Process technology adoption in European coal, 1850-1900:

Mechanical ventilation in coal mines

John E. Murray and Javier Silvestre

murrayj@rhodes.edu and javisil@unizar.es

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Coal was the energy source that powered the Industrial Revolution. Britain's endowment of the mineral, combined with innovations in coking, led to leadership in eighteenth century iron production. On the Continent, Belgium's coal deposits enabled it to industrialize not long after Britain. But most retellings of the Industrial Revolution limit analysis of increased coal production to early process technologies such as the Savery and Newcomen pumps. These machines, which later gave way to separate pumps connected to steam engines with Watt condensers, allowed the search for coal to run ever deeper by removing groundwater. In the time after pumps solved the problem of flooding, written histories shift their attention elsewhere, as if greater coal extraction simply happened without interruption—and without interest. But of course this was not the case. Eighteenth century pump technology addressed one bottleneck among many in the coal production process, albeit an important one. If other constraints had not been solved later in the nineteenth century, the seven-fold increase in European coal production between 1850 and 1900 would not have been possible. One of those constraints was ambient explosive gas. In this paper we consider a particular kind of new process technology in coal mining, mechanical ventilation, that aimed to solve the problem of methane.

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 was flammable and explosive (depending on its density) in the presence of open flames. Open flames were surprisingly common among miners. To light their work, they initially brought candles to the coal face, which led to fatal accidents in the presence of firedamp. Engineers and tinkerers mitigated this problem in many ingenious ways. The best known solution involved the safety lamps of Davy, Stephenson, and Clanny around 1815, a well-known case of nearly simultaneous invention. The safety lamp shielded the flame from the gas with wire gauze. Because mine fires and explosions continued, attention focused on better methods of removing firedamp from the mines. Until the middle of the nineteenth century the primary method of ventilation, the furnace, was based on the observation that heated air rose, and so a furnace at the bottom of an "upcast" shaft would send exhaust air to the surface. Use of furnaces in mines with firedamp presented obvious problems, and the increased fuel requirements of furnaces in ever deeper mines opened doors to mechanical ventilation. Engineers and tinkerers throughout Europe worked on machines to create air currents that would remove methane and replace it with air from the surface.

Those machines are the subject of this paper. Mechanical ventilation was a subject of research and experimentation throughout coal producing areas of Europe. Research proceeded at active mines, in mining colleges, in government inspectorates, and in experimental mines. Much as in Allen's theory of collective invention, experimental information was freely shared, although the resulting machines were often patented and licensed.[1] Inventors tested machines of varying degrees of efficacy. The mining press throughout Europe reported in detail on field trials and tests in functioning mines. Governments in Britain, France, Prussia, Saxony, Belgium, and Austria created firedamp commissions, and charged them with studying mines foreign and domestic and reporting on the ventilation practices that they observed. The most important journal articles were translated and republished in short order.

Research in mining engineering was difficult. The disasters that engineers hoped to prevent were rare events, and witnesses typically were killed and evidence destroyed in the explosion. Thus, a particular difficulty lay in trying to replicate the conditions that caused the accident. Gains from sharing information in the mining press included the reduced probability of

[1] Allen, "Collective Invention."

a work stoppage following an accident, the maintenance of a mine's work force, and the humanitarian concern with avoiding lethal workplace accidents. To go by written descriptions of different ventilation technologies, mine ventilation appears to have been a problem not solved by a single invention, but managed through a process of invention of several different kinds of mechanical ventilators.

The process of research and development of this particular process technology addresses several 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.[2] 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 that the Almighty had conveniently placed near rivers or cities. But the most fortunate natural resource endowments have 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.[3] Pomeranz noted that Chinese mines also suffered from poor ventilation and "spontaneous

[2] Wrigley, *Energy and the English Industrial Revolution*. The necessity of coal for the Industrial Revolution proper has since been disputed by Clark and Jacks, in "Coal," which discounts the importance of new coal production technologies for continued industrialization. The technology they consider, however, is primarily the early pump, and only in England. Further, their period ends at 1860, a time when mechanical ventilation was still new; the Guibal fan as noted below was patented in 1858. See also McCloskey, *Bourgeois Dignity*, pp. 186-196 ("Not Even Coal").
[3] Wright, "Origins of American Industrial Success."

combustion" (presumably from coal dust or methane), the very problems Europeans eventually solved in large part through the mechanical ventilation discussed in this paper.[4]

A short history of mine ventilation

Descriptions of mine ventilation appear as early as the sixteenth century *De Re Metallica*. Metal mines did not encounter problem gasses 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 drift or adit (walk-in) mines driven into hillsides. With a higher and a lower entrance into the same mine, connected in a U- or 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 shaft mines required a stronger method of ventilation. Here mine engineers used their knowledge that warm air rises to sink two shafts, one at each end of the gallery where the coal was mined. The downcast shaft carried air into the mine from above, and the upcast carried stale air and firedamp, which was lighter than air, 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 air (Figure 1). The furnace heated the air in the upcast, thereby pushing it upwards, and drawing fresh air through galleries that were connected to it. Although it was common to build two separate shafts for the up- and downcast, a few single-

[4] Pomeranz, *Great Divergence*.
[5] Agricola, *De Re Metallica*, 203-207.

shaft mines used a brattice (a portable divider made of wooden frame covered by canvas) to split one shaft into two sections side-by-side.

Furnaces were cheap to operate and productive. Fuel was small coal that had been dug from nearby galleries. Furnaces had no moving parts and were reliable, which kept them in use after the introduction of mechanical ventilation which came with the usual initial bugs. As we indicate below they were also used in mines with firedamp. They were effective. In 1876 William Galloway estimated in a particular mine that its furnace reduced firedamp concentration from four percent with natural ventilation to less than one percent.[6] Still, between cost and productivity concerns, an opening remained for mechanical ventilation. An American engineer roughed these out for a typical Midlands mine c. 1870: a mine about 150 feet deep cost about $19 in wages and foregone sales of coal to ventilate with a furnace. With the then popular Guibal fan of 40 feet diameter, the cost of ventilation fell to $6 per day but the volume of cubic air moved through the mine was half again as much as the volume produced by the furnace.[7] Such cost-benefit improvements could well have led to the coal supply curve shifting to the right in the later nineteenth century.[8]

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.[9] 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. Underground furnaces were inexpensive to

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[6] William Galloway. “On Coal-dust Explosions,” pp. 33-34, 65-66.
[7] Clifford, “Furnace,” 69.
[8] Clark and Jacks, “Coal, 69: “…little sign of a technological revolution in coalmining.”
[9] First, Second, and Third Reports from the Select Committee on Accidents in Coal Mines, in Parliamentary Papers, Reports from Committees: 1852-53, Thirteenth Volume.

build and operate while above ground furnaces were scarcely more cost-effective than the exotic new mechanical technologies. Miners themselves showed little interests in the new technologies. Allan Tetlow, a former miner and Lancashire miners' union official, reported that his union brothers were indifferent between furnaces and steam jets, but preferred either to weak and untrustworthy natural ventilation.[10] Regarding the open flame in a potentially gassy mine, Herbert Mackworth, a government mine inspector, considered a furnace with a dumb drift "perfectly safe."[11] 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.[12] That margin and the ability of fans to work safely in gassy mines was an important factor in their adoption.

At mid-century the only alternative to furnace ventilation was steam. Steam 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 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 low cost. Experiments with steam in Belgium, where mines tended to be gassy, 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

[10] Select Committee on Accidents in Coal Mines, Second Report, 69.
[11] *Reports from Committees: Accidents in Coal Mines*, 36.
[12] Kerr, *Practical Coal Mining*, 334.

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.[13]

During this time a few inventors, nearly all Belgian, persisted with attempts to build mechanical ventilators. Early designs had historical precedents. One early prototype aimed to mimic the motions of water pumps that had drained water from mines successfully. This was the plunger and bell machine. The plunger worked like a piston and the so-called bell like a cylinder in a conventional steam engine. Three were custom-made for Belgian mines. These included the horizontal Mahaut ventilator in Charleroi, and two vertical plungers, one each at the Bonne Esperance mine in Seraing and at Grand Buisson (Figure 2). Similar machines appeared 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*.[14] A different, historically oriented approach mimicked 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.[15]

An important step forward was to concentrate on centrifugal fans. Rather than move air parallel to the axis of the fan blades, a centrifugal fan moved air over the axis. Some were in use on the Continent by mid-century. Having already developed his own condenser for a steam engine, Charles Letoret patented a centrifugal ventilator in November 1841, just after testing it at the L'Agrappe colliery, Couchant de Mons, Belgium (Figure 4). Here was the first machine

[13] Wabner, *Bewetterung*, 124-128. Given the interest of historians in methods of mitigating or shifting risk, it is noteworthy to see that the concept influenced mine design and equipment in the later nineteenth century. See for example Aldrich, "Engineers."
[14] Wabner, *Bewetterung*, 125-145; Atkinson, *Key*, 65.
[15] *Bulletin Officiel des lois et arrêtés royale de la Belgique*, 2e semester 1839. Patent number 832, p. 909.

powerful enough to ventilate an entire mine. Within two years Letoret had installed machines of his design at another pit at L'Agrappe and at Grand-Piquery. An unusual shape was patented by the Belgian Theodore Lemielle in 1854 (Figure 5). 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 had a moderate impact. It was developed by Adolphe Lesoinne, a professor of metallurgy in Brussels. In 1845 he introduced his windmill-like fan of 2.7m diameter. It resembled a simple box fan of the present day turned on its side, over the opening of the shaft.[16] The machine successfully worked at the Grand Bac mine in Liège province and by 1858 there were 45 Lemielle ventilators in use. By 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. However, at no point did experimentation on new kinds, or refinements of old kinds, of technologies cease. Further, the center of ventilation technological development was Belgium, known throughout Europe for the high density of firedamp in its mines. Thus, this pattern may represent an example of induced innovation.[17]

The earliest successful technology was a lobe pump. Auguste Fabry, a mine engineer at Charleroi in Hainaut, introduced this ventilator (Figure 6) in 1845. The Fabry ventilator used two interlocking sets of blades that rotated on vertical axes, in opposite directions, to expel air. It met with some early success, first appearing at the Grand Buisson mine in Hainaut in 1850. This ventilator did not scale up successfully due to vibrations at high speeds. Tolerances required to prevent this problem were beyond machinists' skills at the time. As a result it remained in

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[16] Caulier-Mathy, *La Modernisation*, pp. 242-243.
[17] Arnould. *Bassin Houiller*, 120-122; Harzé, "De l'aérage des mines," 201-205; Gonzalès Decamps, "Mémoire Historique," 85-87; Wabner, *Bewetterung*, 151-153 ; Laurent, « On the Lemielle system, » p. 134.

service in spaces where only moderate ventilation was required, such as metalworking and machine shops. Still, as late as 1873, there were 82 Fabry ventilators in Hainaut mines, some of which were kept in reserve in case the primary system failed. The Fabry seems never to have gained a foothold in Britain.[18]

It was Théophile Guibal (1814-1888) who gave European collieries the most successful centrifugal ventilator of the 1850-1890 period (Figure 7). Guibal was born in Toulouse and educated at the Ecole Centrale des Arts et Manufactures de Paris, but his engineering research occurred in Belgium. At age 23 participated in the founding of the School of Mines in Mons (today the engineering faculty of the University of Mons.) Guibal developed a broad research agenda, which included invention of an anemometer and a measure of a mine's resistance to forced air, called temperament, which he expressed as the square of the volume of air moving past a line each second, divided by the pressure needed to cause that air current. His greatest achievement was the centrifugal ventilator that bore his name. He experimented with it as early as 1855, 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 before the mid-1880s. After the diffusion of his machine through Britain, Guibal was elected an honorary member of several engineering societies. On his death a British engineer eulogized him: "What M. Guibal did in his life was of world-wide importance."[19]

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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[18] 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.
[19] Cochrane, "Obituary Notice"; Arnould, *Mémoire Historique,* 121; Gonzalès Decamps, "Mémoire Historique," 87.

from the fan blades, lest it be suctioned back into the machine, thereby reducing efficiency. To this end, Guibal encased the fan and created a distinctive *évasée* chimney that widened as it rose. To connect the fan to the chimney he introduced a sliding shutter in the casing that allowed variation in the quantity of exhaust. This advance was especially useful in an era of steam power, when the ability to adjust the power of a machine was limited. Finally, after some experimentation, he found that angling the blades of the fan back, away from the direction of rotation (like a broom rather than a shovel), allowed it to evacuate more air. As the efficiency of the Guibal fan became known outside Belgium its popularity rose throughout Europe. One estimate in 1875 placed 180 fans in England, 85 in Belgium, 60 in France, and 30 in Germany.[20] Figure 8, shows the numbers of types of ventilators in the Niederrhein-Westfalen region, which included the Ruhr mines. Here the Guibal was the most common fan in use between 1872 and 1890.[21]

The Guibal, like other dominant technologies, faced competition. Figure 8 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. 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

[20] Arnould, *Bassin Houiller*, 121.
[21] Carpenter, “Ventilation,” 7

faster.[22] The next successor, the Pelzer, was a small, high speed fan.[23] 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.[24] 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 rotated at a faster rate (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.[25] 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.

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[22] Hauer, *Die Wettermaschinen*, pp. 118-119.
[23] *Haupt-bericht der preussischen Schlagwetter-commission*, 186.
[24] No author, “The Capell Fan: An Interesting Account of the Invention and Subsequent Improvement of this Wonderfully Efficient Mine Ventilator.” *The Colliery Engineer and Metal Miner* 16 (November 1895), pp. 80-81.
[25] Capell, “Observations,” p. 215.

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 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"; that is, not by Capell himself.[26] Part of the friction he found was due to the widespread opinion among European engineers that the best possible technologies were already in use and so could not be superseded, as Capell was claiming he had done. Wabner criticized the Capell fan because some test results reached levels "demonstrated impossible by Guibal," so that the new fan could not possibly be as powerful as promised. Wabner also complained that it lacked "any theoretical grounds for this peculiar arrangement of the fan blades…which cannot possibly facilitate the passage of air through the fan."[27] And yet, it moved.

Capell defended his patents vigorously. 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.[28] In Germany he licensed production to the R.W. Dinnendahl firm of Essen, which also produced its own line of less successful ventilators.[29] A few engineers could see rather early on that the unlikely inventor Capell really had created an effective fan, despite his university education in the classics and his primary occupation in the church. In 1882 Atkinson, a prominent English

[26] Discussion following Capell, "Observations", pp. 209, 211.
[27] Wabner, *Bewetterung*, 191. See also Le Chatelier, *Le Grisou*, p. 99.
[28] *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.
[29] Hauer, *Wettermaschinen*, 123-125, 192; Jicinsky, *Manual*, p. 148.

mine inspector, expected that, in time, the Capell would prove to be the only ventilator that achieved a low cost in installation, high productivity in use, and steady reliability over time. He was right.[30]

The last notable advance of the nineteenth century was not a machine but a theory of ventilation. A professor at the Ecole Centrale de Paris, Louis Ser (1829-1888), produced the system and one machine that embodied its principles. A civil engineer who concentrated on ventilation of hospitals, Ser wrote the great scientific work of later nineteenth century mine ventilation in 1878.[31] In this article, Ser applied broader principles of fluid dynamics, especially as developed by Bernoulli, to particular problems of centrifugal fans. Ser represents then a shift away from part time (if talented) tinkerers like Capell to full time researchers trained in the sciences. He concluded with some formulas for optimal fan dimensions. With forward curved blades (like shovels rather than brooms), Ser fans 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.[32]

To determine the more productive fans, comparison required a measure of the fan's productivity. Quantifying fan productivity turned out to be a complex task. Laboratory work yielded several measures of useful effect for a given fan depending on the number of revolutions per minute. One figure measured fan productivity in a technical sense, without respect to values

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[30] Atkinson, *Key to Mine Ventilation*, 95.
[31] Ser, "Essai d'une Théorie."
[32] 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.

of costs or benefits. This was the so-called percentage of useful effect (or *Mechanischerwirkungsgrad*). Borrowed from earlier work on water pumps in deep mines, useful effect was defined simply the ratio of horsepower of the work done by the fan to horsepower produced by the engine that drove the fan. Some engineers believed that this was "the fundamental quality to be considered."[33] Regarding useful effect, 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, suggesting some degree of technological progress. A complementary figure considered the work of a fan at an actual mine. After all, the real test of a fan was in the opening to a pit. Here the effectiveness of the fan depended not only on the power of the fan but on the drag created by unique characteristics of each mine. A mine with smooth ceilings and walls and few curves could make an inefficient fan look strong, and a strong fan set above a mine with rough sides and roads splitting at odd angles might ventilate inefficiently. The available figures usually represent the fan's production in one of two situations, either in the lab or at a particular mine. To deal with mine-to-mine discrepancies, the French engineer Daniel Murgue proposed a standardized measure which he called the equivalent orifice, defined as 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.[34]

[33] Galloway, *Course of Lectures*, subject 6—Ventilation, p. 68.
[34] 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.

Fiery mines and the diffusion of mechanical ventilation across Europe

The presence of firedamp created two distinct problems: it suffocated and it exploded. The risk of asphyxia rose along with the proportion of firedamp in the air: one estimate of the lethal proportion was one-third, but miners would know of trouble well below that concentration due to the lengthening of their safety lamp's flames and their changing color.[35] The risk of combustion was nonlinear. Too little firedamp, and no danger existed; too much and the lack of oxygen prevented combustion. The danger zone was in the range of 7 to 33 percent, with a maximum explosion risk at 13 percent firedamp.[36] Even after European mines seemed to have controlled most risks of firedamp, the possibility of explosions persisted due to unexpected interactions with coal dust. German experiments early in the twentieth century found that an atmosphere consisting of 2.5 percent methane could lead to a considerable explosion if coal dust were present.[37]

In European mines firedamp concentrations were found along a broad continuum. Studies of western German mines found firedamp concentrations to range from trace levels to nearly 90 percent, although some of the high concentration samples were collected near blowers. Around the turn of the century J. S. Haldane analyzed several Staffordshire mines, both in the upcast and downcast shafts. His findings ranged from trace amounts of less than a tenth of one percent up to seven percent. Upcast air yielded a proportion of oxygen of about one-fifth, indicating that workers could survive in that atmosphere. As Haldane noted, miners were at risk of a variety of

[35] Abel, *Coal Mine Accidents*, pp. 22-23. The one-third estimate was attributed to Guibal.
[36] Abel, *Coal Mine Accidents*, pp. 24-25.
[37] Rice, *Explosibility of Coal Dust*, p. 113. In other work we study the development of gas detection technologies at this time, and the decline in the estimated concentration of firedamp that could lead to explosions, both with and without coal dust.

deficiencies and impurities underground, whether too little oxygen or too much nitrogen or carbon dioxide.[38]

One result of this complexity was that no single 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 for a mine to be gassy was for the chief engineer of the regional government to declare it so.[39] In somewhat similar fashion, Prussian law left the declaration of a mine as gassy or not to the discretion of state experts and inspectors.[40] 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 firedamp made it "present" 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."[41] 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 had firedamp concentrations that would be considered normal in the basin of the Couchant de Mons. Still, Pernolet and Aguillon allowed, in many fiery English mines levels of firedamp really were "considerable and abundant."[42]

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[38] Le Neve Foster and Haldane, *Investigation*, pp 125-27; *Haupt Bericht*, pp. 60-61.
[39] Pernolet and Aguillon, *Exploitation*, pp. 6-7.
[40] "Ventilation," p. 22.
[41] Steavenson, "Report," p. 7. The law was section 51 of the Coal Mines Regulation Act, 1872.
[42] Pernolet and Aguillon, *Exploitation*, volume 2, pp. 45-47.

All this is to say that no coal producing country in Europe established a universal and explicit bright line that distinguished fiery from non-fiery mines. A Belgian law of 1884 divided gassy mines into three categories: those with little *grisou*, those with *grisou*, and those in which miners made instantaneous contact with *grisou*. No percentage values distinguished a little, from some, from a lot. Typically, a later report observed, pits reached the higher *grisou* ratings at greater depths. In all, a quarter of all Belgian mines in 1887 were found to be not fiery at all, and another quarter fell into the first category.[43] In Prussia around 1880 a slight minority of mines was fiery, but they were the most productive, winning nearly two-thirds of all Prussian coal (Tables 4 and 5). In the Saar basin nearly all mines were gassy, but furnaces accounted for two-fifths of ventilators, implying that many mines were evacuating firedamp with furnaces. In Lower Silesia, there were about 15 furnaces for each mechanical ventilator; yet fiery mines accounted for about three-fifths of production, so it is likely that some mines ventilated by furnaces were fiery.[44] In the Scottish survey what demarcated a fiery from a nonfiery mine was the word of the mine owner or manager. Table 6 reports the proportions of dry and fiery mines. The proportion among all mines, not just those linked between observations, that were fiery fell dramatically from 61 percent in 1873 to 36 percent in 1878, and then hardly changed at 34 percent in 1883. In addition, deeper mines were more likely to be fiery, as in Belgium.

Mechanical fan ventilation was not a single technology that succeeded furnaces or steam, but a variety of different machines that moved air through mines. The one outstanding characteristic of the diffusion of this technology 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

[43] Roberti-Lintermans, “Les Inflammations de grisou,” pp. 218-219.
[44] *Haupt Bericht*, pp. 39, 45.

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 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 yet to reach 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 behind walls, which blasted forth in jets when disturbed by miners ("blowers").[45] To reach deeper coal required new ventilation technologies, such as the Fabry and Lesoinne ventilators. More would follow. Their effects were evident. Although gassy mines were much more common in Belgium than elsewhere in Europe, the rates of death by accident among Belgian miners were comparable, and in some decades the lowest in Europe.[46]

Beyond the pioneering Belgian case, patterns in numbers of ventilating machines suggest that no technology dominated 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. This can be seen, first, in several reports of working machines at a particular time, and, second, in 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 John Cockerill at the St. Marie shaft at Seraing in 1878. It proved to be less efficient

[45] Pernolet and Aguillon, *Exploitation and Réglementation*: Volume I: Belgium, p. 15.
[46] Roberti-Lintermans, "Les Inflammations de Grisou," pp. 219, 222.

than a Guibal fan and so the Kraft remained one of a kind.[47] Many varieties of machines proved to ventilate mines adequately. A royal commission reported in 1886 that the most commonly employed machines on the Continent included seven different kinds (Guibal, Lambert, Winter, Pelzer, Goffint, Harzé, and Fabry). In Britain alone four machines were in widest use: Guibal, Waddle, Schiele, and Capell.[48] In surveying as many sources as we could find over the 1850-1900 period, we found references to 57 different types of fans. 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.

[47] Wabner, *Bewetterung*, 158.
[48] Commissioners Report on Accidents in Mines, p. 10; Atkinson, *Key to Mine Ventilation*, p. 95.

So far we have been able to recover panel data from pit- or mine-level surveys in two 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 (Figure 11). Moore's primary assignment was to see how carefully mine operators followed the Coal Mines Regulation Act of 1872, and so 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.[49] The years for which data happen to be available are of particular interest, as the percentage of Scottish pits with mechanical ventilation rose from about three percent to about 30 percent over this time (Table 6).

Another valuable aspect of the Moore surveys is that he returned to 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

[49] 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.

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.

Here, in Table 7, 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 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.[50] 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 earlier values of independent variables mitigates problems 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 on adoption was unrelated to the mine's status as "fiery", that is, subject to the presence of firedamp, or not.

[50] In each five year period, one pit ventilated by a fan switched to furnace ventilation.

An important regression result is that once mechanical ventilation appeared in Scotland, it was first applied to fiery mines. A notable characteristic of fiery mines in Scotland was the substantial share of them that were ventilated by furnaces. The ability to link Scottish records makes this clear, although the aggregated German data mentioned above are suggestive of the same conclusion. In eastern Scotland of all fiery mines in 1873, nearly 85 percent used furnaces. In 1878 that proportion fell to 58 percent of fiery mines ventilated with furnaces, which then fell to 33 percent in 1883. If gassy mines required mechanical ventilation to be safe enough to work, it seems odd that the Scots would not have substituted mechanical ventilation into their gassy mines much sooner, but again, we do not know exact concentrations of firedamp in these mines. In any case, the regression results indicate that fiery mines with furnaces were much more likely to get new 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 1866 survey is easier to describe than to document its provenance. It appears in a volume of the government statistical annual.[51] 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 8 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 provincial government—which explains why the second survey only covers this one arrondissement.[52]

Now having linked the pits in the two surveys, there are two ways to define a change in ventilation technologies. The first is, qualitatively, 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

[51] Royaume de Belgique, *Documents Statistiques publiés par le Département de l'Intérieur* 12 (1868), pp. 513-537.
[52] Gustave Arnould, *Mémoire Historique et Descriptif: Bassin Houiller du Couchant de Mons*. 1877, pp. 123-128. See p. 122 for statement on the source of the tables.

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 9 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 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 technologies, and the improvement of established ones. Thus the advances introduced earlier might continue. If the initial advances had not been followed up, resource constraints would have caused stagnation. Instead, new complementary technologies and improvements on old technologies enabled productivity advances to continue. In coal mining, 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 an 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.[53] 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

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

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.

References

Abel, Sir Frederick Augustus. *Mining Accidents and their Prevention*. New York: Scientific Publishing Company, 1889.

Agricola, Georgius. *De Re Metallica* (tr Lou Henry Hoover and Herbert Hoover). Mineola, N.Y.: Dover Publications, 1950.

Aldrich, Mark. "Engineers Attack the 'No. One Killer' in Coal Mining: The Bureau of Mines and the Promotion of Roof Bolting, 1947–1969," *Technology & Culture* 57 (2016): 80-118.

Allen, Robert C. "Collective Invention," *Journal of Economic Behavior and Organization* 4 (1983): 1-24.

Atkinson, A. A. *A Key to Mine Ventilation*. Scranton: Colliery Engineer, 1892.

Arnould, Gustave. *Bassin Houiller du Couchant de Mons: Mémoire Historique et Descriptif*. Mons: Hector Manceaux, 1877.

Capell, Rev. G.M. "Observations on Fans of Different Types Working on the Same Upcast Shaft," *Transactions of the Federated Institution of Mining Engineers* 4 (1892): 203-217

Carpenter, R.C. "Ventilation of Buildings—XIX." *Heating and Ventilation* 7 (15 November 1897), pp. 6-8.

Le Chatelier, H. *Le Grisou*, Paris : Gauthier-Villars et Fils, 1892.

"Clifford vs. Capell Fan Litigation Ended," *Coal and Coke Operator* 10 (7 April 1910), pp. 222-223.

Clifford, William, "Furnace versus Fan Ventilation," *Ohio Mining Journal* 26 (1897): 67-82.

Caulier-Mathy, Nicole. *La modernisation des charbonnages liegeois pendant la premiere moitie du XIXe siecle: techniques d'exploitation.* Paris: Societe d'edition Les Belles lettres, 1971.

"A Clergyman Inventor," *Compressed Air Magazine* 20 (1915): 7568.

Clark, Gregory and David Jacks. "Coal and the Industrial Revolution, 1700-1869," *European Review of Economic History* 11 (2007): 39-72.

Decamps, Gonzalès, "Mémoire Historique sur L'Origine et Les Développements de l'Industrie Houillère dans le Basin du Couchant de Mons." *Mémoires et Publications de la Société des Sciences, des Arts, et des Lettres du Hainaut*. Series 5, volume 1 (1888-89), pp. 7-420.

Die Entwickelung des Niederrheinisch -Westfälischen Steinkohlen-Bergbaues in der zweiten Hälfte des 19. Jahrhunderts. *VI: Wetterwirtschaft*. Berlin: Julius Springer, 1903.

Fabry, Auguste. "D'une machine a vapeur rotative et d'un appareil ailmentaire pour les Chaudières a haute pression," *Annales Des Travaux Publics de Belgique* 6 (1847): 205-208.

Galloway, W. *Course of Lectures on Mining*. London: Spottiswoode & Co., 1900.
Galloway, William. "On Coal-dust Explosions," *Iron* (1878): 33-34, 65-66

Harzé, Émile. "De l'aérage des mines et des ventilateurs a force centrifuge exposé d'une nouvelle disposition de ces appareils," *Revue Universelle des Mines* 27 (1870), 193-222, 344-359.

Hasslacher, Anton, editor. *Haupt-bericht der preussischen Schlagwetter-commission: First Half*. Berlin: Ernst and Korn, 1886.

Hauer, Julius Ritter von, *Die Wettermaschinen*. Leipzig: Verlag von Arthur Felix, 1889.

Jicinsky, Jaroslav. *Manuel de la Ventilation des Mines*. Paris : Librairie Polytechnique, 1905.

Kerr, George L. *Practical Coal Mining: A Manual for Managers, Under-managers, Colliery Engineers, and Others*. London: Charles Griffin & Company, 1901.

Laurent. "On the Lemielle System of Ventilation of Mines." *Transactions of the North of England Institute of Mining and Mechanical Engineers* 6 (1858): 129-134.

Le Neve Foster, Sir Clement, and J. S. Haldane, *The Investigation of Mine Air*. London: Charles Griffin & Co., 1905.

Murgue, Daniel, *The Theories and Practice of Centrifugal Ventilating Machines*, translated by A.L. Steavenson. London: E. & F.N. Spon, 1883.

Murray, John E. and Javier Silvestre. "Small Scale Technologies and European Coal Mine Safety, 1850-1900," *Economic History Review* 68 (2015): 887-910.

No author, “The Capell Fan: An Interesting Account of the Invention and Subsequent Improvement of this Wonderfully Efficient Mine Ventilator.” *The Colliery Engineer and Metal Miner* 16 (November 1895), pp. 80-81.

No author, “The Ventilation of Prussian Collieries,” *Transactions of the North of England Institute of Mining Engineers* 32 (1882-83), Abstracts of Foreign Papers, p. 22.

Nuvolari, Alessandro. “Collective Invention during the British Industrial Revolution: The Case of the Cornish Pumping Engine,” *Cambridge Journal of Economics* 28 (2004): 347-363.

Pomeranz, Kenneth. *Great Divergence: China, Europe, and the Making of the Modern World Economy*. Princeton: Princeton University Press, 2000.

Pernolet, A. and L. Aguillon, *Exploitation and Réglementation des Mines a Grisou en Belgique, en Angleterre, et en Allemagne: Rapport de Mission Fait a la Commission Chargée de l’Étude des Moyens Propres a Prévenir les Explosions de Grisou dans les Houillères*. Paris: Libraire des Corps Nationaux des Ponts et Chaussées, des Mines et des Télégraphes, 1881. 3 volumes.

Rice, George S. and others. *The Explosibility of Coal Dust*. Bulletin 425, United States Geological Survey. Washington: GPO, 1910.

Roberti-Lintermans, Frédéric. “Les Inflammations de Grisou dans les Mines de Houille de Belgique,” *Annales des Travaux Publics de Belgique* 51 (1894) 217-400.

Royaume de Belgique, *Documents Statistiques publiés par le Département de l’Intérieur* 12 (1868).

Ser, Louis. “Essai d’une Théorie des Ventilateurs a Force Centrifuge: Détermination de leurs forms et de leurs dimensions,” *Mémoires et compte rendu des travaux de la Société des ingénieurs civils* 1 (1888): 629-672

Steavenson, A.L. “Report upon the Working and Regulation of Fiery Mines in England by Messrs. Pernolet and Aguillon,” *Transactions: North of England Institute of Mining Engineers* 31 (1881-82): 5-31 plus 11 plates.

United States Circuit Courts of Appeals Reports with Annotations (Rochester: Lawyers’ Cooperative Publishing Co., 1909), p. 227, *Clifford v. Capell*.

Wabner, Robert. *Die Bewetterung der Bergwerke*. Leipzig: Verlag von Arthur Felix, 1902.

Wright, Gavin. “Origins of American Industrial Success, 1879-1940,” *American Economic Review* 80 (1990): 651-668.

Wrigley, E.A. *Energy and the English Industrial Revolution*. (New York: Cambridge University Press, 2010).

Parliamentary Papers:

First, Second, and Third Reports from the Select Committee on Accidents in Coal Mines, in Parliamentary Papers, Reports from Committees: 1852-53, Thirteenth Volume.

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.

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.

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.

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

Method	Cost to install (pounds)	Cost to operate (£ 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
1900	Midlands, England	8	Colliery Guardian, 21 June 1901

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

Table 4. Varieties of ventilation methods in Prussia, 1883.

Basin	Number of mines	Mechanical ventilators	Steam pipes	furnace		Steam boilers	total
				Below	Above		
Upper Silesia	18	2	13	15			30
Lower Silesia	16	4	4	32	26		66
N. German forests	4	9		2	1	1	13
Ibbenbüren	2			4			4
Niederrhein-Westfalen	142	101	18	41	22	57	239
Aachen	15	7	8	5			20
Saarbrücken	15	34	1	19			54
Total	212	157	44	118	49	58	426

Source: *Haupt-bericht*…(report of the Prussian Firedamp Commission, p. 45).

Table 5. Share of output and employment in gassy mines in Prussia (*Schlagwetter-Gruben*)

Basin	Share output	Share employment
Lower Silesia	58.0%	60.6%
North German forests	46.0	42.8
Niederrhein-Westfalen	85.4	85.3
Aachen	82.6	80.3
Saarbrücken	94.7	94.5
Total	65.4%	66.4%

Source: *Haupt-bericht*…(report of the Prussian Firedamp Commission, p. 39).

Table 6. 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 7. Scotland: Regressions of fan adoption on previous survey conditions.

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

	mean	Model 1	Model 2	Model 3	Model 4
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	Model 5	Model 6	Model 7	Model 8
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 8. 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 9. 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.

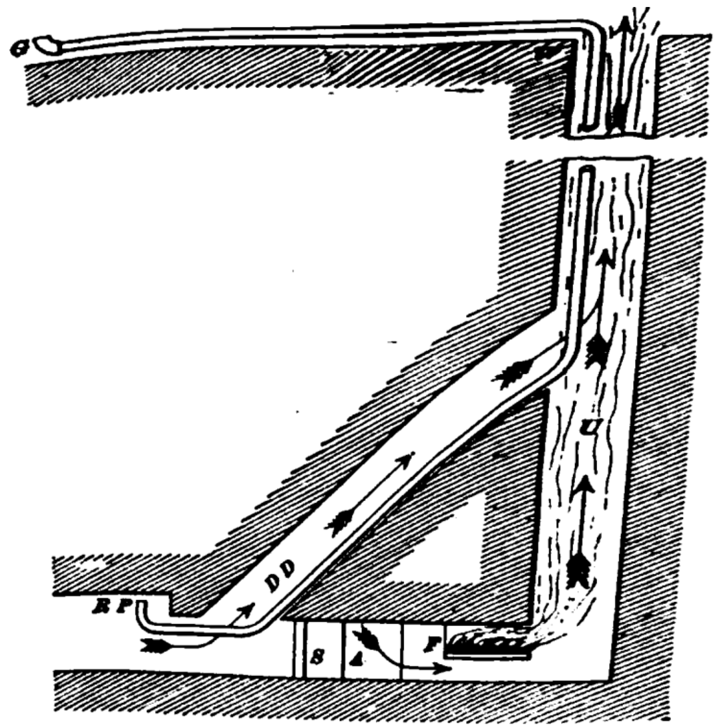


Figure 2. Bell-and-plunger ventilator installed at Grand Buisson mines, Belgium.

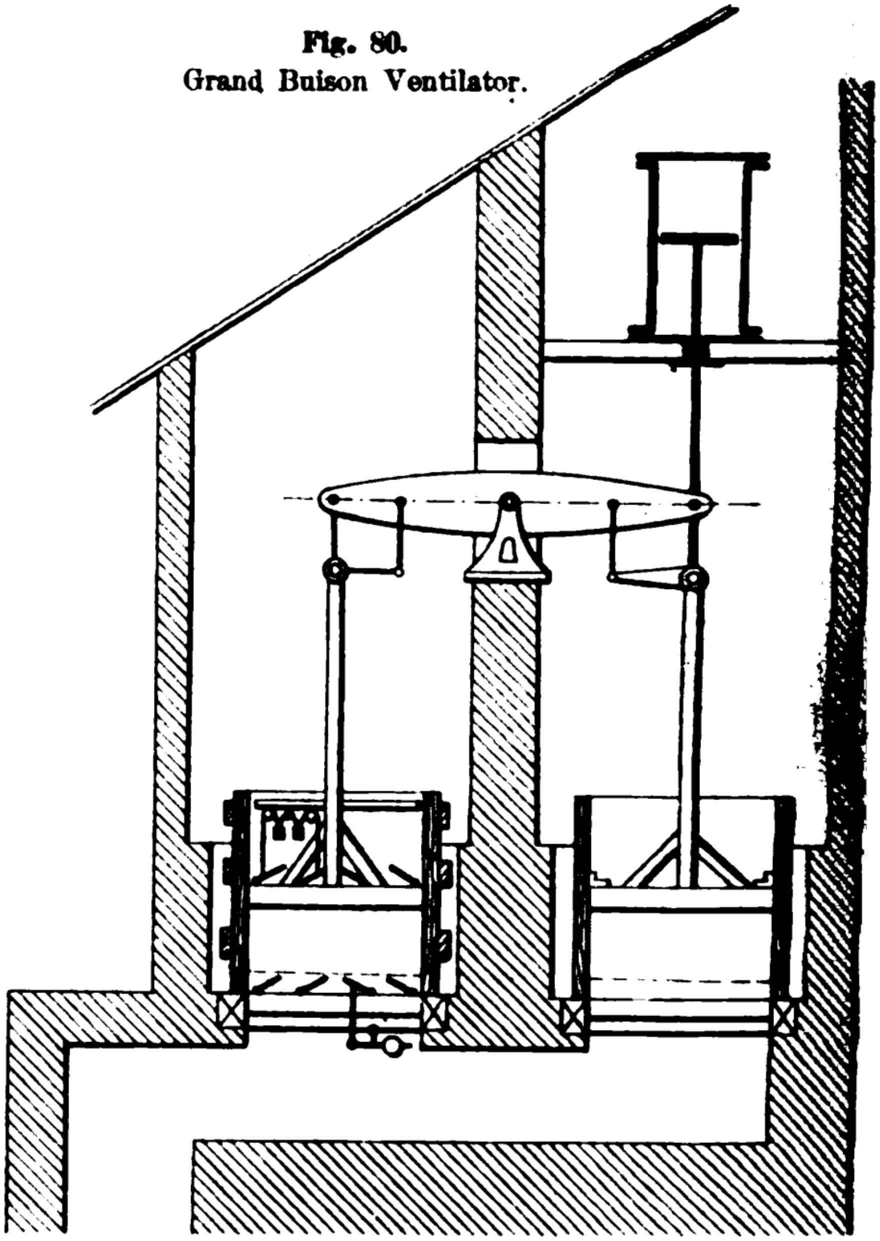


Figure 3. Motte’s pneumatic screw. Source: Parliamentary Papers, Reports from Committees 1852-53.

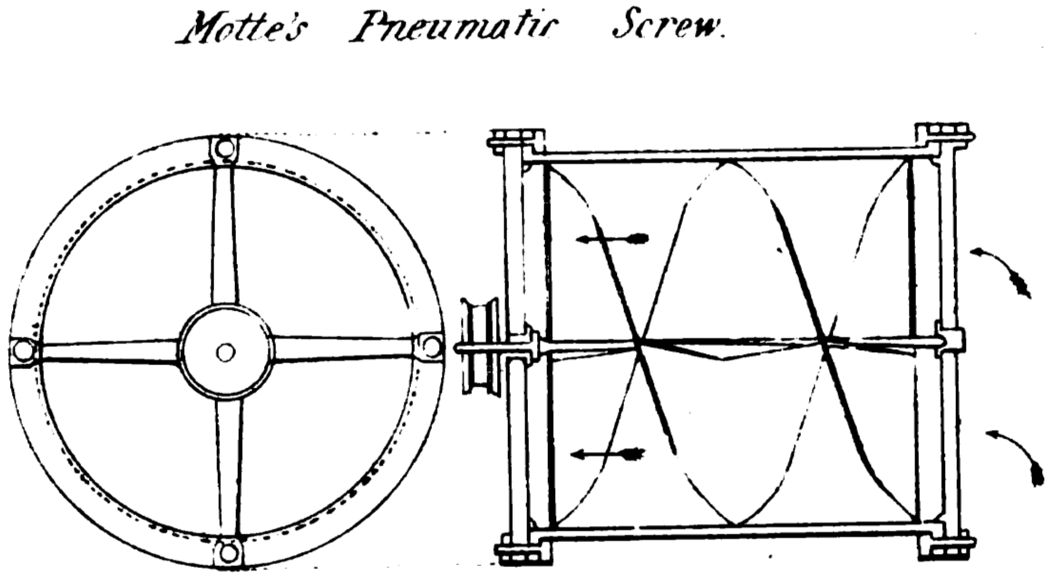


Figure 4. Letoret ventilator, an early centrifugal fan. Source: Parliamentary Papers, Reports from Committees 1852-53.

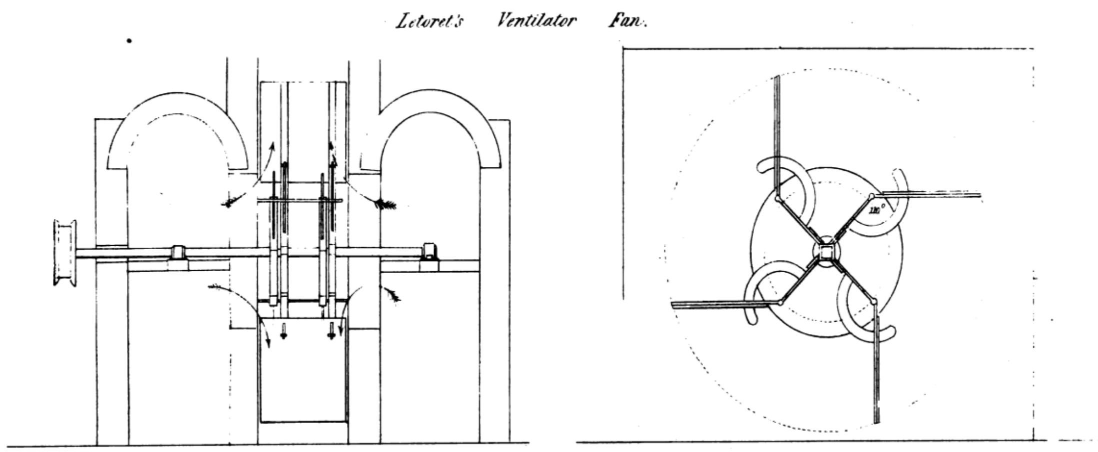
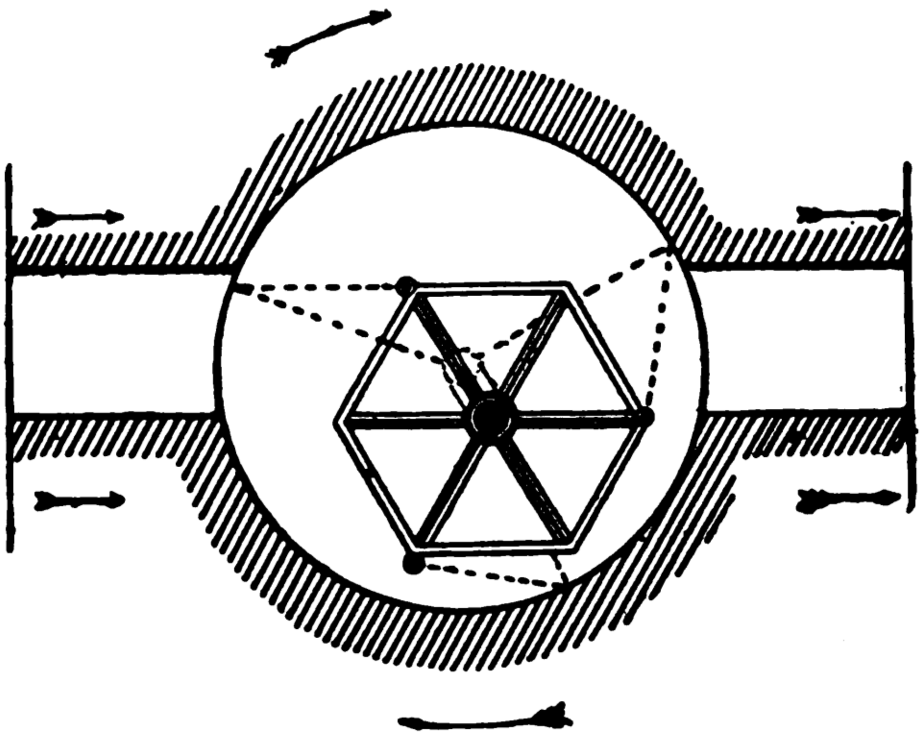


Figure 5. Lemielle ventilator, viewed from side.



Percy, vol. I, after p. 172.

Figure 6. Fabry, as viewed from top. Source: Andre, *Descriptive Treatise,* vol. II.

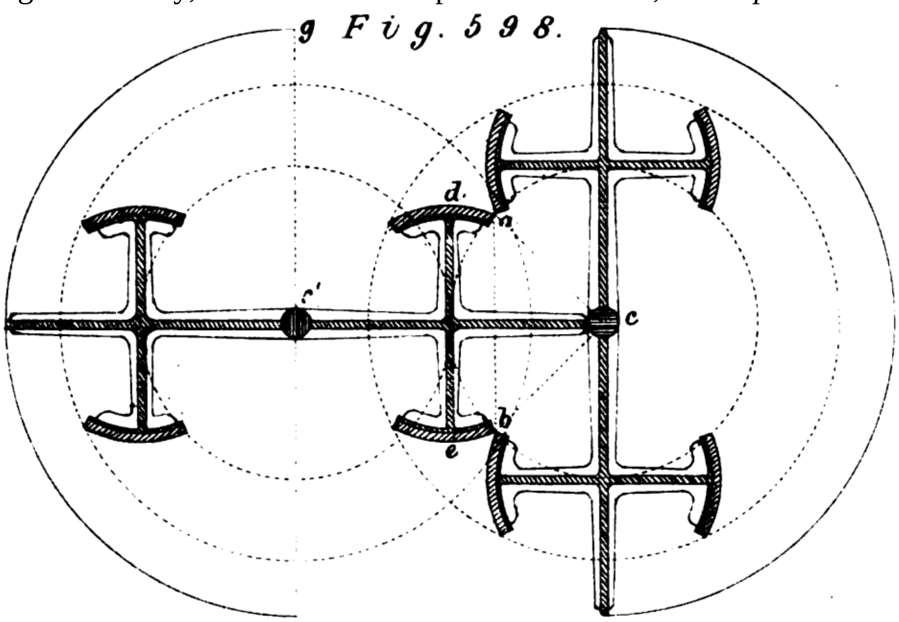
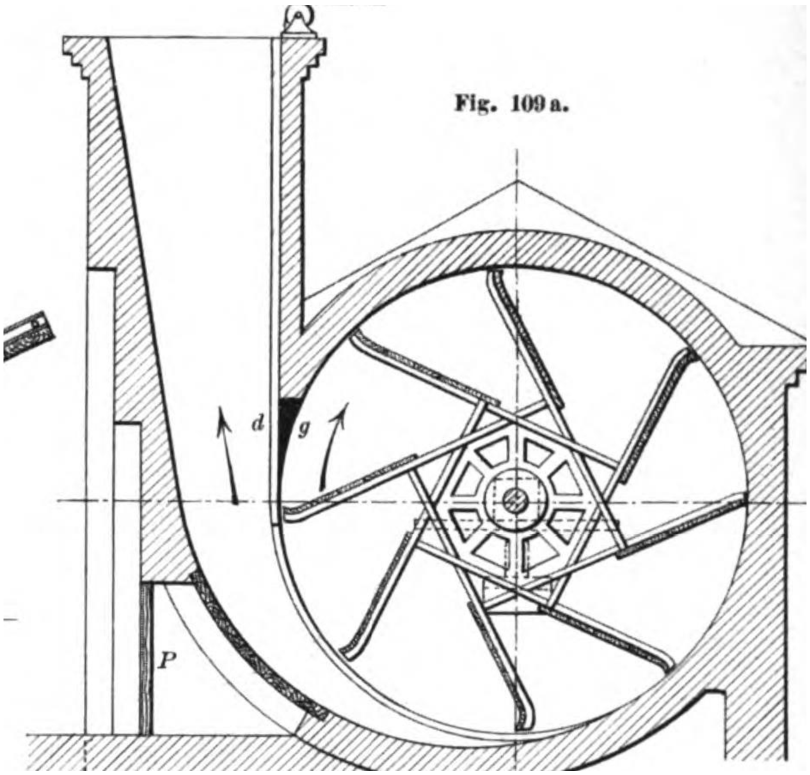


Figure 7. Guibal, view from side. Note *évasée* chimney.



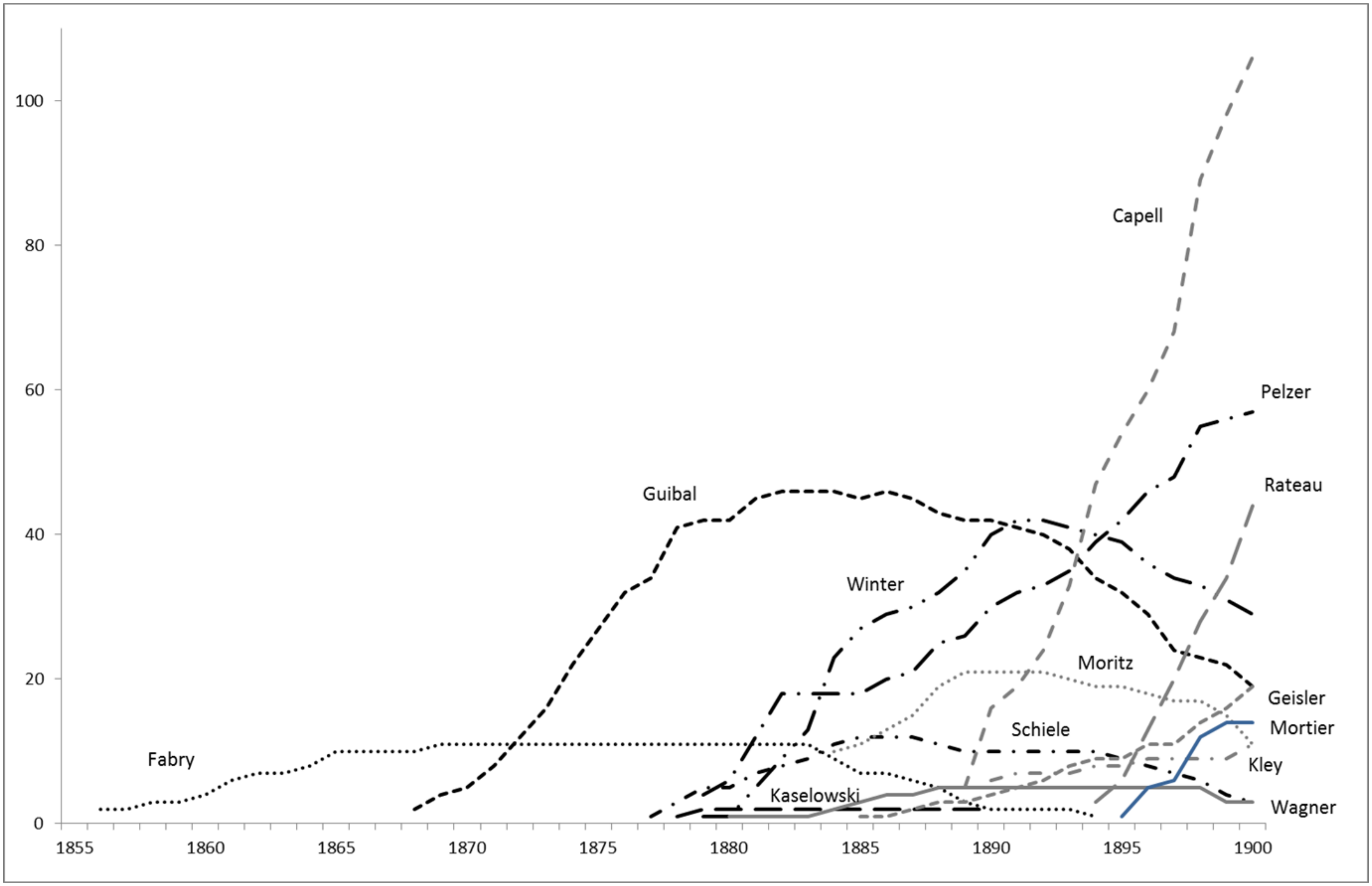


Figure 8. Types of fans in operation in Niederrhein-Westfalen region. Source: *Die Entwickelung*…, Tafel IX.

Figure 9. Capell fan. Note the fan blades attached to outside of cylinder. Cf open axle of cylinder on Guibal.

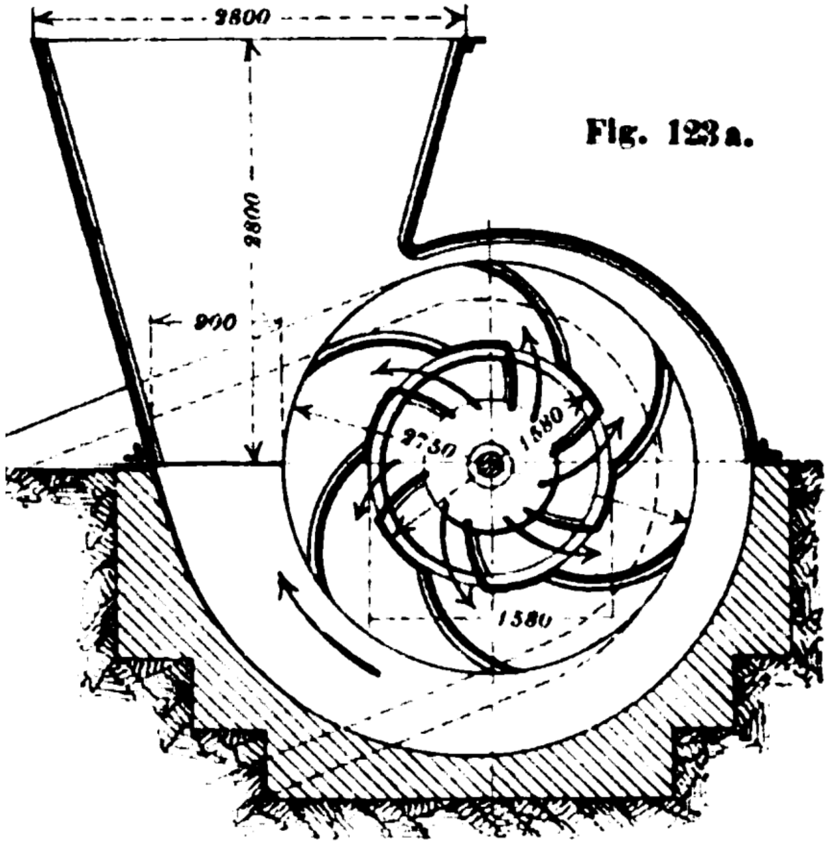
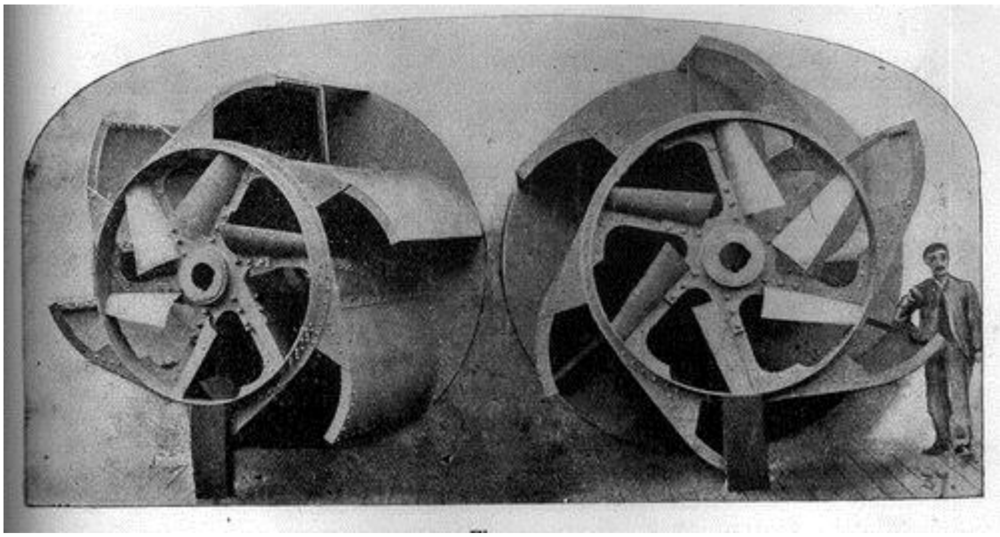


Fig. 123 a.



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.

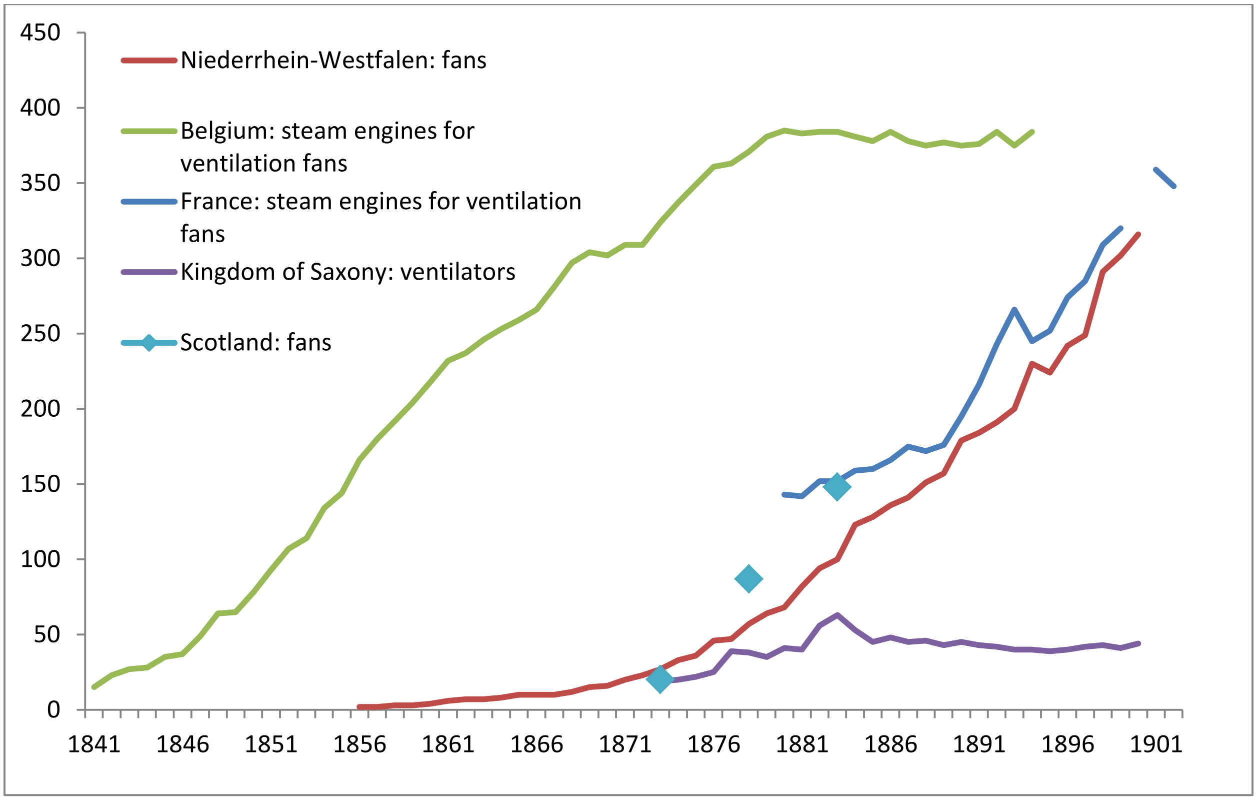


Figure 11. Coal deposits in Scotland.