PERGAMON

Vacuum 53 (1999) 137–149

VACUUM
SURFACE ENGINEERING, SURFACE INSTRUMENTATION & VACUUM TECHNOLOGY

The ultimate vacuum

P.A. Redhead*

Institute for Microstructural Sciences, National Research Council, Ottawa, K1A 0R6, Canada

Abstract

The ultimate vacuum, defined as the lowest pressure that can be produced and measured reproducibly in a vacuum system at room temperature, has decreased by a factor of about 10^{14} since the first measurement of sub-atmospheric pressure by Robert Boyle in about 1660. A brief historical review is presented of the key advances that caused significant decreases in the ultimate vacuum during the period 1660–1900. Much of modern vacuum technology was developed in the period from 1900 to 1950 and it was notable for the limitation of the lowest measurable pressure to about 10^{-8} Torr. In 1950 the principal limitation to the lowest pressure measurable by ionization gauges was finally understood and means for measuring lower pressure developed, this ushered in the modern period of vacuum technology (including the development of the UHV and XHV techniques) when a clearer understanding of the physical and chemical processes limiting the ultimate vacuum has been developed. The major improvements in ultimate vacuum in the period from 1950 to the present are reviewed and the limitations to the ultimate vacuum at the present time examined.

1. Introduction

We shall define the ultimate vacuum, for our present purposes, as the lowest total pressure produced and measured in a vacuum system at room temperature; to be representative of the technology of the era these conditions should be repeatable by other experimenters. This definition does not exclude the use of cryopumps provided that the bulk of the vacuum system is at room temperature. The ultimate vacuum at any period is mainly determined by the state of the existing technology but the motivation to improve the ultimate vacuum results from the requirements of scientific research or the needs of industry.

It is widely believed that a vacuum was first demonstrated in Torricelli's famous experiment with a mercury filled tube in 1643. Middleton [1] has cast doubt on this common knowledge and has shown that Torricelli conceived the experiment but it was actually carried out by Viviani in 1664. The pressure in the space above the mercury column – the Toricellian vacuum – was estimated by von Guericke to be *eine halbe Fingerbreite* or about 10 Torr, as a result of air bubbles between the mercury and the glass. We may take this value to be our starting point in our examination of ultimate vacuum over the years. Some 16 years after the Toricellian experiment the vacuum piston–pump had been invented by von Guericke and Robert Boyle was making the first measurement of a vacuum by means of a mercury manometer in an evacuated bell-jar.

When the ultimate vacuum is obtained in a vacuum system the rate of change of pressure is zero and the ultimate pressure is $Pu = (L + Q + Q_s)/S$ [L is the leak rate, Q the thermal outgassing rate, Q_s the stimulated outgassing rate (electron and photon stimulated desorption), and S is the pumping speed]. Thus, to reduce the ultimate pressure the pumping speed S must be increased, and/or the leak rate L and outgassing rates Q and Q_s minimized. The ultimate measured pressure may be limited by a reduction in the effective speed of the pump(s) at low pressures, or the inability of the gauge to measure low pressures. Different limiting factors have dominated the ultimate vacuum at various stages of the development of vacuum technology; e.g. for the first 100 years or more the problem of minimizing the leak rate was the major problem. This paper reviews the progress of the ultimate vacuum, as defined above, from Robert Boyle's famous experiment in 1660 until the present, and examines the limiting processes and the motivations for seeking a reduction in the ultimate pressure. Several historical reviews of vacuum pumps [2–8] and pressure measurements [9] may be consulted for more details.

*Tel: 00 613 733 1208; fax: 00 613 990 0202; e-mail: redhead@intranet.ca

0042-207X/99/$ – see front matter
PII: S0042-207X(98)00349-2

2. From Boyle (1660) to the great exhibition (1850)

The first significant measurement of a sub-atmospheric pressure was reported [10] by Boyle in 1660 who used a mercury manometer to measure the pressure produced in a bell jar by a piston pump built by Boyle's assistant Robert Hook. The pump used by Boyle (called a *pneumatic engine* by Boyle and known on the continent as the *machina Boyleana*) is shown in Fig. 1. Shapin [11] has called Boyle's pump *the Scientific Revolution's greatest fact finding machine*. Boyle's arrangement to measure pressure with a mercury manometer sealed in a bell-jar is shown in Fig. 2. The ultimate vacuum in 1660, as measured by Boyle, was about 1/4 in of mercury or 6 Torr.

There was great public interest in vacuum (the Torricellian experiment had occurred only 16 years before and the concept of a vacuum was revolutionary and still anathema) and rudimentary experiments in vacuum became the subject of public exhibitions and after-dinner demonstrations designed to amaze and dismay. In 1665 Sam Pepys noted in his diary that he went to a meeting of the Royal Society *and there did see a kitlin killed almost quite* (*but that we could not quite kill her*) *with sucking away the Ayre out of a Receiver where she was put – and then the ayre being let in upon her*, *revives her immediately*. . . *Thence home*, *and thence to Whitehall where the House full of Dukes going tomorrow*; *and thence to St. James*. . . . This type of demonstration, one hesitates to call it an experiment, was popular for more than a

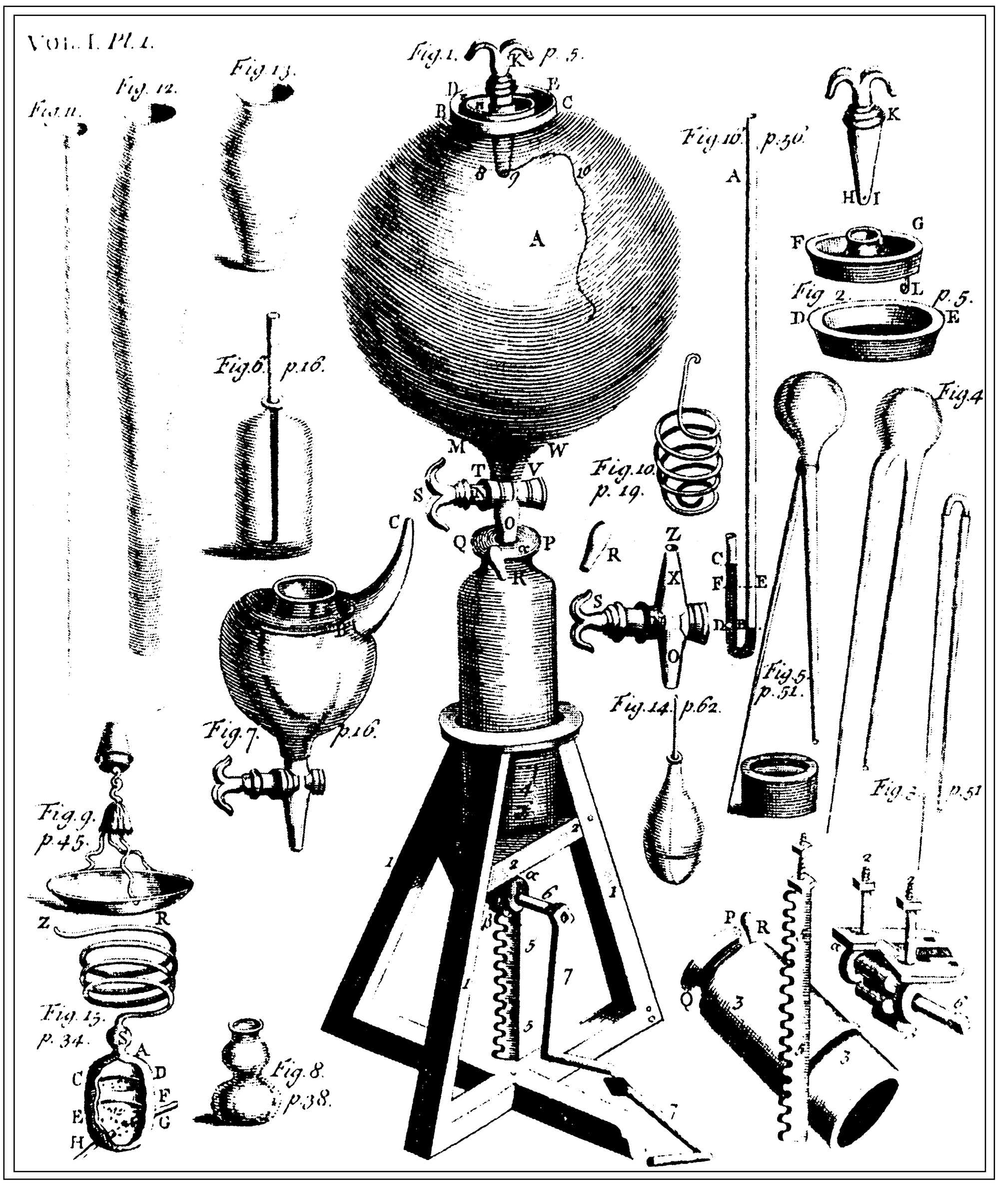

Fig. 1. Piston pump constructed by Robert Hook and used by Robert Boyle in the first measurement of a vacuum in about 1660.

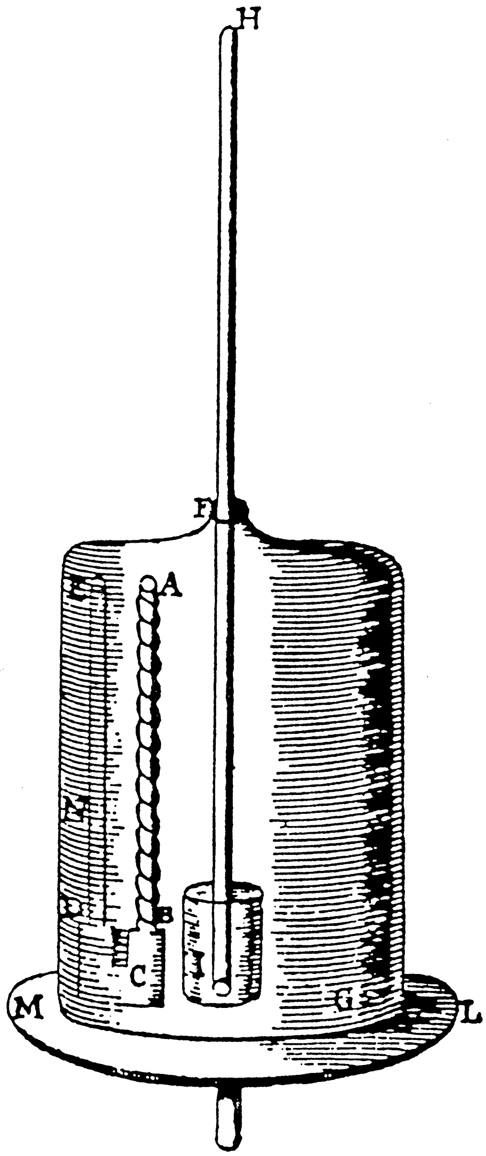

Fig. 2. The first measurement of a sub-atmospheric pressure by Robert Boyle c.1660. A beaker of mercury with a manometer tube more than 32 in long was sealed in a bell jar and evacuated by the pump in Fig. 1.

century. In 1768 Joseph Wright of Derby exhibited his painting of the same demonstration, using a cockatoo rather than a kitten, being performed before a family group (see Fig. 3). Wright's painting is on display in the National Gallery in London. The novelty of this demonstration had not worn off by 1802, Fig. 4 shows a cartoon by James Gillray of a demonstration at the Royal Institution by Thomas Garnett assisted by Humphrey Davy, this time there is a long-suffering frog in the bell-jar. Standing at the right is Count Rumford, one of the founders of the Royal Institution.

Most of the experiments in vacuum for the first 200 years (1660–1860) were concerned with what may be called the mechanical properties of vacuum where an ultimate pressure of a few Torr was quite adequate. Efforts to improve the pumps were directed to increasing the ease of operation rather than to reducing the ultimate pressure. In 1704 Hawksbee [12] produced a significantly improved double-piston pump (Fig. 5) which was much easier to use, it is a version of this pump that can be seen in Wright's painting (Fig. 3). By 1850 the double-piston pump was commercially available as shown in Fig. 6; as can be seen, it was not substantially different in appearance from Hawksbee's pump of 150 years earlier.

The course of the ultimate vacuum over the period 1660–1900 is outlined in Fig. 7; the experiments chosen for inclusion are considered to be representative of their period. At the Great Exhibition in London in 1850 a first prize was awarded to a double-barreled pump with oiled-silk valves and conical pistons manufactured by Watkins and Hill. This pump was capable of reaching a pressure of about 1 Torr, a factor of only 6 less than that achieved by Boyle; the ultimate vacuum had not decreased much in 190 years. There were two reasons for this, there was no great demand for lower pressures from experimenters and the mercury manometer limited the measurable pressure to about 0.5 Torr.

3. The period of major advances, 1850–1900

This period saw the development of several types of liquid-piston pumps and of the McLeod gauge which together allowed the reduction of the ultimate vacuum by a factor of about a million. In 1854 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 [13] published in 1858. This invention was to start the continuing efforts to reduce the ultimate vacuum. The next vital step was McLeod's invention of his vacuum gauge [14] (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. This permitted pressure measurements down to the 10^{-6} Torr range.

In 1862 Töpler [15] invented an improved form of the Geissler pump and in 1865 Sprengel [16] 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 Gimingham, attempted to achieve a vacuum "*approaching perfection*". Fig. 8 shows Crookes' first pumping system [17] using a Sprengel pump. An improved version [18] 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. Since the McLeod gauge does not

Fig. 3. Joseph Wright's painting (1768) of a popular after-dinner demonstration of the effects of vacuum on a small animal. The effects of the lack of atmosphere on a cockatoo is being observed and air was then admitted just in time (in most cases) to save the creature's life.

Fig. 4. James Gillray's cartoon (1802) of a demonstration at the Royal Institution.

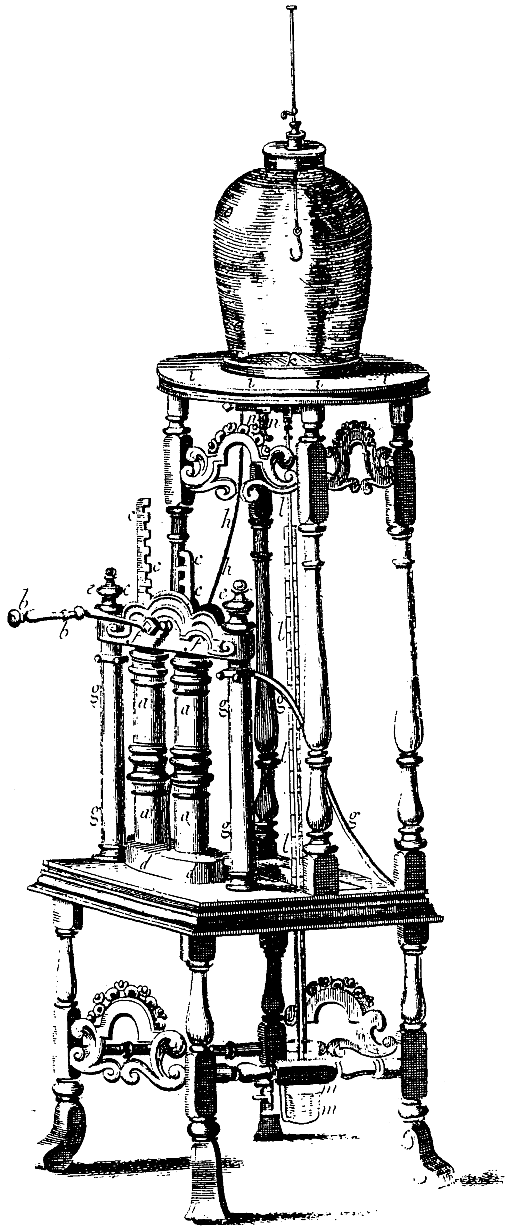

Fig. 5. The double-piston pump of Hawksbee (1704).

measure the pressure of condensible gases, such as water, the true pressure may have been higher. Crookes greatly improved the vacuum conditions by replacing all rubber tube connections with ground glass joints and by heating the apparatus to degas it. By the end of the 1870s these vacuum techniques had moved into industry and were being used by Edison to improve the vacuum in incandescent lamps. Fig. 9 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 [19]. By 1894 Kahlbaum [20] was able to obtain pressures as low as 3×10^{-6} Torr with a Sprengel pump.

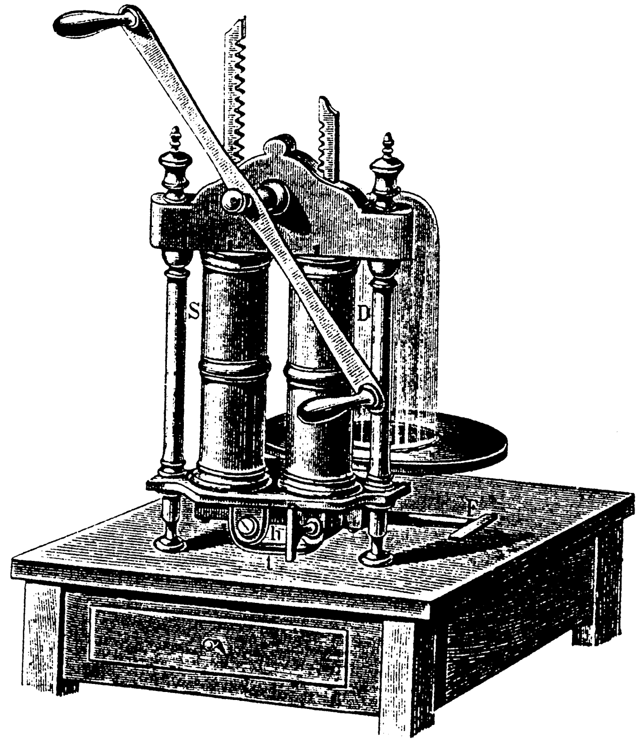

Fig. 6. A commercial double-piston pump from about 1850.

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 [21]. This pump was know as the Geryk pump and was capable of 2×10^{-4} Torr, it was widely used in the lamp industry 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 the ultimate vacuum had reached about 10^{-6} Torr as measured by a McLeod gauge, it had dropped by about six orders of magnitude in 50 years (see Fig. 7). The impetus for this rapid improvement was initially the research requirements of scientists like Plücker and Crookes. Edison very quickly copied Crookes' techniques and applied them in industry. The continuing improvement in vacuum techniques was largely the result of the requirements of the lamp industry and, by 1900, the fledgling vacuum tube industry. The discovery of the electron in 1897 by J.J. Thomson [22] was made possible by the improved vacuum techniques that Thomson acquired from Crookes. The low pressures in Thomson's experiment allowed him to deflect the electron beam electrostatically, previous experimenters with poorer vacuum were unable to observe any deflection because the deflecting electrodes were shielded by a sheath of positive ions produced from the residual gas. This was the first fundamental contribution to the advancement of science made by vacuum technology.

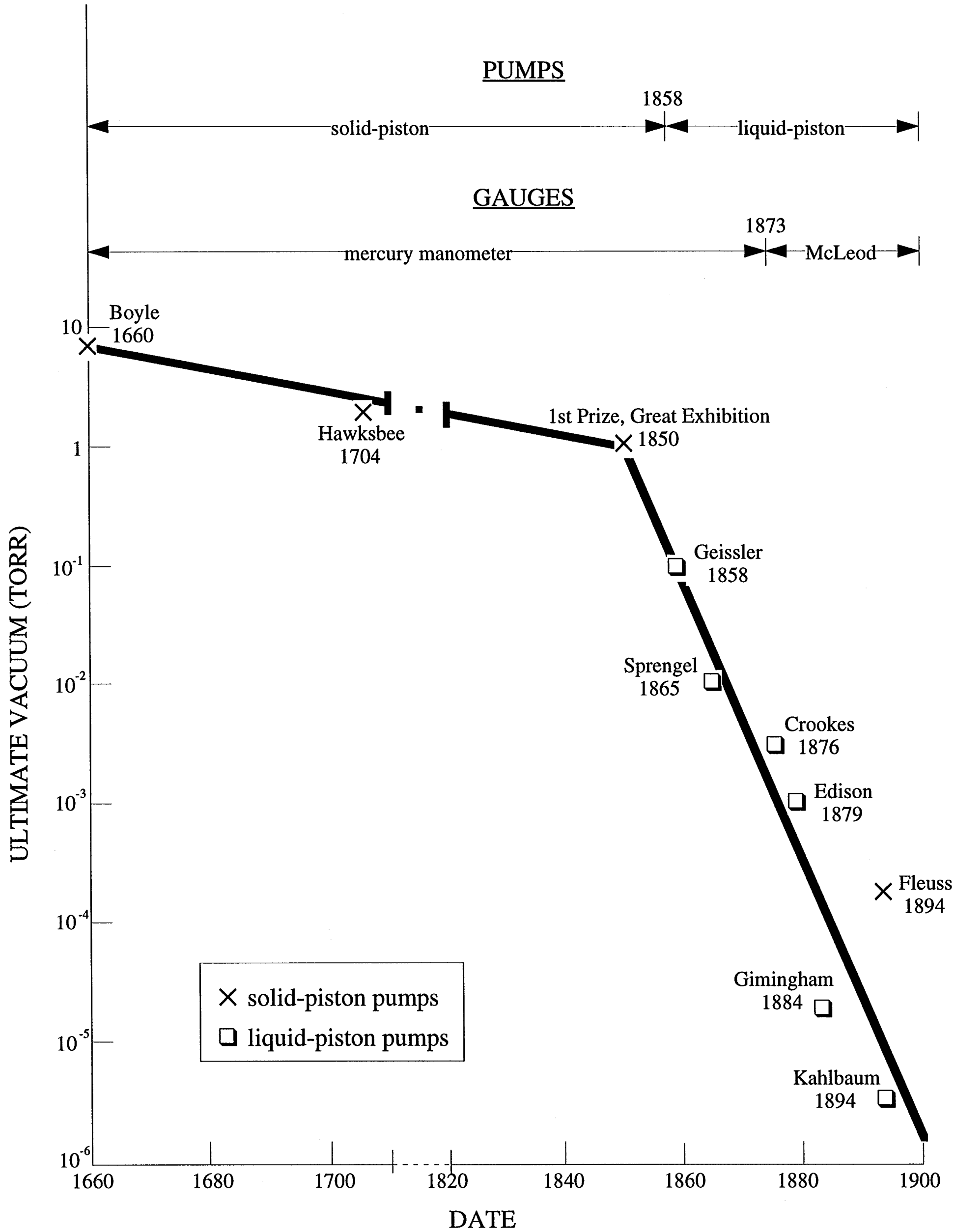

Fig. 7. The ultimate vacuum from 1660 to1900. Note the break in the time scale. The references to the experiments are; Boyle [10], Hawksbee [12], Geissler [13], Sprengel [16], Crookes [17], Edison [19], Fleuss [21], Gimingham [18] Kahlbaum [20].

The large improvement in the ultimate vacuum in this period was due to (a) the reduction in leak rates by the use of all-glass systems without rubber tubing or gaskets, (b) the reduction in outgassing rates by heat treatment of the glass, and (c) the improved performance of liquid-piston pumps.

4. The commercialization of vacuum, 1900–1950

The change in ultimate vacuum in the period 1900–2000, is shown in Fig. 10. 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 [23] in 1905, this was a rotary action, mercury piston-pump which could be motor driven. It could produce pressures in the 10^{-6} Torr range and was widely used in the lamp and vacuum tube industries.

The next major advance in pumping methods was the invention of the molecular-drag pump by Gaede [24]

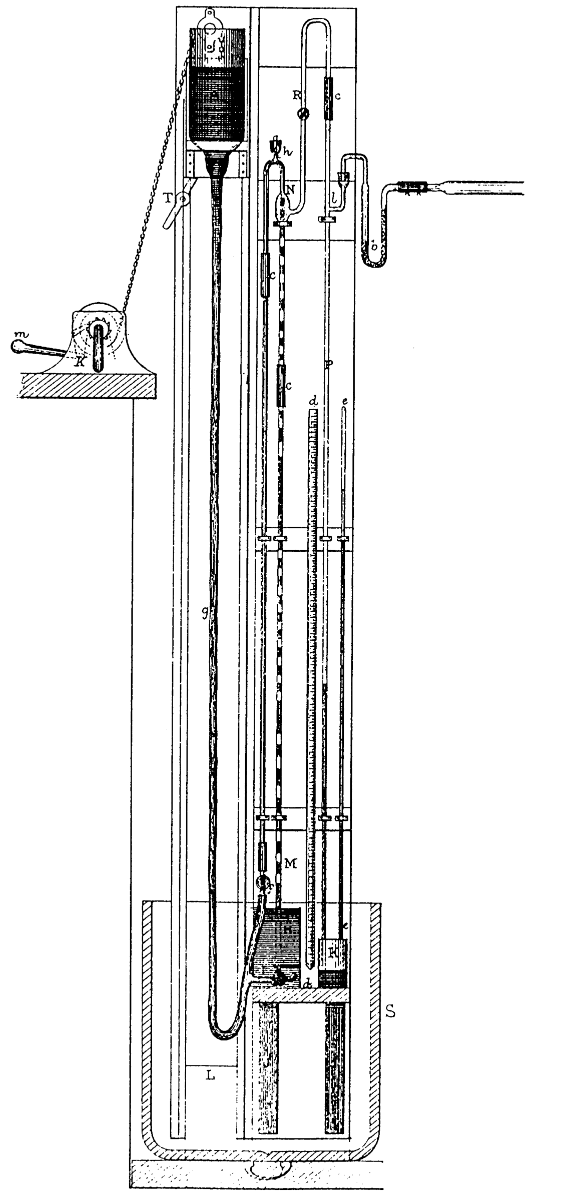

Fig. 8. Crookes's first vacuum system using a single Sprengel pump (1872).

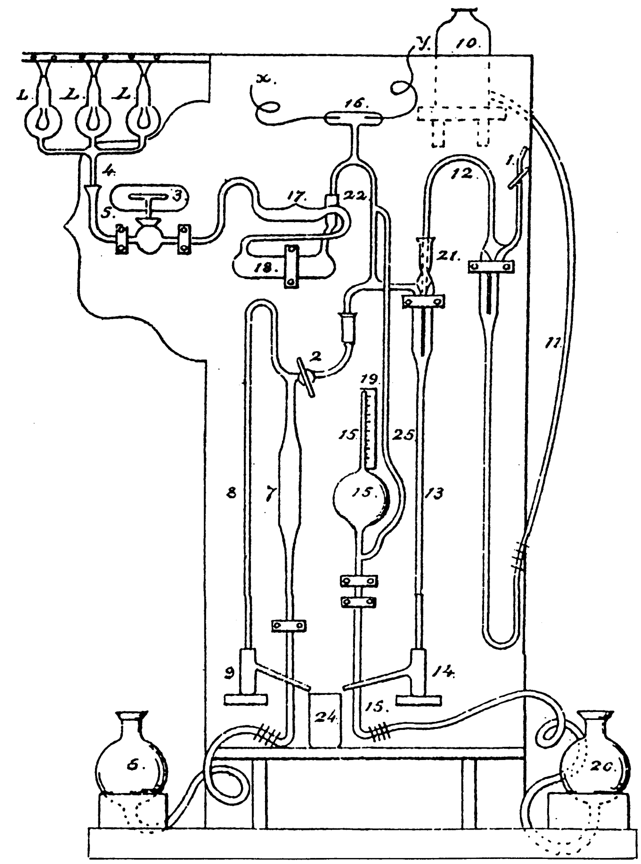

Fig. 9. Edison's apparatus for the evacuation of incandescent lamps.

in1912; Fig. 11 shows the construction of Gaede's pump. Gaede wrote that *the gas is dragged along from the vessel to be exhausted into the fore vacuum by means of a cylinder rotating with high velocity inside a hermetically sealed casing*. With a fore pressure of 2×10^{-2} Torr a pressure of 4×10^{-7} Torr was measured by Dushman [25] at a rotation speed of 8000 rpm. This pump was widely used in the vacuum tube industry. Improved versions of the molecular pump with higher pumping speeds were developed over the next 30 years, pressures in the 10^{-7} Torr range were typically obtained.

The mercury vapour diffusion pump was the first vacuum pump to have no moving parts. It was invented independently by Gaede [26] and Langmuir [27]. in 1915–1916, and oil diffusion pumps were invented by Burch in 1928 [28]. The diffusion pump became the most widely used high-vacuum pump until the sputter-ion pump became available in 1958. Fig. 12 is a diagram of Langmuir's original glass form of his diffusion pump. Both mercury and oil diffusion pumps appeared to have an ultimate pressure of about 10^{-8} Torr as measured by a triode ionization gauge, manufacturers' literature showed curves of the pumping speed of diffusion pumps as a function of pressure with 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 ionization gauges are typified by the work of Sherwood [29] in 1918 who measured an ultimate pressure of 2×10^{-8} Torr.

Measurement of pressure in the high-vacuum range prior to 1916 was difficult, the only available gauges were the Mcleod gauge, the Knudsen gauge, and Dushman's rotating disk gauge, these were all awkward to use and limited to about 10^{-7} Torr. In 1916 Buckley described the hot-cathode ionization gauge [30] (von Baeyer had reported the measurement of pressure in a triode used as an ionization gauge [31] in 1909; however, his work was not followed up and Buckley is generally credited with the invention of the hot-cathode ionization gauge). The

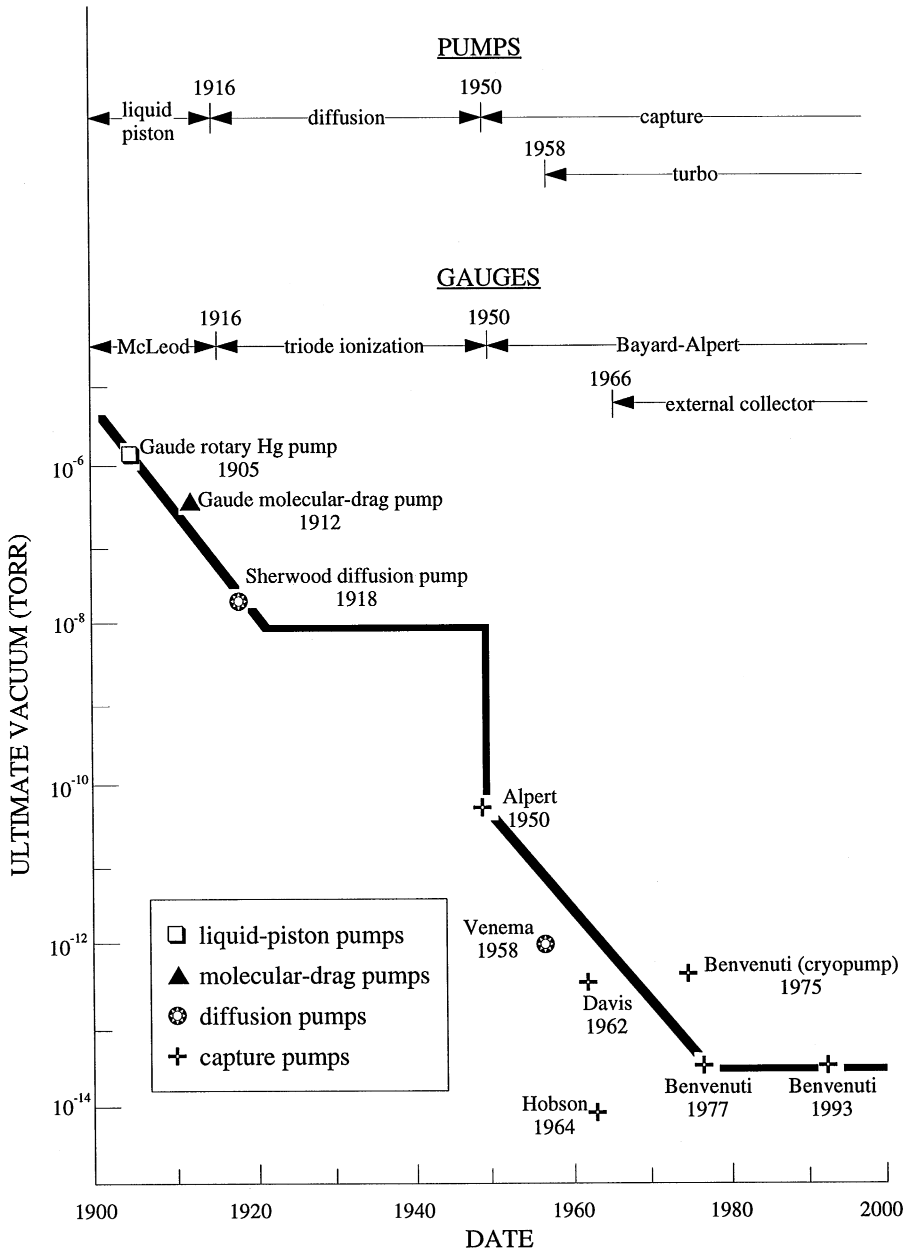

Fig. 10. The ultimate vacuum from 1900 to the present. The references to the experiments are; Gaede (1905) [23], Gaede (1913) [24], Sherwood [29], Bayard and Alpert [35], Venema [38], Davis [43], Hobson [54], Benvenuti (1977) [56], Benvenuti (1979) [57], Benvenuti (1993) [58] .

triode hot-cathode ionization 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. With the use of the hot-cathode ionization gauge the measured ultimate pressure in almost all systems was about 10^{-8} Torr. The ultimate pressure had hit a plateau which 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 [32] and will not be repeated here. Suffice to say there was considerable evidence by the late 1930s that the hot-cathode ionization 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 engineers. The two communities, although closely associated, apparently did not communicate on this subject.

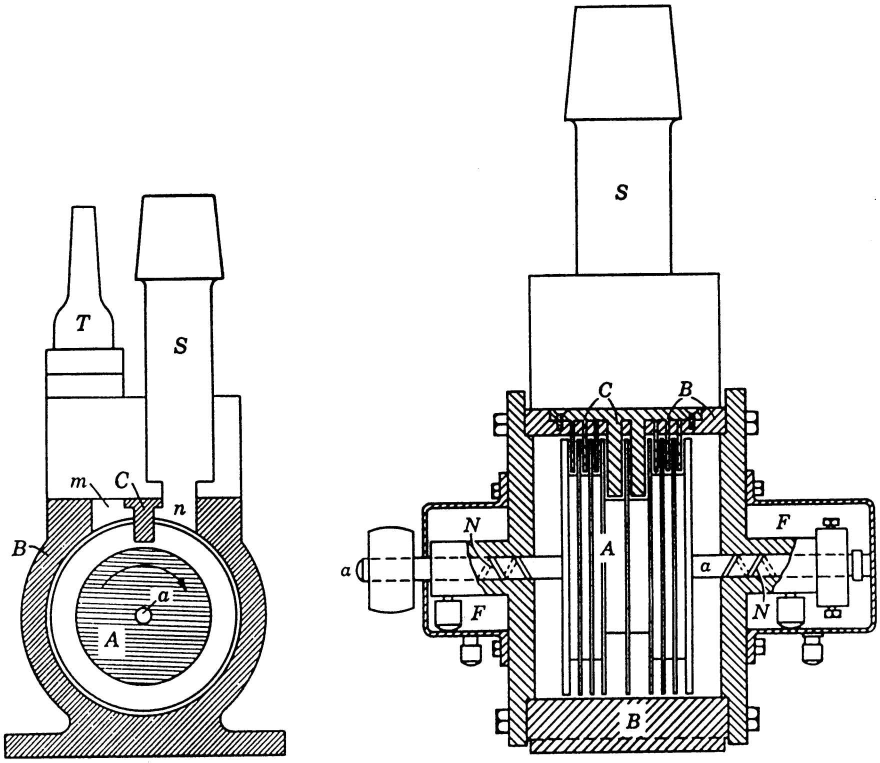

Fig. 11. Gaede's molecular-drag pump (1912). *Left* front view. *Right* side view.

In 1947 Wayne Nottingham remarked at the first post-war meeting of the Physical Electronics Conference held at the Massachusetts Institute of Technology that the limit to hot-cathode gauges was probably the result of soft X-rays (released by electrons striking the positive grid) which created a photo-electron current at the ion collector; this current was indistinguishable from the positive ion current in the measuring circuit. The limit to the ultimate pressure had finally been clearly identified after 30 years. Several experimenters in the USA and the UK designed different gauge structures to minimize the X-ray limit. The successful solution appeared in 1950.

By 1950 the ultimate vacuum 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. [33, 34] but were not able to make definitive measurements of these lower pressures. It had been suggested that the hot-cathode ionization gauge had a limit to the lowest measurable pressure set by an X-ray photocurrent but this had not been proven.

5. Alpert (1950) to the present

At the Physical Electronics Conference at MIT in 1950 Alpert described his elegant method of reducing the X-ray limit of a hot-cathode ionization gauge. His solution was to make the ion-collector a fine wire on the axis of the gauge thus greatly reducing the flux of soft X-rays emanating from the grid that was intercepted by the collector. This reduced the X-ray limit by a factor of more than 100 and permitted measurements in the 10^{-11} Torr range. Fig. 13 shows a diagram of the original Bayard–Alpert gauge and the measurements that demonstrated the reduction of the X-ray limit by the new gauge [35]. At the same time Alpert introduced the use of the ionization gauge as the main pump at low pressures, and the use of all-metal valves to seal-off the system from the pumps used at higher pressures. This led to the development in following years of other types of capture pumps, i.e. pumps that did not remove the gas from the system but rather trapped the gas molecules at surfaces within the system by (a) ion entrapment (ionization pumps), (b) chemisorption (getter pumps), or (c) physisorption at low temperatures (cryopumps). This caused a revolution in vacuum technology, the ultimate pressure dropped from 10^{-8} to the 10^{-11} Torr range almost overnight. Most of the UHV systems used in the next few years were predominantly glass systems with metal valves and some other metal components.

In the next decade modifications were made to the original Bayard–Alpert design which reduced the X-ray limit still further to below 10^{-12}. Torr, these changes included a reduction in the diameter of the collector wire (to 25 μm in one case [36]), and the use of modulation methods [37]. These techniques were exemplified by the

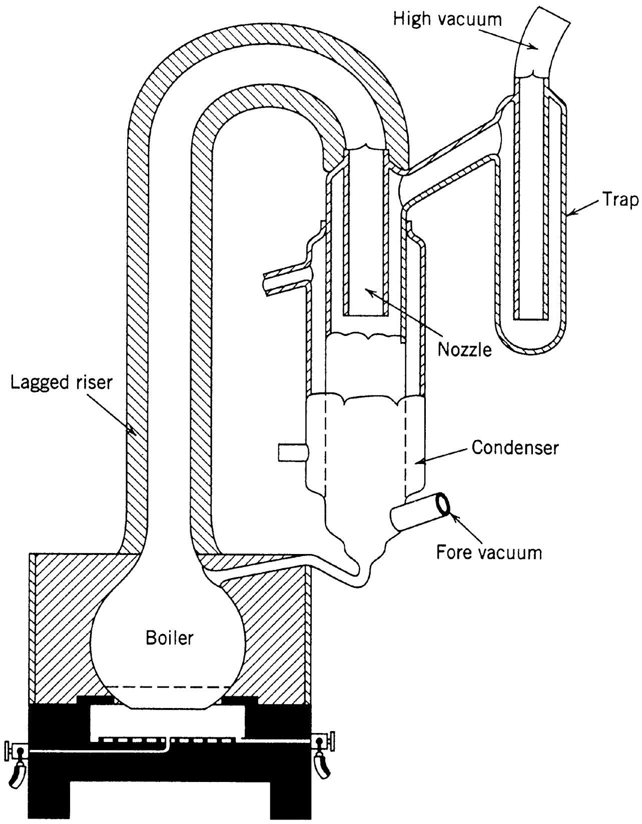

Fig. 12. Langmuir's original mercury vapour diffusion pump (1916).

work of Venema in 1958 who achieved an ultimate pressure of less than 10^{-12} Torr in a glass system pumped by a mercury diffusion pump [38].

By the early 1960s UHV technology had developed significantly. Sputter-ion pumps [39] had become available commercially in 1958, turbomolecular pumps in 1957 [40] and satisfactory metal flanges with copper gaskets were available allowing most UHV systems to be made of stainless steel rather than glass. Residual gas analysis at UHV became possible, a magnetic mass-spectrometer suitable for UHV use was developed [41] in 1960, and in 1958 Paul [42] first described the quadrupole mass filter which was later developed for use as a residual gas analyser. The experiments of Davis [43] are representative of this period, using a sputter-ion pump in a metal system with a magnetic mass-spectrometer with an electron multiplier, he obtained an ultimate pressure in the 10^{-13} Torr range and could measure partial pressures of about 10^{-16} Torr.

An additional process that limits the lowest pressure measurable in an ionization gauge was clearly identified in 1963 [44]. This was the electron stimulated desorption of neutrals and positive ions resulting from electron bombardment of adsorbed gas layers on the grid of the gauge (or ion source of a mass-spectrometer). The ESD ions cannot be distinguished from the gas phase ions except on the basis of their different initial kinetic energy. It was found that the modulated B.A.G. was relatively insensitive to the ESD error. The ESD effect is more difficult to minimize than the X-ray effect. Several hot-cathode ionization gauge designs were later developed that were capable of separating the ESD ions from the gas phase ions; the Extractor gauge (1966) [45], the Bent-beam gauge (1966) [46], the modulating ion current gauge (1984) [47] and the ion spectroscopy gauge (1993) [48]. The X-ray limits of these gauges are approximately 1.5×10^{-12} Torr for the extractor gauge [49], less than 1.5×10^{-14} Torr for the Bent Beam gauge [50], and about 10^{-15} for the ion spectroscopy gauge [51] Methods for separating the ESD ions from gas phase ions in a quadrupole RGA have also been developed [52, 53].

In 1964 Hobson reported his measurements on an aluminosilicate glass system [54] (this glass was used to minimize the permeation of atmospheric helium through the walls). Pressures measured by a modulated Bayard–Alpert gauge and also by a dynamic method were in good agreement. When a glass finger connected to the system was immersed in liquid helium a pressure of 7×10^{-15} Torr was measured. This appears to be the lowest measured pressure that has been reported in a system substantially at room temperature.

In the 1960s and 1970s there were several experiments, which do not meet our criteria for ultimate vacuum, in which vacuum systems were operated at cryogenic temperatures and very low ultimate pressures obtained. For example, Thompson and Hanrahan [55] in 1977 immersed a 30 l stainless-steel system in liquid helium and obtained an ultimate pressure well below the 10^{-14} Torr detectability limit of the mass-spectrometer.

One of the principal uses of UHV and XHV technology in recent years has been in high-energy particle storage rings where major advances in XHV technology have occurred. In 1977 Benvenuti described the advances in XHV technology made at CERN, by modifying the Bent-beam gauge pressures in the low 10^{-14} Torr range were measured [56]. Other experiments at the same laboratory using a cryopump [57] and a combination of sputter-ion pumps and non-evaporable getters [58] have achieved ultimate pressures in the low 10^{-14} Torr range. These results suggest that the ultimate vacuum in the last 20 years has once more reached a plateau, similar to the 1920–1950 plateau, but this time at the low 10^{-14} Torr range. The possible causes of this plateau are discussed in the next section.

6. The present situation

There has been considerable activity in the 1980s and 1990s in the measurement of outgassing rates, and in the

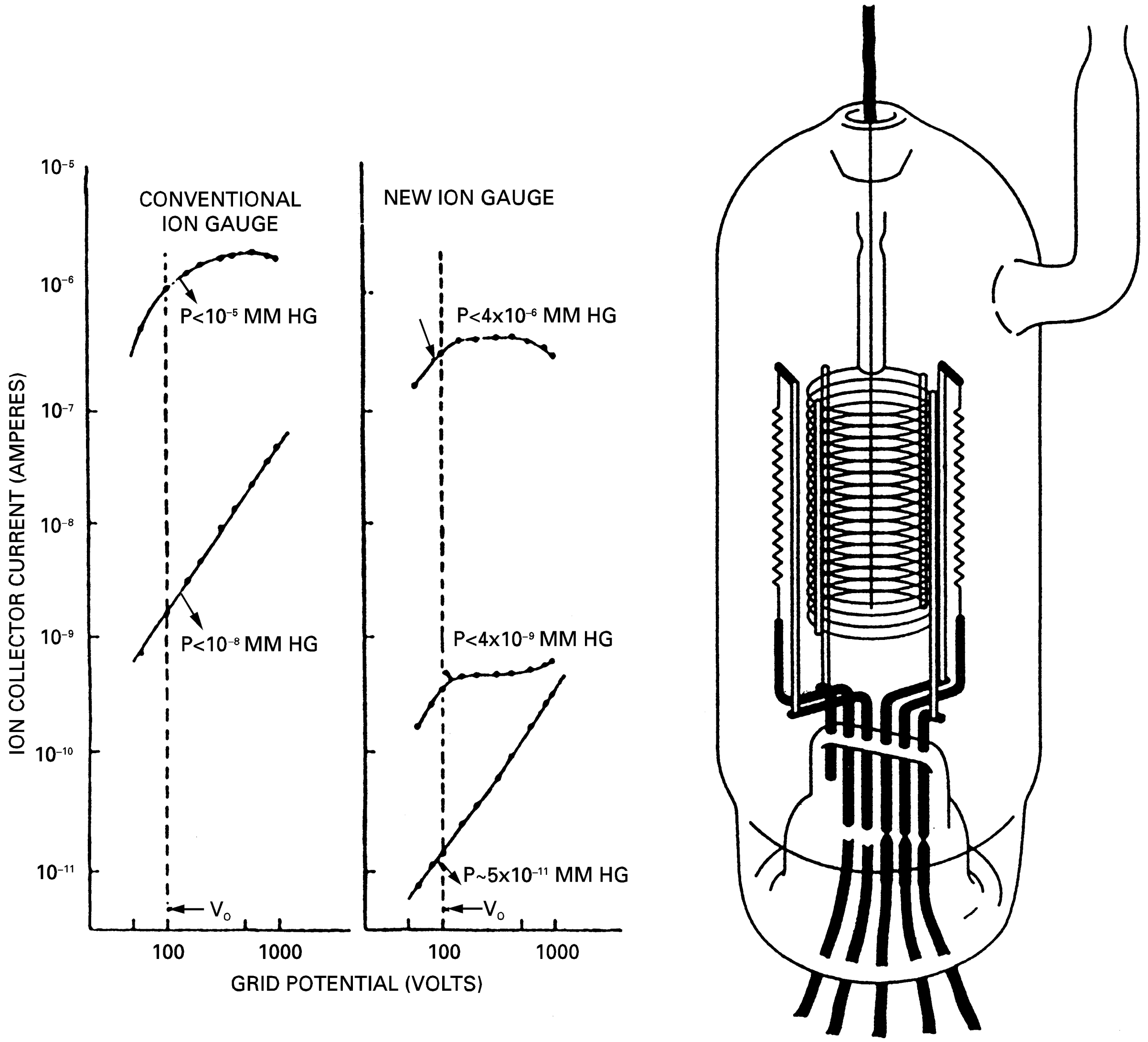

Fig. 13. *Left*. Measurements comparing the convention ion gauge with the new gauge, demonstrating the reduction in X-ray limit. *Right*. Original design of the Bayard–Alpert gauge (1950).

development of methods to reduce outgassing rates, from materials used in the construction of UHV and XHV systems. The work on reducing outgassing rates has been recently reviewed [59]. Table 1 lists some of the lowest measured outgassing rates of the materials more commonly used as vacuum envelopes. Hobson's data on an aluminosilicate glass system is included to indicate that a well degassed system of a glass with low helium permeability can have a lower outgassing rate per unit area than any metal system. In the metal systems the dominant gas at low pressures is hydrogen, whereas in the aluminosilicate system no hydrogen was observed and methane appeared to dominate.

The measurement of pressure in the XHV range is still fraught with difficulty. Mass-spectrometers with electron multipliers can measure to about 10^{-16} Torr. It should be noted that the limits due to electron stimulated desorption in hot cathode gauges may be greater than the X-ray limit and thus it is important that the gauge be capable of separating the gas-phase ions from the ESD ions [60].

It appears that a major source of gas in most XHV systems is the pressure gauge or RGA. There are two sources of outgassing in a gauge or RGA, (a) thermal outgassing from the gauge electrodes and envelope due to radiation from the hot cathode, and (b) the ESD of neutral molecules from the grid of the gauge or ion-source. Thermal desorption can be minimized by the use of room temperature field emission arrays as electron sources, this has not yet been done successfully in the XHV range. Another method is to use copper for the envelope of the gauge, copper has low emissivity, which permits a reduction of cathode heating power, and high conductivity, which lowers the temperature of the

Table 1
Some low, measured outgassing rates

Material	(Hydrogen) $(\mathrm{Pa\,m\,s^{-1}})$	$(\mathrm{Torr\,l\,s^{-1}\,cm^{-2}})$	Reference
Stainless steel (304L) (Air fired 400°C)	1.5×10^{-12}	1×10^{-15}	Marin [63]
Stainless steel (vacuum fired 960°C)	1×10^{-12}	7.5×10^{-16}	Fremery [64]
Copper (OFHC)	5×10^{-13}	4×10^{-16}	Ishikawa [58]
Aluminum	2×10^{-12}	1.5×10^{-15}	Ishikawa and Yoshimura [65]
Titanium nitride on stainless steel	2.5×10^{-13}	2×10^{-16}	Ikeda et al [66]
	(Equivalent nitrogen)		
Aluminosilicate glass	10^{-13}	10^{-16}	Hobson 1964 [53]

envelope [61]. The ESD of neutrals from the grid of an ion-spectroscopy gauge has been observed to constitute the dominant gas component at very low pressures [62], this effect was reduced by heating the grid to 500°C.

There have been many improvements to the performance of pumps at very low pressures in recent years, in particular sputter-ion and turbopumps. Cryopumps and getter pumps do not appear to have any limit to their pumping speed at XHV and thus there is no immediate limitation to the ultimate vacuum by these pumps.

The need for pressures below 10^{-14} Torr has not been pressing. Emphasis in recent years has been on reducing the time taken to reach pressures in the UHV range, and in improvements in pumps, gauges, RGAs, and methods to reduce outgassing rates so that UHV/XHV can be achieved more efficiently and economically. The plateau in the ultimate vacuum for the last 20 years, in spite of reductions in the outgassing rates of materials and improvements in pumps, may result from outgassing from the gauge or RGA (both thermal and ESD) dominating the pressure measurement. If a further reduction in ultimate vacuum is desired then careful attention must be paid to reducing gauge and RGA outgassing.

Acknowledgements

Thanks are due to C. Benvenuti, J.K. Fremery, J.P. Hobson, Y. Ishikawa and F. Watanabe for helpful comments and information.

References

[1] Middleton WEK. The history of the barometer. Baltimore: John Hopkins Press, 1964.
[2] Andrade EN da C. Proc. 1st Int Vac Cong, Oxford: Pergamon, 1958:14
[3] Sparnaay MJ. Adventures in vacuum. Amsterdam: North-Holland, 1992).
[4] Fabel L. Vakuum-Technik 1986;35:128.
[5] van Helden AC. Tractrix 1991;3:149.
[6] Hablanian MH. J Vac Sci Technol A 1984;2:118.
[7] Dayton BB. In: Vacuum science and technology: pioneers of the 20th century. Redhead PA, editor. New York: AIP Press, 1994: 107.
[8] Reich G. In: Vacuum science and technology: pioneers of the 20th century. Redhead PA, editor, New York: AIP Press, 1994:114.
[9] Redhead PA. J Vac Sci Technol A 1984:132.
[10] Boyle R. New Experiments, physico-mechanical, touching the spring of the air and its effects. London, 1660.
[11] Shapin, S. The scientific revolution. Chicago: University of Chicago Press, 1996.
[12] Hawksbee F. Physico-mechanical experiments on various subjects. London 1709. New York: Johnson Reprint Corp., 1970.
[13] Mayer WHT. Über das geschichtete elektrische Licht. Berlin, 1858.
[14] Mcleod HG. Phil Mag 1874;48:110.
[15] Töpler A. Dingler's Polytechnisches J 1862;163:426
[16] Sprengel HTP. J Chem Soc 1865;16:9.
[17] Crookes W. Phil Trans Roy Soc 1873;163:277.
[18] Gimingham CH. J Soc Chem Ind 1884;3:83.
[19] Josephson M, Edison. New York: McGraw-Hill, 1959.
[20] Kahlbaum GWA. Wied Ann 1894;53:199.
[21] Fleuss HA. German Patent. No. 76147, 13/8/1893.
[22] Thomson JJ. The electrician, May 21 1897;34:104.
[23] Gaede W. Phys Zeit 1905;6:758.
[24] Gaede W. Ann Physik 1913;41:337.
[25] Dushman S. Phys Rev 1915;5:224.
[26] Gaede W. Ann Phys 1915;46:357.
[27] Langmuir I. J Franklin Inst 1916;182:719.
[28] Burch CR. Nature 1928;122:729.
[29] Sherwood RG. Phys Rev 1918;12:70.
[30] Buckley OE. Proc Nat Acad Sci 1916;2:683.
[31] von Baeyer O. Phys Zeit 1909,10:169.
[32] Redhead PA. In: Vacuum science and technology. Redhead PA, editor, New York: AIP Press, 1994:133.
[33] Nottingham WB. Phys Rev 1936;49:78. and J Appl Phys 1937; 8:762.
[34] Anderson PA. Phys Rev 1935;47:958; 1936;49:320; 1938;54:753; 1940;57:122.
[35] Bayard RT, Alpert D. Rev Sci Instr 1950;21:571.
[36] Van Oostrom A. Trans 2nd Int Vac Cong, Oxford: Pergamon Press, 1961:443.
[37] Redhead PA. Rev Sci Instr 1960;31:343.
[38] Venema A, Bandringa M. Phil Tech Rev 1958;20:145.
[39] Hall LD. Rev Sci Instr 1958;29:367.

[40] Becker W. Vak Tech 1958;7:149.
[41] Davis W, Vanderslice T. Trans 7th AVS Vac Symp, Oxford: Pergamon Press, 1960:417.
[42] Paul W, Reinhard HP, von Zahn U. Zeit Phys 1958;152:143.
[43] Davis W. Trans 9th AVS Vac Symp 1962:363.
[44] Redhead PA. Vacuum 1963;13:253.
[45] Redhead PA. J Vac Sci Technol 1966;3:173.
[46] Helmer JC, Hayward WH. Rev Sci Instr 1966;37:1652.
[47] Watanabe F, Hiramatsu S, Ishimaru H. J Vac Sci Technol A 1984;2:54.
[48] Watanabe F. J Vac Sci Technol A 1992;10:3333.
[49] Watanabe F. J Vac Sci Technol A 1991;9:2744.
[50] Benvenuti C, Hauer M. Trans 8th Int Vac Cong 1980:199.
[51] Watanabe F. Vacuum 1996;47:583.
[52] Watanabe F, Ishimaru H. J Vac Sci Technol A 1985;3:2192.
[53] Watanabe F, Aono M, Kato S. Vacuum 1996;47:587.
[54] Hobson JP. J Vac Sci Technol 1964;1:1.
[55] Thompson W, Hanrahan, S. J Vac Sci Technol 1977;14:643.
[56] Benvenuti C. Proc 7th Int Vac Congr 1977:1.
[57] Benvenuti C. Vacuum 1979;29:427.
[58] Benvenuti C, Chiggiato P. Vacuum 1993;44:511.
[59] Ishikawa Y. Paper at IUVSTA Workshop on Outgassing Properties of Materials. Sweeden: Gräftåvallen, 1997.
[60] Redhead PA. J Vac Sci Technol A 1992;10:2665.
[61] Watanabe. J Vac Sci TechnolA 1993;11:432.
[62] Watanabe F. Paper at International Vacuum Congress, Birmingham, 1998. Vacuum 1999;53:151.
[63] Marin P, Dialinas M, Lissillour G, Marraud A, Reboux A. Vacuum 1998;49:309.
[64] Fremery JK. Paper at Int Vacuum Congr Birmingham, 1998. Vacuum, in press.
[65] Ishikawa Y, Yoshimura T. J Vac Soc Jpn 1997;40:148.