

HISTORY OF VACUUM DEVICES

P.A. Redhead

National Research Council
Ottawa, Canada

Abstract

An outline of the early history of vacuum devices (pumps and pressure gauges) is presented, from the first recorded experiments on vacuum in the 1640s to the start of the modern period of vacuum technology when ultrahigh vacuum was introduced in 1950.

1. INTRODUCTION

The first experiments to produce a vacuum were proposed in 1631 by Renieri of Leiden in correspondence with Descartes [1]. The first recorded experiment to produce a vacuum appears to have taken place in about 1641 when Gasparo Berti experimented with a water barometer [2], see Fig. 1. The lead tube AB was about 11 metres long, the tube and reservoir were filled with water and the valves G, D, and B were then closed. The valve B was then opened and the water level dropped to L, a vacuum was left in the chamber above L. The experiment was not very convincing since it was assumed that sound would not travel through a vacuum yet a bell M rung in the vacuum space could be clearly heard, the sound was probably transmitted through the supports of the bell. In 1644 Vincenzo Viviani repeated Berti's experiment using a mercury-filled glass tube which was inverted with its open end in a reservoir of mercury. The experiment was probably planned by Evangelista Toricelli who was credited by earlier historians with performing the famous experiment in 1643. The Toricellian experiments convinced most scholars at the time that a vacuum had been created. This was the time of the dual papacy and the concept of vacuum was still considered anathema, thus it was dangerous to continue experiments on vacuum in countries accepting the Roman pope so the experiments were pursued in the reformed countries and in France, where the French pope was inclined to ignore the opinions of the Roman pope.

A few years after these initial experiments on vacuum the first vacuum pumps were created by Otto von Guericke the Burgomaster of Magdeburg, this is when the history of vacuum devices begins. In this paper we examine the development of vacuum devices, in particular vacuum pumps and gauges, from 1650 to the start of modern vacuum technology in 1950 when ultrahigh vacuum was first achieved and measured.

Several histories of vacuum technology may be consulted for further details [3-11].

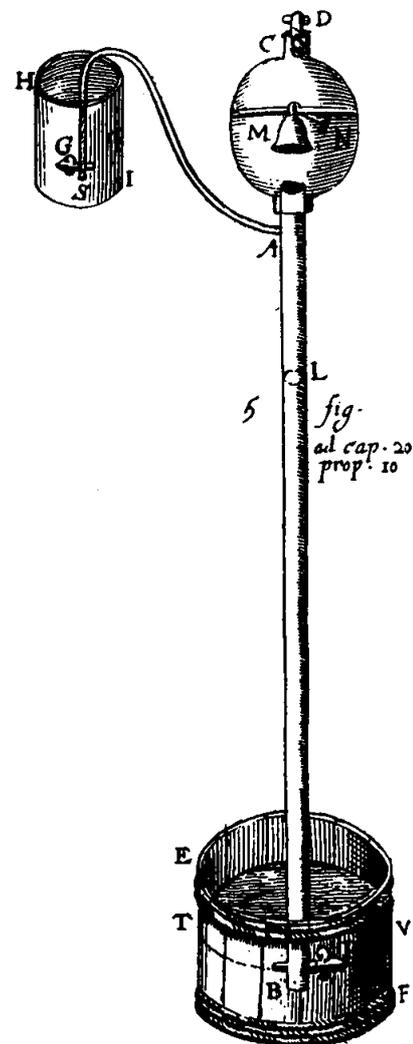


Fig. 1 The apparatus used by Gasparo Berti in about 1641 to produce a vacuum

2. VACUUM FOR FUN AND SCIENCE, THE FIRST TWO CENTURIES, 1650 TO 1850

The vacuum pump was one of the six instruments invented in the 17th century that had a profound impact on experimental science, the others were the pendulum clock, the telescope, the thermometer, the barometer and the microscope. Otto von Guericke started work on air-pumps in the 1640s and his work was first reported by Caspar Schott [12] in 1657. Von Guericke's first two pumps are shown in Fig. 2. These pumps were essentially water pumps being worked backwards. In his first experiment in the 1640s he filled a well-caulked wooden barrel with water and two strong men pumped the water out, as air rushed through the pores in the wood into the empty space a noise was heard. In the second experiment he used a large copper sphere attached to the pump; the water was omitted and the air pumped out directly. When most of the air was pumped out the sphere collapsed with a loud noise, von Guericke realised that this was caused by atmospheric pressure. A more accurately spherical vessel was made and the experiment was then successful.

The news of von Guericke's experiments was spread through Europe by Schott's book and the next improved pump was designed by Robert Boyle [13] and built by Robert Hooke in England in 1658-9. This pump is shown in Fig. 3, it used a rack and pinion to move the piston thus greatly reducing the effort needed to operate the pump. Boyle was the first to make a measurement of vacuum with a mercury manometer placed in a bell-jar (see Fig. 4), his pump was capable of reaching a pressure of about 1/4 inch of Hg (6 Torr). Thus Boyle was the first to design a vacuum pump and combine it with a pressure gauge. The piston pump and the mercury manometer were to remain the only type of vacuum pump and pressure gauge for about two hundred years.

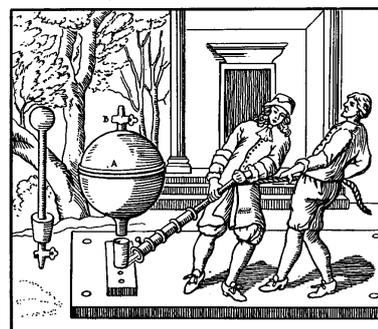


Fig. 2 The pumps of von Guericke in the 1640s. (Top) The first pump with a wooden barrel. (Bottom) The second pump with a copper sphere.



Fig. 3 Piston pump designed by Robert Boyle and built by Robert Hooke in 1658-9.

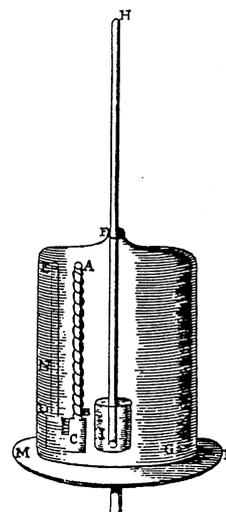


Fig. 4 The first measurement of a sub-atmospheric pressure by Robert Boyle c.1660. A beaker of mercury with a manometer tube more than 32 inches long was sealed in a bell jar and evacuated by the pump of Fig. 3.

Improvements were made to the piston pump in the next two hundred years but the basic design remained the same. The ultimate pressure achieved by these pumps decreased only slightly, the mechanical nature of the vacuum experiments of the time did not require significantly lower pressures, but the new pumps were easier to use. Hawksbee [14] built a pump in 1704 with two cylinders in which the pistons were balanced against each other as they were driven in opposite directions by the rack and pinion (see Fig. 5), this pump was capable of reaching 1.9 Torr in two minutes. At the Great Exhibition of 1851 in London the first prize for vacuum pumps was won by Newman [15] whose pump achieved a pressure of 0.5 Torr. Figure 6 shows a similar commercial pump of about 1850 that is little changed from the construction of the Hawksbee pump of 150 years before.

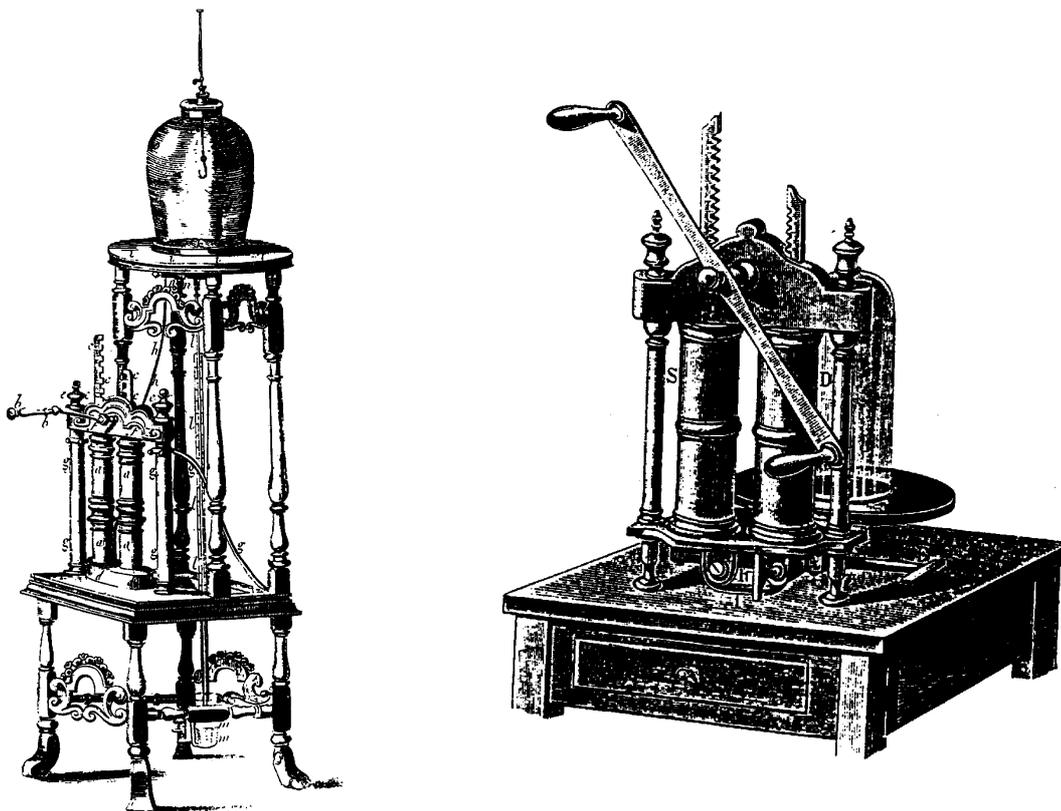


Fig. 5 The double-piston pump of Hawksbee (1704). Fig. 6 A commercial double-piston pump from about 1850.

Figure 7 shows the ultimate pressure achieved by the various pump designs in the period from 1660 to 1900 and clearly indicates the limited reduction in attainable pressure in the first two hundred years. The vacuum pump made important contributions to science in its first two centuries but throughout this period it was widely used as a source of entertainment and instruction because vacuum was a novel and fascinating subject.

3. VACUUM FOR SCIENCE, THE GREAT LEAP FORWARD, 1850 TO 1900

The 50 years from 1850 to the turn of the century produced an intense activity in the development of vacuum technology driven initially by the needs of scientific research and later by the demands of the incandescent lamp industry. In the fifty year period the attainable pressure was reduced by six decades and vacuum equipment, though still awkward, was in use in industry. The need to thoroughly outgas the equipment and to avoid the use of rubber tubing was well established.

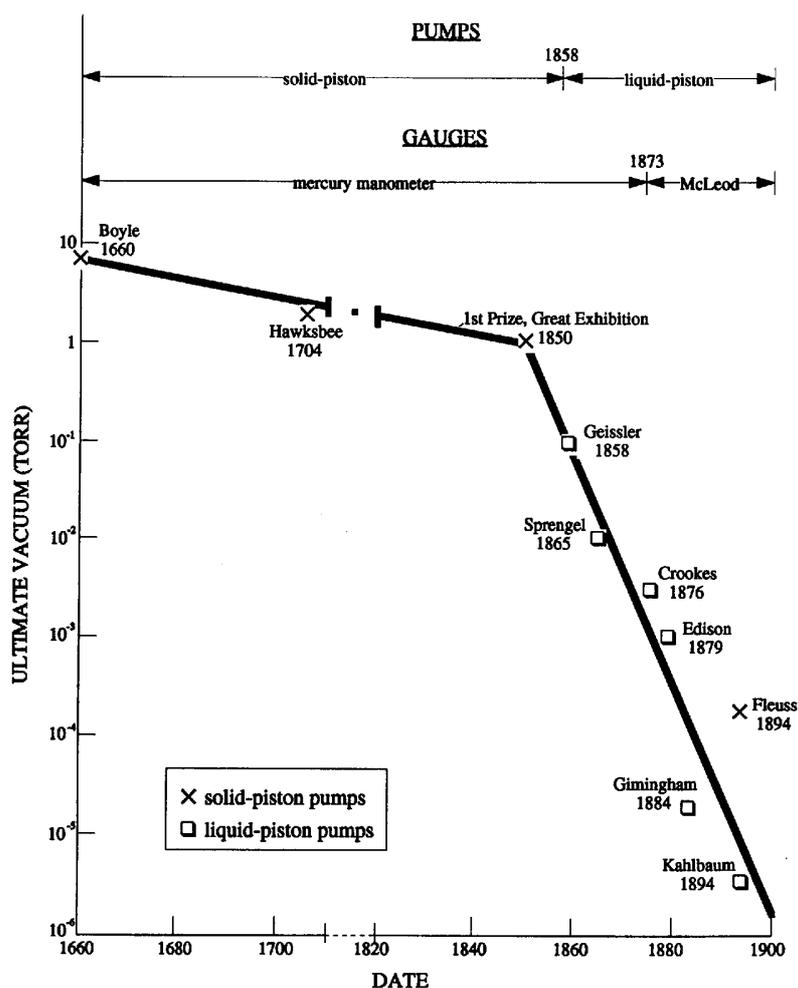


Fig. 7 The ultimate vacuum from 1660 to 1900. Note the break in the time scale. The references to the experiments are; Boyle [13], Hawksbee [14], Geissler [17], Sprengel [18], Crookes [19], Edison [22], Fleuss [24], Gimmingham [20], Kahlbaum [23].

The development of mercury-piston pumps was the major factor in achieving lower pressures. The first step occurred in 1854 when Julius Plücker of the University of Bonn asked Heinrich Geissler, his glass blower, to design a glass pump using a mercury piston to permit experiments on low pressure gas discharges; Geissler built a pump in 1855 capable of reaching 0.1 Torr which was first described in a pamphlet by Mayer [16] published in 1858. In 1862 Töpler [17] invented an improved form of the Geissler pump and in 1865 Sprengel [18] devised a pump in which a train of mercury droplets trapped packets of gas in a glass tube and carried the gas away.

In the 1870s William Crookes, with his assistant Charles Gimmingham, attempted to achieve a vacuum “*approaching perfection*”. Figure 8 shows Crookes’ first pumping system [19] using a Sprengel pump. An improved version [20] of this pumping system using seven fall tubes was capable of achieving a pressure of about 2×10^{-5} Torr as measured by a McLeod gauge. Crookes greatly improved the vacuum conditions by replacing all rubber tube connections with ground glass joints and by heating the apparatus to degas it.

The vital step in pressure measurement was McLeod’s invention of his vacuum gauge [21] in 1874 which was based on the compression of the gas by a mercury column to an easily measured higher pressure, and the use of Boyle’s law to calculate the original pressure (see Fig. 9). This permitted pressure measurements down to the 10^{-6} Torr range. Since the McLeod gauge does not measure the pressure of condensable gases, such as water, the true pressure may have been higher than those reported in this period.

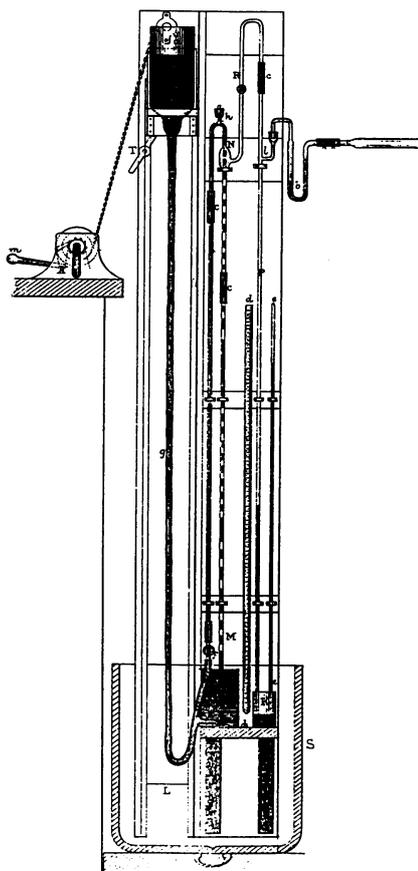


Fig. 8 Crookes' first vacuum system using a single Sprengel pump (1872).

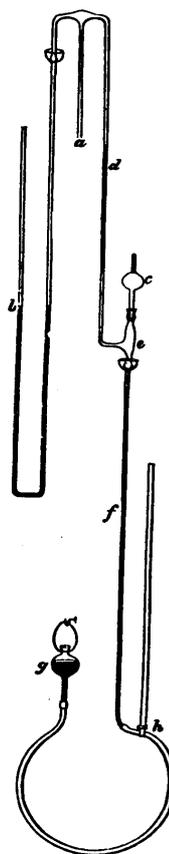


Fig. 9 The first McLeod gauge (1874).

By the end of the 1870s Crookes' vacuum techniques had moved into industry and were being used by Edison to improve the vacuum in incandescent lamps. Figure 10 shows Edison's vacuum system which contained two Sprengel pumps, a Geissler pump, and a McLeod gauge; pressures of about 10^{-3} Torr could be produced [22]. Edison's pumps were operated manually and were slow and clumsy for industrial use. By 1894 Kahlbaum [23] was able to obtain pressures as low as 3×10^{-6} Torr with a Sprengel pump.

In the same period the solid-piston pump was greatly improved, by 1892 Fleuss had manufactured a pump with an oil-sealed piston and valves that were moved mechanically [24]. This pump was known as the Geryk pump and was capable of 2×10^{-4} Torr, it was widely used in the lamp industry to replace the manually operated mercury-piston pumps until the invention of the rotary mercury pump by Gaede in 1905. The Geryk pump and the rotary mercury pump could be motor-driven and thus had the advantage over the older liquid-piston pumps for industrial use. By 1900 pressures of the order of 10^{-6} Torr could be achieved and measured and the pumps for industrial vacuum systems were being motor driven.

4. VACUUM FOR INDUSTRY, 1900 TO 1950

The change in ultimate vacuum in the period 1900 to 1950 is shown in Fig. 11. Vacuum technology made rapid advances in the period 1900 to 1920, the two figures that dominated this period were Gaede in Germany and Langmuir in the USA. The first improvement in high vacuum pump design was the invention of the rotary mercury pump by Gaede [25] in 1905, this was a rotary mercury pump which could be motor driven (see Fig. 12). It could produce pressures in the 10^{-6} Torr range and was manufactured in large quantities and widely used in the lamp and vacuum-tube industries.

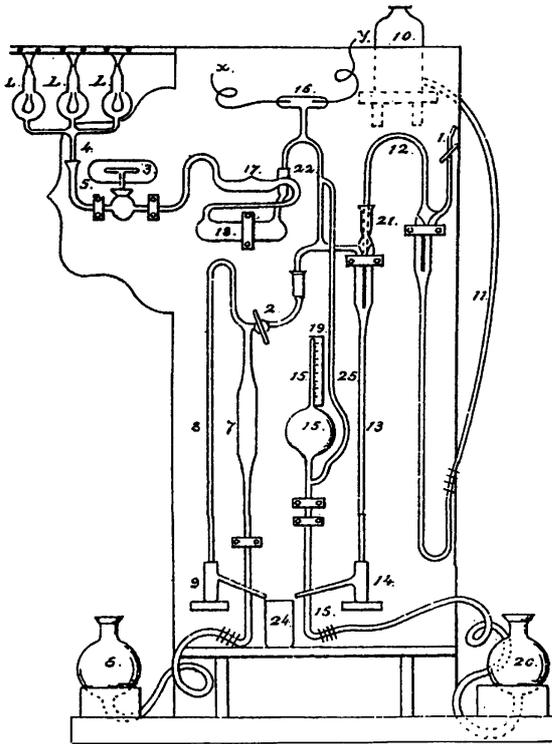


Fig. 10 Diagram of Edison's vacuum system for the production of incandescent lamps (1870s).

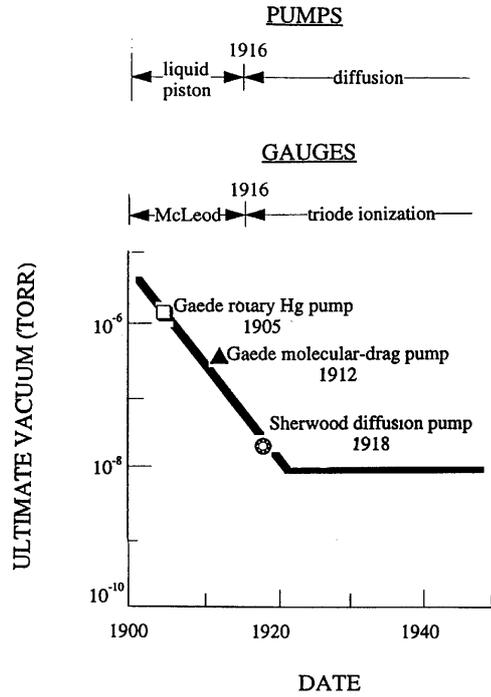


Fig. 11 The ultimate vacuum from 1900 to 1950. The references to the experiments are; Gaede (1905) [25], Gaede (1913) [27], Sherwood [34].

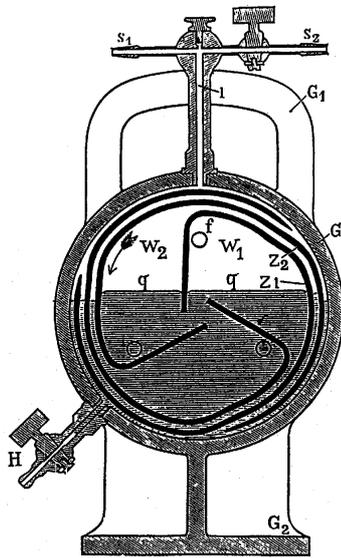


Fig. 12 Gaede's rotary mercury pump (1905).

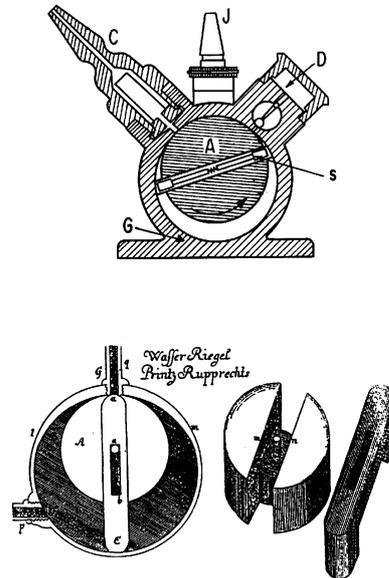


Fig. 13 Rotary oil pump designed by Gaede (1907) compared with Prince Rupert's "Water-Bolt", a water pump invented in about 1650.

In 1907 Gaede developed the rotary oil pump (see Fig. 13) primarily for use as a fore-pump for the rotary mercury pump [26], its close resemblance to the water pump invented by Prince Rupert in about 1650 is evident. The principle of this type of waterpump goes back to at least 1588 with the vane pump of Rumelli.

The next major advance in pumping methods was the invention of the molecular-drag pump by Gaede [27] in 1913 (see Fig. 14). With a fore pressure of 2×10^{-2} Torr a pressure of 4×10^{-7} Torr was measured by Dushman [28] at a rotation speed of 8,000 rpm. This pump was used in the vacuum-tube industry until the arrival of the diffusion pump. Improved versions of the molecular-drag pump with higher pumping speeds were developed over the next 30 years, notably by Holweck [29] in 1923 and Seigbahn [30] in the 1920's, pressures in the 10^{-7} Torr range were typically obtained. Molecular-drag pumps were not much used until the 1970s because their pumping speed was low and their reliability poor as a result of the very close spacing between rotor and stator. They were ahead of their time because the technology for making high-speed rotating machinery with close spacings was still rudimentary. In recent times the molecular-drag pump has been successfully re-introduced, usually in combination with a turbo-pump.

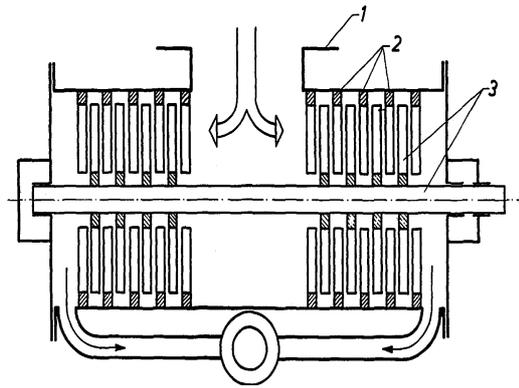


Fig. 14 Schematic diagram of Gaede's molecular-drag pump; 1 pumping port, 2 stators, 3 rotors (1913).

The mercury vapour diffusion pump was the first vacuum pump to have no moving parts. It was invented independently by Gaede [31] (see Fig. 15) and Langmuir [32] (see Fig. 16) in 1915-16. Langmuir's design with its large nozzle had much higher pumping speed and was quickly taken up for industrial use. The use of low-vapour-pressure oils rather than mercury in diffusion pumps was introduced by Burch in 1928 [33]. The diffusion pump became the most widely used high vacuum pump until the sputter-ion pump became available in 1958. Both mercury and oil diffusion pumps appeared to have an ultimate pressure of about 10^{-8} Torr as measured by a triode ionisation gauge, the curves of pumping speed of diffusion pumps as a function of pressure in manufacturers' literature showed the pumping speed going to zero at about 10^{-8} Torr (such curves were still being published as late as the 1960s). The early results using mercury diffusion pumps and ionisation gauges are typified by the work of Sherwood [34] in 1918 who measured an ultimate pressure of 2×10^{-8} Torr.

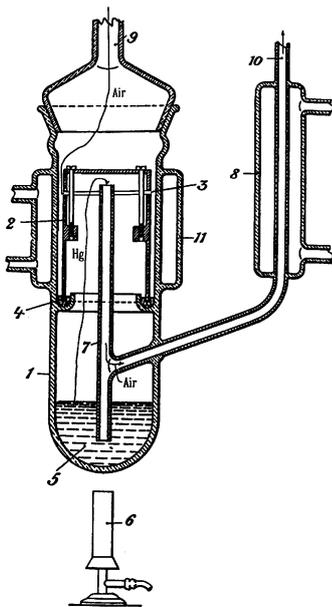


Fig. 15 Gaede's first mercury vapour diffusion pump (1915).

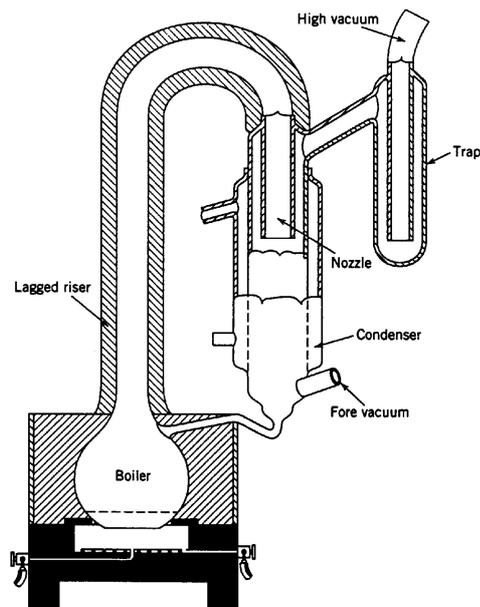


Fig. 16 Langmuir's original mercury vapour diffusion pump (1916).

Several types of pressure gauge were invented after the McLeod gauge in 1874. In 1897 Sutherland [35] invented a gauge depending on the viscosity of the gas, it could measure from 1 to 10^4 Torr. This principle was extended by Langmuir [36] in 1913 who developed a gauge using a quartz fibre which was made to oscillate in the gas, the decrement in amplitude of the oscillations was a measure of the pressure, its pressure range was similar to Sutherland's gauge. Viscosity gauges were not very widely used. In 1906 two gauges which depended on the thermal conductivity of the gas were invented covering the range from atmosphere to 10^4 Torr. The Pirani [37] gauge measured the heat loss from a hot filament to the gas by the change in resistance of the gas. The thermocouple gauge [38] measured the change in temperature of the filament with a thermocouple. In 1910 Knudsen invented the radiometer gauge [39], which with care could measure to 10^6 Torr. Only the Pirani and the thermocouple gauge are still in use. Various mechanical gauges were developed including the Bourdon and the diaphragm gauge, the only one to survive to the present day was the capacitance manometer [40] invented in 1929

Measurement of pressure in the high vacuum range prior to 1916 was difficult, the only available gauges were the McLeod gauge and Dushman's rotating disk gauge [41] (1915), the latter was the precursor to the spinning-rotor gauge, these were both awkward to use and limited to about 10^7 Torr. In 1916 Buckley described the hot-cathode ionisation gauge [42] (von Baeyer had reported the measurement of pressure in a hot-filament triode used as an ionisation gauge [43] in 1909; however, his work was not followed up and Buckley is generally credited with the invention of the hot-cathode ionisation gauge). The triode hot-cathode ionisation gauge was almost universally used to measure high vacuum until 1950. This type of gauge had a cylindrical ion collector of large surface area surrounding the cylindrical grid and axial filament, an early example [44] is shown in Fig. 17. With the use of this type of hot-cathode ionisation gauge the measured ultimate pressure in almost all vacuum systems was about 10^{-8} Torr. The ultimate pressure had hit a plateau that lasted for more than 30 years.

The limit at 10^{-8} Torr was generally assumed to result from a failure of the pumps rather than the gauge, there was initially no suspicion that there might be a limiting process in the gauge at low pressures. The search for a method to reduce the ultimate vacuum in this period has been described in some detail [45] and will not be repeated here. Suffice to say there was considerable evidence by the late 1930s that the hot-cathode ionisation gauge was not capable of measuring below 10^{-8} Torr. The reason for this limit (the x-ray limit as we now know) was not understood by workers in vacuum technology although by the late 1930s the production of photoelectron emission from the grid of a high-power vacuum tube, as a result of soft x-rays produced by electron bombardment of the anode, was well understood by vacuum tube engineer (see Ref. 40 and references therein). The two communities, although closely associated, apparently did not communicate on this subject.

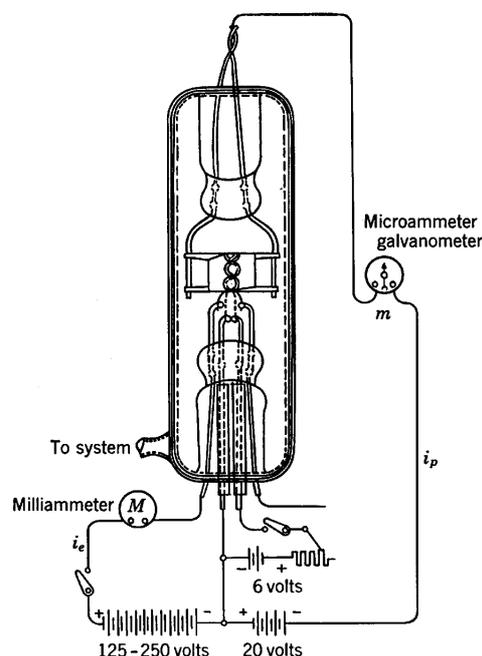


Fig. 17 Triode ionization gauge of Dushman and Found (1921)

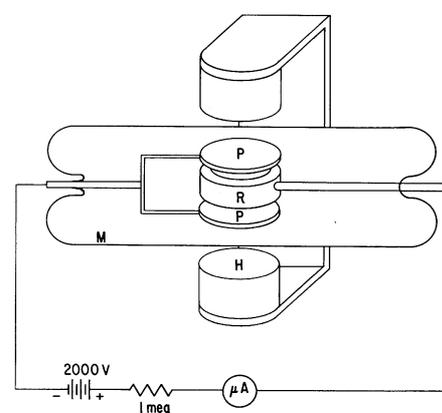


Fig. 18 Diagram of the Penning gauge, the first magnetic, cold-cathode, ionization gauge. P, cathodes, R, anode, H, magnet pole-face (1937).

The cold-cathode discharge in a magnetic field was first demonstrated by Phillips [46] in 1898 but it was not until 1937 that Penning invented the cold-cathode ionisation gauge in a magnetic field, known as the Penning or Phillips gauge [47] (see Fig. 18). This gauge was rugged and reliable but the ion current vs. pressure relation was non-linear and the discharge went out at about 10^{-7} Torr and thus it did not help to solve the pressure limit at 10^{-8} Torr. The gauge was also found to have a significant pumping speed and was the precursor of the sputter-ion pumps designed in the late 1950s. The fact that an electric discharge caused a pumping action had been known since 1858 when Plücker noted [48] “Certain gases react with the platinum cathode and the resulting compounds deposit on the walls. So we approach the absolute vacuum”. In 1916 Vegard observed [49] that there was a change in the pumping speed of a cold-cathode discharge when using different materials for the cathode but not the anode. Penning noted “at high pressures a discharge with high currents should be avoided because of cathodic sputtering ... one has to take care of the fact that the discharge absorbs gas, in air about 1 litre at By 1950 the minimum measured pressure was still 10^{-8} Torr, the same as it had been in 1920. Some experimenters had undoubtedly achieved pressures much lower than 10^{-8} Torr (e.g. W.B. Nottingham [50] and P.A. Anderson [51]) but were not able to make definitive measurements of these lower pressures. It had been suggested that the hot-cathode ionisation gauge had a limit to the lowest measurable pressure set by an x-ray photocurrent but this had not been proven.

1950 is the end of our journey when the revolution in vacuum technology occurred (the Bayard-Alpert gauge [52]) which led to ultrahigh vacuum and the modern era of vacuum devices. Virtually all the new or improved vacuum devices developed since 1950 find their roots in devices developed between 1850 and 1950.

REFERENCES

- [1] Rene Descartes, *Oeuvres*, eds. Chas Adams and Paul Tannery, vol. 1, p. 205 (Paris, 1897).
- [2] W.E.K. Middleton, *The History of the Barometer* (John Hopkins Press, Baltimore, 1964).
- [3] E.N. da C. Andrade, *The History of the Vacuum Pump*, *Adv. Vac. Sci. Tech.*, 1, 14 (Pergamon, Oxford, 1960).
- [4] M.J. Sparnaay, *Adventures in Vacuum* (North Holland, Amsterdam, 1992).
- [5] L. Fabel, *Vakuum-Technik*, **35**, 128 (1986).
- [6] A.C. van Helden, *Tractrix*, **3**, 149 (1991).
- [7] M.H. Hablanian, *Comments on the History of Vacuum Pumps*, *J. Vac. Sci. Technol. A*, **2**, 118 (1984).
- [8] T.E. Madey, *Early Applications of Vacuum, from Aristotle to Langmuir*, *J. Vac. Sci. Technol. A*, **2**, 110 (1984).
- [9] P.A. Redhead, *The Measurement of Vacuum Pressures*, *J. Vac. Sci. Technol. A*, **2**, 132 (1984).
- [10] S. Shapin and S. Schaeffer, *Leviathan and the Air Pump* (Princeton University Press, 1985).
- [11] P.A. Redhead, *The Ultimate Vacuum*, *Vacuum*, **53**, 137 (1999).
- [12] Caspar Schott, *Mechanica Hydraulico-pneumatica* (Wurzburg, 1657).
- [13] Robert Boyle, *new Experiments Physico-Mechanical, Touching the Spring of the Air and its effects*, etc. (Oxford, 1660).
- [14] F. Hawksbee, *Physico-Mechanical Experiments on Various Subjects* (London, 1709, Johnson Reprint Corp., New York, 1970).
- [15] J.A. Bennett, *Science at the great Exhibition* (Whipple Museum, Cambridge, 1983).
- [16] W.H.T. Mayer, *Über das geschichtete elektrische Licht* (Berlin 1858).
- [17] A. Töpler, *Dingler's Polytechnisches Jour.*, **163**, 426 (1862).
- [18] H.T.P. Sprengel, *J. Chem. Soc.*, **16**, 9 (1865).

- [19] W. Crookes, Phil. Trans. Roy. Soc., **163**,277 (1873).
- [20] C.H. Gimmingham, J. Soc. Chem. Ind., **3**, 83 (1884).
- [21] H.G. Mcleod, Phil. Mag, **48**, 110 (1874).
- [22] M. Josephson, Edison (McGraw-Hill, New York, 1959).
- [23] G.W.A. Kahlbaum, Wied. Ann., **53**, 199 (1894).
- [24] H.A. Fleuss, German Patent, No. 76147, 13/8/1893.
- [25] W. Gaede, Phys. Zeit., **6**, 758 (1905).
- [26] G. Meyer, Verh. d. deutsch Phys. Ges., **10**, 753 (1907).
- [27] W. Gaede, Ann. Physik, **41**, 337 (1913).
- [28] S. Dushman, Phys. Rev., **5**, 224 (1915).
- [29] M. Holweck, C.R. Hebd. Seances Acad. Sci., **177**, 43 (1923).
- [30] M. Seigbahn, Arch. Math. Astron. Fys., **30B**, 17, (1944).
- [31] W. Gaede, Ann. Phys. (Leipzig), **46**, 357 (1915).
- [32] I. Langmuir, Gen. Elec. Rev., **19**, 1060 (1916); J. Franklin Inst., 182,719 (1916).
- [33] C.R. Burch, Nature, **122**, 729 (1928).
- [34] R.G. Sherwood, Phys. Rev., **12**, 70 (1918).
- [35] W. Sutherland, Phil. Mag., 43, 83 (1887).
- [36] I. Langmuir, J. Amer. Chem. Soc., **35**,107 (1913).
- [37] M. Pirani, Verh. Physik Ges., **8**, 686 (1906).
- [38] W. Voege, Phys. Zeit., **7**, 498 (1906).
- [39] M. Knudsen, Ann. Phys. (Leipzig), **31**, 633 (1910).
- [40] A.R. Olsen and L.L. Hurst, J. Amer. Chem Soc., **51**, 2378 (1929).
- [41] S. Dushman, Phys. Rev., **5**, 212 (1915).
- [42] O.E. Buckley, Proc. Nat. Acad. Sci., **2**, 683 (1916).
- [43] O. von Baeyer, Phys. Zeit., **10**,169 (1909).
- [44] S. Dushman and G.C. Found, Phys. Rev., **17**, 7 (1921).
- [45] P.A. Redhead, *in* Vacuum Science and Technology, ed. P.A. Redhead, (A.I.P. Press, New York, 1994) p. 133.
- [46] C.E.S. Phillips, Proc. Roy. Soc., **64**, 172 (1898).
- [47] F.M. Penning, Physica, **4**, 71 (1937).
- [48] J. Plucker, Poggendorf's Ann. **103**, 88 (1858); **105**, 84 (1858).
- [49] L. Vegard, Ann. Phys. (Leipzig), **4**, 769 (1916).
- [50] W.B. Nottingham, Phys. Rev. **49**, 78 (1936); J. Appl. Phys., **8**, 762 (1937).
- [51] P.A. Andersen, Phys. Rev. **47**, 958 (1935); **49**, 320 (1936); **54**, 753 (1938); **57**, 122 (1940).
- [52] R.T. Bayard and D. Alpert, Rev. Sci. Instr., **21**, 571 (1950).