Some Recent Developments in Vacuum Techniques for Accelerators and Storage Rings*

Norman Milleron

Lawrence Radiation Laboratory
University of California
Berkelev. California

Introduction

Implicit in this discussion are costs (dollars and machine time lost) chargeable to construction, maintenance, and performance of a vacuum system. As a rule of thumb, a fail-safe vacuum system achieving < "10^{-9} torr" in 12 h from air (bakeout < 100°C being required) will cost ≤ 1/20 of the construction and operating costs of a machine.[1] Even if ultrahigh vacuum is not needed, achieving rapid pump down (< 1 h to < 5 x 10^{-7} torr from air without bakeout) may make techniques discussed here worthwhile to consider. For those with considerable accelerator experience, these claims may appear rash; thus the aims of this discussion are to bring vacuum requirements more clearly into focus and to present evidence showing how 'quick and dirty' the techniques may be.

Perhaps a useful purpose may be served by briefly reviewing ultrahigh vacuum problems peculiar to accelerators and storage rings. The primary objective is to insure that beam interactions with gas are minimal throughout the operating life of a machine. Fail-safe design coping with all foreseeable accidents and malfunctions must be adopted. To do this job the vacuum man needs, among other things, a knowledge of the properties of gases and their interactions with vacuum plumbing and pumps; fabrication techniques, gas measuring equipment (such as ionization gauges and mass spectrometers) and the direct and indirect interaction of beams, gases and walls.

Among direct and indirect interactions between beams and walls are: radiation and thermal damage; desorbtion effects by photoelectrons, secondary electrons and ion sputtering (especially by heavy ions at grazing incidence); and gas bursts from bubbles formed from accumulations of buried heavy noble ion beams.[2] If all the vacuum plumbing cannot be maintained at a low enough temperature (such as 1.5°K)[3] to provide a nearly perfect sink for all gases, (even significant amounts of helium) the direct and indirect interaction of gases and beams with walls determines the system performance. This is because magnet costs dictate pumps be spaced apart ten or more beam pipe diameters, thus the system performance is not improved much by using pumps having entrance areas greater than the cross sectional area of a beam tube.

In our everyday habits of speech we talk about vacuum in terms of residual air at such and such a pressure, tacitly assuming that vacuum is like a fluid that flows and can be pumped, and that conditions with beam on or off will be comparable. These speech habits serve well enough if their implications are not taken too literally. For example, one can observe that vacuum is an environmental quality, specified by a set of parameters that are peculiar to each specified application. In accelerator design the important parameters are often gas concentration, gas desorbtion probability, heat of desorption, surface geometry, pump memory, pump backstreaming and pumping capacity--all as a function of atomic number. As observed by Simpson[4] before 1949, gas pressure is seldom a parameter of consequence. Furthermore, residual gas composition at ultravacuum never approximates the composition of air (unless leaks dominate); rather, hydrogen, water vapor, carbon monoxide, carbon dioxide, and a variety of light hydro-carbons (whether or not we use ion pumping) are likely to be initially, at least, the most abundant gases in the beam path. Gas concentration must be weighed on the scales of atomic number, i.e., one Hg may result in more beam losses than 500 H_2. Fortuitously, the effective atomic number of residual gas mixtures is often not so different from nitrogen, but the interaction of the above gases with walls is not similar to that of nitrogen. The interactions of these gases with walls are dynamical (rather than kinetical) and the probable interactions are complex and require knowledge of the surface structure that is difficult to obtain. The delayed flow of H_2O molecules is an example. To predict the gas concentration and atomic number when the beam will be on, cut-and-try methods are used. For example, samples of the vacuum plumbing are dipped and cooked in various ways, assembled with care, and checked under heating and electron bombardment for outgassing. Outgassing from stainless steel, aluminum alloys, alumina and many other metals and materials is determined by their history, rather than some irreducible property. Thus when we ask what the outgassing rate of a material is, we are asking what its history is. If we are too cavalier in cleaning, joining and general technique, we reap what we sow--a sewer pipe. Because pumps--sputter ion as well as other types may contribute substantial outgassing, to predict results in an actual machine, a systems concept is useful to adopt. Geometries, materials, procedures, pumps and conditions to be used on an actual machine ought to be tested together.

If specifying air or gas pressure is an inadequate way to specify vacuum, what way should be used? As remarked above, vacuum is an intangible environmental quality that may be described by a set of parameters. Vacuum can be viewed as a permissive environment in which to work. As we have indicated, the walls of this environment, often interacting with beams, largely determine

both gas concentration and gas atomic number. Specifying a vacuum will vary from one system to another, the importance of particular parameters being greater or less. At the root of specification is the idea of prediction. One must be able to predict with reasonable certainty that a proper vacuum can be produced, maintained for long periods of time with beam on, and rendered fail-safe against any foreseeable accident. If this total specification can be written within a reasonable amount of money, then the vacuum requirement is feasible.

Let me offer a further illustration. Ionization gauges and mass spectrometers are stationed at infrequent intervals along a long thin beam tube. The vacuum specification says that the gas concentration as a function of atomic number must be minimal, with reasonable assurance, along the tube. What relationship is there between the mass spectrometer and ionization gauge readings and what a beam will see as it passes through the tube? If we take the point of view of the beam in this matter, we find that the character of the tube itself, acted on in addition by the beam, perhaps over long times, primarily establishes the kind and amount of gas the beam encounters. To be sure, pumps can spoil the vacuum, but in no way can the pumps, if spaced apart many pipe diameters, produce the required vacuum environment. Assessing the interaction between beam tube, beam, gases and pumps allows a set of necessary parameters to be established. Once again, it may be noted that gas concentration alone does not comprise this set. If our mass spectrometer indicates a certain concentration of water vapor, what can we say about the concentration of water vapor as a function of length down a beam tube? Only if we take into account the beam tube walls can we make a reasonably accurate estimate of what the water concentration as a function of length will be. Especially in circular machines the presence of the beam itself in the tube can alter both the gas concentration and atomic number spectrum appreciably. For example, if electrons are accelerated in a direction transverse to their motion, they will radiate photons to the walls. These photons have a small desorbtion cross section for gas directly but can create secondary electrons which have a much larger gas desorbtion cross section. If we use pressure only to indicate that the vacuum is tolerable before attempting to store an electron beam, with beam on we may, as others have already, find ourselves asking how we can get a better environment which will permit beam to be stored.

Hardware Testing

For the most part what follows stems from work being carried out to show the feasibility of the Omnitron[1] accelerator-required vacuum.

Ultrahigh Vacuum Pumps

We are not interested in the rated speed of pumps but in their pump down performance and handling of noble gases. Six commercial pumps have been given at least preliminary tests. Five of these pumps, three sputter ion type (Fig. 1-3), one orbitron type (Fig. 4), and one LN-trapped D.P., were operated on reasonably identical 4-in diam x 17-in long stainless steel pipes (see discussion of plumbing) capped by dual tungsten filament nude ionization gauges made by Varian. Cross checks on the plumbing were made showing that the variations in pump down performance were due to outgassing phenomena originating within the pumps themselves (see discussion below of Fig. 5). The sixth pump was a turbo-molecular type tested on a calibration dome (Fig. 6). In the near future the performance of a homemade cryopump, variable between 2.5° and 20°K, will be measured.

Welch Turbo-molecular Pump. A single peak of $m/e \sim 60$ characteristic of the turbine oil lubricating the turbo-molecular bearings was monitored by a Veeco mass spectrometer. The measuring dome (Fig. 6) has an internal tubular ring (not shown) that may be heated or cooled and a large poppet valve carrying two small orifice holes. Thus, by shutting the main valve, either one or the other or both or none of the holes can be open. Three known flow rates can be thus obtained in addition to isolation between the pump being tested and diagnostic gear. By heating and then cooling the surface of the tubular ring to $< 80°K$, thus providing an accumulator for a known time, contamination already in the dome can be distinguished from contamination steadily entering the dome. Results show that, with the pump case at room temperature, $> 10^{10}$ turbine oil molecules issue from the mouth of the turbo-molecular pump per second. With the pump body at 90°C this number increased to $> 10^{11}$ per second. Apparently the turbine oil can diffuse along surfaces by-passing the rotor. Referring to Fig. 7, a short pulse of air was admitted to the foreline of the turbo-molecular pump, raising the foreline pressure to slightly more than 200μ. As shown in Fig. 7, air as well as bearing lubricant passed into the measuring dome requiring approximately a thousand seconds after the pulse for the dome to recover to the former steady state conditions. This bearing effluent could be eliminated by putting a well-designed liquid nitrogen trap over the turbo-molecular pump; however, one might then consider a liquid nitrogen-trapped oil diffusion pump for reasons of cost and increased speed for light gases (see below).

Consolidated LN-trapped D.P. A straight-through, nominal 6 in trap with liquid fill and vent lines on the bottom, made by Davis and Wilder, Inc., was mounted on an oil diffusion pump, PMC-1440, (using DC 704 oil) made by the Consolidated Vacuum Corporation. Liquid nitrogen was supplied automatically from a 160 liter dewar by a controller made by Harvey Control Company. In these tests the same measuring dome (Fig. 6) was used, again having the two orifices and accumulating ring. For these tests a quadrupole mass filter made by Electronics Associates Inc. became available. Using the sensitivity of this instrument, together with the same accumulation and flash-off method, (Fig. 6) no peaks of $m/e > 44$ could be detected after baking the trap neck and dome at 300°C for 24 hours. This 300°C bakeout was necessary to eliminate the contamination from two years of testing wherein quantities

of hydro and fluorocarbon had been admitted to the dome. Also the dome was not (and cannot be) cleaned in the Diversey DS9 process (see discussion below). The point may be raised here about how to keep oil out of plumbing if an accident should occur (see headings, Porous Trap and Valve and Discussion of Pump Test Results, below). In principle, 10^6 molecules/s average was the upper limit of sensitivity due to background noise. (Note: This noise problem was later reduced ~ 100 times as demonstrated by using a Signal Eductor loaned by Princeton Applied Research Corp. Contamination rates have not yet been remeasured, however. Single particle counting can also be done.) Pulsing the foreline pressure of the diffusion pump well above 200μ also yielded no detectable contamination of m/e > 44. With the dome at 150°C, the same nude ionization gauge read 1.4×10^{-10} torr. The ionization gauge and mass filter were calibrated at will by means of the interposable orifices (Fig. 6) either by utilizing residual background gas or leaks of He or N_2. At 150°C, the m/e 18-peak height was the only peak not proportional to the orifice area.

R.C.A. Sputter-Ion Pump. Figure 5 gives some results obtained from pumping down our standard 4-in diam by 17-in long stainless steel assemblies (see discussion below). Curve number 1 shows the response of the BAG as a function of time for the RCA 500 ℓ/s pump shown in Fig. 2. The pump was first roughed down to $< 5 \times 10^{-6}$ torr through the LN-trapped D.P. system shown in Fig. 3, turned on and then pinched off. Upon turning on, the pump immediately outgassed so heavily that its maximum discharge current was exceeded and 15 min were required for the pump to recover its voltage. Referring to Fig. 2, one can see that the RCA pump is very much larger than the standard stainless steel tube assembly. Not only does the pump have a much larger internal surface area than the other pumps loaned by other manufacturers, numerous fingerprints were visible inside the pump body. Thus the rated speed of the pump (available at higher pressures) became operationally zero at 4×10^{-8} torr. The capacity of the pump for heavy noble gases remains to be seen.

Ultek Sputter-Ion Pump. Figure 5, curve number 2 represents performance by a 100 ℓ/s Ultek differential ion pump shown in Fig. 3. After three weeks the BAG response became constant at 1.5×10^{-9} torr.

Varian Sputter-Ion Pump. Figure 5, curve number 3 renders the performance of a Varian 140 ℓ/s diode pump shown in Fig. 1. This pump evolved much less gas upon starting than the other sputter ion pumps. After one month of continuous operation the BAG response became constant at 2.0×10^{-10} torr while the ion current in the pump became 0.06 μA.

N.R.C. Orbitron-Type Pump. Figure 5, curve number 5 gives the performance of the 400 ℓ/s Orb-ion pump made by the National Research Corp. shown in Fig. 4. It should be made clear that curve number 5 was obtained under different procedures and conditions than curves 2 and 3 (discussion below). After operation for one week, the Orb-ion pumpdown curve became constant at a reading of 2.5×10^{-10} torr on the BAG. Both pump filaments burned out after two months at 0.04 A and 8000V. The filament life may be governed by interaction with Titanium. Although the pump started very quickly at 10^{-6} torr, a later test showed the pump very hard to start at 1×10^{-3} torr. Probably due to the geometry of the test, $< 10^{-12}$ A was drawn between BAG and Orb-ion pump.

Discussion of Pumpdown Results

In Fig. 5, curves 1 and 5 only, the vacuum furnace treatment of the stainless assemblies had to be omitted for reasons beyond our control. The Orbitron-type pump and the R.C.A. pump were thus operated on stainless steel assemblies that had been Diversey cleaned and then welded only. Because of this unplanned variation in the procedure, water cooling was not applied to the pump body of the Orb-ion until the pump wall temperature had run at 100°C for an hour. The pump barrel water cooling was then turned on, the BAG response recorded, and the copper pumpout pinched off. Each of the pieces of stainless pipe used in obtaining curves 1-6, Fig. 5, had been welded after careful Diversey cleaning; but only tubes yielding curves 3 and 4 were then fired by electron bombardment from an axial filament to a temperature of 800° < in a vacuum furnace for 30 minutes. Each time the furnace was let up to dry air.

Considering the above pump tests one can ask, "Were the variations in BAG response due to pumps themselves or to the stainless steel tubing assembly?" After being run on the Ultek pump, the 17-in standard assembly used was hooked up to the measuring dome shown in Fig. 6. The measured speed applied to the end of the 17-in pipe was 50 ℓ/s. Curve number 4, Fig. 5, gives the pumpdown history. This information, together with the BAG response when the sputter ion power supplies were turned on and off, shows that variation in pumpdown performance was due to gas load coming from the pumps themselves. This conjecture was fortified by curve number 5, Fig. 5 and by consideration of Fig. 8 (see below). Referring to Fig. 5 again, curve 6 shows the repumping of the same stainless steel tube assembly by the same 50 liter diffusion pump system that generated curve 4. In curve 4, the stainless steel assembly had been covered by aluminum foil but exposed to air during rainy weather for a month. After pumping for several days a BAG reading of 5×10^{-10} torr had been obtained. At this point an all metal valve was closed to the D.P. system and the stainless steel tube assembly was let up to dry helium gas having a principle impurity of one part in ten thousand of nitrogen gas. Repumping the tube then gave curve 6. Unfortunately, the welded bellows in the valve used to separate the test assembly from D.P. system probably was the major source of outgassing.

Figure 5 does not tell the full story especially for the requirements of the Omnitron. Further tests showing the response of various pumps to heavy noble gases must be made.

However, these preliminary tests show that stainless steel plumbing can be assembled using reasonable care, i.e., the wearing of nylon gloves and keeping parts covered with aluminum foil. The far stricter procedures found in clean room practice: filtered air, covers for hair and clothing, etc., were not used. The differences between curves 4 and 6, however, indicate that considerable gains might be made by exercising the utmost precautions to exclude dust, dirt, humid air, etc., and by using cryopumping within its capacities for hydrogen and helium. Cryopumping tests will be begun soon in our Omnitron program.

After about 10 hours of pumping, Fig. 8 shows the BAG response upon turning off the electrical power to the Orb-ion pump. Initially the gauge response rose very rapidly as it did for the sputter ion pumps. Imagine our surprise, however, when the gauge response reached a maximum and began to diminish once again. After a period of 200 minutes the gauge response was close to what had been obtained with the Orb-ion pump operating at 0.04 A and 8 kV. This spectacular behavior is explainable as follows: the major outgassing from the Orb-ion pump comes from the titanium slug and tungsten support being electron bombarded. When the electric power is turned off, these structures cool down so that the gas load from the pump becomes small enough so that the pumping speed of the BAG manifests itself. The known speed of the BAG is sufficient to account for the subsequent reduction in signal. At no time in the history taken on any of the pumps were the BAG's extensively outgassed. A very superficial outgassing was done by increasing the electron current to the grid from 4 to 12 mils. By decreasing the electron current to 1/10 and 1/100 of the normal value, the pumping effect of the BAG on the system could be easily seen. At 4 mA electron current the pumping speed for the BAG was not more than the classical 0.1 ℓ/s.

This performance of the Orb-ion pump on the stainless steel tube assembly shows clearly the very low gas load that can be obtained from a stainless steel assembly even with hot filament ionization gauge on. This low outgassing rate ($< 10^{-14}$ ℓ-t/cm^2/s) was helped at least in the past by titanium coming out of the Orb-ion and by the small gas desorption effects due to the photons from the Orb-ion.

Repairing of Leaks During Pump Tests

Two 1 $\mu\ell$/s air leaks were discovered, one in each brazed joint connecting the copper roughing line to the stainless steel body. Both of these leaks were successfully repaired immediately under vacuum by melting pure indium on the offending joint and wetting the indium to the copper and stainless steel by an ultrasonic soldering tool made by the Sonobond Company. Other much smaller leaks on the roughing side of the subsequent copper pinch-off were repaired by the time-honored method of applying a saturated water solution of table salt. A quadrupole mass filter record was obtained of one such leak repair. Before a salt saturated water drop was placed over the leak, a substantial water signal from incoming air could be seen on the quadrupole. Instantly, upon placing the saturated water drop over the offending leak, the water signal recorded on the quadrupole dropped by a factor of two.

Treatment of Stainless Steel Surfaces

A wide variety of cleaning methods for stainless steel have been reported in the literature. The results sought from all these methods is reduction of surface and bulk outgassing. A partial list of surface cleaning methods follows: treatment with abrasive papers and cloths; sand and bead blasting; vapor degreasing in perchlore and trichlorethlene; pickling in acid; ultrasonic cleaning in H_2O and fluorocarbons; electropolishing; firing in low dewpoint hydrogen at temperatures over 950°C; firing in a vacuum furnace; bombardment by ions and/or electrons in vacuo. Without being able to offer a comparison of methods, let us discuss briefly the cleaning method that has given us very promising results.

Diversey Process DS-9. It would be most helpful to have detailed knowledge of the surfaces resulting after treatment in the chemical bath process DS-9, sold by the Diversey Company, Chicago, Illinois. Our small amount of knowledge of the process and experience with it is reported here.

DS-9 consists of three chemical baths. Following instructions from the Diversey Company, stainless steel and a variety of other metals including copper, invar, and mild steel are dipped sequentially in these baths yielding surfaces that are very bright and pleasing to the eye. The final bath of the process etches away about .0005 inches of 304 stainless steel in five minutes of contact. After removal from the final bath, the part is air dried and remains clean and bright in appearance for at least several months in contact with room air afterward. Apparently, the spongy surface structure on the as is metal is removed by this treatment leaving the real surface area much more nearly equal to the projected area of the metal. Specific outgassing after 12 hours of pumping and no bakeout is predominantly m/e 18 amounting to $< 10^{-12}$ ℓ-t/cm^2/s obtained by a rate of rise method.

Our experience with DS-9 emphasizes the following precautions. Do not use DS-9 on parts with gross internal cracks or voids. Apparently, one need not fear the DS-9 hanging up in the microstructure of the surface. This microstructure is simply chemically milled away. However, experience has shown that gross voids and cracks are difficult to purge successfully once the DS-9 has entered. Apparently the DS-9 rapidly reacts to completion with the metal while in the crack leaving a sludge that, once it is formed, cannot be flushed out. Even treatment in a vacuum furnace at very high temperature does not get rid of this sludge once it is formed. Thin wall parts, if treatable at all in DS-9, need very special handling. We have not found it possible to dip welded bellows or hydroformed bellows of small diameter and narrow convolution. As will be discussed below, our general procedure for making up demountable joints creates a long

narrow internal crack facing the vacuum. We have found that T.I.G. welding parts after Diversey processing does not spoil the benefit from the DS-9. In short, discoloration of the stainless steel during heliarc welding does not compromise in any serious way the lower outgassing obtained from treatment in the DS-9.

Recovery from Accidents and Malfunctions

Any machine, such as the Omnitron,[1] requiring an ultravacuum environment must be designed fail-safe. Recovery from any foreseeable accident or malfunction such as: a rupture admitting air into target or injector systems, electric power failure, cooling water failure, mechanical belt failure, etc., must be assured. Choice of pumps must be carefully weighed against all foreseeable consequences. The porous metal foreline and rough pumping trap with valve (Fig. 9) shows promise and the design is being perfected.

An ultrahigh vacuum porous metal trap with valve remains to be tested, but one 10-in diam operating at room temperature is now built and is being tested for service on an ion source floating at 500 kV. A nominal 10-in oil D.P. made by the Dresser-Clark Company is fitted with a fan louver baffle made by Davis and Wilder, Inc.

Briefly, these porous filter traps are designed to attenuate any shock wave attempting to pass through them to laminar flow; to catch and hold oil on their activated surfaces and, with their valve closed, permit purging and reactivation. Accordingly, the valve with these porous traps can close more slowly (between 1 s and 10 ms depending on size and geometry) but must be bakeable closed to 200°C.

Stopping air shock waves entering a beam tube is another problem. An accoustic delay line reported by Jean and Rauss[7] suggests interesting possibilities that our Laboratory will explore. An LN-cooled porous metal cylinder around the beam path will be tested to determine if contamination from target window rupture accidents can be attenuated. A valve,[8] actuated by inrushing air, shows promising application.

Porous Foretrap with Valve. Some homemade components were especially useful in these diffusion pump tests; however, these must be developed and tested further before they can be fully recommended. These were porous metal filter traps[5] (Fig. 8) to stop oil coming from oil-sealed mechanical roughing pumps during roughing, steady state and accidents. A poppet valve with a Viton O-ring seat capable of closing in less than 10 ms under force from a cocked spring was an integral part of each. A McClure switch[6] in the foreline provided a fail-safe overpressure trigger to actuate this poppet valve and to interlock all instrumentation and the electrical power to the diffusion pump. This diffusion pump system was thus rendered fail-safe against electrical power failure, cooling water failure, forepump belt breakage, and foreline leakage. In future a porous metal filter in a liquid nitrogen trap, together with a valve bakeable to 200°C closed, closing in < 10 ms must be built and tested.

Fan Louver Baffle. Another component in the diffusion pump system is worth mentioning. Two of these baffles are shown in Fig. 8. Louvers, approximately 1/16-in wide, of 0.015-in thick copper, formed into an optically dense fan around a hub, are inserted over the top jet of the diffusion pump. These louvers keep oil from reaching the liquid nitrogen trap at a rate greater than the vapor pressure of the oil at the baffle temperature. This baffle also stops excess backstreaming during starting and stopping the pump and during operation of the pump even up to a fine pressure of 200 μ of air. The fan louver shape provides efficient drainage of the oil back into the pump and a conductance for free molecular gas of 60% of an orifice of equivalent diameter.

Weld and Cut Joints

At the author's suggestion, R. Wolgast of the Lawrence Radiation Laboratory, Berkeley, has designed and tested a successful pair of tools that substantially reduce the cost of demountable stainless joints while insuring unmatched vacuum and radiation integrity. Fig. 11 shows a tool for joints opened by forcing a standard tubing cutter wheel through a parent metal-edge weld joining 1/16-in thick 304 stainless steel flanges. This cutter wheel can be seen silhouetted in the top half of the tool. Fig. 12 shows an edge view of this same tool plus a 4-in stainless steel cross having a welded joint on top. Its other openings have flanges ready for mates. The right hand side of Fig. 13 shows two flanges cut open. The burr raised during cutting can be seen and must be removed before re-welding. The metal lost in this burr accounts for most of the 0.005 in used up on the flange radius per cut-weld cycle.

Fig. 14 shows the automatic welding head used with the driving motor in view. As with the cutter, the tool is carried by flanged metal wheels riding on the OD of the flanges. Figure 15 shows the tungsten welding electrode positioned ready for action.

Alumina Beam Tube

Taking a cue from the Cambridge Electron Accelerator Center, we have tested the outgassing of metalized alumina beam tubes done by Litton Industries, especially for the 200 GeV study at Berkeley (see paper G-3, this volume, by Peter T. Clee). These results have now been checked against outgassing from a 304 stainless steel coating evaporated on the inside of 2-7/16 in ID 99.7% alumina tube. The stainless steel coating without bakeout yields $< 10^{-12}$ torr $-\ell/cm^2/s$ or about 1/5 the specific outgassing from the Litton process. The stainless steel coating offers a cost saving over the Litton method, because only one heat in a vacuum furnace is necessary to: 1) braze 0.01 in stainless steel flanges onto the ends of the alumina, 2) coat the inside with evaporated stainless steel, and 3) outgass the beam tube ready for installation.

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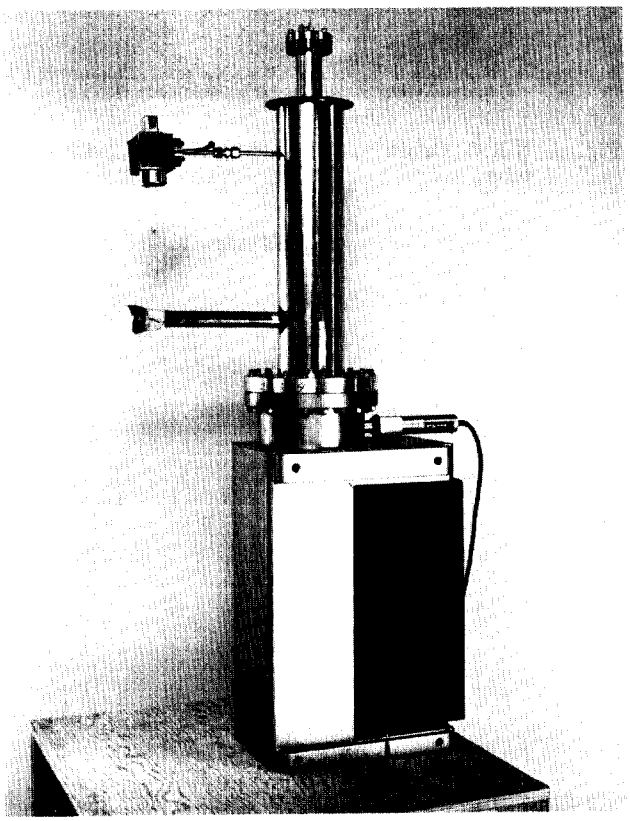

Fig. 1. Varian sputter ion pump, 140 ℓ/s, with std. 4-in diam × 17-in s.s. tube.

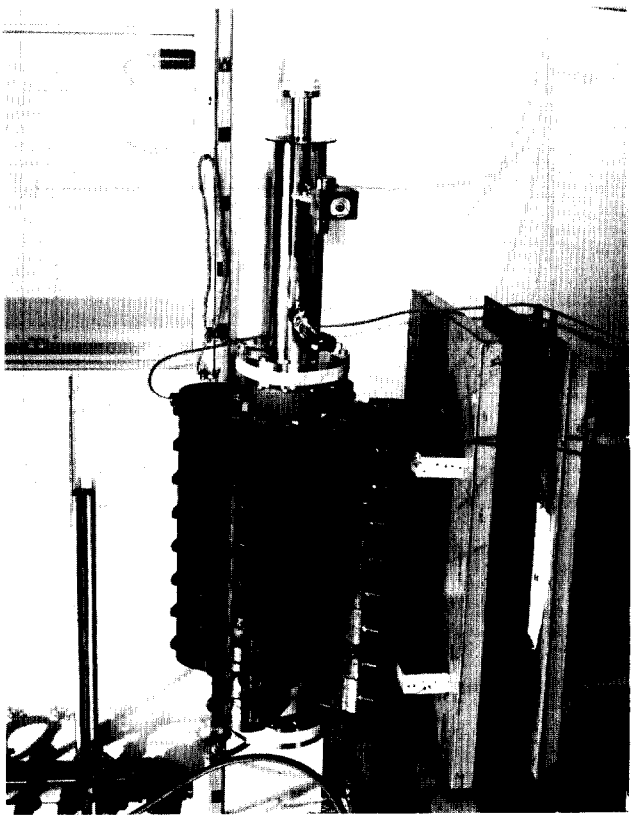

Fig. 2. R.C.A. sputter ion pump, 500 ℓ/s, with std. tube.

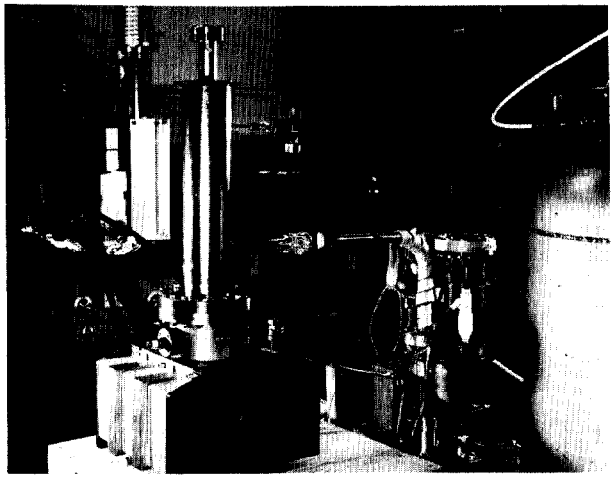

Fig. 3. Ultek sputter ion pump, 100 ℓ/s, with std. tube showing LN trapped D.P. roughing system.

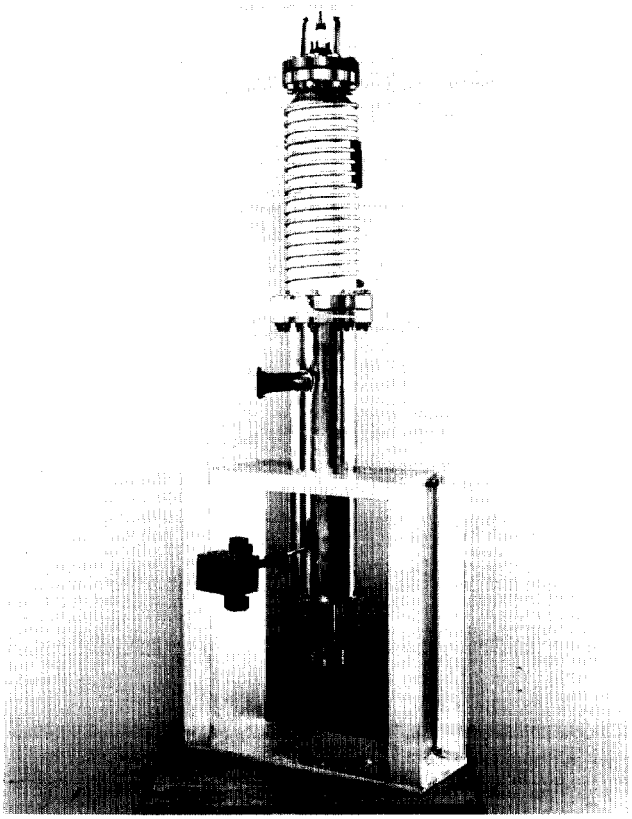

Fig. 4. N.R.C. Orbitron-type pump, 400 ℓ/s, with std. tube.

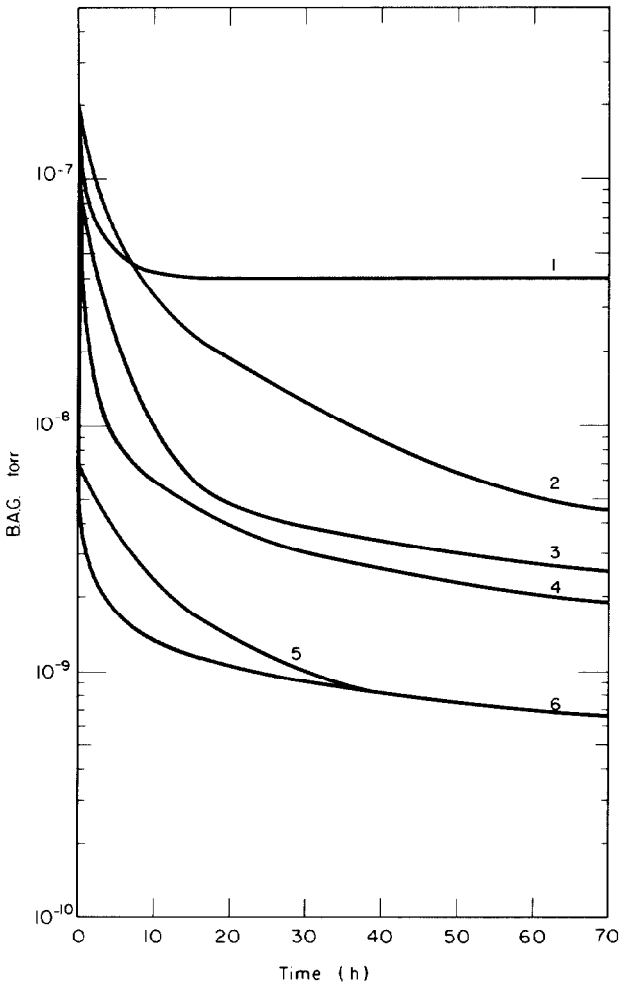

Fig. 5. Plots of pumpdown performance for pumps operating on 4-in diam × 17-in long s.s. tubing (Figs. 1-4).

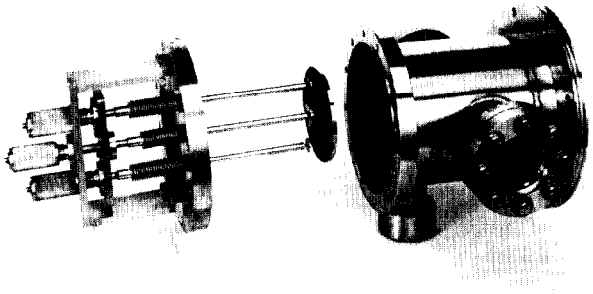

Fig. 6. Stainless steel measuring dome with main valve and two orifice valves.

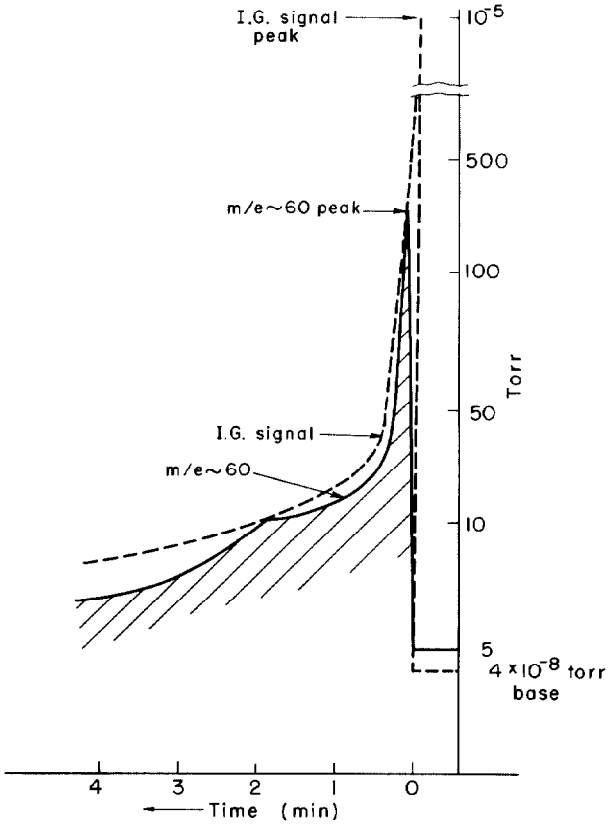

Fig. 7. Plot of single peak and BAG response to 200 μ gas pulse in foreline of Welch turbo-molecular pump.

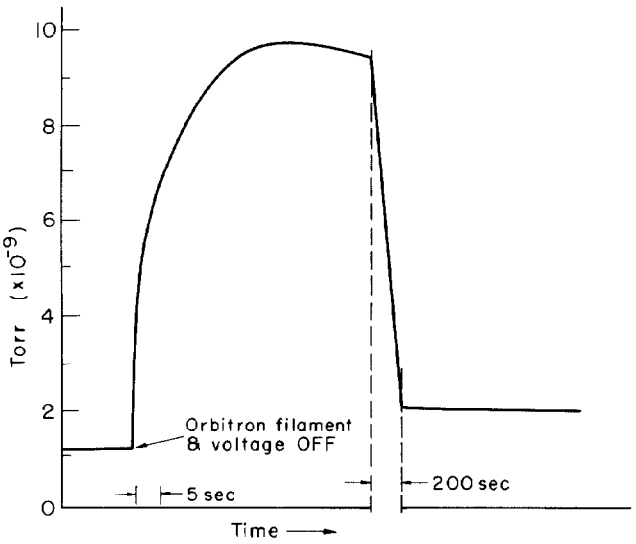

Fig. 8. BAG response vs time upon cutting off power to Orb-ion pump.

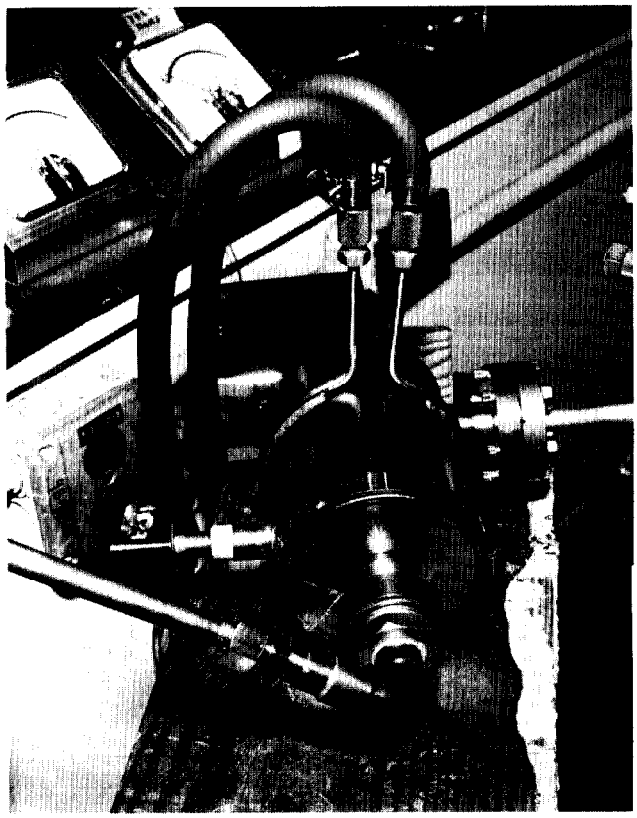

Fig. 9. Porous metal filter foreline trap and valve combination. Note electrode for I^2R heating porous metal directly.

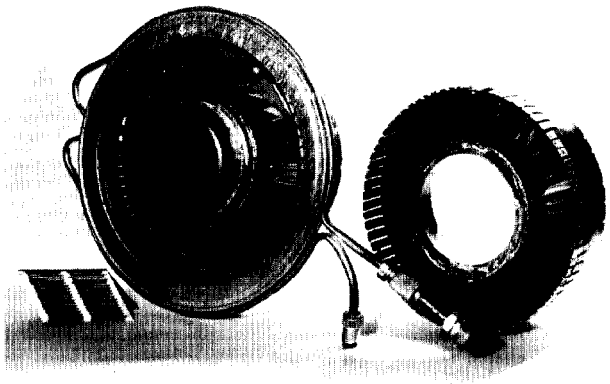

Fig. 10. Two copper fan louver baffles for 6-in nom. oil diffusion pump.

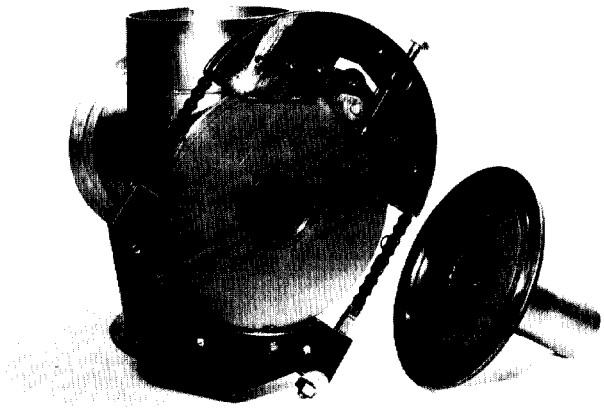

Fig. 11. Tool for cutting open edge welded flanges.

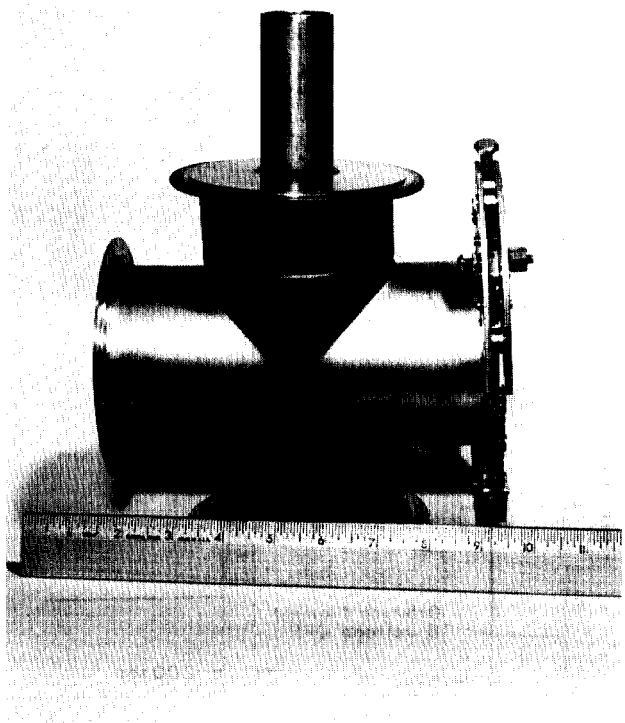

Fig. 12. Side view of Fig. 11 cutting tool on 4-in cross.

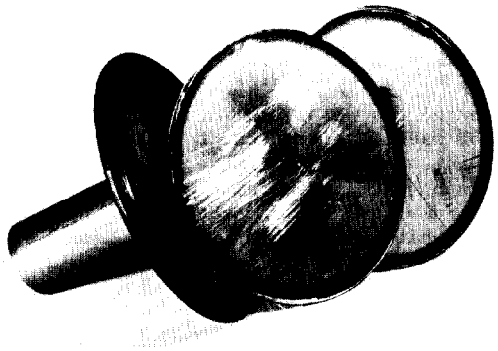

Fig. 13. View of edge weld and burr on cut open flanges.

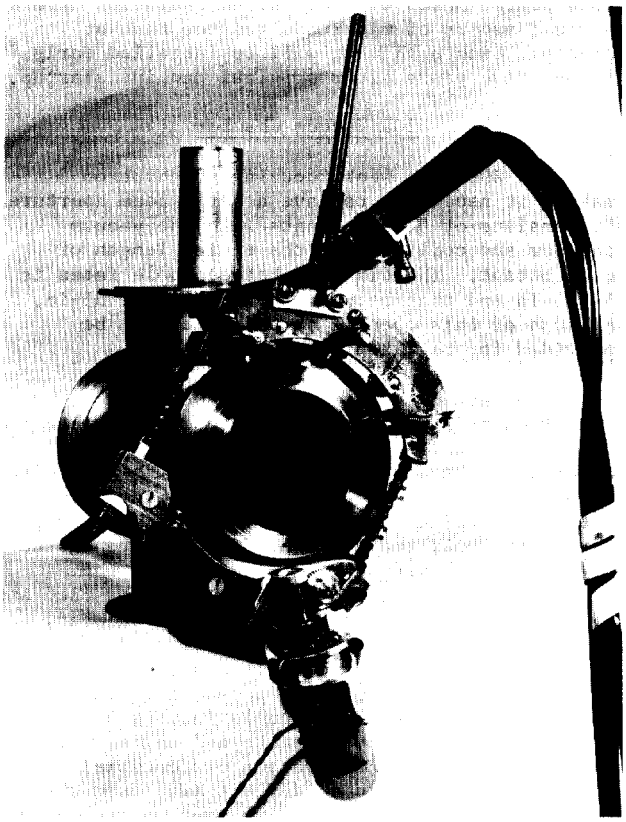

Fig. 14. Automatic edge welding tool showing motor drive.

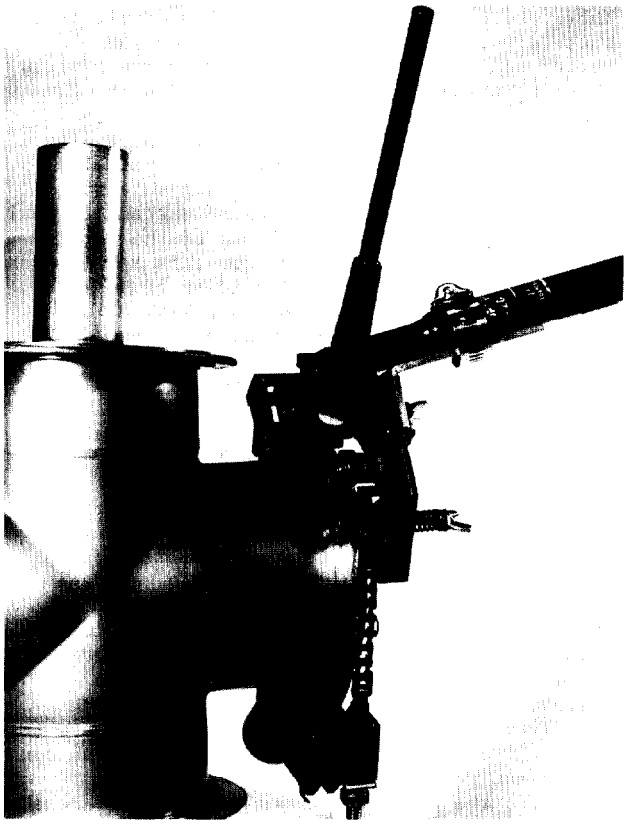

Fig. 15. Automatic edge welding tool showing T.I.G. stinger.