THE AGE OF THE AIR-PUMP

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In 1985 Steven Shapin and Simon Schaffer published their *Leviathan and the air-pump*, the first integrated treatment of the role of the air-pump in seventeenth-century science. The book soon acquired the status of the most authoritative source on early air-pumps. Yet, *Leviathan and the air-pump* was not meant to be a full account of the early history of these instruments. As Shapin and Schaffer themselves put it, their objective was to study "the nature and status of experimental practices".[1] Their treatment of Boyle's pneumatical research is a case study in the social history of scientific knowledge. Roughly stated, their claim is that the extent to which experiments were thought to provide scientific knowledge, depended on the theoretical framework, the philosophical stance and the political views of the scientist.

As one product of their variegated pursuit Shapin and Schaffer contributed much to the historiography of the air-pump. In this paper, some additional historical facts will be examined, from a somewhat different angle, to take the analysis of the role of the air-pump in seventeenth- and early eighteenth-century science one step further. At first glance, one might think that the air-pump had settled the century-old vacuum debate. But this is not what happened, and, so long as it was applied to the vacuum debate, the air-pump was of little significance. It was only when Boyle employed the instrument to address entirely new questions, that the air-pump became important. His usage of the 'pneumatical engine' to search for the properties of a vacuum became very influential. Many young scientists took much more interest in Boyle's new branch of science than in the old debate. During and after Boyle's time the instrument gradually changed from a specialist piece of equipment into a readily available demonstration tool. And in the course of this process the scientist's role in designing and constructing air-pumps was taken over by the instrument makers.

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[1] Steven Shapin and Simon Schaffer, *Leviathan and the air-pump. Hobbes, Boyle and the experimental life* (Princeton: Princeton University Press, 1985), p. 3.

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The vacuum discussion

To refresh the reader's memory, it may be useful to give a brief sketch of pre-pump thinking on the vacuum.[2] Medieval philosophy was overwhelmingly influenced by Aristotelian thought. Aristotle considered a void to be logically impossible, for a variety of reasons. Thus, he reasoned that if space were three-dimensional, it would be a body. And it could not be both three-dimensional and void of body. According to medieval thinking, Aristotle's dislike of a vacuum was projected onto nature itself. Nature was thought to abhor empty space. This 'horror vacui' would always prevent the creation of a void. Medieval scholasticism placed great importance on the non-existence of a vacuum. Nevertheless, a debate around this theme lasted from medieval times till the end of the seventeenth century. It was a complicated discussion, with theological, logical and empirical implications. For instance, the belief in a void was considered to be a threat to religion because if was associated with atomism and materialism. Another typical argument was linked to the thought-experiment concerning a pair of bellows.[3] The idea was that the sides of the bellows, from which all air had been pressed, could not be separated. For, if the sides were to be separated, a vacuum would occur. Characteristically, this argument was reversed to prove the existence of a void. If the bellow was strong enough, the sides could be separated, leaving a perfectly empty space.

The old discussion received new impetus through Galilei. When his attention was called to the fact that suction-pumps could not raise water more than about 30 feet, he identified the space above the water as a vacuum. His explanation was that the water column broke under its own weight. His student Torricelli explained the phenomenon in terms of an equilibrium between the weight of the water-column and the weight of the surrounding air. His 1644 'barometer-experiment' attracted much attention. A glass tube was filled with mercury and inserted top-down in a mercury bath. As Torricelli had predicted, the level in the tube dropped to about 30 inches, leaving an apparently empty space above. To the vacuists this was a void, to the plenists a problem. Their solution was to consider this space to be filled with air, ether or the spirit of mercury. Neither party achieved consensus on the cause of the phenomenon. Was it the force of the vacuum, a restricted horror vacui, or the pressure of the surrounding air?

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[2] I will not give extensive references on the various aspects of the vacuum debate. A detailed account of the debate is given in Edward Grant, *Much ado about nothing. Theories of space and vacuum from the Middle Ages to the Scientific Revolution* (Cambridge: Cambridge University Press, 1981).

[3] Charles B. Schmitt, "Experimental evidence for and against a void: the sixteenth-century arguments", *Isis* 58, 1967, pp. 352-366, on pp. 355-357.

It was mainly in France that this new phenomenon gave rise to considerable research. Pascal, for instance, established the connection between the height of the mercury column and atmospheric pressure. He also performed a void within a void experiment. A torricellian tube was placed within the empty space above the mercury column of a second tube. In the inner 'barometer' the level of the mercury in the tube was equal to the level in the bath. In the absence of air, the mercury column was not sustained, and thus it seemed clear that the pressure of the surrounding air was the cause of the elevation of the mercury in Torricelli's experiment. The plenists, however, were not convinced. The experiment could well be explained by a restricted horror vacui. Moreover, they considered air to be a light element, and thus the explanation using the pressure or weight of air, according to the plenists, was absurd.

The above example clearly demonstrates one of the characteristics permeating the discussion. This is a phenomenon similar to that pointed to by Shapin and Schaffer in the Hobbes-Boyle-controversy: the arguments that were used were valid only within the system of thought of those who presented them. This did not improve the chances of reaching consensus.

The air-pump enters the stage

Unaware of most of the discussion, the Magdeburg Burgomaster Otto (von) G(u)ericke started experimenting with his air-pump around 1647.[4] His aim was to establish the existence of a vacuum by creating one.[5] Although his research fitted well into the on-going discussion, Von Guericke's involvement was spurred by a different concern. The invention of his machine had as its main purpose the refutation of Descartes' cosmology and his related ideas on space and matter.[6] On completing his instrument, Von Guericke began research in pneumatics and meteorology. His measurements of the weight and pressure of air were of most significance, but initially these remained unpublished. Instead he gave spectacular demonstrations at the German courts,[7] using them to publicize his city. The scientific world gained knowledge of the new development in 1657 through a book entitled *Mechanica hydraulica-pneumatica*, authored by the Jesuit Kaspar Schott. In was only in 1672 that Von Guericke's own description of his experiments and the various pumps he designed appeared, too late to have any

[4] Fritz Krafft, *Otto von Guericke* (Darmstadt: Wissenschaftliche Buchgesellschaft, 1978), pp. 55-57.

[5] *Ibid.*, pp. 53-54.

[6] *Ibid.*, pp. 29, 51-55.

[7] *Ibid.*, pp. 28-29.

influence.[8]

One would expect the air-pump to have aroused much interest. After all, this was a completely new proof of the vacuum. Yet, no boom in creating or using air-pumps followed. It seems that Christiaan Huygens' reaction was characteristic. In describing Schott's book to a friend, he stated that the air-pump was merely a new way of creating a void.[9] There was nothing more to be said about it. The air-pump seemed to create a vacuum, but so did Torricelli's tube, and in a much more lucid way. Von Guericke used his air-pump to measure the atmospheric pressure, but it was no real improvement on Pascal's more widely-known work. Thus the general indifference is not surprising. Indeed, so long as the air-pump was applied to the old vacuum debate, it did not have much to offer, not even to the experimental philosophers. Many philosophers were still totally opposed to experimental work, and, obviously, they were even less enthusiastic about the air-pump.

There was one exception to this general attitude: Robert Boyle. Boyle recognized the air-pump as a perfect tool for investigating the properties of the vacuum and of air. Indeed, as a research tool the air-pump had significant advantages over the Torricellian tube.[10] Recipients of any shape could be emptied, and, of great importance, various instruments could be placed in these recipients. Employing these new means, Boyle began to research pneumatics systematically. Opening up an entirely new branch of Baconian science, he also carried out most of the research, or rather, his assistant Robert Hooke did.[11] In contrast to the air-pump itself, this research carried out with it did attract attention. It was of course meat and drink to the English circle of Baconian scientists within the Royal Society. In fact, it exemplified in one of the best ways the kind of research they had in mind. And outside of England, the work also gained much recognition. It achieved such popularity, that even on the continent the air-pump became known as the "Machina Boyleana," rather than as Von Guericke's machine.[12]

Boyle's work did not always meet with approval. Shapin and Schaffer have pointed out that Boyle was attacked for working with vacua and his use of

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[8] Otto von Guericke, *Experimenta nova (ut vocantur) Magdeburgia de vacuo spatio* (Amsterdam: Van Waesberge, 1672)

[9] Christiaan Huygens, *Oevres complètes*, 22 vols (The Hague: Martinus Nijhoff, 1888-1950), vol. 2, p. 389

[10] Shapin and Schaffer (n. 1), p. 231; J.B. Conant, *On understanding science. An historical approach* (New York: The New American Library of World Literature, 1951), p. 53.

[11] R.E.W. Maddison, *The life of the honourable Robert Boyle F.R.S* (London, Taylor & Francis, 1969), p. 93.

[12] *Ibid.*, p. 228.

experimental techniques.[13] Given the severity of the attacks, one would almost think that the use of experiments was a phenomenon new to the 1660s, but it was not. Galilei, Torricelli, Pascal and many others had also used experiments as a reliable scientific method.

One of Boyle's most important supporters was Christiaan Huygens, who joined the 'pumping party' after his visit to the Royal Society in 1661.[14] As stated above, he had not been enthusiastic about the pump as a mere creator of a void. But when Boyle pointed out its other possibilities, he was convinced. On returning to Holland, Huygens immediately started to construct his own pump, using a design similar to that of Boyle. It was finished in the same year, and Huygens started doing research and improving the design of the instrument. By the end of 1662 his second pump, employing a design of his own, was finished. Huygens' most important contribution to pneumatics was his discovery of anomalous suspension in 1661.[15] He had purged water of air, and filled a barometer with this water. Next he put the barometer under his recipient and evacuated it. To his astonishment, the water in the barometer did not descend. Today, the phenomenon is attributed to adhesion between the water and the glass tube, but in Huygen's time it was rather puzzling. Boyle initially denied the effect, because he could not produce it with his own pump.[16] He suggested that Huygens' pump could not evacuate sufficiently. Huygens on the other hand (correctly) believed it was Boyle's pump that was defective.[17]

There was much discussion between Boyle and Huygens on the construction of the piston and the kind of wax that was to be used to seal connections, but both competitors stressed the importance of decreasing leakage.[18] Leakage was a serious problem, as the plenists' attacks focused on this point.[19] Typically the plenists responded to Boyle's work by denying that the pumping resulted in a vacuum. Air would always leak in. And even if all the air were taken out, ether would fill the empty space.[20] Boyle, on the other hand, took a pragmatic stand, stating that he did not know whether or not he had created a literally empty

[13] Shapin and Schaffer (n. 1), pp. 110-154.

[14] On Huygens and air-pumps see: Alice Stroup, "Christiaan Huygens & the development of the air pump", *Janus* 68, 1981, pp. 129-158 and Shapin and Schaffer (n. 1), pp. 235-248, 265-276.

[15] Shapin and Schaffer (n. 1), p. 241.

[16] *Ibid.*, p. 245.

[17] *Ibid.*, p. 248.

[18] *Ibid.*, pp. 236-249.

[19] *Ibid.*, pp. 30, 116-119.

[20] *Ibid.*, pp. 116, 252.

space. He merely claimed that he was emptying his vessels of air.[21]

There is no indication that any plenist was converted as the result of the introduction of the air-pump. Christiaan Huygens seems to have been the only scholar to have changed his opinion on the basis of experimental evidence. But his was a complicated case. He was already convinced of the existence of the vacuum when Boyle inspired him to build an air-pump. Yet when he started working with the air-pump himself, his discovery of anomalous suspension converted him from a vacuist to a plenist.[22]

Clearly, the air-pump did not settle the old vacuum debate. It could only convince the convinced. So long as it was applied to the vacuum discussion, the instrument was of little significance. Apart from Huygens, no one seems to have altered his opinion on the basis of pump-experiments. The air-pump became influential only when Boyle used it to answer other, completely new, questions. Whether or not a vacuum existed was not interesting, how it behaved was. The old discussion was never settled, it simply faded away. As the older generation died out, a new generation of scientists with no interest in the problem took their place. The questions to be discussed were the ones posed by Boyle. These had the merit of being both Baconian and solvable. Obviously the air-pump has been instrumental in bringing about this shift of interest.

From specialist instrument to object of commerce

Initially, the use of an air-pump was restricted to a select group of people. Von Guericke, Boyle and Huygens all had one, but hardly anybody else did in the early 1660s. When air-pumps were needed, these had to be made by craftsmen such as brass-founders and clockmakers, who had no prior experience of this kind of work. Obviously, the initiative for making a pump lay entirely with the scientists. But gradually the instrument makers took over. They started making pumps without the supervision of a scientific authority, and even developed their own designs. Apparently, the demand for air-pumps was growing, even though they remained expensive. It was not unusual to pay half a professor's annual salary for an air-pump with accessories. Despite this, the air-pump had become a fairly common instrument by the mid-eighteenth century. It was sold almost from stock by various instrument makers throughout Europe. Typical customers were universities, private demonstrators and wealthy citizens and noblemen. With a few exceptions, the air-pumps were not purchased to carry out research in pneumatics, but to demonstrate either the wonders of the physics of Boyle

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[21] *Ibid.*, pp. 45-46, 119.

[22] *Ibid.*, p. 253; Stroup (n. 14), p. 137

and Newton or the owner's involvement with this new science. In the meantime, the instrument itself underwent considerable development. Mirroring the air-pump's changing role, from a specialists' instrument to a demonstration tool, it is worthwhile taking a closer look at this development.

Pioneer pumps

In principle the air-pump did not differ much from an ordinary liquid-pump. In both instruments there was a piston moving to and fro within a cylinder. The exhaust-stroke caused the piston to be pulled and air (or water) was sucked in through an opened valve. In the compression-stroke this valve closed and the content was pressed out of the pump through a second valve. Given the similarity between the two instruments the obvious supposition is that the air-pump developed out of the water-pump. To some extent this is true, but the connection is not as straightforward as is often suggested.[23] Von Guericke, for instance, did not adapt a water-pump to create his "antlia pneumatica," but a fire-syringe.[24] The syringe was supplied with a leather valve to keep the air from flowing back into the emptied vessel. A simple stopper was used to prevent outside air from being sucked in. These valves differed significantly from the kind used in water-pumps and the stopper did not represent an improvement.[25]

Thus, although, Von Guericke knew how water-pumps worked, he may have been unfamiliar with the details of their design. The situation amongst his followers was not much different. For instance, the employment of more than one cylinder only became common in the early eighteenth century, while with water-pumps their usage had been widespread long before. Likewise, crankshafts were commonly used in sixteenth century water-pumps to drive the rectilinearly moving pistons in a circular motion. These were not applied to air-pumps until the nineteenth century. Apparently the air-pump pioneers relied on their own ingenuity. They did not consult experienced pump-builders, nor did they ask them to construct their air-pumps. The scientists preferred to do business with craftsmen they were accustomed to dealing with, such as instrument makers and clockmakers.

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[23] For instance: Conant (n. 10), p. 52 and Ditmar Schneider, "Zur Entwicklung der Luftpumpen - Initiatoren und erste Reife bis 1730", *Wissenschaftliche Zeitschrift der Technische Hochschule "Otto von Guericke" Magdeburg* 30, 1986, Heft 1/2, pp. 49-65, on pp. 50-51.

[24] A detailed description of Von Guericke's air-pumps is to be found in Schneider (n. 23).

[25] On water-pumps see: Sheldon Shapiro, "The origin of the suction-pump", *Technology & Culture* 5, 1964, pp. 566-574.

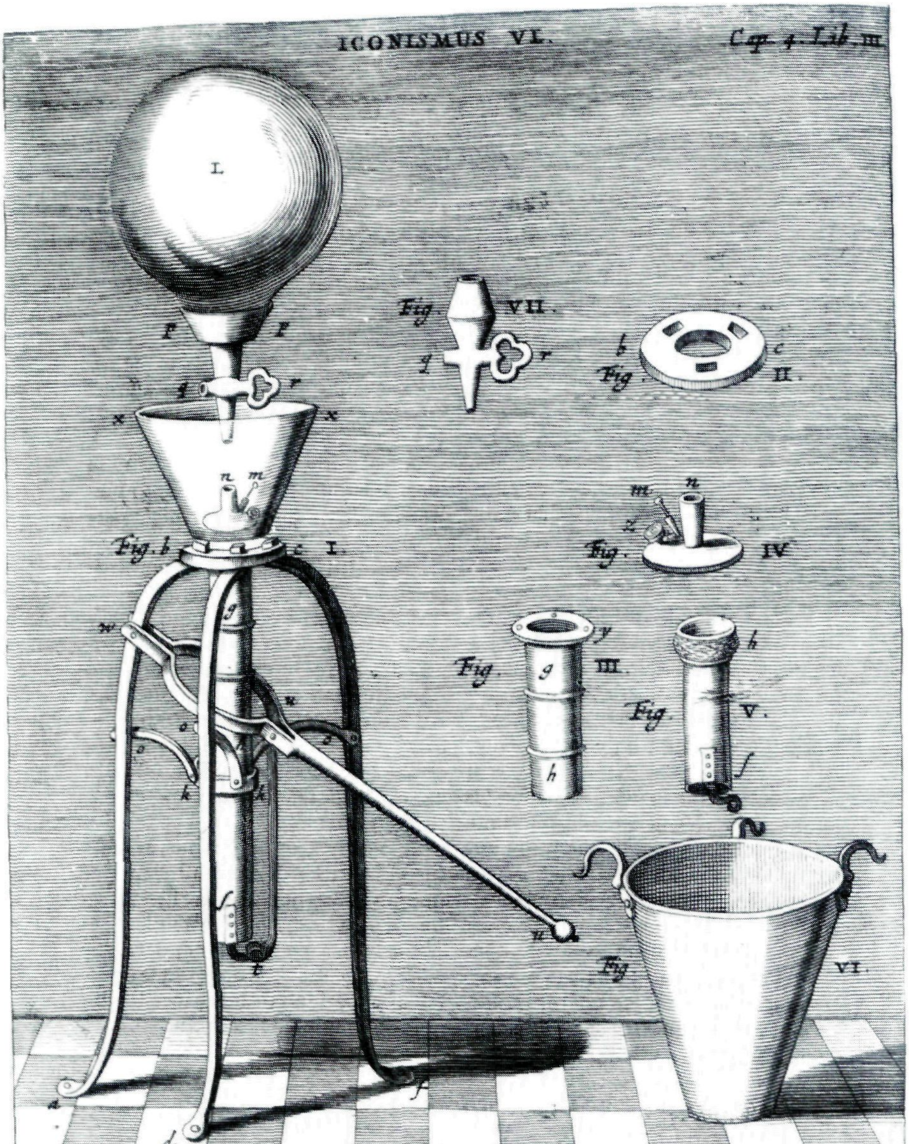

Figure 1 – Von Guericke's travel-pump (1663) from Von Guericke (n. 8)

As for Von Guericke, he remained loyal to use of a fire-syringe in all his pumps. The improvements on his air-pumps were limited to the introduction of a lever, to lighten the labour, and several measures to decrease leakage. Von Guericke used water-basins in which possible leaks were immersed, and this use of water-seals was adopted by almost all subsequent designers. Von Guericke's final design was finished in 1663. In his own description, published in 1672, he explained how his pump worked.[26] He used Boyle's concept of a spring of air to explain how the air opened the valve. However, when almost all the air was removed from the recipient, the air's elasticity would not be sufficiently strong to open the valve. To remove the remaining air, Von Guericke constructed a special device to open the valve from outside. The air would drop out of the recipient through the opened valve because of its own weight. Apparently, he thought that fully expanded air behaved as a liquid. Considering the fact that the distinction between gas and liquid was not yet clear, this was not such a strange supposition. It was only natural to expect the fully expanded gas to collect at the bottom of the recipient. Thus the obvious place for the hole, through which the air was drawn out, was at the bottom of the recipient. And indeed, with all early air-pumps this is where the hole was made.

Von Guericke became the prime source of air-pumps in seventeenth-century Germany. His very first pump was used by Kaspar Schott to confirm his results.[27] The Elector of Brandenburg acquired one through Von Guericke in 1663, but he seems not to have used it to any significant end.[28] Three more pumps are known to have been made in Germany in the seventeenth century. Two of these followed Von Guericke's design and may have been made under his supervision.[29] J.S. Doppelmayr seems to have had one in Nuremberg.[30] The other was bought in Germany by the Swedish physician C. Heraeus who

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[26] Otto von Guericke, *Neue (sogenannte) Magdeburger Versuche über den leeren Raum* (Düsseldorf: VDI-Verlag, 1968), p. 86.

[27] Krafft (n. 4), p. 98.

[28] This is the oldest surviving pump. It is now kept in the Deutsches Museum in Munich (*Ibid.*, p. 102).

[29] The third pump is similar to Hooke's design as published in Robert Boyle, *New experiments physico-mechanical touching the spring of air* (Oxford: H. Hall, 1660). Through an unknown route, it entered the physics cabinet of Leiden University before 1711 (Peter de Clercq, *The Leiden cabinet of physics* (Leiden: Museum Boerhaave, 1989)), p. 17. The instrument is now kept in the Museum Boerhaave in Leiden.

[30] Curtis Wilson cites a description by Doppelmayr's son of a vase-like air-pump in "Doppelmayr, Johann Gabriel", in *Dictionary of Scientific Biography*, ed. C.C. Gillispie, 16 vols. (New York: Charles Scribner's sons, 1970-1980), vol. 4, pp. 166-167, on p. 166. This was probably a Guericke-type.

transported it to his homeland in 1676.[31] After passing through various hands, it entered the instrument cabinet of the University of Lund.

As mentioned above, Boyle dismissed anomalous suspension because he could not reproduce it himself. In general he more or less decided which pneumatic experiments could be regarded as 'facts'. Boyle must have played a dominant role in English pneumatics, and this may be one of the reasons why England produced relatively few air-pump during the seventeenth century. Apart from the ones in Boyle's house and in the Royal Society, only two more pumps are known, one in Cambridge and one in Halifax in Yorkshire.[32] It seems the demand for air-pumps was not very great. After all, most of the eminent Baconians had access to the Royal Society, where Boyle's experiments were demonstrated before their eyes.

Boyle's first air-pump was constructed on the basis of a hearsay description of that of Von Guericke.[33] The result was disappointing. According to Boyle's assistant Robert Hooke it was too coarsely built.[34] Hooke therefore designed a new machine in 1659. The most important innovation was the large glass receiver, in which experiments could be done. Von Guericke's inlet-valve was replaced by a cock, and the piston-rod was supplied with a rack-and-pinion mechanism. Rack-and-pinion was to become a constant feature of air-pump design, because it decreased the labour required to operate the air-pump. Also notable is the total absence of water-seals in Hooke's design. Perhaps he was simply not aware of the possibility. At any rate, he and Boyle started experimenting with water-seals as early as 1661, and in Hooke's second design of 1662 the entire barrel was immersed in water.[35]

Hooke's first design served as a model for Huygens' first pump.[36] There was only one important difference. Huygens did not use a large glass sphere as a recipient, because he could not find a capable glass-blower to make it. Instead he used a bell-jar on a plate. Although a product of necessity, this adaptation proved very handy. It was even easier to put in instruments into a bell-jar, than a glass sphere. It would have been uncharacteristic of Huygens, if he had not tried

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[31] J.G. Tandberg, *Die Triewaldsche Sammlung am Physikal. Institut der Universität zu Lund und die Original-Luftpumpe Guerickes (Lund: Håkan Ohlssons Buchdruckerei, 1920), p. 25.* The instrument is now kept by the Kunskapstivoli in Malmö. The Technische Hochschule in Braunschweig possesses a pump that is supposed to have come from Von Guericke's collection, but its history can only be traced back to the early eighteenth century (compare Kraft (n. 4), pp. 102-103).

[32] Shapin and Schaffer (n. 1), pp. 38-39, 229.

[33] A full account of Boyle's air-pumps is given in Shapin and Schaffer (n. 1), pp. 26-39.

[34] Maddison (n. 11), p. 92.

[35] *Ibid.*, p. 261.

[36] An overview of Huygens' designs is given in Stroup (n. 14).

FIG. 5. Reproduction of a wood engraving of Boyle's first air pump, from his own book.

Figure 2 – Hooke's first design (1659) from Robert Boyle, *New experiments touching the spring of air* (1660)

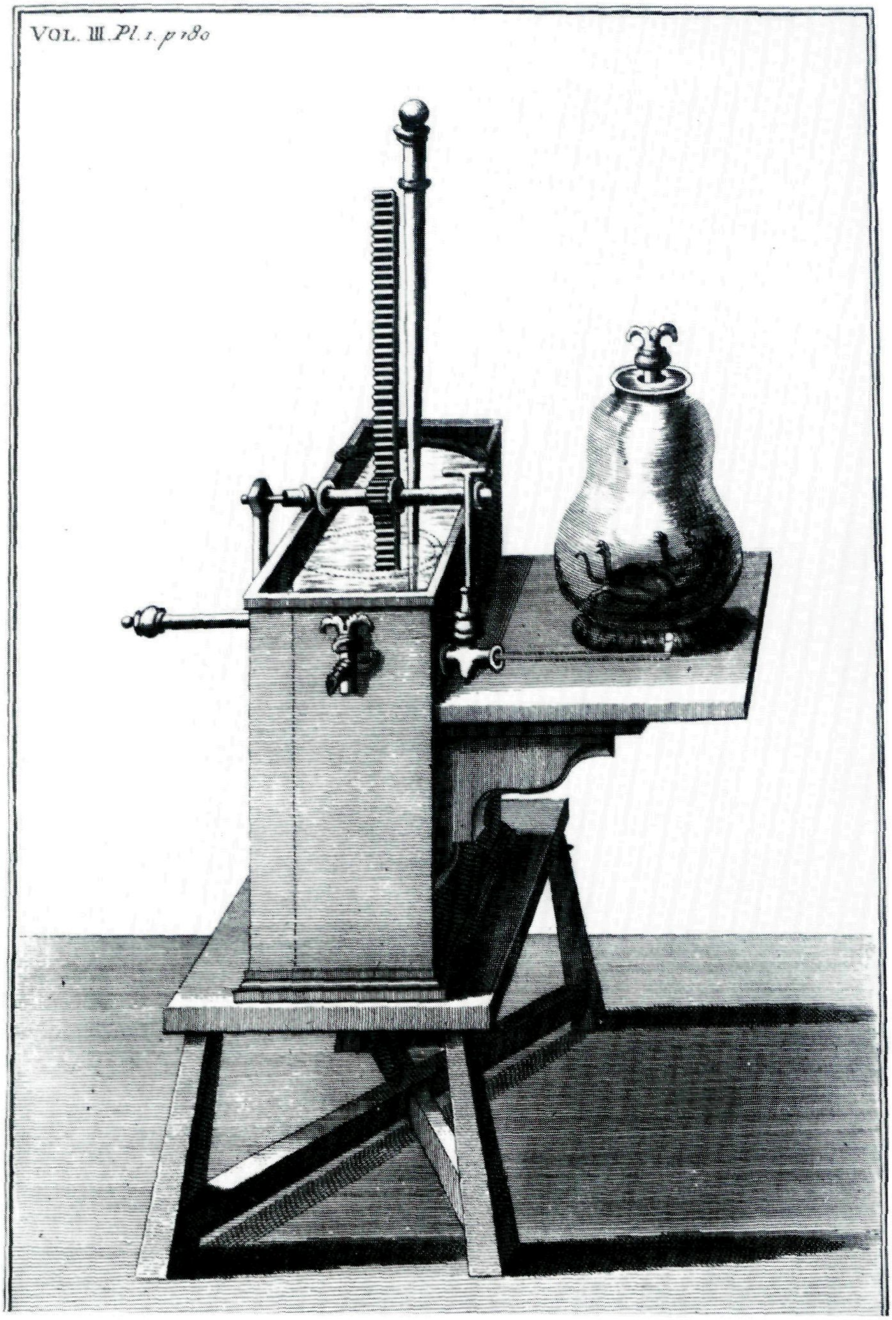

Figure 3 – Second design by Hooke (1662) from Boyle, *A continuation of new experiments* ... (1669)

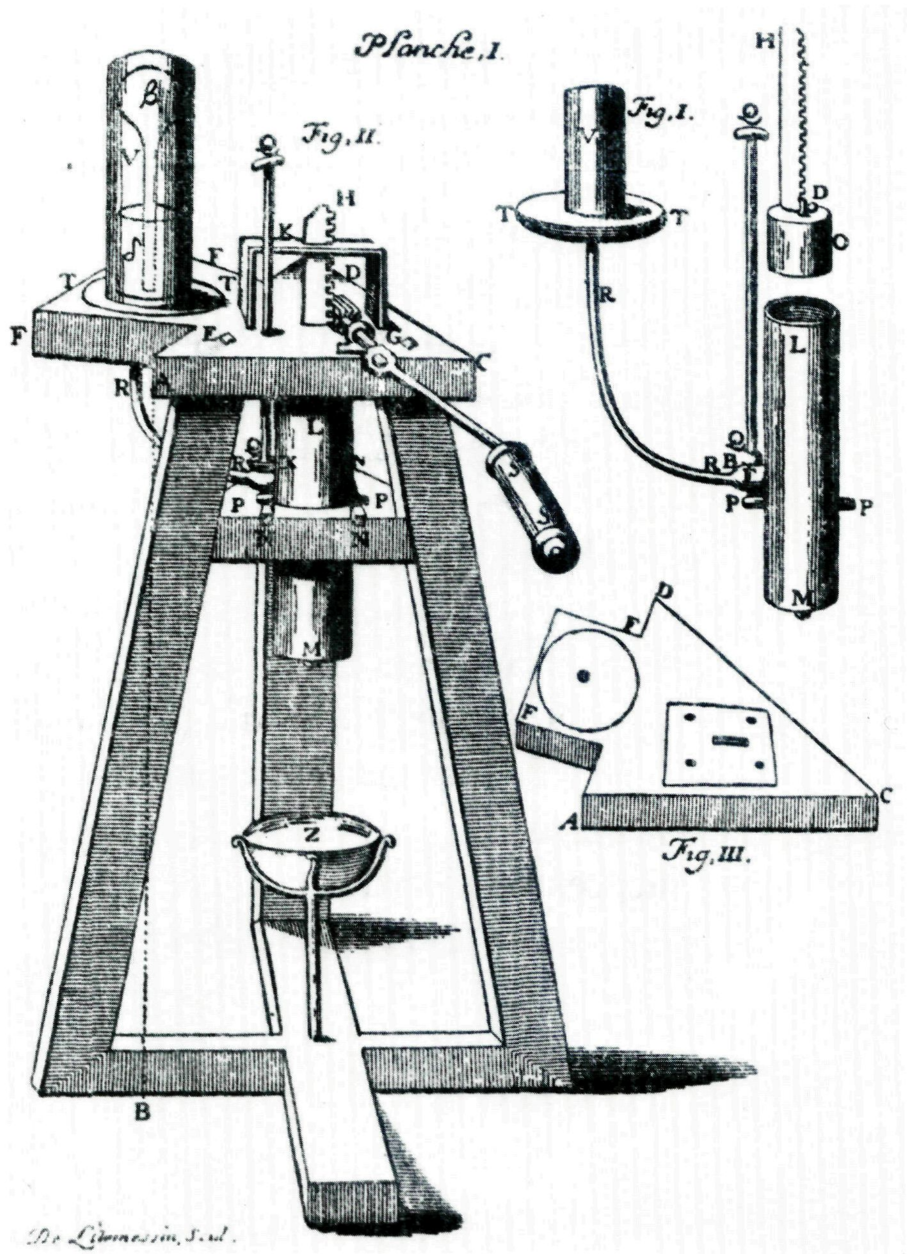

Figure 4 – Huygens' air-pump (1662) as published in Denis Papin (n. 39)

to further improve the air-pump, and he struggled to solve the problem of leakage around the piston. Various piston constructions were tried, but Huygens was not satisfied. When he heard that Boyle and Hooke were experimenting with water-seals, he decided to give these a try. His inversion of the cylinder was an attempt to achieve this end, causing the piston to be pulled upward instead of down. Thus water could be poured onto the piston to improve its airtight quality. Huygens was convinced that his pump was superior to that of Hooke. And when he was asked to construct a pump for the Montmor Academy in 1663 and for the Académie Royal in 1668, he drew upon his own design. He personally supervised their assembly, as the local instrument makers were not capable of undertaking this task.

Eleven likely pump sites can be traced in the period 1647-1670,[37] and it can be surmised that the total number of air-pumps made up to that time did not exceed fifteen. Most of these were made under the direct influence of either Von Guericke, Boyle or Huygens. Clearly, pump making was initiated by the needs of a small group of scientists, who employed technicians to put their ideas into practice. No instrument maker is known to have entered the pump-making market on his own initiative before 1670. All three pioneers of pumping attempted to decrease leakage as much as possible. Shapin and Schaffer have pointed out that this was an important condition for the acceptance of the air-pump as a reliable scientific tool, but this probably was not the only reason for their efforts. The scientist's need to have the best research tool possible must also have been of great importance.

Instrument makers take over

From 1670 onwards instrument makers gradually started making air-pumps on a commercial basis. France was the first country to develop anything like a pump building industry. Huygens was of course the leading figure in the French scientific world. But he was less influential than Boyle was in England. It was not easy for French scientists to witness his experiments, as these were usually carried out in Holland. Moreover, Huygens' research was much less wide-ranging than that of Boyle. Naturally, the French were more stimulated than the

[37] The following persons and institutions possessed one or more air-pump before 1670: Von Guericke in Magdeburg, Schott in Würzburg, the Elector of Brandenburg, Boyle in Oxford, the Royal Society in London, Henry Power in Halifax, Christ's College in Cambridge, the Montmor Academy and Académie Royal, both in Paris, and Huygens in The Hague. Johann Christoph Sturm had an air-pump in 1675 (J.C. Sturm, *Collegium experimentale sive Curiosum* ... (Nuremberg: W.M. Endterus, 1676), pp. 100-120). As this instrument follows Von Guericke's first design, it is likely to have been made before 1672.

English to build their own pumps, and at least three craftsmen responded to the challenge. Gaudron, Hubin and Dalancé are known to have built air-pumps in Paris in the 1670s.[38] This trio seems to have built for the French market only, and there is no indication that they exported their pumps outside of France.

Customers had the choice between three types of air-pumps. Dalancé constructed a Guericke-type pump, while Gaudron made a Huygens' variant and a design by Papin.[39] Denis Papin had learned the trade in the service of Huygens. Nevertheless he disregarded Huygens' important contribution of the inverted plunger with a water-layer on top of it. Instead, he incorporated the water-seal into the plunger. This complicated structure consisted of two pistons on one rod (see figure 5). The lower piston carried a quantity of water that sealed off possible leaks at the topmost piston. The aim was to have an airtight piston with a downward exhaust-stroke. By supplying the piston-rod with a stirrup, the relatively trying exhaust-stroke could be done with the foot. Thus the task of pumping became less fatiguing. Moreover, it left one hand free to operate the cock. This cock was very special; the inlet-valve and the outlet-valve were combined in one three-way-cock. This was much easier to handle than a separate inlet-cock and stopper. And it made the air-pump usable as a compressor as well.

Holland was the next country to develop a pump industry. Or rather the brothers Samuel and Johan van Musschenbroek did. Around 1675 their workshop in Leiden was beginning to specialize in instrument making, and in the following years it developed into Europe's most important supplier of philosophical instruments in general and air-pumps in particular. They exported air-pumps to Germany, Italy, Scotland and Sweden.[40] In fact, the Van Musschenbroeks more or less monopolized the market. During the last quarter of the seventeenth century they were by far the most important, if not the only, commercial makers of air-pumps outside of France. Their first air-pump was constructed in 1675 at the request of the Leiden professor of physics De Volder.[41] De Volder had just returned from a visit to London, and, full of enthusiasm, he decided to construct an air-pump based on Hooke's second design. The Van Musschenbroeks must have done a good job, for the instrument was kept in use for over a century.

But, good though it was, Hooke's design, or De Volder's variant, was not the workshop's best seller. It was much too cumbersome, two men being required to operate it. This motivated De Volder's colleague Wolferd Senguerd to design a

[38] *Ibid.*, note 63.

[39] *Ibid.*, note 63; Papin published his design in *Nouvelles expériences du vuide (1674)*, reprinted in Christiaan Huygens (n. 9), vol 19, pp. 216-238.

[40] Peter de Clercq, private communication

[41] De Clercq (n. 29), p. 14.

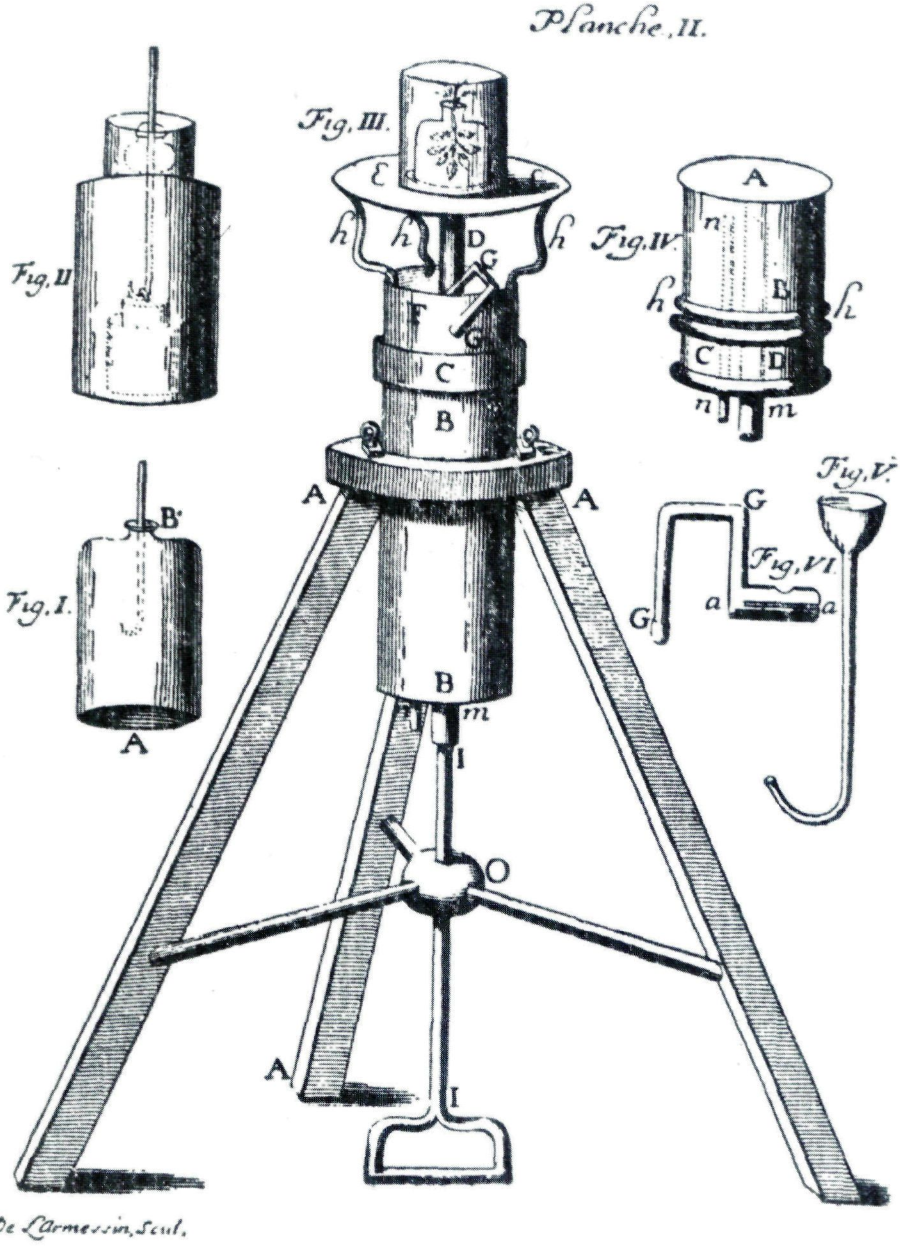

Figure 5 – Papin's design (1674) from Papin (n. 39)

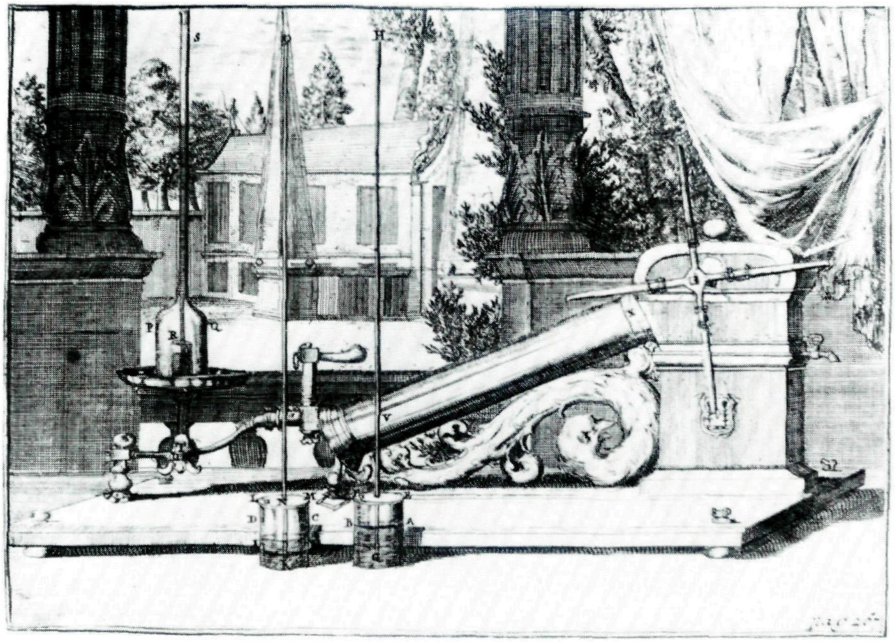

Figure 6 – Senguerd's inclined air-pump (1679) from Senguerdus, *Philosofia naturalis* (1685)

more practical instrument in 1679.[42] He took Hooke's design of 1662 as a starting point, adapting it to his demands. First of all he tilted the barrel. This meant that the cock could be reached by the man at the handles, who could now operate the pump by himself. Next, he supplied it with a three-way-cock instead of a separate cock and stopper. Senguerd was not the first to invent a three-way-cock, but apparently he was unaware of Papin's prior work. At least he did not give any reference to Papin, and his cock is of a different construction. Moreover, had he known, there would have been no reason to develop an air-pump of his own. After all, Papin's pump was just what Senguerd had in mind: an easy-to-use instrument that could also be used as a compressor. Just as Papin's air-pump was popular in France, Senguerd's design dominated the production of pumps on the rest of the continent. It was produced in large numbers by the Van Musschenbroek workshop and from around 1700 onwards by Jacob

[42] Wolferdus Senguerdius, *Rationis atque experientiae connubium* (Leiden, 1715), p. 4.

Leupold of Leipzig.[43] Even as late as the 1770s instruments following this design were produced by Georg Friedrich Brander of Augsburg.[44]

A reliable estimate of the total production of Senguerd-type air-pumps is not easy to give, but it must have been considerable. Of the 30 air-pumps the Leupold workshop constructed between 1700 and 1726, probably 10 to 20 were Senguerd-type instruments.[45] The Van Musschenbroeks must have made more, for they were active for a longer period, and more of their products have survived (compare table 2). Thus, in the early eighteenth century, the proliferation of air-pumps was well under way. This is quite surprising, because the air-pump was a very expensive instrument. Van Musschenbroek offered the Senguerd-type air-pump with accessories for 500 guilders, about half a professor's annual salary.[46] But the workshop also produced a small horizontal air-pump. It was designed by Johan van Musschenbroek around 1680, to meet the demand for a relatively cheap air-pump. This small instrument must have been popular. The demand was large enough for Van Musschenbroek to have the instructions for use printed.[47]

The Senguerd-type was superseded by the double-barrel air-pump. This new type was invented in 1676 by Papin, who was then working for Boyle.[48] Characteristic of Papin's design was the use of self-acting valves. The two pistons were connected by a rope that passed over a pulley; by turning the pulley the pistons were driven. Double-barrel air-pumps were first produced on a commercial basis by the London instrument maker Francis Hauksbee (the elder) from 1703 onward.[49] Hauksbee's design followed Papin's general outline, except that it had a rack-and-pinion mechanism instead of a rope and pulley. The 'index mercurialis' was a standard accessory of Hauksbee's air-pumps. This tube, filled with mercury, measured the pressure in the recipient, and thus indicated the quality of the vacuum.

The use of two cylinders doubled the speed. And it also decreased the required labour, as the forces on the two pistons partly compensated one

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[43] Compare table 2.

[44] Alto Brachner et. al., *G.F. Brander, 1713-1783, Wissenschaftliche Instrumente aus seiner Werkstatt (Munich: Deutsches Museum, 1983), pp. 296, 302-303.*

[45] Lothar Hiersemann, *Jacob Leupold - ein Wegbereiter der technischen Bildung in Leipzig (Leipzig: Technische Hochschule Leipzig, 1982), p. 28*

[46] See the article by Peter de Clercq ("Exporting scientific instruments around 1700: the Musschenbroek documents in Marburg") in this issue.

[47] Jan van Musschenbroek, *Descriptio antliae pneumaticae et inst[r]umentorum ad eam inprimis pertinentium* [1694].

[48] Maddison (n. 110, p. 227, plate 20; Shapin and Schaffer (n. 1), p. 28.

[49] Hauksbee published his design in 1709 in his *Physico-mechanical experiments on various subjects* (London, 1709), but his instrument was first shown to the Royal Society in 1703.

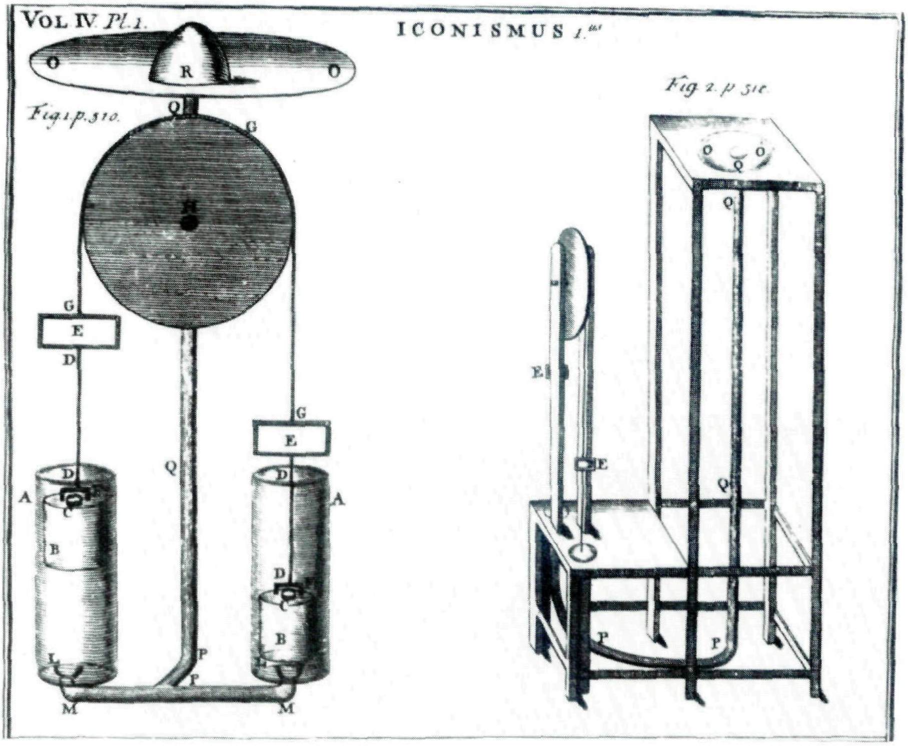

Figure 7 – Papin's Double barrel air-pump (1676) from Boyle, *A second continuation* ... (1680)

another under specific conditions. Valves were used to create such conditions, even though these had a theoretical disadvantage. Valves always needed a finite pressure to open them, which implied a lower boundary on the pressure that could be reached. The problem was of little practical significance, but nevertheless it is striking that it did not damage the Hauksbee-pump's popularity. Though the problem was not unknown, perhaps it was not fully recognized. Von Guericke had mentioned it explicitly in 1672,[50] and in Holland Willem Jacob 's Gravesande seems to have been aware of it in 1714.[51] The fact that little or no attention was paid to a problem like this is a clear indication that the

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[50] Von Guericke (n. 26), p. 86.

[51] W.J. 's Gravesande, "Remarques sur la construction des machines pneumatiques & sur les dimensions qu'il faut leur donner", *Journal Literaire* 4, 1714, part 1, pp. 182-208, on p. 185.

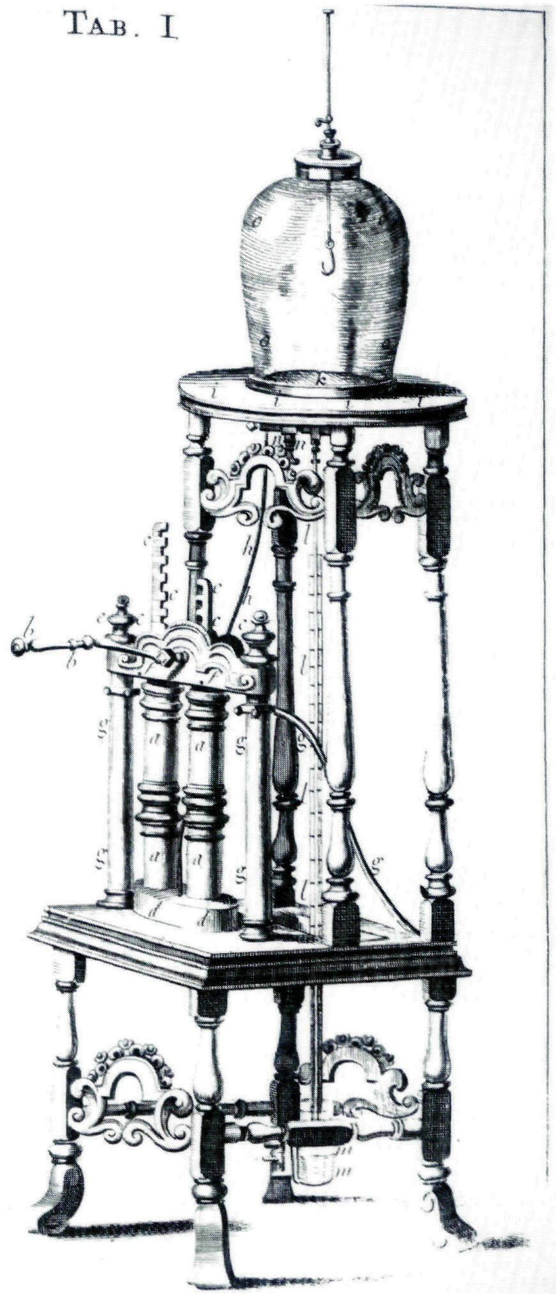

Figure 8 – Hauksbee's design (c. 1700) from Hauksbee (n. 49)

emphasis at that time was not on the best possible vacuum. In fact, between 1675 and 1750 all developments aimed at improving the speed of operation and the ease of handling.[52] And in this respect, the double-barrel air-pump was clearly a major breakthrough.

Hauksbee-type air-pumps were the first pneumatic instruments to cross the Channel. Three of these are now kept in museums in Munich, Paris and Padua. The one in Padua is known to have been bought in England. Judging by the design and decoration, the Munich and Paris copies were also English. Continental instrument makers soon took Hauksbee's design for production purposes. Leupold of Leipzig started producing them to a slightly adapted design.[53] Leupold replaced the rack-and-pinion mechanism by a lever. Van Musschenbroek also produced double-barrel air-pumps, but it is not certain whether he used the designs of Hauksbee or Papin. The only illustration of this product, however, suggests that it was Papin's design.[54]

In 1722 's Gravesande redesigned the double-barrel air-pump.[55] He used three-way-cocks instead of valves. His pump, therefore, did not suffer from the minimum pressure required by valves to open, but it also lacked some the advantages of the double-barrel pump. The forces on the two pistons would not compensate one another, and with each stroke two cocks would have to be operated. 's Gravesande solved the second problem with a automatic cock-operating mechanism. The first problem was solved by supplying the outlets of the cocks with valves. These valves too suffered from the minimum-pressure-problem, but, as it was on the outlet-side only, it was not significant.

As a university professor, 's Gravesande was an exception among eighteenth-century designers of air-pumps. The others were primarily or initially instrument makers. These technicians had gradually taken over the initiative from the scientists. They began making air-pumps without a supervising authority. France and Holland were the first countries where this development took place. England and Germany caught up around 1700. The air-pump itself had changed. in conjunction with this development. In the 1660s it had been a delicate tool for specialized scientists, who had emphasized the importance of decreasing leakage.

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[52] The first to attack the fundamental limitations of the piston-pump was John Smeaton around 1750.

[53] Hiersemann (n. 45), p. 28

[54] W.J. 's Gravesande, *Physices elementa mathematica* (Leiden: Van der Aa, 1720), vol. 1, plate 27.

[55] The design was published in 1725 (W.J. 's Gravesande, *Physices elementa mathematica* (Leiden: Van der Aa, 1725), pp. 310-313). 's Gravesande's own pump is extant (now in the Museum Boerhaave in Leiden) and dated 1722. 's Gravesande also designed a single-barrel air-pump (Jan van Musschenbroek, *Beschrijving der nieuwe soorten van luchtpompen, zo dubbelde, als enkelde* [Leiden, 1736], pp. 13-18), but no copy has been preserved.

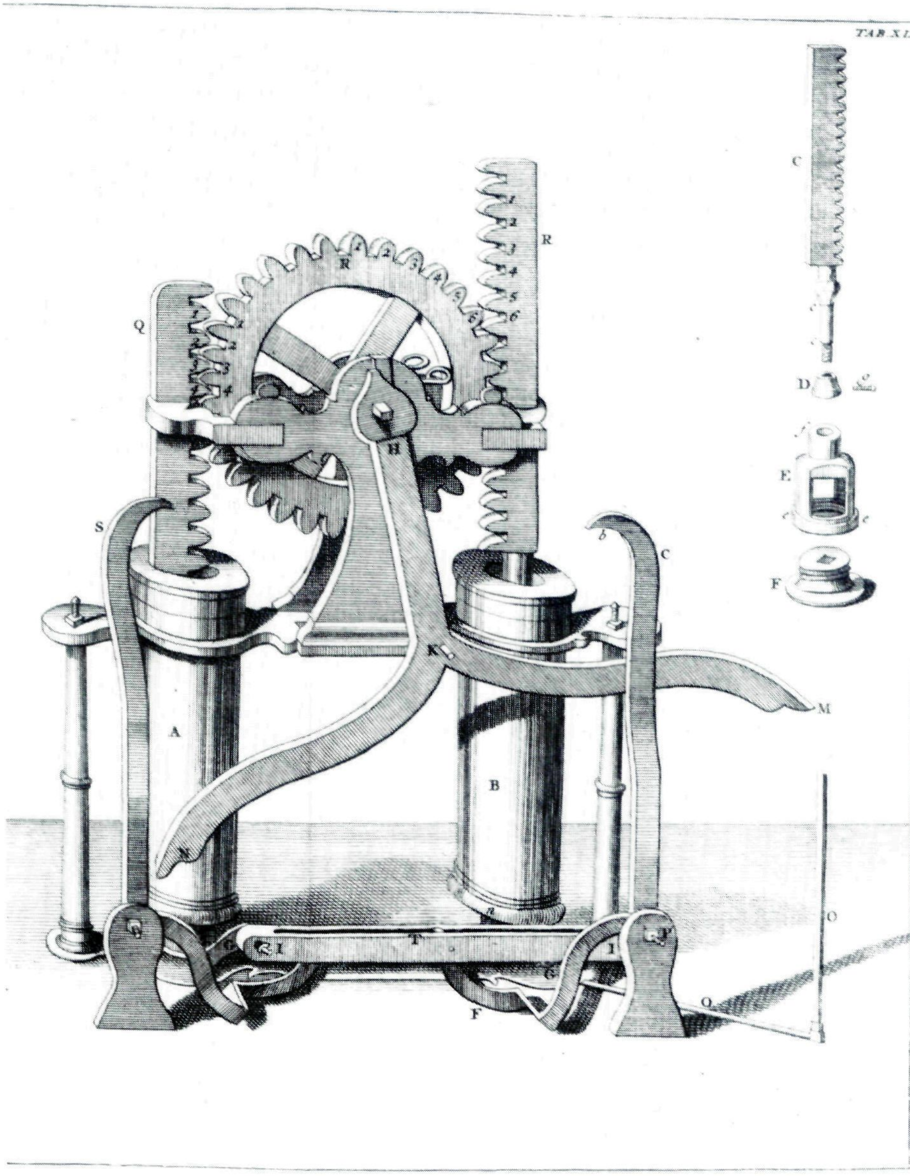

Figure 9 – 's Gravesande's design (1722) from 's Gravesande (n. 55)

But as soon as the air-pump had been established as a reliable scientific instrument, the stress on leakage diminished. Simultaneously, the craftsmanship of specialist constructors had brought the problem under control, but in the eighteenth century there was no drive to further improve on this. Clearly the air-pump was no longer a specialist research tool, but a popular demonstration device. In fact, it had become a symbol of the new experimental philosophy.[56] Indeed no instrument tuned in better than the air-pump with the rise of Baconi-anism that so greatly influenced the scientific world in the late seventeenth and early eighteenth century.

Summary

The idea that the invention of the air-pump in 1647 settled the old vacuum debate at the end of the seventeenth century is appealing, but untrue. To prove the existence of a void by creating one was not an original notion. It had been done before employing Torricelli's tube. Moreover, the proof was convincing only to those who were already convinced. Nevertheless, the air-pump was an important instrument, because it facilitated the posing and answering of entirely new questions. A growing number of scientists became more interested in searching for the properties of the vacuum, rather than in discussing its existence. Thus the old debate faded away. In the meantime, the air-pump itself developed from a specialist research tool into a readily available demonstration device. A survey of the various types of air-pump that were introduced before 1740, makes it clear that designers initially aimed at decreasing leakage. With the growing popularity of the instrument, the emphasis gradually shifted to improving the ease of handling.

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The Netherlands

[56] Shapin and Schaffer (n. 1), pp. 30-35.

Table 1. Air-pump designs up to 1740

	designer	date of design	number of cylinders	valve system	piston movement	remarks
1	Otto von Guericke	c. 1647	1	valves	simple pull	partly immersed in water
2	Otto von Guericke	c. 1656	1	valves	lever	waterseals on all possible leaks
2a	Otto von Guericke	1663	1	valves	lever	travel-version of number 2
3	Robert Hooke	1659	1	cock & stopper	rack-and-pinion	no waterseals; glass receiver
3a	Christiaan Huygens	1661	1	cock and valve	rack-and-pinion	no waterseals; glass jar on table
4	Robert Hooke	1662	1	cock & stopper	rack-and-pinion	cylinder immersed in water
5	Christiaan Huygens	1662	1	cock & valve	rack-and-pinion	water on the piston
6	Denis Papin	< 1674	1	three way cock	stirrup	piston with built-in waterseal
6a	J.A. Nollet	c. 1740	1	three way cock	stirrup	no waterseals
7	Wolferd Senguerd	1679	1	three way cock	rack-and-pinion	inclined cylinder
7a	Musschenbroek workshop	c. 1680	1	three way cock	rack-and-pinion	small horizontal; no waterseals
8	Denis Papin	1676	2	valves	rope over pulley	
9	Francis Hauksbee	< 1703	2	valves	rack-and-pinion	built-in pressure gauge
9a	Jacob Leupold	c. 1710	2	valves	lever	
9b	William Vream	1717	2	valves	rack-and-pinion	driven with continuous circular movement
10	W.J. 's Gravesande	1722	2	three way cocks	rack-and-pinion	automatic cock operation
11	W.J. 's Gravesande	< 1736	1	three way cock	rack-and-pinion	automatic cock operation

Table 2. Extant air-pumps

type	maker	date	first owner	present keeper
2a		1663	Otto von Guericke	Deutsches Museum, Munich
2a		< 1674	C. Heraeus	Kunstkapstivoli, Malmö
2a		1675-1725	Otto von Guericke (?)	Technische Hochschule, Braunschweig
3		1660-1700		Museum Boerhaave, Leiden
4	Samuel van Musschenbroek	1675	Leiden University	Museum Boerhaave, Leiden
6a		c. 1740	J.A. Nollet	C.N.A.M., Paris
6a		c. 1740		C.N.A.M., Paris
7	Johan van Musschenbroek	1686	Count of Hesse-Kassel	H.L.M., Kassel
7	Johan van Musschenbroek	1697		Domus Galilaeana, Pisa
7	Johan van Musschenbroek	1698	Groningen University	Museum Boerhaave, Leiden
7	Jan van Musschenbroek	1706	Utrecht University	University Museum, Utrecht
7	Jan van Musschenbroek	1708		Deutsches Museum, Munich
7	Jacob Leupold	1709	Elector of Saxony	Zwinger, Dresden
7a	Johan van Musschenbroek	1675-1700		Museum Boerhaave, Leiden
9	Francis Hauksbee	c. 1708	Royal Society	Science Museum London
9		c. 1710		private collector
9		c. 1730		M.H.S., Oxford
9		1700-1750		Deutsches Museum, Munich
9		1700-1750	Cristino Martinelli	University of Padua
9		1743		M.S.S., Florence
9a		c. 1720		N.M.S., Edinburgh
9a		1725-1750		C.N.A.M., Paris
10	Jan van Musschenbroek	1722	W.J. 's Gravesande	Museum Boerhaave, Leiden
10	Jan van Musschenbroek	c. 1735	Franeker University	Museum Boerhaave, Leiden
	Jacob Leupold	1700-1725		Deutsches Museum, Munich

The list is exhaustive only for seventeenth century air-pumps.