurgy in Brussels. In 1845 he introduced his windmill-like fan of 2.7m diameter. The machine successfully worked at the Grand Bac mine in Liège province. By

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[12] *Bulletin Officiel des lois et arrêtés royale de la Belgique*, 2e semester 1839. Patent number 832, p. 909.

[13] Arnould. *Bassin Houiller*, 121; Fabry, "D'une machine"; Harzé, "De l'aérage des mines," 202; Gonzalès Decamps, "Mémoire Historique," 86-88; Wabner, *Bewetterung*, 145-148.

1866 this machine ventilated about a tenth of all Belgian pits. To summarize the state of mechanical mine ventilation at mid-century, no dominant technology had emerged yet, but at no point did experimentation on new kinds, or refinements of old kinds, of technologies cease.[14]

It was Théophile Guibal (1814-1888) who gave European collieries the most successful centrifugal ventilator of the 1850-1890 period (Figure 7). Born in Toulouse, Guibal was educated at the Ecole Centrale des Arts et Manufactures de Paris, and at age 23 participated in the founding of the School of Mines in Mons, which continues to the present as the engineering faculty of the University of Mons. He developed a broad research agenda, which included invention of an anemometer and creation of a measure of a mine's resistance to forced air, which he called its temperament, expressed as the square of the volume of air moving past a line each second, divided by the pressure need to induce that current. His greatest achievement was the centrifugal ventilator that bore his name. He experimented with it as early as 1855, also at l'Agrappe, and patented his basic machine in 1858. Its effect was not immediate, but it was permanent. Many mines across Europe switched to the Guibal, but we have found none that switched from his design away to any other type of ventilator until the mid-1880s. After the introduction of his machine to Britain, Guibal was elected an honorary member of British engineering societies. He was eulogized by one British engineer: "What M. Guibal did in his life was of world-wide importance."[15]

Guibal's ventilator represented a true step forward along several dimensions. Probably the most important came from his realization that exhaust air at the surface had to be isolated

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[14] Arnould. *Bassin Houiller*, 120-122; Harzé, "De l'aérage des mines," 201-205; Gonzalès Decamps, "Mémoire Historique," 85-87; Wabner, *Bewetterung*, 151-153. Caulier-Mathy, *La modernisation*, 242.

[15] Cochrane, "Obituary Notice"; Arnould, *Mémoire Historique*, 121; Gonzalès Decamps, "Mémoire Historique," 87.

from the fan blades, lest it be suctioned back into the machine, which reduced efficiency considerably. To this end, Guibal encased the fan and created a distinctive *évasée* chimney that widened as it rose. To connect them he introduced a sliding shutter in the casing that allowed variation in the quantity of exhaust. Finally, after some experimentation, he found that angling the blades of the fan back, away from the direction of rotation, allowed it to evacuate more air. As the efficiency of the Guibal fan became known outside Belgium this model became popular throughout Europe. One estimate of its numbers in 1875 placed 180 fans in England, 85 in Belgium, 60 in France, and 30 in Germany.[16] Figure 8, showing the numbers of types of ventilators in the Niederrhein-Westfalen region, which included the Ruhr mines, indicates that the Guibal was the most common fan in use between 1872 and 1890.[17]

Figure 8 also indicates a series of lifecycles for different mechanical ventilation technologies. While limited to the Niederrhein-Westfalen area, the openness of those mines to new machines invented abroad makes it a convenient location to examine the process of technological succession. The first decade plus (1854-1867) illustrates the novelty of the Fabry ventilator, which was the only mechanical method adopted. Then from 1870 to 1890 the Guibal was the most commonly used fan. After 1875 several new types appeared, all of which were variations on the basic centrifugal ventilator. The Winter fan, which featured blades curved forward, briefly became the most popular ventilator even while it was losing ground to newer types; the Guibal was losing ground even faster.[18] The next successor, the Pelzer, was a small,

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[16] Arnould, *Bassin Houiller*, 121.

[17] Carpenter, “Ventilation,” 7

[18] Hauer, Die Wettermaschinen, pp. 118-119.

high speed fan.[19] The eventual champion by the turn of the century was a machine invented by an Englishman.

George Marie Capell (1845-1915), nephew of the sixth Earl of Essex, was born in London and was graduated from Pembroke College, Oxford. He received holy orders and lived most of his life as the (Anglican) parish priest at Passenham, Northamptonshire, dying a mere six weeks before his oldest son was killed in battle in France. While something of a natural tinkerer--at the time of his death he was working on a design for an airplane propeller--Capell invented his mining ventilator while aiming to solve a different, but related, problem. He felt he had lost too much grain from his glebe lands to moisture related problems, and so to dry the grain he designed a blower which the local blacksmith built to order.[20] This prototype did scale up, and in 1883 Capell and Macbean, the blacksmith patented their ventilator in Britain, Canada, and the next year in Germany and the United States. Capell alone continued to patent improvements on his basic design into the twentieth century. The Capell fan was much smaller than the Guibal, but turned faster (Figure 9). Thus, a trial at Marles collieries in France compared a Guibal of 23 feet diameter with a Capell of 12.5 feet; the Guibal operated at 75 revolutions per minute, the Capell at 305.[21] The novelty lay in the additional set of fan blades that Capell attached to the main cylinder. The main cylinder still held blades that drew air over the main axle, but the additional side propeller drew air into the cylinder more rapidly than previously. The blades attached to the open cylinder then pulled the air outwards and into a chimney.

Initially the Rev. Capell found it difficult to persuade career mining engineers and inventors of the value of his new fan. Part of the problem was his tendency to produce figures

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[19] *Haupt-bericht der preussischen Schlagwetter-commission*, 186.
[20] No author, “The Capell Fan.”
[21] Capell, Observations, p. 215.

from field trials that compared dissimilar features of different machines. Hence one engineer demurred that "he was very skeptical of the accuracy of the observations quoted in Mr. Capell's paper." Another suggested the need for estimates "taken by persons whom they could trust," not by Capell himself.[22] At root was a feeling that the available technologies were the best possible. Wabner criticized the lack of "any theoretical grounds for this peculiar arrangement of the fan blades…which cannot possibly facilitate the passage of air through the fan." Further, because some test results for the Capell reached levels "demonstrated impossible by Guibal" it was unlikely that the new fan was as powerful as promised.[23]

Perhaps as a result of the troubled launch of his invention, Capell proved to be a vigorous defender of his patents. He sued licensees who produced his fans on their own account as well as inventors of similar machines. Having lost one case, a version of his ventilator became known as the Capell-Clifford fan in the United States, and in response he organized the Capell Fan & Manufacturing Company in Monongahela, Pennsylvania.[24] In Germany he licensed production to the R.W. Dinnendahl firm of Essen, which also produced its own line of less successful ventilators.[25] Of course, some engineers could see rather early on that Capell had created an unusually effective fan, despite his university education in the classics and his primary occupation in the church. In 1882 Atkinson, a mine inspector, wrote that he expected the Capell to be the only ventilator in use to achieve a low cost in installation, productivity in use, and reliability over time. He was right.[26]

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[22] Discussion following Capell, "Observations", pp. 209, 211.
[23] Wabner, *Bewetterung*, 191
[24] *United States Circuit Courts of Appeals Reports with Annotations* (Rochester: Lawyers' Cooperative Publishing Co., 1909), p. 227, *Clifford v. Capell*. "Clifford vs. Capell Fan Litigation Ended," *Coal and Coke Operator* 10 (7 April 1910), pp. 222-223.
[25] Hauer, *Wettermaschinen*, 123-125, 192.
[26] Atkinson, *Key to Mine Ventilation*, 95.

The last notable advance of the nineteenth century offered a system of ventilation that was embodied in a particular machine. A professor at the Ecole Centrale de Paris, Louis Ser (1829-1888), produced both the system and the machine. A civil engineer who concentrated on ventilation of hospitals, Ser wrote the great scientific work of later nineteenth century mine ventilation in 1878.[27] In this article, Ser applied broader principles of fluid dynamics, especially as developed by Bernoulli, to particular problems of centrifugal fans. He concluded with some formulas for optimal fan dimensions. Fans built in accordance with his principles were called Ser fans. With forward curved blades, they were smaller still than Capell fans and their bladed cylinder rotated even faster. As Table 2 notes, it was slightly cheaper to install and operate than the Capell, although it was somewhat less efficient. By the end of the century Ser fans had become widely used in France, almost entirely displacing large Guibal fans, especially in mines with narrow openings (i.e., small equivalent orifices).[28]

One way of measuring fan production, in a technical sense without respect to costs or value of benefits, was the percentage of so-called useful effect (or *Mechanischerwirkungsgrad*). Borrowed from earlier work on water pumps in deep mines, useful effect was defined simply the ratio of horsepower from the engine that drove the fan to horsepower of the work done by the fan. This measure was thought, in some circles, to be "the fundamental quality to be considered."[29] Measuring fan productivity turns out to be quite difficult. Laboratory work yielded several useful effect figures for a given fan depending on the number of revolutions per minute. The real test of a fan was in the opening to a pit, and here the effectiveness of the fan

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[27] Ser, "Essai d'une Théorie."

[28] Wabner, *Bewetterung*, 193-194. See also p. 43 of *Publications de la Société des ingénieurs sortis de l'École Provinciale d'Industrie et des Mines du Hainaut*, 3rd series, volume 2 (1892), p. 43.

[29] Galloway, *Course of Lectures*, subject 6—Ventilation, p. 68.

depended on the drag created by characteristics of the mine. A mine with smooth ceilings and walls and few curves could make a fan look strong, and a strong fan set above a mine with rough sides and roads splitting at odd angles could ventilate inefficiently. The available figures usually represent one of these two situations, the lab or a particular machine at a particular mine. To deal with these mine-to-mine discrepancies, the French engineer Daniel Murgue proposed a standardized measure which he called the equivalent orifice, or the area in square meters of an opening through which the same pressure would force the same volume of air in the same time. Murgue himself visited many mines across northern Europe to establish a set of equivalent orifices.[30] Table 1 indicates that by mid-century superior furnaces were, by this measure, as productive as the best available mechanical ventilator (the Fabry) but much cheaper in use. Towards the end of the century (Table 2) the typical useful effects in many machines had risen substantially.

Diffusion of mechanical ventilation across Europe

Mechanical fan ventilation was not a single technology that succeeded furnaces or steam, but a variety of different machines that moved air through mines. Most used some kind of centrifugal force but marshalled that force in different ways. There was really only a single outstanding characteristic of the diffusion of this technology, and that was that Belgium was about three decades or so ahead of the rest of Europe in ventilating mines mechanically (Figure 10). When the Ruhr area was installing its first mechanical ventilator, there were already over 200 in use in Belgium. The reasons for the Belgian advantage were twofold, and might be described as supply and demand factors. The demand for mechanical ventilation stemmed from Belgium's unusual

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[30] See for example pp. 38-43, 54-55, and 66-69 in the English translation, *Theories and Practice*. The number of mines for which Murgue estimated an equivalent orifice was 106.

geology. Its mines were deep: an 1866 survey found the deepest to be 769 meters, whereas seven years later the deepest mine in Scotland had barely reached 300 meters, and seventeen years later the deepest mine in Prussia was still less than 700 meters. Further, Belgian mines were plagued with firedamp in different forms, some with ambient firedamp continuously emitted by coalfaces, others by gas under pressure in pockets, which blasted forth in jets when disturbed by miners.[31] To reach this coal required new ventilation technologies. In a type of induced innovation, the first successful mechanical ventilators appeared in Belgium. These were the Fabry and Lesoinne ventilators, the latter resembling a windmill or propeller, which both were made public in 1845. More would follow.

Beyond the pioneering Belgian case, the numbers of ventilating machines suggest no particular pattern. That is, there was no dominant technology for long. A large number of engineers, inventors, and tinkerers tried an enormous number of new methods and variations on old ones to make a machine that was just marginally more efficient. Two ways to see this are in several reports of working machines at a particular time, and the continuous survey of the Niederrhein-Westfalen mines in Germany. Table 3 presents the results of the surveys, some from all Europe and others for regions within countries. In each case, several technologies—even several dozen at times—proved viable, and many different types had been tried. Now some of these figures include machines of custom design that were not replicated. For example, only one Kraft turbine was built by Cockerill at the St. Marie shaft at Seraing in 1878. It proved to be less efficient than a Guibal fan and so the Kraft remained one of a kind.[32] But the larger numbers reflect the reality of many different kinds of machines in operation. A royal commission reported in 1886 that the most commonly employed machines on the Continent included seven different

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[31] Pernolet and Aguillon, *Exploitation and Réglementation*: Volume I: Belgium, p. 15.
[32] Wabner, *Bewetterung*, 158.

kinds (Guibal, Lambert, Winter, Pelzer, Goffint, Harzé, and Fabry). In Britain alone four machines were in widest use: Guibal, Waddle, Schiele, and Capell.[33] In surveying as many sources as we could find over the 1850-1900 period, we found references to 57 different types of fans. It was an active field of research.

Each individual fan passed through its own life-cycle. Because the German state of Niederrhein-Westfalen monitored mine ventilation unusually closely we can see the life cycles of these technologies through the second half of the century (Figure 8). Because this state included the Ruhr region, which became the most productive in Germany, its experience with ventilation technologies is of particular importance. We might propose four different periods. First, from 1856 to 1867 represented a time when only the Fabry wheels offered an alternative to natural ventilation, which was more common in Germany than furnaces. Even so, Fabry machines were not widely adopted. If it had remained the only technology it appears likely that mechanical ventilation would not have diffused through the Ruhr. From 1867 to 1877, however, the Guibal presented a much better alternative, and within a few years appeared in about five times more mines than the Fabry. From 1877 to 1885, seven new models entered service, which in turn made the number of active Guibal fans stagnate, and eventually decline. Finally, in 1889 the Capell fans became available in Germany, becoming the most popular in 1894. By the end of the century there were nearly twice as many Capells in Ruhr area mines as the next most popular type, with neither the Capell, nor the Pelzer in second place, nor the Rateau in third place, showing any signs of exhausting its market. Older models such as the Guibal, the Winter, and the Moritz, were being replaced by the newer fans. The implication here is that the market for mechanical fan ventilation was a dynamic one, with no one technology holding the dominant

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[33] Commissioners Report on Accidents in Mines, p. 10; Atkinson, *Key to Mine Ventilation*, p. 95.

position for more than a decade or so.[34] Many inventors, and their investors, worked hard and imaginatively to stake a claim in this market. Some, like Guibal and Capell, succeeded, and other fans, like those by Kaselowski and Wagner, failed, as did others too ephemeral to have sold any units at all in this region. The pan-European side of all this innovation can be seen in the country of origin of the leading fans. Ruhr mine operators initially used fans of Belgian design (Fabry, Guibal), and later one of English design (Capell). Other machines of German (Pelzer) and French (Rateau) design also met with favor. The market for mine technology covered all of Europe in the second half of the nineteenth century.

Adoption of new technologies

We would like to examine the question of characteristics of mines that adopted the new technology relative to those that did not. There are three ways to view this question. First we can ask which mines switched from furnaces or natural ventilation to mechanical ventilation. Second, we can ask which mines that had already installed mechanical ventilators switched to newer makes or models. Third, we can consider national differences. With the data we have collected from European government publications, we can address these questions in roughly that order of decreasing confidence in our answers.

So far we have been able to recover data from pit- or mine-level surveys in three regions. The most consistent data are from the East of Scotland. Here as part of regular reports by mine inspectors to the government, a particularly industrious agent named Ralph Moore surveyed the mines in his district, which consisted of Lanark, Stirling, Linlithgow, Fife, and Edinburgh, and nearby areas. Moore's primary assignment was to see how carefully the Coal Mines Regulation

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[34] All figures from *Die Entwickelung*, Table IX.

Act of 1872 was being followed and much of his reports concerned safety conditions. Still, he visited each mine, noting in the 1879 report that he and his assistant had covered 19,600 miles along the way. He recorded pit-by-pit (many mines having several pits) information about their depth, the seams they worked, accidents, and methods of ventilation. In terms of employment and production, the 300 or so mines in his remit accounted for about eight percent of all British mines. He included his survey results in his reports of 1873, 1878, and 1883, which were then published.[35] The years for which data happen to be available are of particular interest, as the share of Scottish pits with mechanical ventilation rose from about three percent to about 30 percent over this time (Table 4).

Another valuable aspect of the Moore surveys is that he returned to many of the same mines each time, even the same pits at the same mines. Thus, he created a panel of two- to three hundred mines observed three times five years apart. The broad and shallow panel offers a way out of statistical problems of identification. For example, if mechanical ventilators were installed first at mines with the worst firedamp problems, statistically it could easily appear that the ventilators caused the firedamp problems. Thus, a single cross section, with suitable caution, can be used to study correlation but not causation. However, a panel can be analyzed so as to increase the likelihood of identifying a causal relationship in ways that would be impossible with a cross section.

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[35] 1873: Reports from Commissioners: Twenty-three Volumes. Factories; Mines. Session 5 March-7 August 1874, Volume 13. *Reports of the Inspectors of Mines to her Majesty's Secretary of State for the Year 1873* (1874), pp. 136-200. 1878: Reports from Commissioners, Inspectors, and Others: Twenty-seven volumes. Part 4: Mines, Session 5 December 1878-15 August 1879, Volume 18 (1878-79), pp. 183-228. 1883: Reports from Commissioners, Inspectors, and Others: Thirty Volumes. Part 3: Mines; Rivers Pollution Prevention Act. Session 5 February – 14 August 1884. Volume 19 (1884): pp. 95-120.

Here, in Table 5, we show the results of the following regressions. Each regression uses data from two years *t* and *t+5* (where t=1873 or 1878). The independent, right hand side variables take on values from the earlier year *t*. The dependent regressand on the left-hand side is a difference. In each regression only pits with furnace, steam, or natural ventilation in the earlier period were considered. The dependent variable for those pits that switched to fan ventilation in the next survey five years on took the value of 1, and for those pits that continued to use the same method the variable took on the value of zero. Regressing this switching variable on the early values of independent variables reduces the problem of reverse causation.

In each regression we consider the role of the earlier ventilation system, the presence of firedamp, and the depth of the mine. In addition dummies for region and type of ownership (corporation, peer) were included but were found to be insignificant and so were not reported. Panel A used the earlier data and Panel B the later years. We used OLS but the results are robust to estimation by logit. The two panels suggest differing processes. In the first, from 1873 to 1878, the most consistent feature of the mines that adopted mechanical ventilation was their greater depth than those that remained with natural or furnace ventilation (the omitted category is steam). The effect of depth was unrelated to the mine's status as "fiery", that is, subject to the presence of firedamp, or not.

As noted previously, the presence of firedamp created two distinct problems: it suffocated and it exploded. The risk of asphyxia rose along with its proportion of the air: one estimate of the lethal proportion was one-third, but miners would know of trouble well below that level because a mere five percent proportion of firedamp would extinguish a safety lamp.[36] The risk of fire, however, was nonlinear. Too little firedamp, and no danger existed; too much

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[36] Abel, *Coal Mine Accidents*, pp. 22-23. The one-third estimate was attributed to Guibal.

and the lack of oxygen prevented combustion. The danger zone was thought to be in the range of 7 – 33 percent, with a maximum explosion risk at 13 percent firedamp. Between 33 and 50 percent firedamp risk of explosion was replaced by simple ignition.[37] Even after European mines had brought problems with firedamp under control, the risk of explosions persisted due to the unexpected interactions with coal dust. German experiments early in the twentieth century found that an atmosphere consisting of a mere 2.5 percent methane could lead to a considerable explosion in the presence of coal dust.[38]

One result of this complexity was that no one value of the proportion of firedamp marked the boundary between a dangerous and a manageable level of firedamp. Belgian law aimed for the broadest possible definition of gassy mines, but concluded that once a royal decree of 1876 was in place, the only requirement in practice was for the chief engineer of the regional government to describe a mine as gassy.[39] In somewhat similar fashion, British law distinguished between findings of the presence of firedamp in mines in the previous three months and in the previous twelve months—but did not specify how much constituted its presence in the first place. As a result, wrote one prominent inspector, "these distinctions made in the law are purely theoretical, and…in reality no notice is taken of them in practice."[40] These ambiguities may have allowed for different levels of gas to constitute a gassy mine in different places. Pernolet and Aguillon, charged by the French Firedamp Commission with visiting mines elsewhere in Europe and reporting on their firedamp management practices, proposed that eastern Lanark held mines with "notable" levels of firedamp, especially near Hamilton. In England, though, some mines described as fiery would be considered normal in the basin of the Couchant de Mons. Still, they

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[37] Abel, *Coal Mine Accidents*, pp. 24-25.
[38] Rice, *Explosibility of Coal Dust*, p. 113.
[39] Pernolet and Aguillon, *Exploitation*, pp. 6-7.
[40] Steavenson, "Report," p. 7. The law was section 51 of the Coal Mines Regulation Act, 1872.

allowed, in many fiery English mines levels of firedamp really were “considerable and abundant.”[41]

All this is to say that there was no universal and explicit bright line that divided fiery from non-fiery mines. In the Scottish survey what demarcated a fiery from a nonfiery mine was the word of the mine owner or manager. Tables 4 report the proportions of mines that were or were not described as fiery. The proportion among all mines, not just those linked between observations, fell dramatically from 61 percent in 1873 to 36 percent in 1878, and then hardly changed at 34 percent in 1883. This trend appears in the linked samples as well. Clearly the big question in the earliest sample is what happened to all the fiery mines, which we will consider in our revising. They might have closed, they might have been reclassified for no reason, or the introduction of mechanical ventilation might have worked so well that they actually have lost all their methane in the intervening years.

The somewhat surprising part of fiery mines in Scotland was the substantial share of them that were ventilated by furnaces. Of all fiery mines in 1873, nearly 85 percent used furnaces. In 1878 that proportion fell to 58 percent, and then to 33 percent in 1883. Given the standard explanation in the Belgian case, that gassy mines necessitated mechanical ventilation, it seems odd that the Scots would not have substituted mechanical ventilation into their gassy mines much sooner. It may be, as traditionally thought, a result of differing methane levels in the two locations to determine fiery status. It may also be that British mine engineers had developed more effective furnace ventilation than was available on the Continent. In any case, once mechanical ventilation appeared in Scotland, it was first applied to fiery mines. In particular, the regression results indicate that fiery mines with furnaces were much more likely to get new

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[41] Pernolet and Aguillon, *Exploitation*, volume 2, pp. 45-47.

ventilating machines than either steam or naturally ventilated fiery mines or non-fiery mines ventilated by furnaces.

In the next five years (1878-83) attention shifted, perhaps as a result of having addressed the most serious problems of furnace ventilation in fiery mines. Most fiery mines in the linked sample were still ventilated by furnace, but the share of mines with firedamp problems had fallen in half. Because the drop was less in the cross sections, probably between 1873 and 1878 fiery mines were more likely to close, and thus not to be linked. At any rate in this later period the impact of firedamp appeared only in deep mines. Deep mines with firedamp problems were especially likely to switch to mechanical ventilation in this later period. It may have been that once the initial problems with furnace ventilation of fiery mines were addressed, the next problems were found in deep and fiery mines.

These results can be compared to those from a smaller and less complete set of mines in Belgium. The source of the earlier survey is easier to describe than to document its provenance. It appears in a volume of the government statistical annual.[42] No similar tables were published in the volumes before or after, nor did the volume with survey results mention anything about method or the identity of the investigators. The 1877 survey is different; we know quite a bit about its investigator, and as table 6 shows, its results line up reasonably well with the previous survey. However, the later figures concern not even a province, but an arrondissement within a province: the first in Hainaut. This is not as obscure as it might seem, as Hainaut produced about 2.5 times the amount of coal that Liège did, and about 40 times that of Namur. The source of the survey is clear: Arnould says that he drew the data from a report by the chief engineer to the

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[42] Royaume de Belgique, *Documents Statistiques publiés par le Département de l'Intérieur* 12 (1868), pp. 513-537.

provincial government—which explains why the second survey only covers this one arrondissement.[43]

Now having linked the pits in the two surveys, there are two ways to define a change in ventilation technologies. The first is, literally, if the ventilation system in the later survey differed from that in the first. If so, the dependent variable called *different ventilator* was set to 1 and zero otherwise. Alternatively, the 1877 survey provided the date at which the existing ventilator had started its service. If that date was later than 1866, then the dependent variable *new ventilator* was set equal to one and to zero otherwise. Different independent variables were available from the Scottish case: the number of mines owned by the parent firm loosely indicated the size of the controlling firm, perhaps an indicator of economies or diseconomies of scale. Similarly, the average per day coal production at the pit helped address scale economies. The number of splits in the pit reflected the simultaneous directions in which the ventilator had to draw or push air, and the depth in yards measured roughly how far the air supply had to travel. Finally a dummy recorded the ventilator's status as reserve (=1) or on first-line duty (=0).

Table 7 reports the results of both OLS and logit regressions. The results are not dramatic, but the observation period occurred when adoption of mechanical ventilation in Belgium was well underway (Figure 10), whereas the Scottish data discussed above describes the situation when mechanical ventilation was just beginning to take hold. In the Belgian case only two relations appear. First, pits in the possession of large mining firms that owned several other mines were less likely to see new ventilators installed, and less likely to see switches to other technologies. With the data at hand we cannot say if this was due to slow communications within the parent firm, or indeed whether the parent firm had already obtained leading technologies by

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[43] Arnould, *Mémoire Historique*. pp. 123-128. See p. 122 for source of the tables.

the time of the first observation in 1866. The other relation, much weaker, was that ventilators that were kept in reserve were less likely to be replaced. Intuitively it makes sense that the less used reserve ventilators were a low priority for updating.

The regression analysis suggests the following relationships. The differences between Scotland and Belgium may indeed be due to cultural or legal differences in the two lands. However, it might also be the case that the earliest adoptions of new technologies proceeded in a more orderly fashion that depended roughly on the local geology. The initial examples of Scottish mines that switched to mechanical ventilation were those that used furnaces to ventilate gassy shafts. Once these rather more immediate problems were addressed, the next mines to shift to the new technologies were those with firedamp in their deeper reaches. No sign of variation in adoption according to ownership structure was found. In the mature case of Belgium, the one variable that did consistently matter was the scale of ownership interests. It may have been the case that, in general, mines addressed geological issues first, and then decided to replace older mechanical ventilators according to processes at the corporate level. That is a generalization that we hope to test in the future.

Conclusions

The Industrial Revolution in Europe consisted of two processes: the invention of new mining and manufacturing technologies, and their improvement, so that the advances introduced earlier might continue. If the initial advances had not been followed up, they might have been lost as time moved forward. Instead, new complementary technologies and improvements on old technologies enabled productivity advances to continue. In coal production, the well-known early eighteenth century steam engine and pump developments enabled mines to sink deeper, at least until they encountered firedamp. To manage this lesser-known problem that could have thwarted coal production just as surely as excess water could have, a broad base of European mining engineers and operators, mining college instructors, and talented amateurs explored the possibilities of improved furnaces, air pumps analogous to water pumps, pneumatic screws, and finally centrifugal fans. Firedamp management became a international project.

The most obvious characteristics of this project were imagination and perseverance. Inventors worked off analogies to older water pumps and smaller grain dryers. After they introduced new machines, those machines were subject to relentless testing, with the results widely publicized. As a result, newer vintages of technologies outperformed the old ones, and as firedamp became a more manageable problem in more coal fields, the cost production in terms of human life fell.[44] The broad perspective on the European economy before the Great War usually focuses on the extent of international trade. But the role of competition in production of new technologies, and the easy exchange of information regarding these new products, suggests a similar Continent-wide phenomenon of specialization and trade. As of the *fin de siècle*, the efforts of each coal producing country to protect its own miners and to sink deeper shafts led to continent-wide advances—as if by an invisible hand.

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[44] Murray and Silvestre, "Small scale technologies."

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Table 1. Costs of ventilation methods, c. 1850.

Method	Cost to install (pounds)	Cost to operate (L per year)	Efficiency (useful effect/transmitted power in percent)
Furnace in upcast	6.5	49	50
Motte pneumatic screw	201	70	20-24
Letoret ventilator	244	92.5	16-20
Steam jets (Pelletan)	247	225	6-7
Cylinder pump	267	263	23
Fabry ventilator	617	109.6	55
Furnace at surface	923	616	4-5.5

Source: Parliamentary papers, reports 1852-53, pp. 142-47.

Table 2. Costs and benefits c. 1890, Wabner, Bewetterung, p. 196, citing Revue universelle des mines 1892 and Österreichicher Z.f.B.H. 1893.

	Mechanical efficiency (%)	Installation costs for fan alone (Marks)	Total installation costs (Marks)	Operating costs per day (Marks)
Guibal	51.3	5084	23975	1.596
Ser	47	7173	21100	1.404
Capell	57.5	6550	26000	2.085
Rateau	60.8	9300	23000	2.786

Average of four reported tests for each type

Table 3. Numbers of ventilation systems in mine surveys.

Survey date	Location	Number of different kinds of ventilators	Source
1869	Belgium	14	Harzé
1877	Couchant de Mons	9	Arnould
1882	Europe	19	Atkinson
1883	Prussia	14*	Prussian Firedamp Commission
1889	Europe	34	Von Hauer
1890-95	Lower Rhine-Westphalia	13	*Die Entwickelung*…. Table IX
1900	Europe	35	Wabner

*includes two types of steam jet apparatus, but excludes steam boilers on surface.

Table 4. Presence of firedamp and type of ventilation, Scotland.

Panel A, 1873:

	Fan	Furnace	Natural	Steam	total
Non-fiery	4	171	18	21	214
Fiery	14	284	21	14	333
Total	18	455	39	35	547

Panel B, 1878:

	Fan	Furnace	Natural	Steam	total
Non-fiery	31	222	20	11	284
fiery	56	92	1	9	158
total	87	314	21	20	442

Panel C, 1883:

	Fan	Furnace	Natural	Steam	total
Non-fiery	56	196	16	16	284
fiery	92	48	2	4	146
total	148	244	18	20	430

Note: all figures from complete samples (i.e., not the matched samples).

Table 5. Scotland: Regressions of fan adoption on previous survey conditions.

A. 1873-1878 (OLS); n=311. Mean of dependent variable= 0.22

	mean				
Natural	0.04	-0.01 (0.15)	-0.02 (0.14)	-0.003 (0.14)	-0.01 (0.14)
Furnace	0.90	-0.14 (0.10)	-0.42*** (0.14)	-0.13 (0.10)	-0.41*** (0.14)
Firedamp	0.65	0.06 (0.06)	-0.34** (0.16)	0.14 (0.10)	-0.27 (0.18)
Furnace*firedamp	0.59		0.44*** (0.16)		0.43*** (0.16)
Depth (feet)	306 (180)	0.08*** (0.01)	0.08*** (0.01)	0.11*** (0.03)	0.10*** (0.03)
Depth*firedamp	21.5 (21.7)			-0.35 (0.30)	-0.26 (0.30)
R2		0.18	0.20	0.18	0.20

B. 1878-1883 (OLS); n=219. Mean of dependent variable = 0.22.

	mean				
Natural	0.07	0.14 (0.16)	0.18 (0.18)	0.11 (0.16)	0.11 (0.18)
Furnace	0.88	-0.07 (0.12)	-0.02 (0.16)	-0.06 (0.12)	-0.06 (0.16)
Firedamp	0.31	0.28*** (0.07)	0.38* (0.22)	0.06 (0.12)	0.07 (0.25)
Furnace*firedamp	0.28		-0.10 (0.22)		-0.01 (0.22)
Depth (feet)	307 (226)	-0.004 (0.01)	-0.005 (0.01)	-0.02 (0.02)	-0.02 (0.02)
Depth*firedamp	13.1 (2.28)			0.06** (0.03)	0.06** (0.03)
R2		0.17	0.16	0.19	0.19

Table 6. Belgium: Types of ventilators in 1866, 1877 surveys

	1866 Belgium	1866 Couchant de Mons	1877 Couchant de Mons
Fabry	179	12	15
Guibal	39	8	10
Lambert	7		
Lemielle	23	12	12
Lesoinne	37		
Letoret	4		1
Mahaux	5		
Motte	5		
Pasquet	9		
Ordinary centrifugal fan	47	43	45
Other	6	2	3
Natural or furnace	9	9	
Total	362	86	86

It is likely that most “Ordinary centrifugal fans” were in fact of the Guibal design.

Table 7. Belgium: Regression of changes in ventilation 1866-77 on conditions in 1866.

		OLS		logit	
	Mean value	New ventilator	Different ventilator	New ventilator	Different ventilator
Dependent mean				41=1; 31=0	27=1; 45=0
Intercept		0.73** (0.37)	0.44 (0.35)	1.00 (1.53)	-0.25 (1.64)
Number of mines owned by parent	2.19 (1.74)	-0.06* (0.04)	-0.07** (0.03)	-0.27* (0.15)	-0.40** (0.20)
Number splits of air current	1.1 (0.33)	-0.19 (0.18)	-0.14 (0.17)	-0.82 (0.75)	-0.65 (0.80)
Depth in yards	448 (86)	0.06 (0.07)	0.03 (0.07)	0.25 (0.29)	0.14 (0.31)
Coal production per day	186 (95)	-0.03 (0.06)	0.09 (0.06)	-0.12 (0.27)	0.46 (0.30)
Reserve ventilator	0.19	-0.15 (0.15)	-0.27* (0.14)	-0.65 (0.60)	-1.35* (0.74)
Adj R2		0.01	0.07		

Figure 1. Furnace with dumb drift.

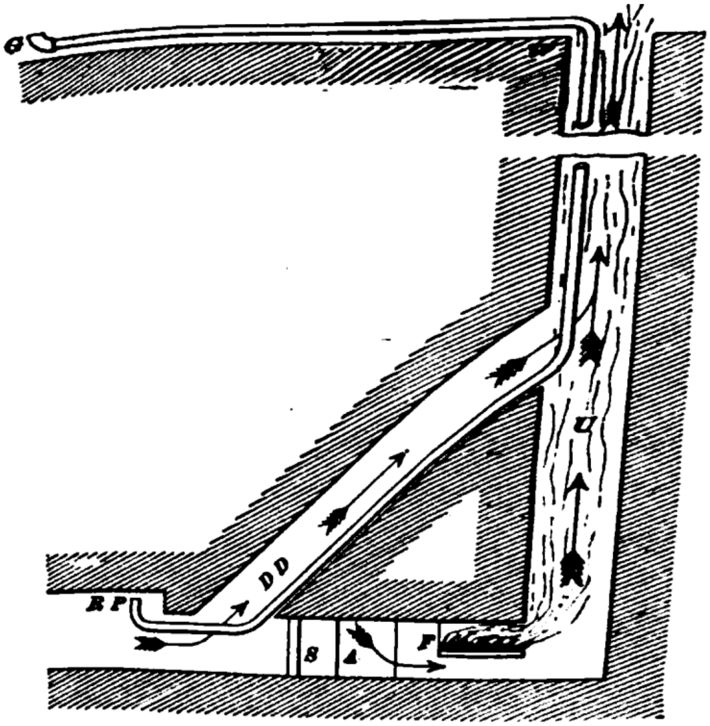


Figure 2. Bell-and-plunger ventilator installed at Grand Buisson mines, Belgium.

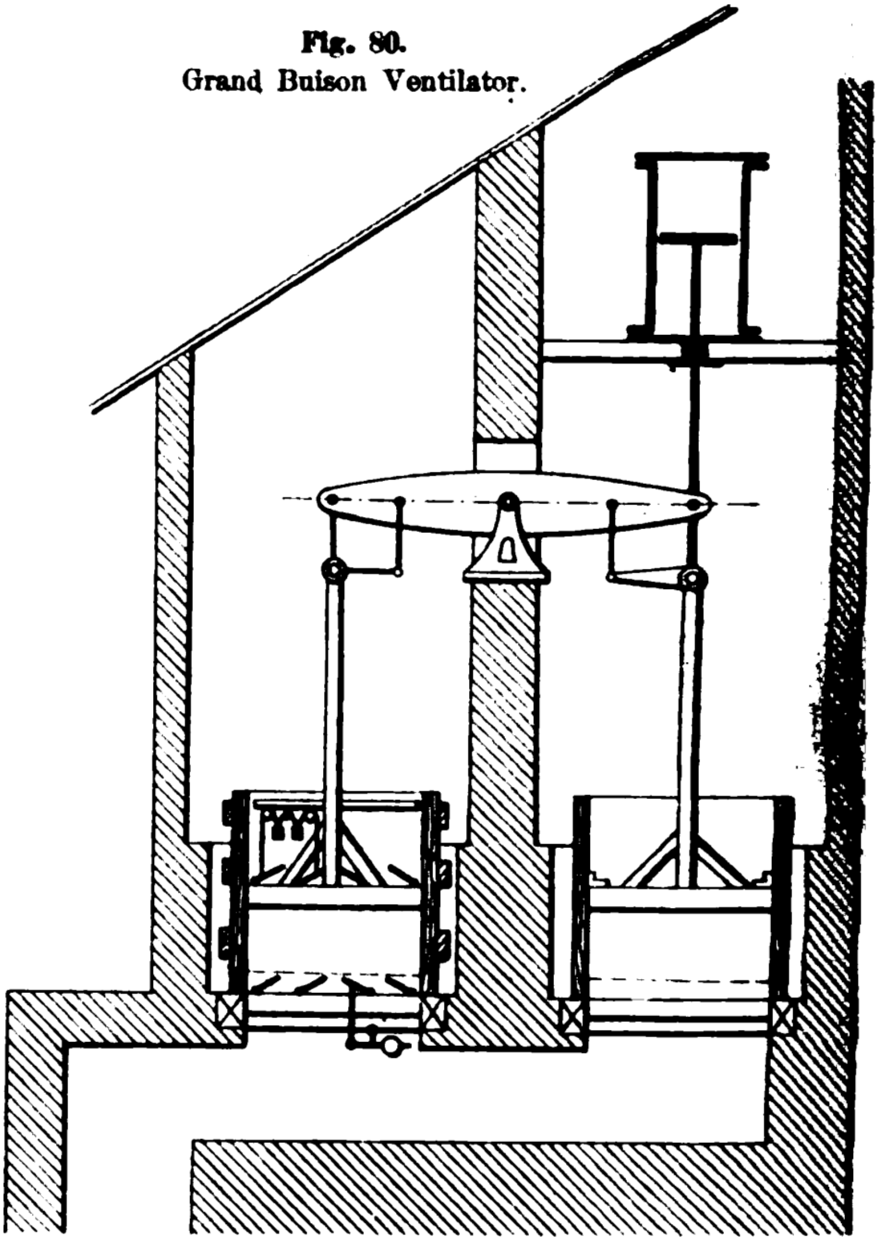


Fig. 80.
Grand Buison Ventilator.

Figure 3. Fabry, as viewed from top. Source: Andre, *Descriptive Treatise,* vol. II.

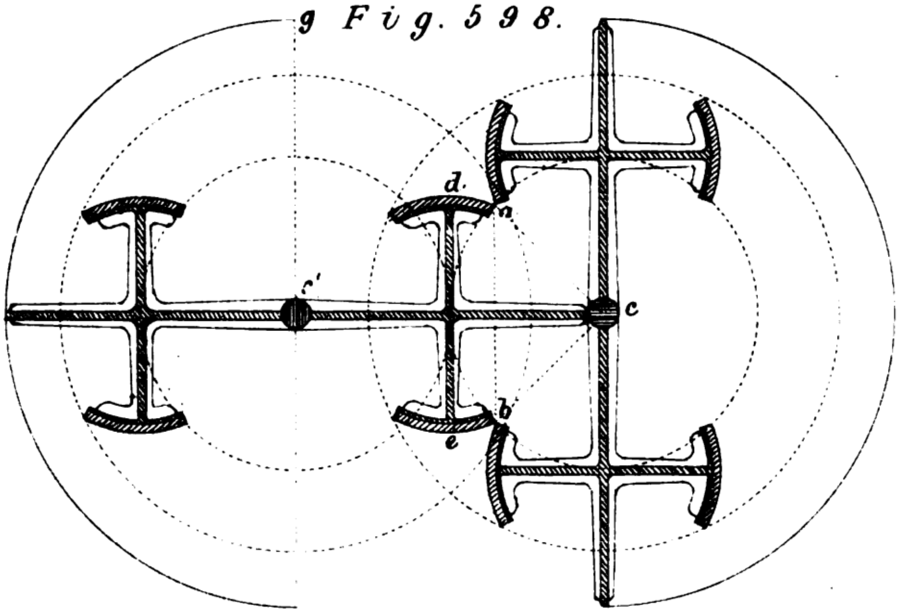


Figure 4. Motte's pneumatic screw. Source: Parliamentary Papers, Reports from Committees 1852-53.

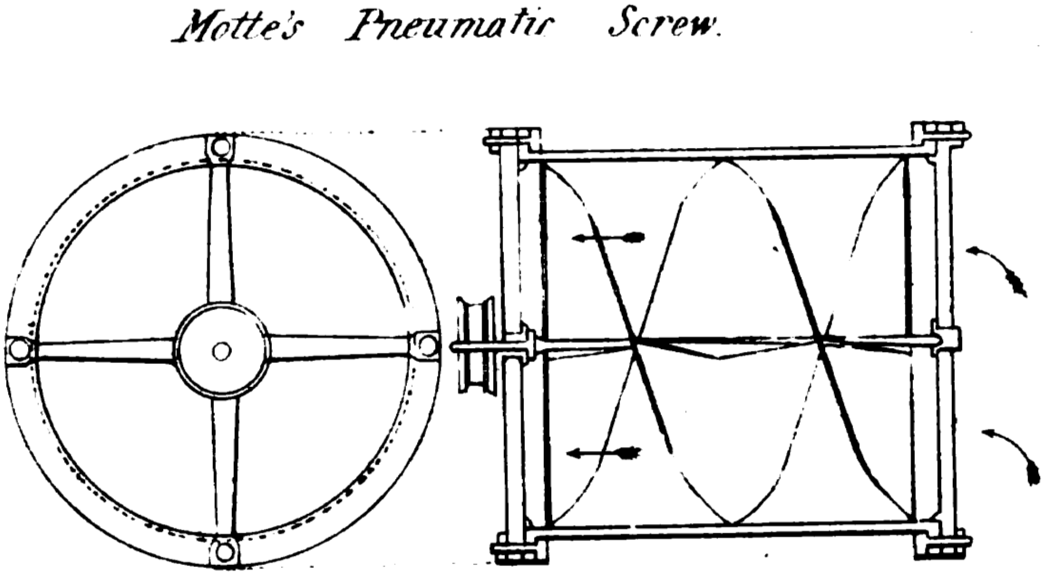


Figure 5. Letoret ventilator, an early centrifugal fan. Source: Parliamentary Papers, Reports from Committees 1852-53.

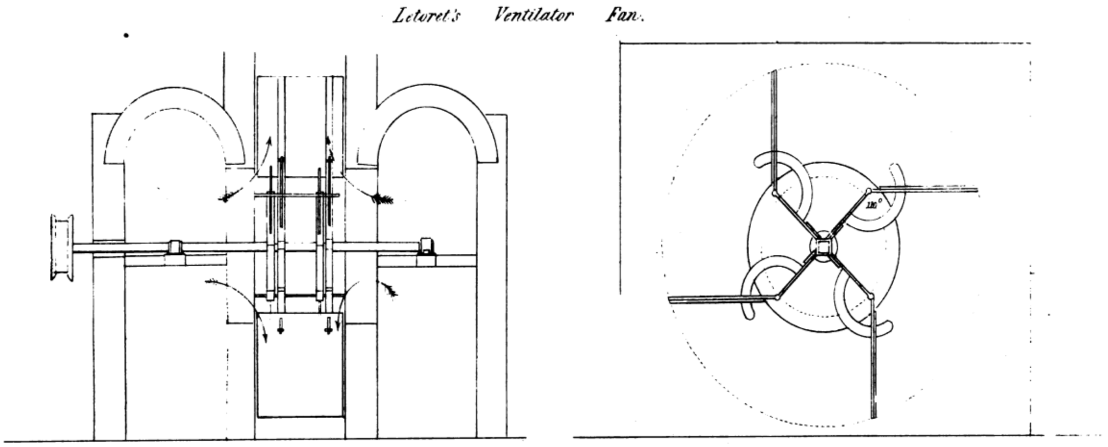
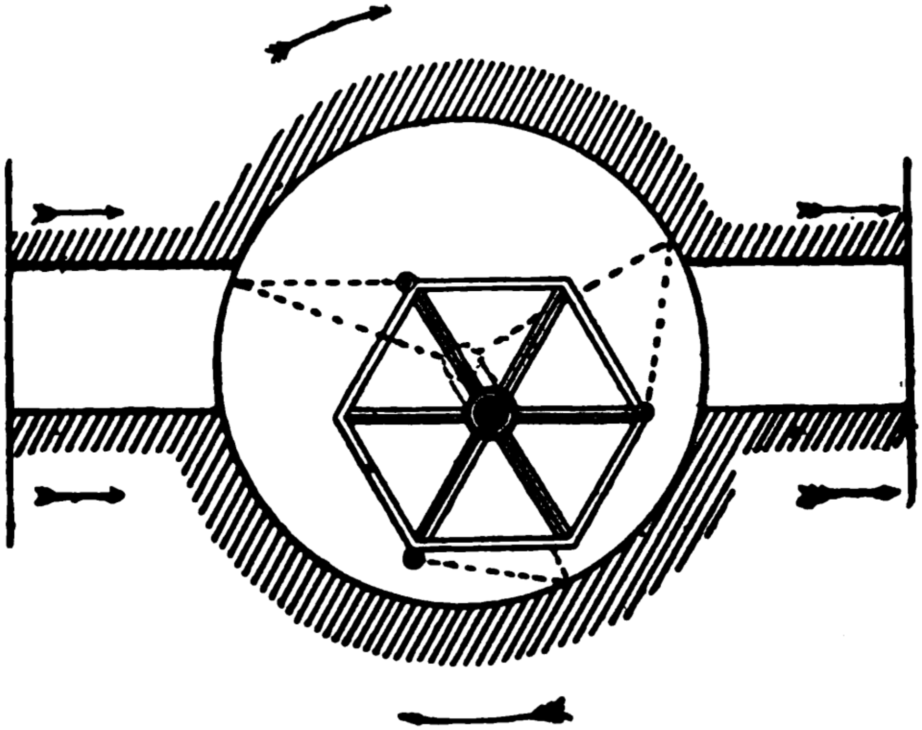


Figure 6. Lemielle ventilator, viewed from side.



Percy, vol. I, after p. 172.

Figure 7. Guibal, view from side. Note *évasée* chimney.

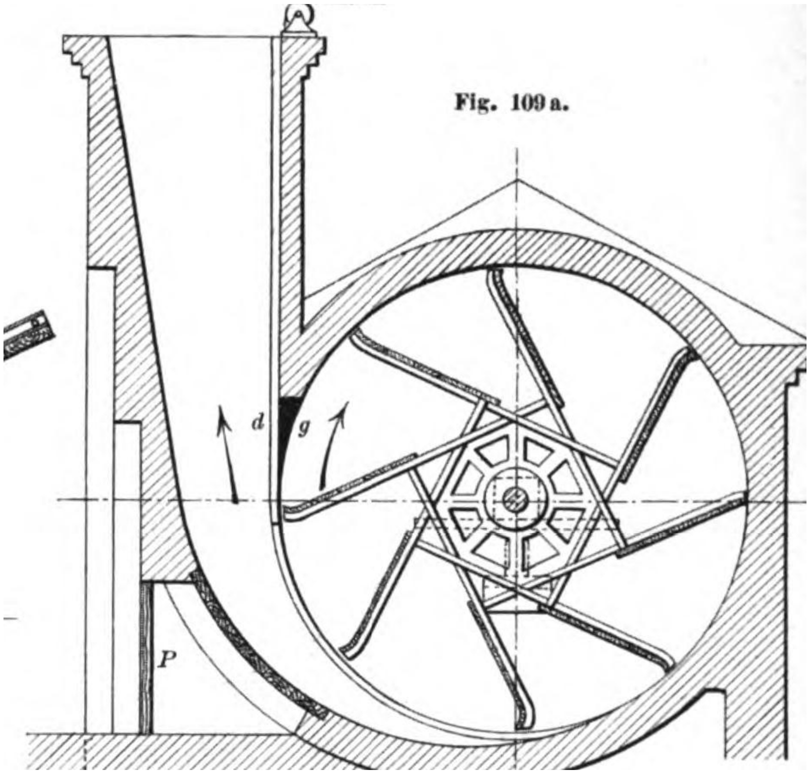


Fig. 109 a.

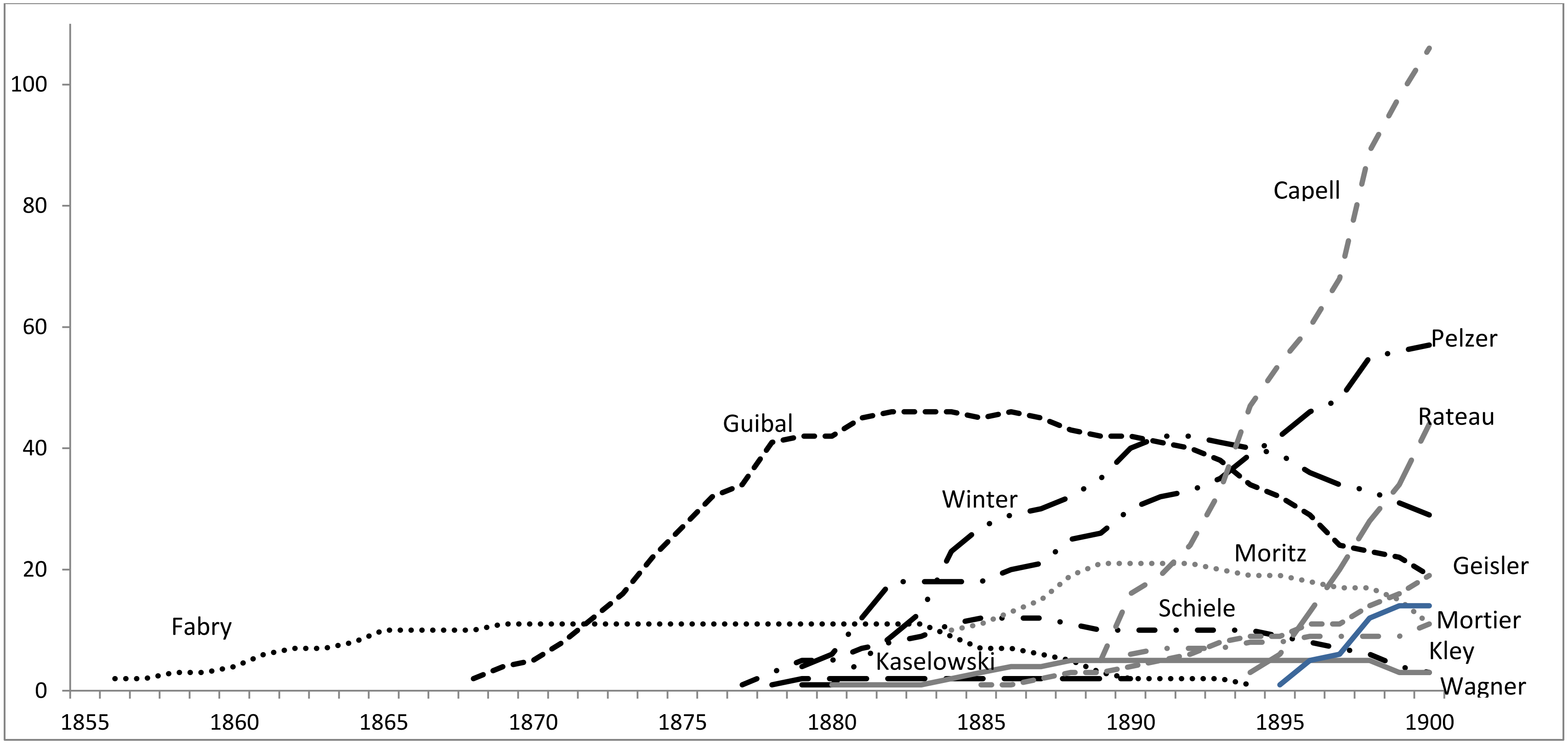


Figure 8. Types of fans in operation in Nordrhein-Westfalen region. Source: *Die Entwickelung*…, Tafel IX.

Figures 9a and 9b. Capell fan. Note the fan blades attached to outside of cylinder. Cf open axle of cylinder on Guibal.

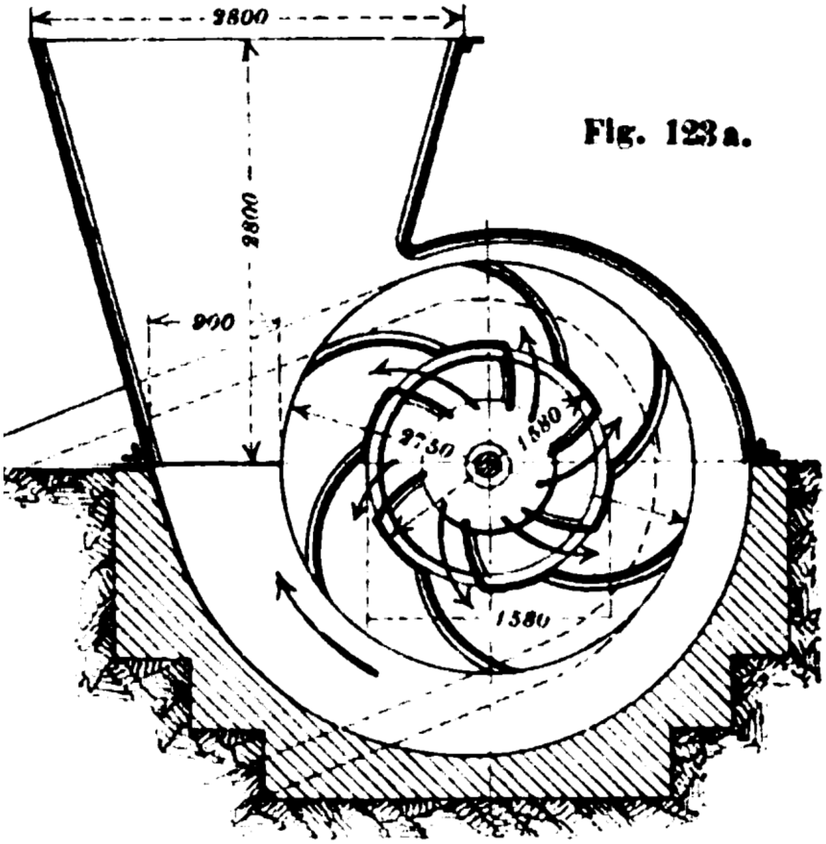
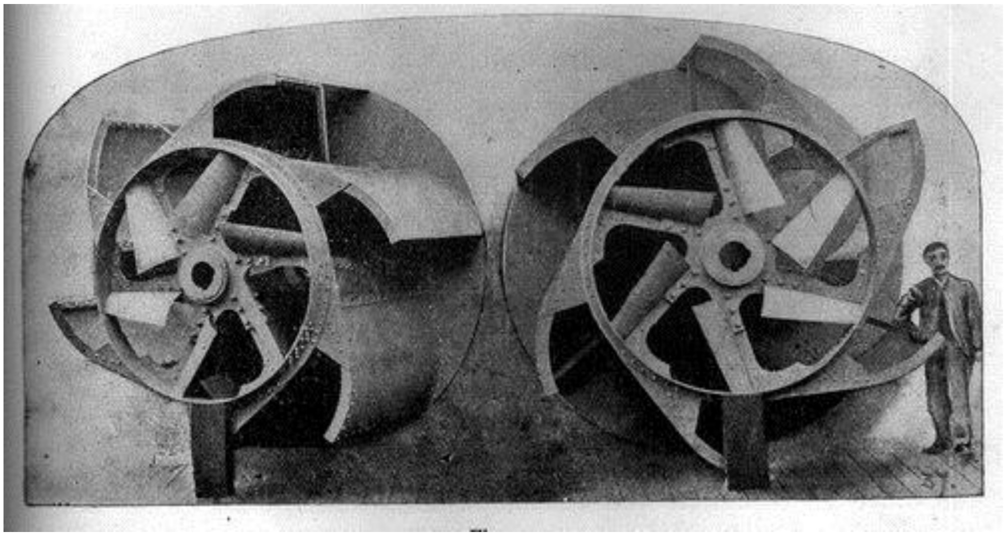


Fig. 123a.



Capell fans with better view of “scoop” on outside of cylinder. (http://www.pleasley-colliery.org.uk/html/capell.htm)

Figure 10. Coal mine ventilation throughout mining regions in Europe.