The future of vacuum technology

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For 30 years vacuum technology has responded to spontaneous efforts to extend the limits of vacuum production and measurement and to the demands of diverse fields of application. In the future it is predicted that: vacuum pumps will see incremental improvements, particularly cryogenic pumps; more fundamental and less empirical research will take place on seals and outgassing leading to major improvements; vacuum gauges will improve incrementally; calibration will improve greatly and will be extended to 10^{-13} Pa (10^{-15} Torr); calibration methods will utilize cryogenics; leak detectors with sensitivities approaching 10^{-13} cm^3 STP s^{-1} will appear commercially; a gauge to assess directly the interaction of ambient gases on surfaces will be developed; more special purpose vacuum facilities, such as storage rings and fusion reactors, will be built; portable systems at ultrahigh vacuum will multiply; microelectronics under vacuum will master the control of fabrication from 10 to 10 000 Å and new products will appear, in particular three-dimensional structures; there will be a synthesis of vacuum technology with lasers, superconductors, catalysis, and solar energy; pervading all these developments will be an ever-increasing application of microprocessors and computers to vacuum systems of all kinds.

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I. INTRODUCTION

On the occasion of this 30th National Symposium of the American Vacuum Society, and in particular in this session on the History of Vacuum Science and Technology, it is appropriate that one paper be devoted to the future of vacuum technology. However, it should be noted that this paper is unlike a scientific paper in the normal sense, wherein the evidence for the conclusions is clearly and objectively presented, and predictions of the future, if any, are limited. In this paper evidence for the conclusions certainly exists but is massive in scope, the detailed relationships between the evidence and the conclusions are, to a large degree, subjective; and finally, the entire purpose of the paper is to predict the future. The paper is thus a sort of essay rather than a true scientific paper, although some basis for the conclusions is to be found in a paper by the author[1] entitled "The Limits of Vacuum Production and Measurement." It may be noted that the title of this paper does not include "vacuum science," only "vacuum technology." While the main reason for this is that the session organizer asked for this title, nevertheless, after some consideration the author has decided to retain it. Interest in vacuum has always been, and will remain, primarily in what can be done with it (technology) rather that in its detailed physical mechanisms (science). The number of users of vacuum systems will always far exceed the number of vacuum scientists and engineers. What is done in vacuum systems will continue to upstage the design and operation of the systems themselves. This is not to say that the stature of the vacuum scientist and engineer has not risen in the last 30 years. It has gone from that of second class citizen, whose responsibility terminated where the pumping pipe entered the experiment, to full partner in a complex team of experts. What can be done with vacuum technology today is based inextricably upon the physical understanding and imagination of scientists and engineers. It is the understanding of this role of the vacuum scientist and engineer that has made the American Vacuum Society the fastest growing member of the American Institute of Physics, and has made the courses given by the American Vacuum Society the most advanced and focused anywhere, ahead of educational institutions. In dramatic sequence the space program, all manner of surface investigations (including fundamental studies, catalysis, and solar energy), high energy accelerators and storage rings, the microelectronics industry, the search for economical thermonuclear fusion, have all called on vacuum technology for solutions to their immediate problems. A great cross fertilization has already taken place, although surprising gaps have been left. However, already in this brief introduction we know as we examine below the various subfields of vacuum technology, that we must be prepared in any prediction of the future to synthesize the conclusions from many fields, not only at a technical level, but perhaps also at the level of society itself. Because it is a convenient date not too far away we define the year 2000 as the future.

II. VACUUM PUMPS

The speed of vacuum pumps is inherently limited by the expression

$$S = 3.64\,(T/M)^{1/2}\,\mathrm{l\,s^{-1}\,cm^{-2}}, \tag{1}$$

with T absolute temperature and M molecular weight of gas being pumped. With the exception of rotary mechanical pumps all the ultrahigh vacuum and high vacuum pumps (see Fig. 1) can reach close to the limits of Eq. (1) in ideal circumstances, but practical constraints often reduce pumping speeds to perhaps 1/3 or 1/4 these values. Thus, with existing apendage pumps only incremental improvements in speed are foreseen (see Table I). Extensions in size, both larger and smaller, in orientation, along with reductions in power, and a diversification in applications may be foreseen. New pump materials: fluids in diffusion pumps, rotor materials and lubricants in turbomolecular pumps, cathode materials in ion pumps, pumping surfaces in all types of getter pumps, improvements of efficiency in cryopumps with increases in sorption capacity—all these seem certain in the future. The past 30 years has seen the turbomolecular pump, the ion pump, the nonevaporable getter pump, and the cryopump all move from relative obscurity to important roles today. What are the chances that new types of pumps will develop similarly in the future? In the author's view they are not great, primarily because new principles are required, and while there have been new pumping principles suggested,[9,10] they seem unlikely to develop beyond specialized applications. In terms of the lowest pressures achievable (see Fig. 1) the cryopump would seem to have the greatest promise since it can universally pump all gases if the temperature is low enough, and it has been shown that even helium, the most difficult gas to pump cryogenically, can be pumped to extremely low pressures ($P \leqslant 10^{-20}$ Pa) in significant amounts on a porous surface[11] at 4.2 K, which is a temperature readily achieved (as long as the world's supply of helium lasts). Predictions for appendage vacuum pumps are given in Table I. However, in the area of pumps which are an integral part of the experiment (i.e., nonappendage pumps), advances are currently taking place and considerable developments may be expected. Examples are given later under the appropriate application (Sec. V).

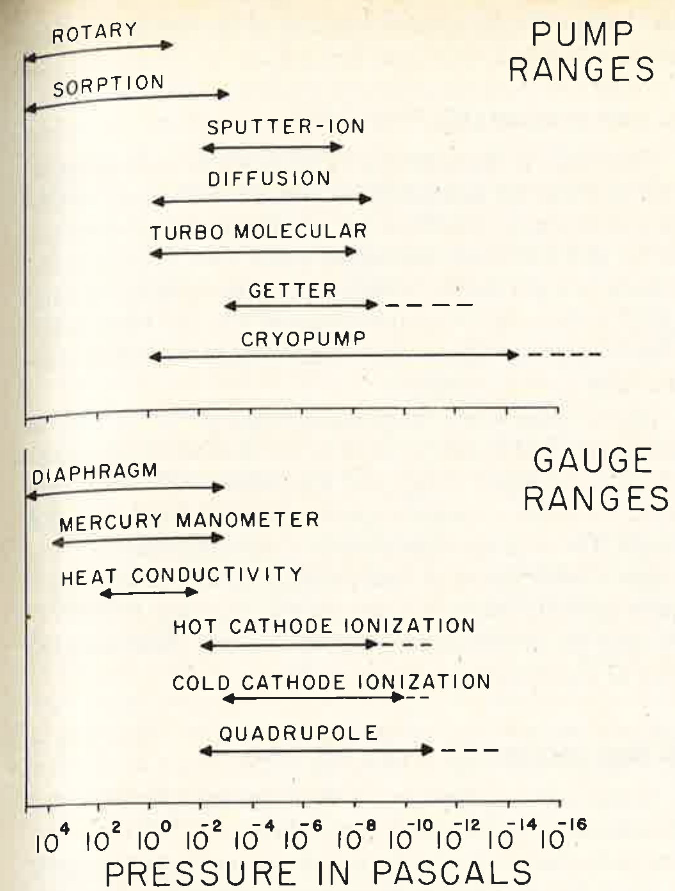

FIG. 1. Main operating ranges of pumps and gauges.

TABLE I. The future of appendage vacuum pumps.

Pumps	Prediction
New types of pumps	No new major types will appear.
Rotary and sorption	Incremental improvements.
Diffusion and turbomolecular (Refs. 2 and 3)	Minor improvements and reduction in base pressure to 10^{-10} Pa.
Ion (Refs. 4 and 5) evaporable getter, nonevaporable getter (Ref. 6)	Improved materials providing higher capacities and somewhat higher speeds and reduced base pressures. Broader range of operating temperatures.
Cryopumps (Refs. 7 and 8)	Greater use of liquid helium temperatures will yield large reductions in base pressure. Capacities of cryosurfaces will increase.

III. VACUUM MATERIALS

The material dominating the construction of vacuum systems today is stainless steel, which appears to have gained prominence in the early 1960's in response to the demands of the space program. The choice was made at a time when exhaustive measurements had not been made on the outgassing properties of materials. Stainless steel was known to be structurally strong, machinable, and capable of being outgassed to adequate levels with acceptable temperature treatments. Bellows and diaphragms of stainless steel were developed and welding techniques found for junctions to kovar and thus to transparent glass windows, and to ceramic for electrical feedthroughs. Stainless steel was matched with gaskets of copper in the widely used Conflat flange. Glass itself, particularly Pyrex, is a "complete" vacuum material in that entire systems can be constructed from it.[12] It was used extensively in the 1950's and early 1960's for experimental purposes and remains a flexible research material, but has lost ground to stainless steel, essentially because of its fragility and minimal machinability. Aluminum and aluminum alloys are perhaps the third group of complete vacuum material, developed in particular by the Japanese in their High Energy Physics Institute.[13] Aluminum has a great advantage in being cheap and readily extruded to yield piping of arbitary cross-sectional configuration. Since long lengths of such tubing are to be found in large accelerators and storage rings, it is here that aluminum - based systems have seen the most development. It has been found that aluminum outgassing is reduced by the synchrotron radiation itself in electron storage rings. Achievable outgassing rates with stainless steel and aluminum are in the range of 10^{-14}–10^{-12} Pa l cm^{-2} s^{-1} and consist mostly of H_2.[14,15] True outgassing rates of glass are comparable and permeation of atmospheric helium through Pyrex is about 5×10^{-13} Pa l cm^{-2} s^{-1}. The search for vacuum materials with specialized properties is currently intense in the research and development leading to thermonuclear fusion. New material properties for mechanical stability under intense neutron and ion fluxes are being sought, as well as means for reducing both spontaneous outgassing under plasma fluxes. Wall discharge cleaning in both argon and hydrogen are under active study. Outgassing rates will be reduced to 10^{-14} Pa l cm^{-2} s^{-1} more routinely in the future.

It is inevitable that in this intense search for new materials for particular purposes that vacuum technology will be changed, but perhaps once again in an incremental rather than a qualitative way. At this stage in the development of vacuum technology with the first thrust of the search for specialized vacuum materials past, the search will be less empirical and more fundamental.

Permanent seals (welds, glass-to-metal seals, explosive bonds, etc.), semipermanent seals (demountable flanges), and temporary seals (valve seals) are an area where significant developments may be expected, both in new materials and in design. The Conflat seal, reliable in general, can still suffer from leaks following a bake, particularly in the smaller sizes. A general theory of seals is beginning to emerge,[16] which may well place the science of seals on a more theoretical and predictable rather than empirical basis. New combinations of materials which can be hermetically sealed together are being found (e.g., aluminum can be explosively bonded to stainless steel). The whole science of valves which seal repeatedly to conductances below 10^{-13} l s^{-1} is only beginning to emerge. Here the leak paths are of atomic dimensions. An immense data base of the adherence of one material to another is emerging from the microelectronic industry, which will very likely have a spin-off into vacuum technology.

IV. VACUUM MEASUREMENT

Vacuum is here defined as all pressures below atmospheric (i.e., $P \leqslant 10^5$ Pa or 760 Torr). Figure 1 shows the main existing gauges available for measurement. The subatmospheric pressure range will be divided into three regions: 10^{+5}–10^{-1} Pa; 10^{-1}–10^{-7} Pa; $\leqslant 10^{-7}$ Pa. Predictions are given in Table II.

TABLE II. The future of vacuum gauges.

Gages	Prediction
Diaphragm	A simple, reliable, widely used total pressure gauge for the range 10^5 to 10 Pa will be developed.
High pressure mass analyzer	A simple widely used mass analyzer for the pressure range 10 to 10^{-1} Pa will be developed.
Heat conductivity	Incremental improvements.
Hot cathode ionization (Refs. 17 and 18)	Incremental improvement.
Cold cathode ionization (Refs. 19 and 20)	Improvements in stability and extension of linearity by an order of magnitude to 10^{-10} Pa.
Low pressure mass analyzer (Refs. 17 and 21)	Major improvements in outgassing of ion sources. Improvements in partial pressure sensitivity to 10^{-15} Pa using counting detection.
Gauge calibration (Refs. 23 and 24)	Will be extended to lower pressures ($\sim 10^{-13}$ Pa) using cryopumps. Major improvements in reproducibility and absolute accuracy. The spinning rotor gauge will be widely used as a secondary standard.

A. Low vacuum (10^{+5}–10^{-1} Pa)

This range is characterized by applications such as freeze drying, sintering, sputtering, reactive ion etching, etc. While gauges measuring true force (e.g., the diaphragm manometer or the McLeod gauge) exist down to 10^{-4} Pa, there is a surprising lack of a simple, widely used, direct reading vacuum gauge in the range from atmosphere to 1.3×10^2 Pa (1 Torr). This is not to say that gauges do not exist in this range, only that they are not routine.

On the other hand, the pressure range 10^2 to 10^{-1} Pa is universally and simply serviced by the thermal conductivity gauge — a rugged, cheap, and adequately accurate instrument, in which no major improvements are foreseen in the future. The need for mass analysis in this range has not been urgent to date; however, many semiconductor processes require carefully controlled gas purity in the range 10 to 10^{-1} Pa, and the development of an appropriate mass analyzer may be anticipated.

B. High vacuum ($10^{-7} \leqslant P \leqslant 10^{-1}$ Pa)

In this region and below, pressures (actually densities) are measured by the ionization gauge. At 5×10^{-2} Pa the mean free path of molecules in the gas phase at room temperature is about 10 cm. Thus, as the pressure falls below 10^{-2} Pa, molecule–wall collisions become more frequent than collisions in the gas phase. Thus, with falling pressure events become more and more determined by the interaction of molecules, electrons, ions, and photons with surfaces. Simply stated, this is the central problem of vacuum measurement at low pressure. In the high vacuum range it is successfully managed by controlling particle trajectories to emphasize the desired gas phase ionization and to suppress the surface reactions. Mass spectrometers of various designs make this problem simpler, and electron multipliers as detectors are not essential. In general, apart from the question of quantitative gauge calibration, vacuum measurement is satisfactory in the high vacuum range, and major changes are not anticipated in the future.

C. Ultrahigh vacuum ($P \leqslant 10^{-7}$Pa)

Here surface preparation becomes important to reduce unwanted surface contributions. However, finally, the design problem of a hot cathode total pressure gauge is one of identifying unambiguously the small gas phase signal amidst several possible surface contributions. The present limit of these gauges is about 10^{-10} Pa without multipliers and is not expected to be reduced much in the future. The cold cathode gauge, inherently very attractive at low pressures because of its low power consumption, suffers much less from surface effects (if we exclude electrical leakage across insulators), but has difficulty maintaining a stable discharge and linearity as the gas density diminishes. It can be used with some caution to 10^{-10} Pa and might well be developed to become more stable and reliable in the future.

As noted above the mass analyzer inherently solves some

of the difficulties of the hot cathode total pressure gauge, as well as providing much more information about the gas phase. For UHV, multiplier detectors are important and are almost universally used. With them the partial pressure sensitivities of modern commercial mass spectrometers are about 10^{-12} Pa; although frequently this is a misleading figure since the ion sources of these instruments cannot be outgassed to reach these levels. A major improvement in the latter area is foreseen in the future with a more modest improvement in the partial pressure sensitivity. The quadrupole mass analyzer dominates this field today and the simplicity of its construction with no magnetic field required is expected to maintain this dominaton into the future. However, to the best of the author's knowledge, the lowest partial pressure sensitivity reported was with a magnetic sector instrument many years ago[21] (10^{-15} Pa).

Frequently at UHV the experimenter is less interested in the pressure in the gas phase than in how the gases affect the conditions upon a surface of interest. Simple methods for answering this question are at present not well developed and might well be the subject of future activity. The field emission pattern of a surface changes with the adsorption of gases and the time taken between flashing clean and the appearance of a certain pattern could be used as a measure of the contaminating power of the gas phase.[22]

D. Gauge calibration

Truly quantitative vacuum gauge calibration is still in its infancy. A number of countries have set up gauge calibration laboratories, and the intercomparison of secondary standards is underway.[23,24] In Europe agreement has been found to $\pm$ 2.5% over the pressure range 10^{-4} to 10^{-1}Pa. However, an intercomparison in the U.S. has led to less satisfactory results. The uncertainties increase as the pressure diminishes. The lowest pressure today at which a quantitative gauge sensitivity has been claimed[25] is $\pm$ 30% in the 10^{-10} Pa range.

A method has been proposed[26] for achieving quantitative pressures of helium of 10^{-18} Pa (10^{-20} Torr) using the physcal adsorption of helium at temperatures $\leqslant 4.2$ K. This cryogenic method could be developed for gauge calibration, although care would be needed with corrections for thermal transpiration. At 10^{-14} Pa there is only 1 molecule cm^{-3} at room temperature. Hence, counting techniques rather than the measurement of continuous currents will be necessary. It would seem possible to do direct experiments to verify the statistical laws for the desorption of molecules from surfaces, etc. A major expansion of gauge calibration into the UHV range is predicted for the future.

E. Leak detection

The present limiting sensitivity of leak detection[27] is in the range of 10^{-14} cm^3 STP s^{-1} which is well below the normal commercial leak detector limit of 10^{-10} cm^3 STP s^{-1}. It is predicted that the latter will be reduced to 10^{-13} cm^3 STP s^{-1} and that large leaks of 10^{-3} cm^3 STP s^{-1} and above will be detected with a sensor other than the main mass spectrometer.

V. VACUUM APPLICATIONS

A. Space science

Pressures encountered naturally in the space program extend through the entire subatmospheric range under discussion (10^{-5} Pa at shuttle altitude, 10^{-8}–10^{-10} Pa on the moon's surface, 10^{-13} Pa in geostationary orbit), and it was the demands of the space program that provided the first major postwar stimulus to vacuum technology. Space simulation chambers for test, new pumps, gauges, and materials were all developed rapidly and successfully. At shuttle altitudes the pressure is about 10^{-5} Pa and the full difficulties of friction at UHV are not encountered. The Canadarm works successfully.[28] While it seems unlikely that the space vacuum at shuttle altitudes will be used as a vacuum system, there is a reasonable probability that manufacturing under vacuum in the microgravity of shuttle orbit will develop.[29] While the space program will continue to stimulate vacuum technology in specialized ways, its main impact is over and likely will not return.

B. Surface science

As noted in the Introduction there is a synergistic relationship between vacuum technology and surface science.[30] Vacuum technology provides the means for performing modern experiments in surface science, while surface science provides vacuum technology with the fundamental information necessary to improve its products, as well as a demand for new products (e.g., UHV rotary drives, long stroke bellows, sample carousels, etc.). A great number of different types of surface analytic instruments operating at UHV are today available commercially and a number of others are to be found in the laboratory. The most commonly used are LEED, AES, RHEED, SIMS, ESCA, UPS, XPS, TEAM, etc. Most commonly, three or four of these instruments are mounted in the same vacuum system and their beams can be directed at a single target, which is often a single crystal. This forms the well-known multiport surface analytic system. In recent years the growing of epitaxial films on samples (MBE) has become important and is approaching the production facility stage. In the future the various steps of production will be verified on line with surface analytic instruments. It is generally important that surfaces to which some change has been made not be exposed to the atmosphere. Thus, analysis has to be done either within the same chamber with some sort of mechanical motion,[31] or the sample has to be transferred for surface analysis with a vacuum transfer device.[32] To avoid the long delays in pumping vacuum systems from atmosphere to very low pressures, load lock sample entry systems have been developed. A general development of all these aspects of surface science is to be expected in the future and many ingenious designs may be anticipated. Surface science has been driven in part by important industrial fields such as catalysis,[33] solar energy,[34] corrosion, etc.

C. Accelerators and storage rings

The impact of large accelerators and storage rings upon vacuum technology was difficult to foresee 20 years ago. In hindsight the impact has been of the greatest importance, essentially because the ring engineers and scientists, particularly at CERN, soon realized that vacuum and surface conditions played a first-order role in the operation of proton storage rings, and every advance they made in these areas led to an increase in stored beam current and thus to an increased sensitivity in the detection of new particles. It was discovered that if the residual pressure was reduced below about 10^{-9} Pa, a circulating proton beam became its own ion pump. At Brookhaven[35] and in Japan[36] the concept of the distributed ion pump around the circumference of the beam tube, utilizing the magnetic fields necessary for beam bending, has been used in the National Synchrotron facilities. The photodesorption of gases from the walls caused by synchrotron radiation became of major concern and study. In the Tevatron (10^{12} eV) at Fermilab[37] the proton storage ring 6 km in circumference successfully operates with 92% of its length at 4.6 K (i.e., a vacuum system with 92% of its wall surface, a powerful cryopump with no baffles), a temperature derived from the bending and focusing superconducting magnets. The next accelerating storage ring is considered likely to be of energy 2×10^{13} eV, 160 km in circumference, to be located in a desert and to be called the "Desertron."

D. Fusion technology

The most formidable challenge facing vacuum technology today is undoubtedly the fusion program.[38] There are several very formidable and currently unanswered problems. Even the most efficient configuration: inertial confinement, magnetic mirror, and tokamak, is not yet clear. Many of these major problems belong in the domain of vacuum technology, along with a whole series of others outside this domain, all of which must be solved simultaneously before thermonuclear fusion becomes a reality. All are under intense study around the world. The full panoply of vacuum technology and surface science is being directed toward their solution. Immense liquid helium pumps for the hydrogen isotopes are being developed for neutral beam injection into the plasma[39]; samples of material are being inserted into discharges and withdrawn under vacuum for surface analysis,[31] methods of leak detection using directional detectors within the vacuum chamber are being evaluated because the exterior of the vacuum vessel is too cluttered to make conventional leak testing practical; and so forth. What will the outcome be? That is an important question not only for vacuum technology but for all of mankind. Feasibility or lack of it should be established before the year 2000.

E. Semiconductor technology and thin films

While neither the general vacuum range used in the semiconductor and thin film industries[40,41] nor its specific vacuum problems appear as severe as those of other areas, nevertheless, it is in the modern fabrication of integrated circuits and other related thin films devices that the greatest synthesis of vacuum processes and control takes place.

A modern VLSI (very large scale integration) circuit is fabricated in some 200 separate steps, the majority of which are done under vacuum. Current production aims at lithography dimensions down to 1 μ (10 000 Å). The wavelength of visible yellow light is about 5000 Å and hence, further major advances in lithography will use x-ray, electron, or ion beams of high resolution. These are the basic tools of surface science which have already been carried to resolutions of 10 Å in the case of electron beams. For lithography they will require modification and above all positional computerized control, but beyond this the basic technology already developed should be applicable. Integrated circuit production does involve substantial mechanical motion of the wafer under vacuum. This too requires computer control, which is under extensive current development. Of course all the other applications of vacuum technology that we have mentioned are experiencing computer control and frequently involve mechanical motions under vacuum, but it is thought that the semiconductor industry will carry these developments to their highest level. It is predicted that by the year 2000 the most impressive developments in semiconductor technology will have been in three-dimensional structures built up a layer at a time utilizing an extension of current MBE instruments.

TABLE III. Vacuum application in the future.

Application	Prediction
Space Science	Will be a customer of state-of-the-art vacuum technology but not a driver. May demand space manufacturing facilities under vacuum, at zero gravity.
Surface Science	Will experience major advances in complexity of instrumentation and in automatic control; a limited number of new instruments will come into general use. There will be many applications to industrial processes.
Accelerators and storage rings	The "Desertron," 160 km in circumference, will be built using cold bore. Superconductivity and cryopumping will combine in many other large installations.
Fusion technology	Will be the area of the most intense search for new (vacuum) materials and ways of using them. This field will be the main driver of new developments in vacuum technology.
Semiconductor technology and thin films	An intense synthesis of existing technology with automation will occur. Production lines will have many surface science instruments on line for quality control. Molecular beam epitaxy will develop into a means of building new three-dimensional devices.

VI. SUMMARY

Tables I–III provide the author's main predictions in the area of vacuum technology and its applications. There are other fields undergoing intense development: lasers, superconductors, computers, microprocessors, robotics, information science, medical engineering, biotechnology, etc. Vacuum technology will interact dynamically with all of them.

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