Hydraulic Pumps of Agricola's *De Re Metallica* (1556)

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"I have omitted all those things which I have not myself seen, or have not read or heard of from persons upon whom I can rely. That which I have neither seen, nor carefully considered after reading, or hearing of, I have not written about…I have devoted much labor and care, and have even gone to some expense upon it; for with regard to the tools,... and machines, I have not only described them, but have also hired illustrators to delineate their forms, lest descriptions which are conveyed by words should either not be understood by men of our own times, or should cause difficulty to posterity…"—Georgius Agricola, *De Re Metallica*, 1556

These are the lucid and explicit statements made by Georgius Agricola in the preface to his *De Re Metallica*. Agricola is universally known for this book that, for the first time in the history of arts, offers a detailed and systematic treatment of mining engineering. The treatise is known primarily as a milestone in 16th century science and technology, as well as for its spectacular engravings. Agricola, born at Glauchau, Germany, on March 24, 1494, was a scholar with many interests. He lived in a period rich in important spiritual and scientific movements. Suffice it to mention humanism, which spread beyond the Alps thanks to Erasmus of Rotterdam, Luther's reformation, the battle fought by Paracelsus against arid bookish science, Vesalius' reform of anatomy, and the theories propounded by Copernicus, which revolutionized astronomy. Agricola, whose real name was Georg Bauer, studied philosophy and theology at the University of Leipzig. In 1523 he moved to Bologna, Italy, as a student of the famous anatomist Berengario da Carpi, and graduated in medicine. Subsequently he spent the years 1524 to 1526 in Venice as editor at the printing house founded by Aldo Manuzio. Although Venice was a city with a rich spiritual and commercial life, Agricola was haunted by memories of the mineral richness of his native country and soon felt a craving to learn more about minerals and engineering. So, he went back to St. Joachimsthal, Saxony, Germany, in the Erzgebirge mining district. There he was appointed physician and pharmacist, and, in addition to his daily work, devoted himself to technology. During his lifetime he held several positions of prestige and power, such as burgomaster of Chemnitz and ambassador extraordinary to the court of the Emperor Charles V and King Ferdinand of Austria. He died on November 21, 1555, in Chemnitz, Germany.

De Re Metallica

Agricola's *De Re Metallica* is considered a leading 16th century book on machines. Existing originally as military engineering treatises, books on machinery began to cover almost every technical sector in the 15th and 16th centuries. Besides the precursors such as Mariano Taccola (1438), Francesco di Giorgio (circa 1450), and Roberto Valturio (1472), the most authoritative writings on machines were those of Jacques Besson (1578), Guidubaldo dal Monte (1577), and Agostino Ramelli (1588). In *De Re Metallica*, Agricola goes into considerable depth when describing the advanced machinery of the Erzgebirge mines, in particular, pumps to drain off water and hoists to extract ore. In *De Re Metallica* Agricola also tackles subjects of considerable cultural weight that proved to be fundamental for Diderot and D'Alembert when putting into practice the train of thought that characterized the whole of their *Encyclopédie*. He defended the mechanical arts against the accusation of being "unworthy and base" compared with the liberal arts. In those days there was a tendency to belittle the activity of the technically minded, treating it exclusively as manual work which is more in need of exertion and ingenuity than of knowledge and scientific content.

De Re Metallica is written in the fluent, pleasing Latin of all great humanists. Its favorable reception as soon as it was published meant that Agricola's treatise was translated into various languages. These included the old German (1557) and Italian (1563) translations, and the modern translations in several languages, including English, Spanish, French, Czech, Hungarian, and Japanese. *De Re Metallica* has always received the attention of scholars of science history, but also of engineers. Herbert Clark Hoover, a mining engineer later to be president of the United States, prepared a critical English translation, published in 1912, which spread knowledge of *De Re Metallica*.

The Pumps of *De Re Metallica*

After the fall of the Roman Empire the demand for minerals and metals moved from the Mediterranean to the new and more prolific mines of central Europe. For more than a millennium, mining techniques and water drainage systems did not radically change, at least with respect to equipment and methods. The only systems used continued to be the manual bailing, norias, Archimedean screws, chain of buckets, and rudimental piston pumps. However, important progress was made in research on more powerful driving systems without human use. Of great importance were windmills, dating back to the late Middle Ages. Equally important were the diffusion and the improvement of both the water wheel and the crank motion system, a mechanical element that was unknown to the Classical age, in that engineers had never added a flywheel to overcome the dead points.

In Book VI of *De Re Metallica*, Agricola discusses *metal machines*, i.e., machines used in underground mining. Here one can find meticulous descriptions of the "devices with which water is

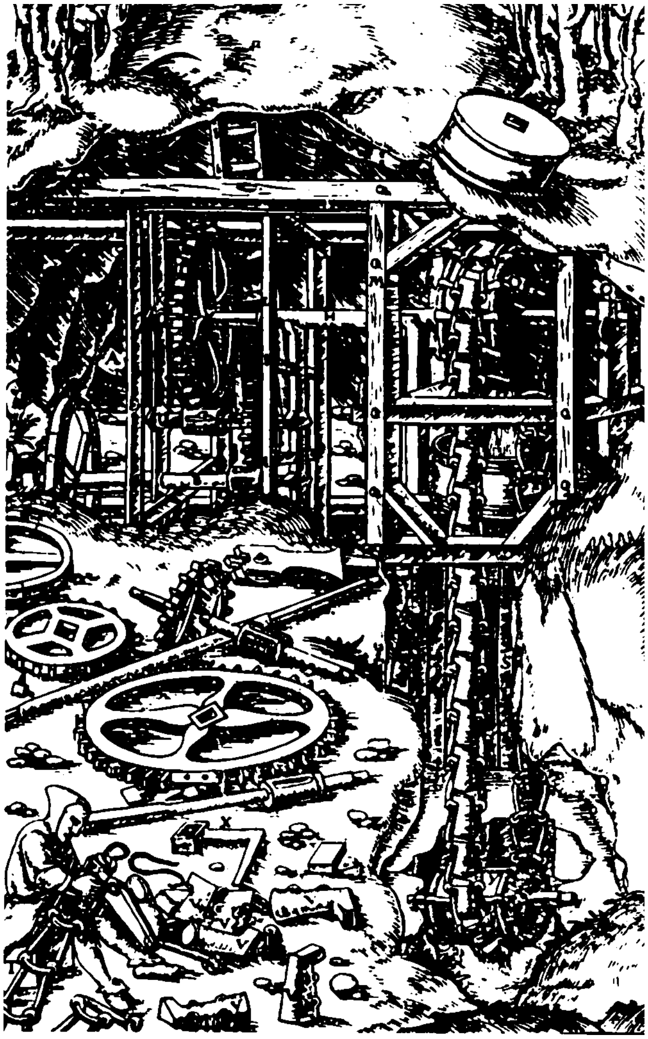

Fig. 1. Chain of buckets pump, manually operated by means of an elaborate train of gears, acting as a reducer with details of spare parts, and assembling

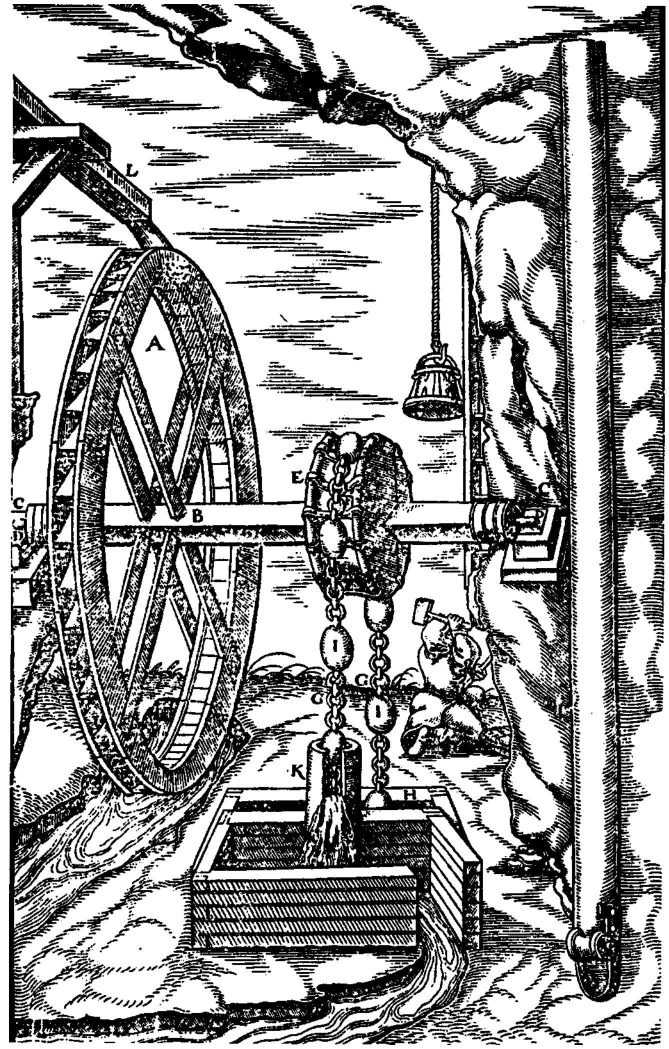

Fig. 2. *Pater noster* (or rag and chain) pump, powered by a large overshot water wheel. The chain is fitted with spheres made from leather stuffed with horsehair, having the same diameter as the inside of the pipe

drawn out of shafts, because the abundance of the same prevents mining." The presence of consistent water infiltrations impedes the regular course of underground operations. Where there is no drainage gallery, a suitable collecting well has to be dug, and a pump has to be positioned to lower the water table. A long section of this book is dedicated to the description of these pumps. In particular, Agricola points to a novel technical breakthrough, and describes a new kind of pump that revolutionized the mining techniques. Following the usual rigorous taxonomical criteria typical of his work, he describes various kinds of pumping systems, either discontinuous (buckets, goatskins, or tubs aided by ordinary hoists) or continuous, using a chain of buckets, reciprocating piston pumps, or *pater noster* pumps.

Chain of Buckets Pump

This pump, already known and documented in Greek and Roman antiquity, was also used throughout the Middle Ages. Generally, wheel pumps are known in two forms, the noria (or Egyptian wheel) and the chain of buckets, which is frequently, though inexcusably, confused with the noria. The noria consists of a large wheel having a series of containers fastened inside of the circumference. Buckets are partially filled with water as they pass through the stream and they begin to discharge before they have reached the top. When water was to be raised to greater heights, or when relatively deep wells were involved, the noria was modified by attaching the buckets to a belt that passed over drums at the top and bottom of the lift. Such an apparatus had no specific limits beyond the amount of power available. Agricola describes several types of chain of buckets pumps: the basic type (Fig. 1) is manually operated by means of an elaborate train of gears, acting as a reducer.

Pater noster *Pumps*

This is a "machine that draws up water by means of spheres." The apparatus is nearly identical to the Cornish "rag and chain" pump of the same period. It is composed of a closed-loop chain sliding inside a hollow pipe (the pump body), made from a perforated trunk. The chain slides along on the inside of the pump body by means of a friction pulley that is keyed into the axle of a water wheel. A first type (Fig. 2) is a machine operated by a large overshot water wheel and is fitted with spheres spaced out at 6 ft apart along the chain. The attainable drainage depth reported for

Fig. 3. Manually operated single-action piston pump with details of rods, pipe drilling, flapper valves, and leather gaskets

this machine is 70 m with an 8-m-diameter wheel, and 80 m when a 10-m-diameter wheel is used. A second type was constructed with two lines of rag and chain. Another arrangement is the use of elaborate horizontal wheels driven by means of animals. Motion is transmitted to the pump by means of wooden crown wheels and pinions, a drive mechanism that was tried and tested in medieval mills. It seems that this pump succeeded in raising water from a depth of 80 m using eight horses working in four-hour shifts.

Piston Pumps

Single-action piston pumps derived from Ctesibius' hydraulic pump (3rd century B.C.). Agricola analyzed several configurations of piston pumps that are improved in design compared with those used in the Middle Ages, and are characterized by a more precise construction of the valves and the seal between the pipe and the piston. The basic type is illustrated in Fig. 3. The pump is operated manually, reciprocating the driving rod without the aid of levers. Other kinds of piston pumps are illustrated in some of the most beautiful plates of *De Re Metallica*. These plates are rich in construction details and in detail blow-ups, making here their first appearance in technical literature. Fig. 4 reports a pump

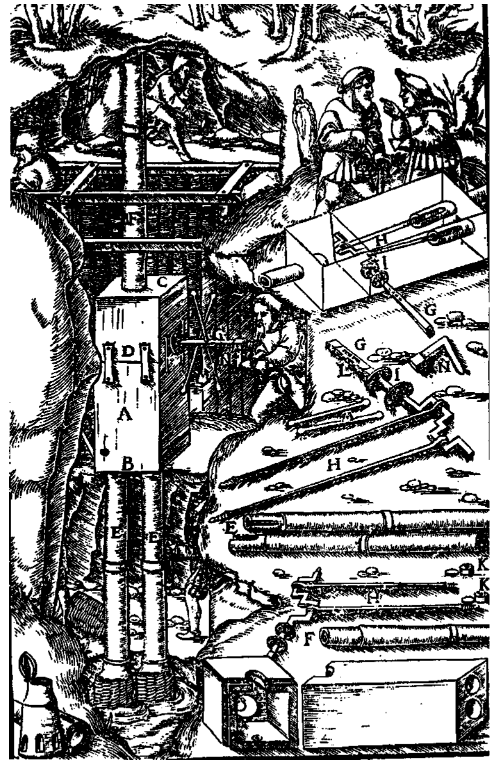

Fig. 4. Piston pumps driven by a horizontal crankshaft, operated manually with detail blow-up of the crankshafts and the connecting rods

made up by two parallel pipes coupled together, the pistons of which are driven by a horizontal crankshaft. A critical point of this pump, still driven manually, is the low resistance to pipe bursting. In fact, pipes were made from a trunk, carefully drilled and milled with special tools in the piston stroke area. A further system involved the use of three parallel pumps. For this particular layout, the mechanism to transform rotational motion into reciprocating motion is a rotating shaft with square cams, still more common in those years than the crank drive. It is reported that these devices drained off water from wells up to about 30 m deep.

A New Machine For Water Drainage

The prospect that mines would be closed down on a large scale was imminent as the underground works went deeper and deeper. This critical situation and lack of innovative technology was the boost that brought about the invention of a new machine that could solve the problem of the restricted drainage depths provided for by machines up until the early 16th century. The last type of piston pump described in *De Re Metallica* is of enormous importance in the history of mining and pumping technology. It overcomes the intrinsic limitations of all the previous devices in which the pumping depth and the capacity were limited by the flapper valves and the length of the pipes that would be feasible and compatible with the stress imposed by the hydraulic head. In the new system, the length of the pump body is independent from the depth to be drained. The basic concept was quite simple. Single-action piston pumps were arranged in sequence, one above the other and driven with a common shaft. Given this arrangement, the pumping depth was increased as required, since the water is emptied into a small basin at each stage and the water in

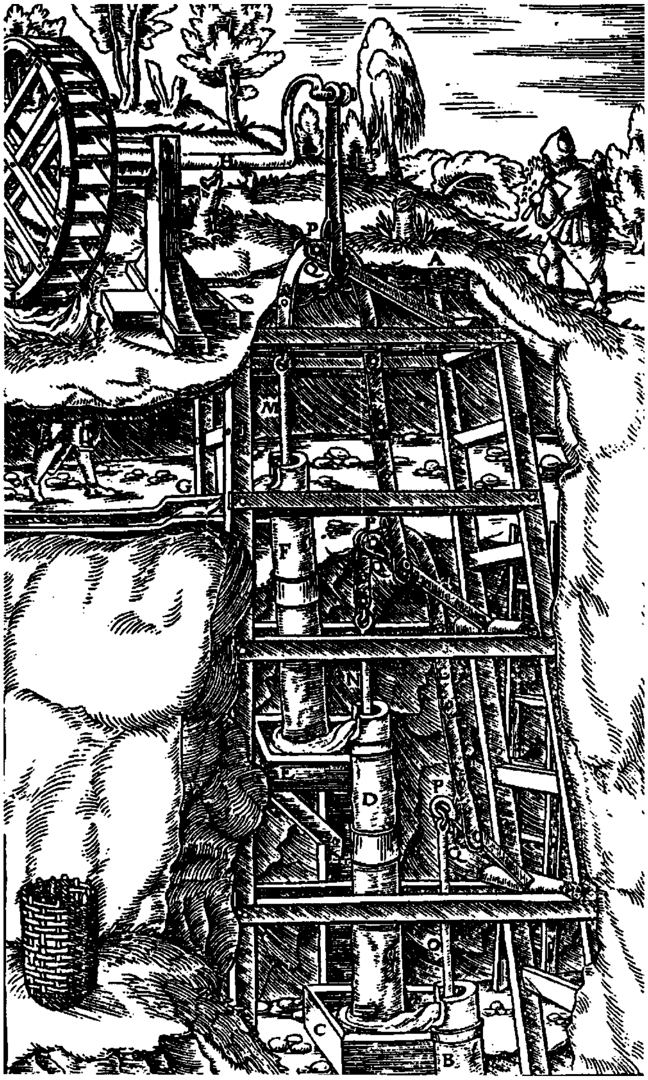

Fig. 5. Three piston pumps synchronically driven by a water wheel. The transmission mechanism, composed of shaped rods and small connecting levers, is kinematically redundant, so its performance, at least in the initial versions, must have been very poor.

this basin is then moved up to the next stage. These machines were only suitable for vertical shafts and needed considerable power due to the complicated mechanical transmission. Agricola, emphasizing the innovativeness of this pump, introduced around 1540 in the Erzgebirge mining district, clearly recognizes its application potentials. He in fact called it “ingenious, durable and useful, and not even costly”.

The simpler version (Fig. 5) is a machine built with three piston pumps in sequence, the rods of which are synchronically driven by a single water wheel. Such a pump, as described by Agricola, is still rather rudimentary, and the absence of certain technical requirements will mean that it has to be replaced after just a few decades. Although the first machines were not well developed and extremely complex, these pumps proved to be so satisfactory that they were immediately judged as durable, useful, and above all economical by the people in the field. Their advantages were clear even to other mining engineers of the day who, just after a short time, recognized the enormous savings that were made possible by these systems. Accounts of the time tell of cases where the savings were around 90% of the total drainage costs. The successive applications of this kind of machine led to additional mechanical improvements. Just 60 years later, Georg Löhneiss (1617) described a complicated machine constructed with a set of 20 pumps that was able to drain water at about 200 m depth. The machine had an enormous success in Europe, showing both a wide geographical diffusion and long-lasting success in its applications. These machines were further refined and improved upon and were consequently linked to the driving force of large water wheels and, from the 18th century onwards, to the power of the new steam engines. In fact, the first industrial application of steam was made using this pump design. In England, Thomas Savery (1702) patented his steam pump, which was a rudimentary engine coupled with a multistage piston pump, described above. These pumps remained in widespread use until about 1870 and continued to be mentioned in classic textbooks on mine drainage until the first half of the 20th century.

Concluding Comments

Herbert Hoover, who prefaced his 1912 translation with the following, perhaps best summarized the impact of Agricola’s book:

> We need make no apologies for *De Re Metallica*. During 180 years it was not superseded as the textbook and guide to miners and metallurgists, for until Schluter’s great work on metallurgy in 1738, it had no equal. That it passed through some ten editions in three languages at a period when the printing of such a volume was no ordinary undertaking, is in itself sufficient evidence of the importance in which it was held, and is a record that no other volume upon the same subjects has equaled since.

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