

Vacuum

Selecting materials and hardware

Gaskets, joints, lubricants and other components must be easily cleanable, unharmed by high temperature and chemically nonreactive; some substances approach this ideal better than others.

William R. Wheeler

The primary function of very high and ultrahigh vacuum equipment is to provide an environment that is superbly nonreactive: so neutral that molecular, electron and other submolecular beams can travel uninhibited; that chemically reactive metals can be heated to any temperature and be improved rather than degraded; that physiochemical reactions can be precisely controlled without contamination problems.

We get some idea of the cleanliness of a vacuum system by equating various pressures with the equivalent contamination level in a gas at atmospheric pressure. A 10^{-3} -torr vacuum, for example, is equal to a 1.3 parts-per-million contamination level, and 10^{-9} torr is equal to 1.3 parts in 10^{12} . Such low pressures are readily attained and easily measured, and there is no need to identify the residual gas species to determine the total contamination level. Contamination levels in gaseous atmospheres, by contrast, are difficult to identify and to measure below 1 ppm except in special cases, and maintaining gas purity even to 1 ppm is complex and difficult.

To assure the performance of vacuum equipment, great care must be taken in selecting construction materials. Here I shall describe some of the general contamination and purification problems and then discuss the require-

ments for particular vacuum components—joints, valves and feedthroughs.

A material selected for vacuum construction should not, as we have noted, degrade the vacuum or contaminate the work. In addition, it should fulfill the other requirements of its particular application. These requirements are extremely diverse, because virtually any operation normally carried out in other atmospheres will often be done in vacuum. The broad categories of vacuum-system parts are listed in Table 1, along with the preferred materials.

Gas-surface interactions

To understand some of the requirements for vacuum materials, we should examine the process of achieving a satisfactory vacuum. After a "roughing" pump removes the bulk gas, the system pressure P is determined by the outgassing rate Q of all the inner surfaces divided by the pumping speed S of the "fine" pump:

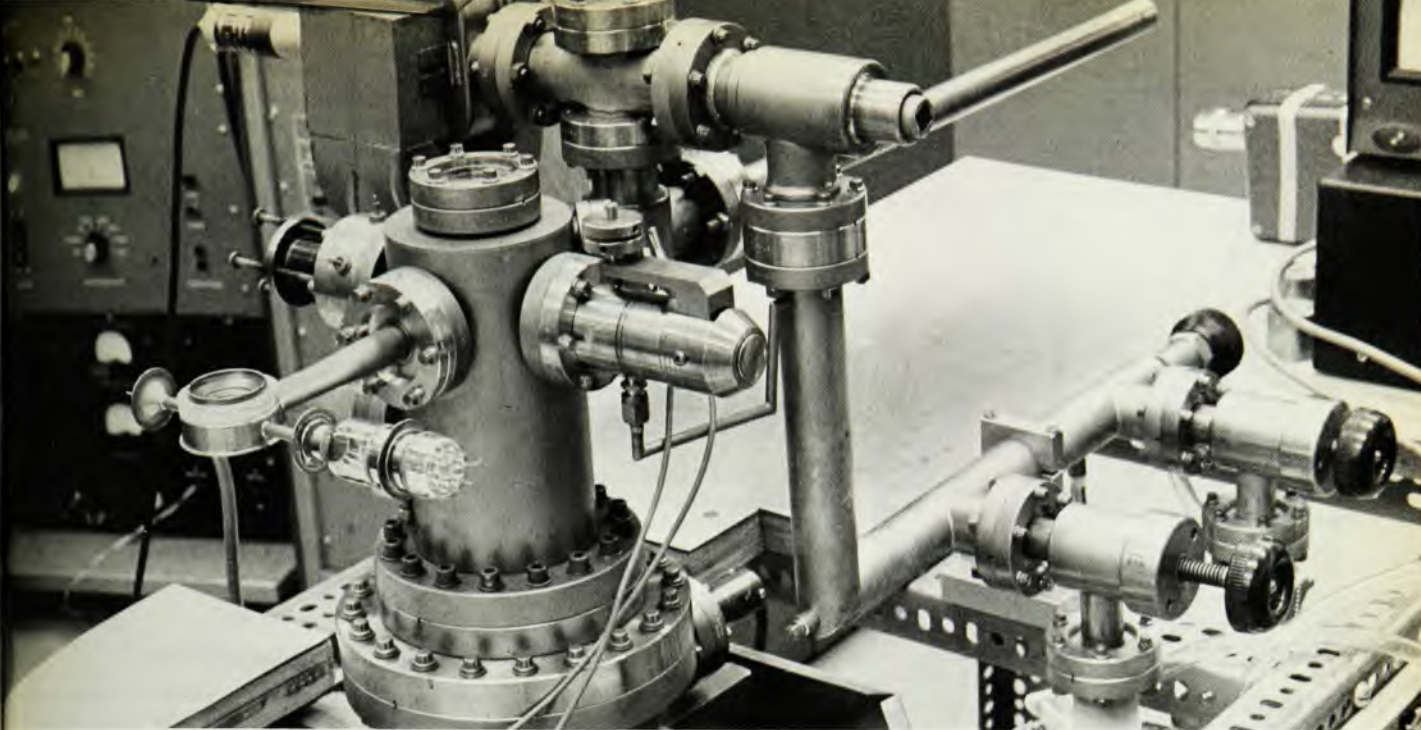
$$P = Q/S$$

Q is the total outgassing from all possible sources, such as the vapor pressure of the base materials and of any surface impurities, decomposition products of unstable compounds on or near the surface, release of physically sorbed or chemisorbed gases on the surface or buried close to the surface, composition products formed on surfaces or in energetic collisions, or release of gas that has diffused through the bulk of the base material, perhaps permeating from outside the vessel.

Although it is possible to observe all these phenomena simultaneously, it is more informative to look closely at the case involving a typical system pumpdown. Our "typical" system is made of "304" stainless steel (the least expensive widely available acceptable type of steel), it exposes little or no elastomer material to vacuum, it has been acid cleaned before assembly and has been baked during a previous pumpdown. It has now been vented to room atmosphere and has adsorbed gases on its inside surface.

The gases are either physisorbed or chemisorbed onto the surfaces. Only truly inert gases are physisorbed exclusively; others are chemisorbed after physisorption and are held by what is variously called binding energy, heat of adsorption or activation energy of desorption (or simply activation energy). The bonding energies of physisorption are quite low; those of chemisorption are much higher, as is evident from Table 2 when we compare the low desorption energy of argon with that of the other gases. The amount of gas sorbed is apparently an exponential function of the binding energy between the gas and the surface until monolayer coverage is achieved and a function of lower binding energies (approaching the gas-to-gas-binding energy, or heat of vaporization) as successive layers form. When the equilibrium established between the sorbed surface-gas concentration and the room atmosphere is disturbed by removal of the bulk gas, outgassing of the surface

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Bell-jar vacuum system is designed for LEED-Auger studies of the surfaces. The major material here is stainless steel, with some copper components and specially selected motion and optical feedthroughs. Photo from Varian Associates, Palo Alto, California.

proceeds at rates that are an inverse exponential function of the binding energies. As can be seen from Table 2, many monolayers of H_2O are likely to be sorbed, because of its relatively high heat of evaporation. The outer layers will outgas readily, however, compared to monolayer coverages, because the gas-to-surface binding energies are much higher than the heats of evaporation. This combination of characteristics results in a very high percentage of H_2O outgassing in the early stages of pumpdown.

Unfortunately, the binding energy between particular gas and metal species is not a single-valued function. There are several energy states that can be involved, and particular molecules may change state during a pumpdown. In addition, stainless steel presents a highly complex surface of mixed metals and oxides, so that a broad spectrum of binding energy values can be measured for a given gas. Table 2, for example, shows a column of activation energies of desorption for stainless steel measured in a vacuum chamber cooling after a 30-hour bake at 150 deg C, but the values are true only for gases desorbing in that particular situation and are lower than values observed after higher-temperature outgassing. The numbers are useful only for predicting the relative outgassing of various gases.

The outgassing phenomena of the typical system we have defined consists primarily of surface desorption of air gases, diffusion of H_2 from the material

bulk and desorption of the gases produced at the surfaces such as CO , CH_4 and C_3H_8 . CO is formed by adsorbed oxygen and carbon at the metal surface; CH_4 and C_3H_8 are formed by hydrogen from the metal bulk or from dissociated water reacting with carbon near the surface. We can formulate rates for the first two outgassing phenomena, but there is no complete description available of the processes by which gas compounds are formed at the surface; the situation has been too complex for resolution to date.

The desorption rate of molecules from the surface may be described as

$$d\sigma/dt = \nu_0 \sigma_0 \theta^n e^{Q/RT} \quad (1)$$

where σ is the surface coverage in molecules per cm^2 , ν_0 and σ_0 are constants, θ equals σ/σ_0 , n is the order of the desorption process, Q is the activation energy of desorption, R is the gas constant, and T is the temperature of the surface. The degassing rate is an exponential function of the binding energy and of the temperature. But, because the binding energies are so variable, equation 1 cannot ordinarily be used to predict pumpdown curves or outgassing rates. Such data are best obtained empirically (see Table 3).

The rate of hydrogen evolution from the bulk material is limited by the diffusion rate θ which may be described by

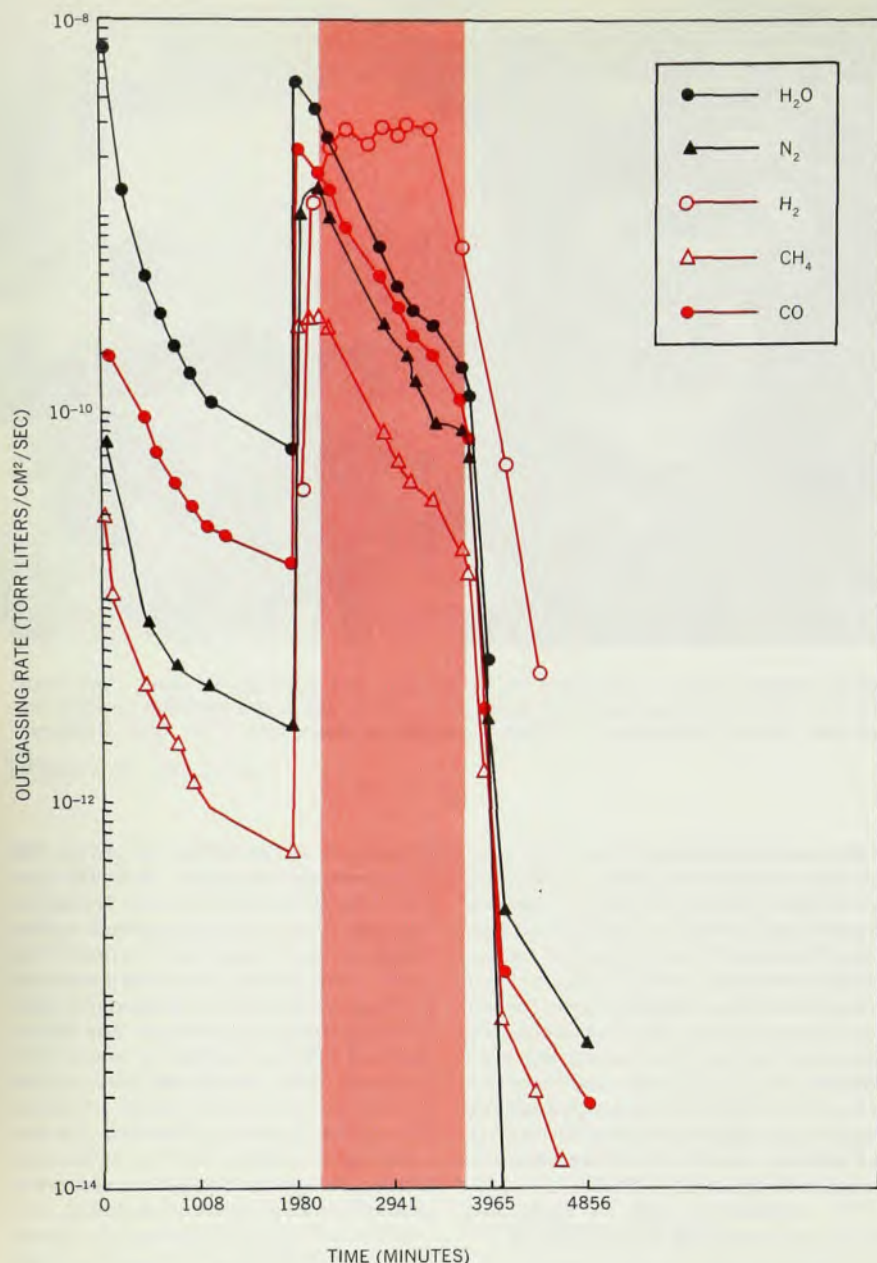
$$\theta = K(P_1 - P_2)^{1/2} e^{-Q/RT}$$

where P_1 is the equilibrium pressure of H_2 dissolved, P_2 is the vacuum system

pressure, Q is the activation energy for H_2 dissolving in metal, R is the gas constant, T is the absolute temperature and K is a constant related to the metal, its area and its thickness. As can be seen, if the pressure of dissolved H_2 remains essentially unchanged, and the temperature is constant, the diffusion and desorption will be essentially constant. This has been observed to be true in the typical system. On the other hand, both formulas show the exponential dependency of desorption on temperature, which explains the powerful effect of bakeout on outgassing.

When our typical system is valved into the fine pump after roughing, H_2O constitutes 75-95% of the desorbed gas. Because seven to eight monolayers of H_2O may have been sorbed during air exposure, the outer layers are bound only by the heat of vaporization and will desorb readily. As the pressure falls below 10^{-6} torr, H_2O and CO are prominent. CO , N_2 and H_2 are prominent at 10^{-9} torr, CO and H_2 at 10^{-10} torr and H_2 at 10^{-11} torr and below. Bakeout is used to reach 10^{-9} torr or less. Temperatures of 150 to 450 deg C are effective in degassing the surfaces, with longer times required at the lower temperature.

Outgassing rates for several individual gas species are shown in figure 1. Yale Strausser² obtained these data by pumping a conditioned 304 stainless steel tank, 30 inches high with 18 inches outside diameter. The curves show the effect of a 30-hour bake at 150 deg C. Table 3 is a compilation of out-



Outgassing rates of five prevalent gases from type-304 stainless steel before, during (colored area) and after a 30-hour bakeout to 150 deg C. Water and carbon monoxide are the predominant gases seen before bakeout, whereas hydrogen, carbon monoxide and nitrogen are the dominant gases after cooling. The stainless steel had been previously cleaned with 33% hydrofluoric acid.

Figure 1

gassing rates for various metals, recommended by Strausser for typical vacuum-system performance calculations.

Surface cleaning

Vacuum materials are cleaned for several reasons: to facilitate reliable brazing and welding, because foreign debris can cause porosity in the joints and lead to cracks or leaks; to avoid contamination of the work in the chamber; to reduce the outgassing load.

The cleaning techniques used were first developed in the electron-tube industry. The first steps generally consist

of degreasing in a vapor degreaser, washing in an industrial detergent, and hot and cold water rinses. An additional alcohol rinse may be all that is needed for relatively clean machined parts. But parts with surfaces as received from the mill, or that have been oxidized by welding or contaminated by other means, are subjected to a more thorough cleansing. This will consist of light acid etch, electropolishing, glass-bead blasting or sodium hydroxide for aluminum. All of these techniques help reduce the outgassing of the surfaces, because they reduce the effective surface area by removing

a small amount of the material, leaving a new, smoother surface. (This surface area reduction is in strong contrast with the case of anodized aluminum, whose thick, porous oxide may increase its effective gas sorbing area by as much as 100 times.) Cleaning is followed by a series of rinses to remove any traces of residue from the acid or alkali.

Certain kinds of cleaning can be accomplished with heat. Ceramics are air fired at 900-1000 deg C after acid treatment to remove any metal contamination. Many oxides may be reduced or volatilized by a hydrogen or vacuum firing. And permanent benefit can often be obtained by a high-temperature outgassing in a vacuum furnace.

Joining vacuum elements

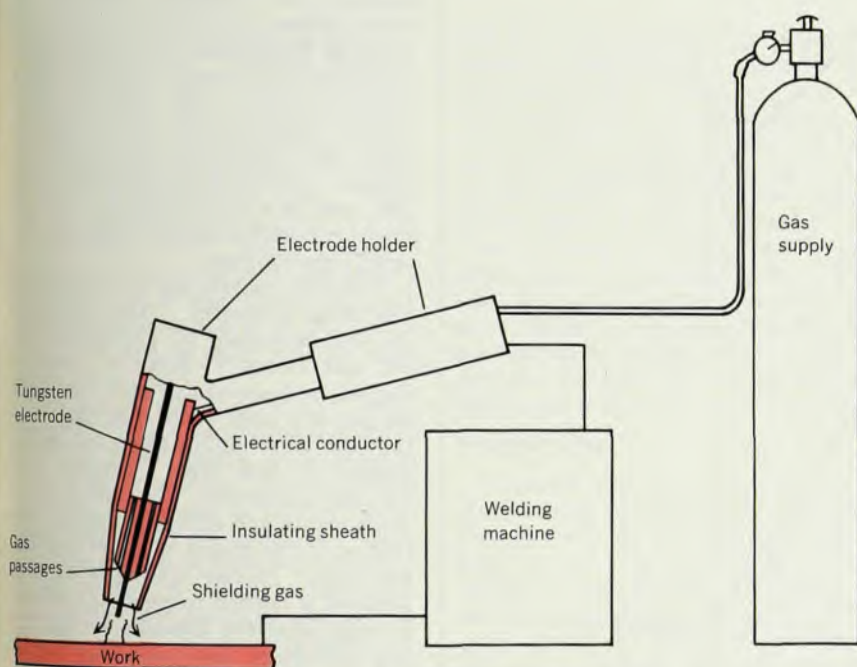
The degree to which vacuum joints must be leak tight has made them a critical part of vacuum technology development. In the 1930's and 1940's, brazing was used for permanent joints in metal systems, and various forms of rubber gaskets served for demountable joints. Glass systems were generally used for pressures below 10⁻⁵ torr. When the Bayard-Alpert gauge (see the article by W.J. Lange in this issue) made it possible to measure low pressures in 1950, work at ultrahigh vacuum was still largely done in glass, because the technology was not available for reliable, bakeable metal gasket seals. Early designs of bakeable metal gasket seals appeared during the late 1950's and led to development of a highly reliable sexless seal in 1961. In the meantime, the virtues of tungsten inert-gas (TIG) welding had been recognized in the improvement of the construction of vacuum vessels. The importance of these two developments can be appreciated when it is realized that the present ultrahigh-vacuum industry is based in large part on five innovations:

- ▶ the Bayard-Alpert gauge
- ▶ the helium mass-spectrometer leak detector
- ▶ tungsten inert-gas welding of stainless-steel vessels (permanent joints)
- ▶ reliable metal gasket compression seals (demountable joints)
- ▶ the sputter-ion pump

Brazing is an ancient art, by contrast to TIG welding, and this high-temperature form of soldering is still valid for the most refined vacuum equipment. Gold-silver and gold-copper-silver filler alloys were in use 2800 years ago and, remarkably enough, these are still popular filler alloys for vacuum purposes. What was once a secret, empirical art is now a reasonably understood science: The performance of a new filler alloy can be predicted on the basis of established metallographic and physiochemical principles.

Table 1. Variety of Vacuum Materials

System part	Material preferred for vacuum and high vacuum	Material preferred for very high and ultrahigh vacuum
Envelope and internal support members	Steel, stainless steel	Stainless steel
Gaskets	Butyl rubber, Neoprene	Viton, polyimide, copper, gold
Viewports	Glass	7056 glass, Pyrex, sapphire
Electrical conductors	Copper, stainless steel	Copper, stainless steel
Insulators	Plastics, glass ceramics	Dense high-alumina ceramic
Lubricants	Low vapor-pressure oils and greases	Molybdenum and tungsten disulfide and diselenide
Heating elements	Nichrome, molybdenum	Molybdenum, tungsten, tungsten-rhenium
Electron emitters	Thoria-coated iridium	Tungsten, thoria-coated iridium



Tungsten-inert-gas welder is nearly ideal for joining parts made of stainless steel. The tungsten electrode is connected to the negative pole of a low-impedance dc power supply. The inert gas, usually argon, floods the work area, protecting the electrode, as well as the work, from oxidation. Melting points between 650 deg C (magnesium) and 2620 deg C (molybdenum) can be easily accommodated.

Figure 2

Brazing offers some advantages over welding. Precision in assembly can be maintained, because all the parts are uniformly heated so that no stresses occur to cause distortion. Brazing can easily be used to join many dissimilar materials (whereas welding is limited to certain combinations) and is indispensable for joining ceramic to metal.

For vacuum system use, the bond between the filler metal and the part must be both strong and intimate. At least some alloying must take place at the interface to make this possible. The degree of alloying or wetting that occurs is a function of the total free

surface energy available at the brazing temperature. It can be observed empirically as the wetting angle between a drop of liquid filler metal and the part's surface; a low wetting angle provides the driving force for capillary attraction, which is active in filling braze joints.

Virtually all brazing of vacuum components is done in a controlled-atmosphere furnace: either hydrogen (alternatively, dissociated ammonia) or vacuum. The furnaces are designed to heat the brazements uniformly and to control the temperature precisely. Many hydrogen furnaces are of the

"push through" type whose hot zone is maintained continuously at braze temperature. Brazements are pushed into the hot zone, left for a timed interval, and pushed into a cooling zone. Bell-jar furnaces with either hydrogen or vacuum atmosphere cycle the heating elements from room temperature and are inherently slower in operation than the push-through type.

The TIG welding process offers a combination of reliability, cleanliness, ease and low cost that is nearly ideal for joining parts made of stainless steel. The basic apparatus is shown in figure 2. A tungsten electrode is connected to the negative pole of the low-impedance dc power supply. A gas discharge is initiated with a high-voltage spark that quickly progresses to a low voltage (22-25 volts) gas arc. The noble gas, usually argon, flows through the welding torch and floods the work area, protecting the tungsten electrode as well as the work from oxidation and aiding the welder in maintaining a smooth stable arc. The narrow arc column allows power density as high as 10^5 watts per cm^2 with 40-50% of the power here consumed in melting the metal.

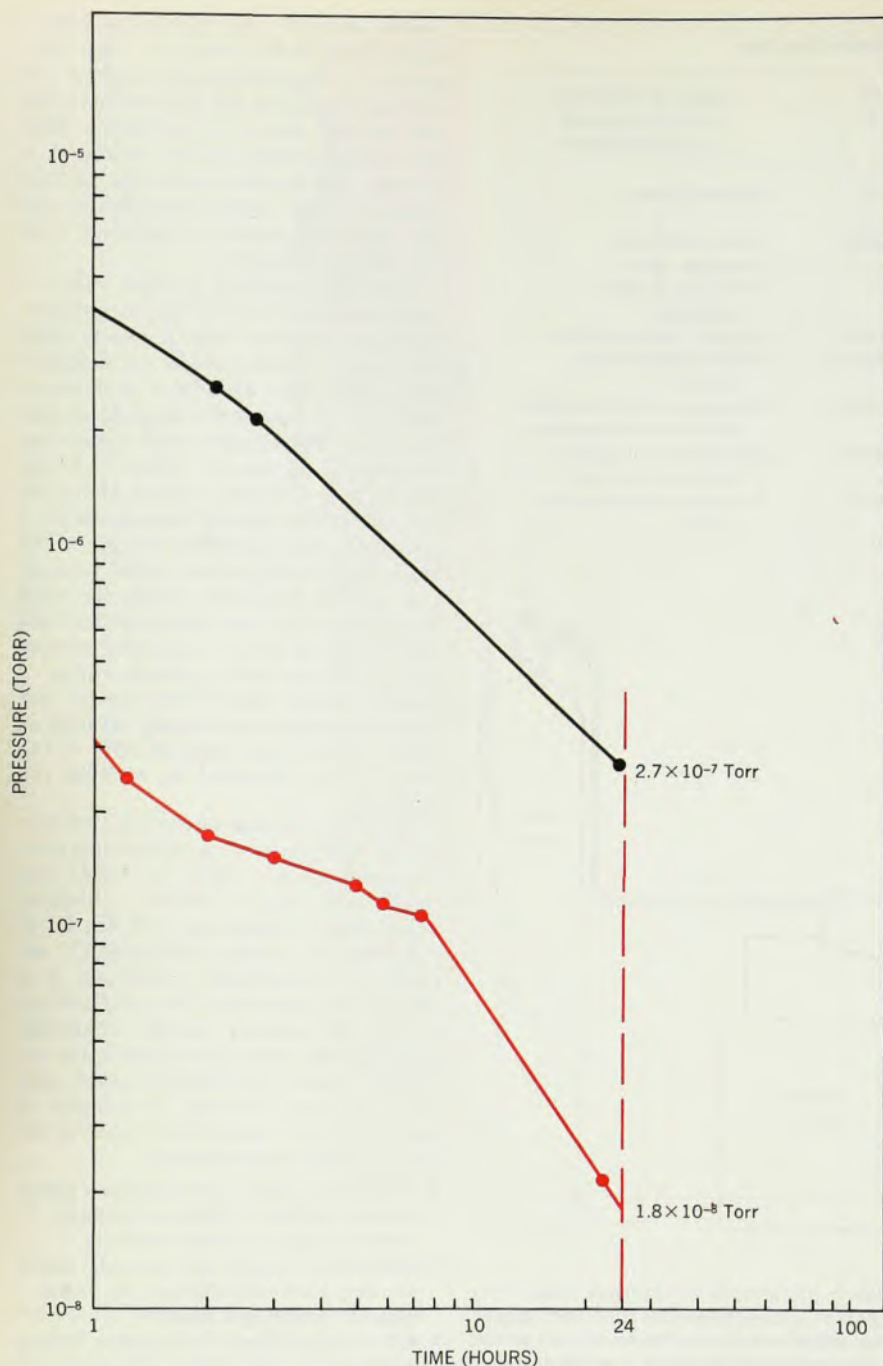
The TIG welding torch is a versatile tool in the hands of a skilled operator. Materials from 0.003- to 0.500-inch thick are readily welded. Melting points from magnesium (650 deg C) to molybdenum (about 2620 deg C) are easily accommodated. Although it is usually recommended that only similar metals be welded, certain dissimilar combinations make good joints, for example, copper to stainless steel and stainless steel to kovar. A number of practices have been found effective for welding vacuum equipment:

- Inside or 100% penetration welds should be made whenever possible to preserve smooth inside contours.
- Continuous inside and outside welds on one joint should not be made—virtual leaks might result.
- All surfaces must be cleaned before welding.
- Weld edges should be closely mated to limit distortion.
- Grooves or locally thinned sections should be used to localize distortion.

Electron beam welding is technically more desirable than TIG welding, but high cost prevents its widespread use. In this method a high-voltage electron beam operating in a vacuum chamber and focused to a very small spot produces welds with a very narrow heat zone and great penetration. Distortion is greatly reduced and there is no gas contamination of sensitive metals.

Demountable joints

Those vacuum joints that are designed to be readily disassembled must be as leak tight as permanent joints. There must be no connecting voids



Effect of Viton in an elastomer sealed valve. During a 24-hour pumpdown at room temperature, a valve with a reduced amount of Viton (colored curve) allows pressures as low as 1.8×10^{-8} torr, whereas a system with a standard valve (black curve) reaches only 2.7×10^{-7} torr. In the new valve, the surface area of Viton exposed in the open position is lower, by a factor of 2.2, than in the standard valve.

Figure 3

larger than molecular dimensions at the interfaces between the gasket and seal surfaces. For ultrahigh vacuum work, leaks less than 10^{-9} cc per sec (STP) are the limit.

Table 4 lists the pertinent properties of gasket materials. The synthetic rubbers exhibit high outgassing rates and low temperature tolerance, which restricts their use to medium-vacuum application. Viton is improved in both of these characteristics and has been found useful on systems pumped to

10^{-10} torr, provided that only a small area is exposed. The outgassing from elastomers can dominate the pressure performance of a system, as seen in figure 3. The two pumpdown curves show the effect of reducing the amount of Viton in an elastomer sealed valve; the two versions of the valve were compared in their open positions on a small system consisting of an 8-liter per sec sputter-ion pump and an all-metal roughing valve.

Metal gasket seals are used routinely

in very high and ultrahigh vacuum systems. Since 1961 their convenience and reliability even to temperatures as high as 500 deg C has been the equal of elastomer gasket seals. The successful models are designed to generate interface pressures many times the yield strength of the gasket material in order to force a fit of molecular intimacy. They must then maintain a large percentage of the initial pressure during bakeout when the gasket loses yield strength. This is accomplished by a geometry that prevents motion of gasket material away from the area of the seal.

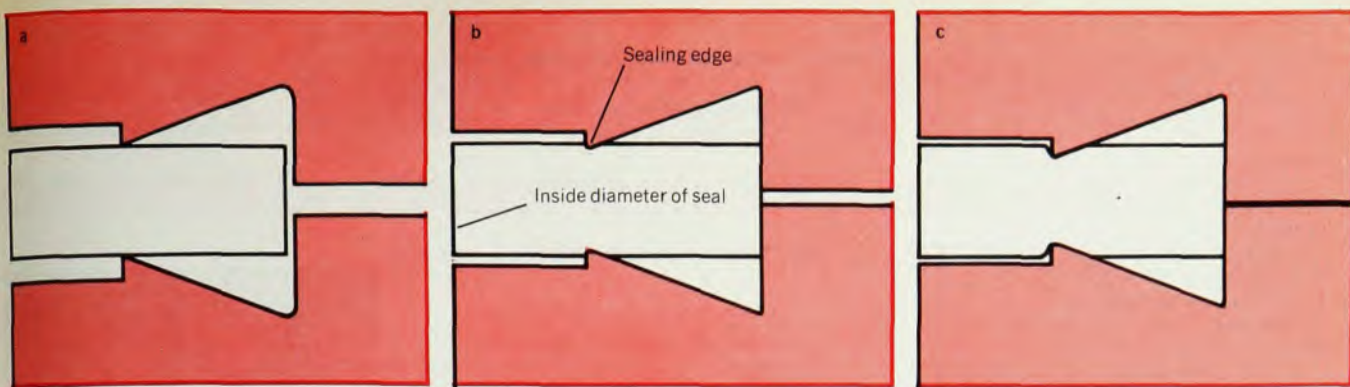
In the "ConFlat Flange" seal, now used worldwide, the outer edge of a flat copper gasket is captured in a triangle of stainless steel formed by 20-deg angle sealing edges and vertical walls. Figure 4 shows three stages of seal closure; the interface pressure can reach values as high as 180 000 psi. ConFlat Flange seals have been baked to 500 deg C for more than 150 cycles without failure. The triangular capturing geometry can be applied in many seal situations, such as for copper wire seals of large dimension. It is also used as a valve main seal, as compression ports for copper tubing and for small tube couplers.

Very thin gaskets are another form of capturing geometry. The aluminum foil seal developed by Thomas H. Batzer and James F. Ryan of Lawrence Radiation Laboratory⁴ and the plated copper and gold seals first offered by the Granville-Phillips Company are examples of this type. Viscosity and friction counteract the lateral force components and effectively prevent extrusion of the gasket material from the seal area. Precise mating of the seal surfaces is needed to generate uniformly high interface pressure around the seal periphery with gaskets as thin as 0.002 inch.

Flanges are typically designed so that the required closing force deforms the bolts and flanges elastically. The energy stored in this high-rate spring can help compensate for loss of interface pressure induced by gasket creep at high temperature or by differential thermal expansion.

Varieties of valves

Valves are used in vacuum systems to isolate the roughing or the fine pumps from the chamber, to isolate parts of the chamber or to leak gas for pressure control or air return. They are made with elastomer or metal gaskets in the bonnet and main seals and sometimes with elastomer stem seals. All the requirements for static seals apply to the bonnet seal. The uses of the main seal impose some additional requirements: The seal must be capable of hundreds or thousands of cycles, and it must close after the seal surfaces



Closing a ConFlat Flange seal. As the sealing edges contact the copper gasket (a), there is clearance around the gasket's outer edge. With the flange partially closed (b) the gasket edge, forced outward by sealing-edge penetration, hits the cavity wall. With the flange fully closed (c), penetration increases and the interface pressure can reach 180 000 psi. ConFlat Flange seals have been baked to 500 deg C for more than 150 cycles without any failure occurring. Figure 4

have been pumped clean of water or hydrocarbon films. The first requirement is readily met by well designed seals, but the second poses problems because the surface films formed during room-atmosphere exposure normally aid in making a seal tight. When the film is removed by a bake or long-term pumping in a "clean" pumped system, an elastomer seal will leak if particles such as lint bridge the seal. A metal gasket seal may need three to five times the normal sealing force after such a bake.

The moving seal stem of right-angle and gate valves is vacuum sealed by an elastomer gasket against a sliding shaft or by a metal bellows. Some gate and butterfly valves use a rotating shaft feedthrough with elastomer "O" rings. Dynamic elastomer seals will eventually leak as friction wears the elastomer. The sliding shaft generates greater friction because of its longer relative motion, and because it is apt to drag abrasive particles into the seal. It incidentally introduces a fresh load of gas, condensed on the shaft, into the system each time it is operated.

The rotary shaft actuator avoids these problems. It is often designed with two elastomer seals and a vacuum fitting for pump-out or a grease fitting for lubrication. Use of a metal bellows entirely eliminates the possibility of intermittent leaks and reduces the outgassing rate. The welded style of metal bellows has much greater compactness and longer life than the formed or convoluted style; lifetimes of 20 000 to 100 000 cycles can be obtained with welded stainless-steel bellows.

Valves with synthetic rubber seals are not bakeable beyond 100 deg C. Viton gaskets allow baking to 200 deg C, provided that care is taken in the design to prevent gasket extrusion. This can be done by providing excess volume in the gasket cavity or by lim-

iting the force applied to the gasket by a series spring loading. Polyimide is a high-temperature organic material hard enough to be immune to the extrusion hazard. It is used in both bonnet and main seals to 300 deg C in a straightforward compression design. Valves with copper gaskets of the ConFlat type are bakeable to 450 deg C in the open or closed positions. Valves with gold-plated main seals have the same rating in the open position but are limited to 250 deg C in the closed position, because the higher diffusion rate of gold in steel can cause sticking.

Feedthroughs

Chamber, pumps and valves provide the vacuum environment, but feedthroughs provide the services for doing work in it. The variety of services needed is considerable, and there are two or three equipment quality levels made for each basic requirement to suit use in medium, high and ultrahigh vacuum. For example, electrical feedthroughs are made for at least seven requirements:

- ▶ high voltage, to 100 kilovolts
- ▶ high current, to 2000 amps
- ▶ high impedance, to 10^{15} ohms for electrometers
- ▶ thermocouples
- ▶ multipin, to 20 or more pins per feedthrough
- ▶ rf signal leads
- ▶ rf power leads

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Feedthroughs intended for medium and high vacuum have elastomer "O" ring seals and, for electrical insulation, plastics or ceramics. They are usually rated for voltage and current only. Ultrahigh vacuum units are usually insulated with brazed ceramics and are designed for use with copper gasket seals. They are rated for maximum current and voltage, bake temperature, thermal cycling, humidity and strength.

Liquid feedthroughs carry cooling or heating liquids. They are simple, brazed tubing assemblies for water lines at ground potential. Electrical isolation is often needed, and insulators are provided according to performance requirements. For thermal isolation, liquid cryogenic feedthroughs are provided with a thin wall stainless-steel tube stand-off.

Optical feedthroughs allow observation both visual and by instruments

Table 2. Gas-Metal and Gas-Liquid Binding Energies

Gas	Activation energy of desorption (Kcal/mole)		Heat of vaporization (Kcal/mole)
	On tungsten	On stainless steel	
H ₂ O		22.4	9.72
N ₂	85	16.6	6.03
O ₂	194	17.0	1.63
CO ₂	100	15.8	6.03
CO	46	17.7	1.44
CH ₄		12.2	
C ₃ H ₈		17.4	
Ar	1.9		1.56
H ₂	46		0.22

Table 3. Recommended Outgassing Rates

Material	Outgassing rates, unbaked (torr liters/cm ² /sec)				Outgassing rates after bakeout (torr liters/cm ² /sec)
	1 hour	4 hours	10 hours	40 hours	
Copper					
Oxygen-free, high conductivity (OFHC), as received, surface removed	2×10^{-9}	8×10^{-10}	1.5×10^{-10}	4×10^{-11}	
Copper OFHC, as received, surface not removed	2×10^{-8}	7×10^{-9}	1×10^{-9}	3×10^{-10}	
Copper not OFHC, as received, surface removed	4×10^{-9}	1.5×10^{-9}	3.5×10^{-10}	9×10^{-11}	
Copper not OFHC, as received, surface not removed	4×10^{-8}	1.5×10^{-8}	4×10^{-9}	8×10^{-10}	
Aluminum anodized	2×10^{-6}	6×10^{-7}	1×10^{-7}	3×10^{-9}	
Aluminum clean, but with some oxide	1×10^{-8}	3×10^{-9}	1×10^{-9}	3×10^{-10}	
Stainless steel only degreased	2×10^{-9}	1×10^{-9}	2.5×10^{-10}	8×10^{-11}	4×10^{-12} after either 24 hr at 150 deg C or 25 hr at 300 deg C
Stainless steel Varian standard cleaning	3×10^{-9}	5×10^{-10}	1.5×10^{-10}	4×10^{-11}	4×10^{-12} after 24 hr at 150 deg C

from outside the system into the vacuum chamber, as well as a means for irradiating work with various wavelength and intensities of photon energy. All transparent materials may be sealed with elastomer "O" rings for nonbaked applications. Bakeable viewports are made with Corning 7056 glass fused to kovar sleeves or with Pyrex glass sealed (by Mr Housekeeper's technique) to copper or stainless-steel sleeves; these viewports are bakeable to 400 and 450 deg C respectively. Sapphire viewports are used for ultraviolet and near-infrared transmission. The sapphire is brazed to kovar sleeves by the ceramic-to-metal brazing technique. Small quartz viewports are made by fusing the window to elaborate graded glass seals; larger windows can be made with a metal-bonding technique, but they are very expensive.

Motion feedthroughs are made in many different designs, but they basically provide rotary or linear motions or a combination of the two. They are used, for example, to adjust beam targets, operate shutters or move substrates in sputtering systems. Elastomer "O" ring or lip seals are widely used at medium and high vacuum. A magnetic liquid seal is now in use for high-speed rotary shafts: Ultrasmall magnetic particles suspended in a low vapor-pressure liquid are held in place by permanent magnets at the seal.

Bakeable motion feedthroughs use an expanding and contracting metal bellows to seal an axially moving shaft or a rocking bellows to transmit rotary motion via bearings through a crank or wobble-stick articulation. Probably the most elaborate motion feedthrough available is a surface-research manipulator that provides movement in three rectangular coordinates as well as polar and azimuthal coordinates, for positioning a crystal surface under investigation.

Table 4. Properties of Gasket Materials

Materials	Outgassing rate after 1 hour under vacuum (torr liters/ sec/cm ²)	Outgassing rate after bakeout (torr liters/ sec/cm ²)	Upper temperature limit (deg C)	Elastic properties
Butyl rubber	2×10^{-6}		100	Good
Neoprene	2.6×10^{-6}		100	Good
Viton	4×10^{-7}	5×10^{-10}	200	Fair
OFHC copper with surface removed	2×10^{-9}	4×10^{-12}	500	Negligible
Polyimide	8×10^{-7}	3×10^{-10}	300	Very small percentage springback

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