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ION- AND DIFFUSION-PUMP HIGH VACUUM SYSTEMS

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I. INTRODUCTION

The relative advantages and disadvantages of diffusion-pump and ion-pump vacuum systems in obtaining a clean, high vacuum are discussed in this report. The scope of this study is limited to the more important features of the systems; more detailed accounts of these features and others are given by the investigators listed in the references and bibliographies.

Dynamic vacuum systems have a variety of applications [1, 2, 3]. The design and selection of components will determine the properties of the systems. In general the evaluation of a vacuum device will depend upon its intended use, its operating pressures, the outgassing parameters of the surfaces exposed to vacuum, the length of the cycle, the desired pump-down time, the degree of cleanliness required, and cost.

Five basic methods of gas evacuation are used to achieve a vacuum [2]:

1. Kinetic: mechanical and diffusion pumps used
2. Ionic: gas molecules electrically charged and driven to a surface capable of sorption
3. Chemical: gases converted into stable low-vapor-pressure solid compounds
4. Absorption: large, clean surface is exposed to gas to which it has affinity
5. Cryogenic: change gas to liquids or solids having low vapor pressure at low temperatures.

This report deals with vacuum systems based upon the first two methods, in which pressures in the very high vacuum region are achieved by getter-ion pumping with bakeout and diffusion pumping with bakeout [3].

II. DIFFUSION PUMPS

A. General

The interdependence and operation of the individual components of a diffusion pump determine the performance characteristics of the pump [4]. Fundamentally they consist of a boiler,

jet assembly, casing, and fluid [5]. The casing is flanged at the top and one side, is closed at the bottom, and is enclosed in a ring of cooling coils so that the fluid vapors contacting the walls will condense and return to the boiler. Since the diffusion pump alone can exhaust only to a fore pressure, a fore pump is used. To further extend the operating pressure to the ultrahigh vacuum (uhv) range, vapor traps are employed [6]. Liquid-nitrogen traps usually are positioned between the pump and vacuum chamber to condense oil vapor migrating from the pump [7].

The three main types of fore pumping are mechanical, sorption into cryogenically cooled zeolite, and a combination of mechanical and sorption pump systems. Munro [8] notes that the choice of system to be used will be based upon the cost and the technical requirements. The choice of roughing pumps, based upon technical considerations, will depend upon how important it is to eliminate hydrocarbons from the system. If a completely oil-free system is required, sorption pumping rather than mechanical must be used for roughing because even in the best trapped mechanical pump some hydrocarbons backstream at lower roughing pressures.

B. Advantages

The diffusion pump operation is simple and can easily be made automatic [1]. Since the gases are removed from the system instead of being buried as in the ion type, the pump has no "memory." It is able to handle a large amount of gas and can recover quickly from a pressure burst. It can operate in the high micron range (that is, at close to atmospheric pressure). This capability is derived from its high throughput and high fore-pressure tolerance. Another consequence is fast cycling and rapid chamber evacuation. Most gases are pumped at the same speed, and the lighter gases are pumped at higher than the normal plateau speed. Other advantages are a comparatively lower initial cost, no problems due to a magnetic field, and no high-voltage-shock hazard.

C. Operational Problems

Operational problems characteristic of diffusion pump vacuum systems relate to pump oils, explosions, and backstreaming.

1. Pump Oils. Diffusion pump oils, complex compounds, are subject to decomposition even under normal operating conditions [3]. They decompose when exposed to air at their working temperature, and for silicone oils, upon prolonged exposure to air. Decomposition is accelerated when the oils are exposed to electrical discharge and the high temperatures of boilers and hot filaments. The decomposition products can be harmful to electrical instrumentation through the formation of undesirable conducting paths.

2. Pump Explosions. Of the 74 explosions in diffusion pump systems reported by members of the American Vacuum Society [9], 2 occurred under steady-state high-vacuum conditions and 72 under conditions listed in the following four categories:

1. While the diffusion pump was in operation the fore pump or roughing pump was turned off.
2. Liquid nitrogen in the cold trap was removed, with the consequence of rapid expansion of the trapped gases.
3. Pressurization of a hot diffusion pump with air or oxygen: this occurred as a result of improper sequencing of valves, leaky seals, a break in the system, or any emergency pressurization procedure. In many cases an ionization gage or a hot filament was present and could have been the source of ignition.
4. Removing oxygen from the system with a mechanical pump.

Farrell and O'Neill [9] state, "This history of diffusion-pump problems appeared to contradict the results of a previous study conducted by IIT Research Institute for NASA, Houston . . . The difference could result from either contamination or from degradation of the fluid in the field during usage. All previous laboratory tests were conducted on fresh unused fluids."

3. Backstreaming. The movement of vapor molecules (by scattering from hot vapor jets or evaporation from hot nozzle parts) in the direction of the mouth or inlet of a vapor pump is called backstreaming [3]. This vapor movement is distinguished from back migration, which is defined as the passage of vapor molecules into a vacuum system by reevaporation from baffles, the inside surface of the pump caging, and connections to the pumping system.

The sources of backstreaming in an oil diffusion pump have been analyzed by Kobayashi and Otake [10], who enumerate them as: (1) the drains of the jet surface, (2) the vaporization of cold oil drains on the upper wall of the pump cylinder, (3) the scattering of oil vapor stream, and (4) the reflection of oil vapor stream. Their conclusion is that the oil drains on the jet surface are the main source of oil-vapor backstreaming. Of the other three sources, scattering and reflection cause three times as much backstreaming as evaporation from the cold oil drain.

A certain amount of backstreaming occurs in all diffusion pumps [11]. For many, the backstreaming rate can be effectively reduced by using cold caps around the top nozzle. Hablanian and Steinherz [11], working with various pumps, obtained reductions of one-fiftieth to one-hundredths of the rate shown without cold caps.

The most common troubles in pump operation arise from the exposure of pump fluid to the atmosphere [3]. This may result in contamination of the entire working volume of fluid, with the additional consequence of high ultimate pressure, damage to vacuum components (mercury, for example), interference with various vacuum processes, and nozzle blockage by gummy oil residues which would result in a drop in pumping speed or complete stoppage.

Interruption of coolant flow is another cause of diffusion pump trouble, since it could lead to extensive backstreaming, fluid migration, and decomposition of oil with consequent interference with vacuum processes and the formation of gummy residues on the nozzle assembly.

Pagano [6] notes that a diffusion pump can contribute gas to a vacuum chamber through decomposition of the fluid. Organic fluids used in the pump system are thermally unstable and form large amounts of lighter-fraction components, including methane and hydrogen. The ultimate pressure of the pump, therefore, is determined by the decomposition rate of the pump fluid at the operating temperature.

According to Kennedy [12], random compression waves from eruptive boiling in a diffusion pump are an important source

of backstreaming, especially in baffled systems. His experimental evidence supports this hypothesis.

Pressure bursts in vacuum systems, discussed by several investigators [13], have been traced to leaks and eruptive boiling in the pump boiler.

III. GETTER-ION PUMPS

A. General

Getter-ion pumps depend on ionizing and gettering action to remove gases and vapors. Getters are materials included in a vacuum system or device for removing gas by sorption [14]. The sorption of gases and vapors under any circumstances constitutes a pumping action. Getter-ion pumps fall into two major classes: those in which the getter material is dispersed by evaporation, and those in which the getter material is dispersed by sputtering from a cold cathode as result of ion bombardment [15]. The former is called the evapor-ion pump. The latter is commonly called the Penning or sputter-ion pump, and is the most important and widely used type of getter-ion pump. Titanium in both types is usually used as the gettering material. Kumagai [16] relates that the titanium evapor-ion pump acts as a pump in three ways: (1) by chemical reaction between titanium and gases, (2) by forced combination of titanium atoms and gas particles excited or ionized by electrical discharges, and (3) by occlusion of gas particles in successively formed titanium layers on the wall. Except for minor modifications a typical Penning discharge configuration consists of a cylindrical anode, two cold cathode plates across the ends of the anode, and a magnetic field which extends axially through the anode [17]. In the magnetic field of a sputter-ion pump, a Penning discharge occurs in which electrons have a long spiral path, ensuring a high probability of ionizing collisions with gas molecules [8]. The higher the energy of the bombarding ions and the greater the chemical activity between gas and electrode material, the more pronounced the pumping [18]. The positive ions formed in the Penning discharge are accelerated toward the cathodes, and each electron remains in orbit, continuing the ionizing process until such time as its energy

level is too low. When the pressure is not below a certain point, the discharge is not confined to the cells and the pump will not start. For this reason, it is necessary to use a fore pump or roughing pump in combination with an ion pump. Mechanical pumps and sorption pumps can be used. For an oil-free system sorption pumps are used [3]. The use of cold traps between mechanical pump and sputter-ion pump will achieve much the same results.

The pumping speed of ion pumps is related to a combination of factors including molecular size and weight of the gas, ionizing probability, chemical activity, and the intensity of the cold cathode gas discharge.

Rutherford [19] notes that large systems with large sputter-ion pumps consistently reached lower pressure than small sputter-ion pumps on small systems. These observations take into account differences in ratios of surface area to volume and assure the same system treatment.

There are three important differences between large and small systems [19]. The large pumps have more anode cells than small pumps, the large pumps generally operate at higher voltages, and, because of more efficient magnet design, large pumps have higher magnetic fields.

In bakeable ion pump systems, evapor-ion pumps are difficult to bake thoroughly because of their basic design and constructional materials. Sputter-ion pumps, however, can be baked somewhat more readily.

B. Advantages

Getter-ion pumps can be used to produce very low pressures with a constant pumping speed over a wide pressure range. There is a more efficient use of pump speed because baffles are not required, and the system is clean because oil is not used. No cryogenic liquids are needed for traps and no cooling water is necessary; therefore, long-term operation is possible. Power requirements are low and power failures are not a serious problem. The pumps are not damaged by accidental let-down to air. They are silent in operation and can operate in any position, which is important in some applications.

C. Disadvantages

Getter-ion pumps are not suitable for routine handling of large bursts of gas [3], nor for handling large quantities of inert gases. Generally they are not suitable for use in systems operating through cycles, being let down to air periodically. In comparison with diffusion pumps at higher pressures (10^{-5} to 10^{-4} torr, or 133×10^{-5} to 133×10^{-4} N/m^2), they cost more to operate. This is because they require more power as the pressure increases whereas for diffusion pumps the power required is constant over the pressure range through which they operate.

D. Operational Problems

In this discussion the operational problems characteristic of getter-ion pumps relate mainly to reemission.

Two phenomena influencing ultimate pressure in uhv systems pumped by ionic pumping are the desorption of adsorbed gas and the reemission of gas previously pumped. The distribution and quantity of hydrocarbons evolved from an ion pump, observed over a period of time, is a function of its past history. When a sputter-ion pump is shut off or baked, the occurrence of hydrogen, methane, ethane, and several inert gases is to be expected, especially in systems very recently exposed to air [20]. It has been found that hydrocarbons observed emanating from an ion pump are synthesized from the hydrogen- and carbon-containing molecules (not necessarily hydrocarbons) being pumped [21]. The carbon and hydrogen impurities in titanium getters are known to produce hydrocarbons [22]. Formed by reaction between carbon and hydrogen impurities present in the getter material, these hydrocarbons are mainly produced when the hydrogen content of the titanium in the vacuum atmosphere is low. High-mass hydrocarbon molecules may be produced when there is a high ratio of carbon to hydrogen in the getter, that is, the hydrogen is insufficient to produce saturated molecules and the unsaturated lower-mass numbers combine. Water likely is synthesized within the sputter-ion pump, and ammonia has been reported in an electrical discharge under conditions similar to those prevailing within a sputter-ion pump [23]. Most complex molecules are dissociated and broken up when they enter the high-intensity discharge region of the ion pump [18]. Water vapor, carbon monoxide, carbon dioxide,

ammonia, and hydrocarbons are all readily pumped by sputter-ion pumps. The hydrocarbon molecules are removed by the ion pump probably as a result of decomposition and ion burial, whereas in the hot-cathode type, it dissociates the organic molecules, permitting the active components to be sorbed [22].

In ionic pumping the reemission of one gas during ionic pumping of another is possible [24]. Since ions impacting on a surface cause sputtering of the surface atoms, the earlier trapped gas on the surface may be released by ionic pumping. This effect may be important in some experiments if the incoming and outgoing gas are different, and particularly if the emitted gas is difficult to pump.

The pumping mechanism is not the same for all gases [8, 18]. Argon is pumped by ion burial in the cathode. Ions of nitrogen or oxygen may combine chemically on impact with the titanium surface, forming stable chemical compounds. These compounds may become dissociated or may be sputtered intact under subsequent ion bombardment and deposited on the opposite cathode or the anode interior. When the cathode becomes saturated with argon, the initially high pumping speed of argon falls off very rapidly. The hydrogen and helium ions, being light, produce relatively little sputtering. Both are pumped by being buried in the titanium deposited on the anode by the sputtering caused by heavier ions, and in the cathode itself. Hydrogen has a strong chemical affinity with titanium, and a significant amount of neutral hydrogen can be pumped by direct molecular contact with the cathode surfaces. Helium appears to be pumped mainly by ion burial, followed by limited diffusion into the cathode.

Most of the material deposited on the cathode is eventually resputtered, whereas deposits on the anode remain undisturbed. Under certain conditions hydrogen and helium can reevolve, probably as a result of heat energy released under ion bombardment. Since heavy-ion bombardment tends to release argon, this gas, too, may be reevolved.

It should be noted that the consumption of titanium is higher at higher pressures than at lower pressures. The consumption of titanium at very low pressure is extremely small.

IV. OTHER PUMP FEATURES AND PROBLEMS

A. Baffles and Traps

There are many designs for traps used to keep pump vapor out of the vacuum chamber. None are completely efficient. Pagano [6] outlines two ways by which pump fluids pass through a trap. One is by a line-of-sight transmission or reflection from the pump to the vacuum chamber, and the other is by migration of the pump fluid along the walls of the chamber. Farkass and Vanderschmidt [25] note that the addition of complex baffles does not appear to improve the performance of a pump using very simple baffles. Guthrie [3], too, states the incomplete efficiency of baffles in stopping vapor molecules. Therefore, when traces of pump fluid vapor cannot be tolerated, as in vacuum systems operating at pressures well below the pump-fluid vapor pressure, refrigerated traps are added. However, during shutdown of the trap or inadvertent warming, the previously pumped gases are released [6]. The vapor molecules emanating from the trap move about randomly, and therefore are free to return to the vacuum chamber as well as to the pump.

B. Sorption Agents

Activated charcoal, zeolite, and activated alumina are the most commonly used sorption agents in refrigerated and nonrefrigerated traps [3]. The sorption capacity of these materials is greatly increased at liquid-nitrogen temperatures. The atmospheric gases, including the rare gases, are sorbed by activated charcoal with different degrees of efficiency. Zeolites are particularly effective in sorbing water vapor and carbon dioxide at room temperature. Activated alumina is comparable to zeolites in its ability to sorb atmospheric gases and vapor.

C. Gas Residuals Admitted to the System

The limit on the ultimate vacuum pressure reached is set by the gases and vapors, sorbed by the vacuum-system material, which are only gradually released. The gas composition depends upon the type of system used, the pump, and the measuring device [26]. Baking is used to degas the materials while pumping goes on. This baked system accelerates outgassing so that lower pressures can be reached in a reasonable time.

The absorption and adsorption of water in vacuum materials is one of the main causes of slow pump-down [3]. Since water can enter the vacuum chamber from a diffusion pump, the effectiveness of the cold trap will determine the rate of its entry. Water can enter the vacuum system through the chamber surfaces because of its strong adsorbability to surfaces at atmospheric pressure [27]. Objects placed inside the system may be another source of water contamination. Because it takes a long time to evacuate water, the chamber is baked to reduce pumping time. Being active, water vapor may easily oxidize many metals. Water vapor is the prime contaminator of glass surfaces. Therefore, glass systems, when not degassed properly, will produce more water vapor then metal systems. Water vapor can be reduced chemically, leaving hydrogen.

Carbon dioxide, also a contaminator of glass surfaces, will accumulate on a liquid-nitrogen trap during the bakeout of a vacuum chamber [27]. After bakeout, the carbon dioxide outgassing can limit the ultimate pressure. A technique for eliminating carbon dioxide is to evaporate it by warming the trap so that the gas can be pumped. However, if the trap is warmed too much, water or pump oil can enter the system. Carbon dioxide can be reduced chemically to carbon monoxide.

Hydrocarbons can originate from pump oils. Methane, ethane, ethylene, etc. can form by a reaction of water vapor or hydrogen with the carbon-containing materials present in active metals after reaction with carbon monoxide [26]. The hydrocarbons decompose at high temperatures, leaving carbon and hydrogen. Hydrogen may also appear as a reaction product of water vapor when the system bakeout was insufficient.

D. Contamination Effects

Oil contamination is difficult or impossible to avoid during spacecraft testing. If there is contamination prior to a spacecraft test, a lengthy (10 to 30 days) hand-cleaning process must be conducted, since it is very difficult to remove oil deposited on the chamber. Saunders [28] notes that oil from an oil diffusion pump backstreaming into the test chamber, even in very minute quantities, can coat a spacecraft and change its thermo-optical characteristics. A monomolecular layer of oil

can have significant effects. For example, a layer of oil can change the ratio of optical absorptivity to emissivity of thermal-control coatings on the exterior of the spacecraft by as much as 20 percent, thus changing its thermal-equilibrium control capability. In addition, once there is contamination, the possibility exists of oil being trapped in a crevice; later it could sublimate during flight and cover an optical aperture of experimental equipment, consequently degrading or aborting the mission.

Holland [29] observed that chemically cleaned glass or oxidized metal surfaces normally are covered with adsorbed water, which prevents chemisorption of silicone molecules. Polar molecules can be strongly adsorbed to surfaces covered by adsorbed water, but diffusion pump fluids such as Apiezon and hydrocarbons emitted by elastomers are nonpolar. The chemically cleaned glass or oxidized metal surface will be partially covered by a "physically" adsorbed layer of water in equilibrium with the organic vapor. If now the surface is baked or exposed to an electron stream, the weakly adsorbed organic molecules may become permanently fixed to the surface by thermal decomposition, polymerization, or chemisorption.

When a surface has been cleaned it can become contaminated if organic molecules are present in the vacuum atmosphere [29]. Thus, if a bakeable system is evacuated with an oil diffusion pump that is trapped with only a water-cooled baffle during bakeout (the refrigerated trap being degassed), the partial pressure of oil vapor in the vessel is sufficient to cause contamination of chemically cleaned glass substrates [29]. Holland showed that under conditions of saturated vapor pressure, silicon 705 contaminates clean glass and silica surfaces at about one-half the rate of silicone 704. He also found that organic contamination is increased during bakeout in uhv oil diffusion pump systems if the system is operated with only one liquid-nitrogen trap. Oil vapor condensed on the trap during uhv pumping is liberated into the vessel during subsequent bakeout. To avoid this contamination a second trap must be fitted and cooled whenever the diffusion pump is operating. In this double-trapped system the contamination rate for silicone 705 is between one-quarter to one-half that of silicone 704 on an electron-bombarded target.

Holland observed organic contamination when a Penning pump was initially exhausted by a mechanical oil pump. Most

Penning pumps are used with cooled zeolite traps for prepumping. A Penning pump system with a zeolite roughing pump shows a low rate of organic contamination during uhv pumping. (Tests were not made during pump degassing.)

Monro [8] states: "If we need a completely organic free system, then an ion pump has to be used since no trap is 100 percent efficient. If long-term testing has to be done at high vacuum, again an ion pump has to be used for reliability in the event of power cuts, etc., and sometimes because of the risk of failure of liquid nitrogen controlling devices. Generally speaking, it is easier to obtain pressures of better than 10^{-10} torr with ion pumps than with diffusion pumps. However, when the runs being made are short, where the backstreaming of diffusion pump oils is not detrimental to the work, the cost of an ion pump is prohibitive."

In relation to future space probes, they will probably include magnetometers for the measurement of space fields [28]. Most of the new generation of vacuum pumps, the ion-sublimation types, produce fields great enough to affect the very low residual magnetism and magnetic moment of the spacecraft. Therefore, if one tries, when it is possible and desirable, to eliminate oil contamination by switching to ion-sublimation pumps, one inherits undesired magnetism.

The objectives of investigations by Buckley, Swikert, and Johnson [30] were to determine in vacuum (10^{-6} to 10^{-7} torr or 133×10^{-6} to 133×10^{-7} N/m^2) the evaporation rates of various organic and inorganic lubricants and solid lubricant coatings, the friction and wear properties of unlubricated slider materials for reference, and the friction and wear properties of these slider materials coated with solid lubricant films. Oil contamination was observed on samples undergoing the lubrication tests in a diffusion-pumped system. When oil contamination could not be eliminated, a sputter-ion pump system was substituted. The authors state: "One of the problems associated with conventional oil diffusion pump systems is that of back-migration of oil vapors from the pump to the test chamber. This back-migration even with cold traps and baffles can serve as a source of specimen contamination and result in a pronounced reduction in friction and wear."

A conventional oil diffusion pump was the first high-vacuum pump to be used with their vacuum friction and wear apparatus.

The methods taken by the authors to eliminate contamination were: First, to place a liquid-nitrogen spiral cold trap between the chamber and the oil diffusion pump. Second, an optical baffle plate was added between the cold trap and specimens. Third, a honeycomb copper structure as a baffle was fitted to the optical baffle and placed above the liquid-nitrogen cold trap. Fourth, a heater was attached to the optical baffle (previously used) for the purpose of decomposing the oil vapors migrating to the specimen chamber. This unit was then placed between the liquid-nitrogen cold trap. Fifth, the heater plate was then replaced by a heater grid of tungsten coils. Sixth, a tungsten-wound heater coil was then placed in the specimen chamber directly beneath the disk and rider. All these arrangements were insufficient in eliminating specimen contamination.

The previously used optical baffle design was altered and used in conjunction with the liquid-nitrogen cold trap. A tungsten heater grid was added below the baffle. Oil contamination in the system still remained.

A heater-baffle assembly then replaced the expansion bellows of the apparatus, which was between the specimen chamber and the liquid-nitrogen cold trap. The heater-baffle assembly consisted of two water-cooled optical baffle plates with a tungsten-wound heater grid between the plates. This assembly in conjunction with the liquid-nitrogen cold trap minimized the specimen contamination, but did not eliminate it.

The authors considered a liquid-nitrogen-cooled plate-type chevron baffle. However, since experimental evidence by their colleagues showed that this configuration also allowed test-chamber contamination, it was not used.

The authors state: "The inability to completely eliminate the back-migration of oil vapors from the oil diffusion pump resulted in the replacement of the oil diffusion pump with an ionization pump. This pump employs no fluid or vapors in its operation."

An assessment of this work was made by Hablanian and Jackson [5], who dispute some of the interpretations. They state: "Unable to eliminate this contamination, the authors concluded that oil diffusion pumps are not suitable for this type of work and changed to a sputter-ion pump. However, an examination of the types of baffles used shows that the problem was a result of insufficient trapping of the oil molecules. Two significant points emerge:

(1) The spiral liquid nitrogen baffle used did not insure at least one contact on a liquid nitrogen cooled surface by molecules coming from any direction. Molecules can pass directly into the vacuum system between the spiral baffle and the outer shell. Also, molecules happening to travel along the spiral and "bouncing" off the warm shell will reach the system.

(2) All the other baffle arrangements above the liquid nitrogen baffle were ineffective because they were not cooled at all or only water cooled. Only additional liquid nitrogen or other cryogenic surfaces or molecular sieve surfaces can further reduce the concentration of oil molecules. The heater grids as used by the authors may drive decomposition products into the chamber. Such devices might be more effective below the liquid nitrogen trap."

The following excerpts indicate vacuums essentially free of heavier hydrocarbons can be obtained with oil diffusion pumps.

In measurements of low partial gas pressure with the mass spectrometer [Drawin and Brunee in Refs. 5 and 30], the following partial pressures were obtained with mercury diffusion pumps:

Hydrogen		1×10^{-9} torr	$(133 \times 10^{-9}\ N/m^2)$
Water		1×10^{-10} torr	$(133 \times 10^{-10}\ N/m^2)$
Carbon Monoxide		5×10^{-10} torr	$(667 \times 10^{-10}\ N/m^2)$
Nitrogen		5×10^{-10} torr	$(667 \times 10^{-10}\ N/m^2)$
Carbon Dioxide	less than	1.5×10^{-10} torr	$(200 \times 10^{-10}\ N/m^2)$
Hydrocarbons	less than	1×10^{-10} torr	$(133 \times 10^{-10}\ N/m^2)$
Mercury	less than	1×10^{-10} torr	$(133 \times 10^{-10}\ N/m^2)$
Total Pressure	less than	3.3×10^{-9} torr	$(440 \times 10^{-9}\ N/m^2)$

Using oil diffusion pumps, very similar results were obtained at total pressure of 3×10^{-9} torr ($400\ N/m^2$). Drawin and

Brunee state: "With both pump types, about the same ultimate partial pressure can be obtained with the exception of hydrogen. The partial pressure of hydrogen was at least ten times higher with the oil diffusion pumps compared to the mercury pumps." (It may be noted also that reduction of foreline pressure of a diffusion pump reduces the amount of hydrogen on the high vacuum side.)

Milleron has stated [5, 30]: "Diffusion pumps have been demonstrated to be inherently clean . . . . First, diffusion pumps, both mercury and oil, can be completely trapped. No oil or cracked hydrocarbon spectrum, and no mercury, down to partial pressures of 10^{-11} torr for oil and 10^{-16} torr for mercury is detected."

Hahn and Zahringer [5, 30] present additional evidence for the cleanliness of diffusion-pump operation: "A very sensitive mass spectrometer — allowing the measurement of partial pressures below 10^{-12} torr — was used to investigate the composition of the residual gas in a vacuum system, as obtained with oil diffusion pumps plus nonrefrigerated baffles, and with an ion-getter pump. The spectrum of the residual gas was checked daily during several weeks, whereby different types of pumps, baffles and pumping fluids have been used.

The investigations have shown that the combination two-stage pump plus silicone ultra fluid plus aluminum oxide trap has been proven suitable for production of ultra high vacuum. The pressure remains constant for many weeks at its initial value and the residual gases from the pump are only methane and hydrogen."

Hablanian and Jackson sum up this evidence: "Experiments which greatly depend on surface conditions must be conducted with very careful vacuum design and techniques, or contamination is possible with both diffusion pumps and ion-getter pumps when used together with mechanical pumps."

The following conclusion has been expressed by Buckley, Swikert, and Johnson: "It is reasonable to expect that the problem of back migration "can" be solved. The efforts described in the above, however, did "not" solve the problem. Rather than

to spend more effort, the problem was avoided by using an ion pump. The ion pumped system is not free from problems but fortunately they are different than the one of primary concern here.

The references cited by the discussers are indicated to suggest that systems "essentially" free of back migration can be obtained. The problem in friction wear, and lubrication studies is that systems must be "absolutely" free of organic contamination."

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