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SOME REMARKS CONCERNING THE ACHIEVEMENT OF PRESSURES IN THE LOW 10^{-9} TORR RANGE, OR BETTER, IN THE NAL STORAGE RING

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Over the past several years many of the myths concerning the achievement of ultra high (10^{-10} Torr range) vacuums have been dispelled. It is, in fact, possible in some cases to reach these pressures without the traditional high temperature bake-out. To substantiate this claim, a brief description of the vacuum chamber and its performance of the PSL electron storage ring will be given. The chamber is 10 meters in circumference and has over the major part of this circumference a 5 x 10 cm elliptical cross section. It is equipped with five 100-liter sec^{-1} ion pumps. The chamber is constructed in four sections, these sections being joined together at four long straight sections arranged symmetrically about the machine. In three of these straight sections the chamber is formed of a 25-cm diameter pipe 50 cm long. Attachment is at each end of this pipe by means of copper gasketed flanges. The fourth long straight section is occupied by the rf cavity and the vacuum chamber cross section here is a 10-cm diameter pipe. Again, two copper gasketed flanges are employed to attach the rf straight section "box" to the vacuum chamber.

Three of the vacuum pumps are attached to normal long straight section boxes, while the remaining two pumps connect through 60 cm lengths of 5 x 10 cm elliptical pipe to the chamber, one on each side of the rf cavity. The sum of the pumping speeds of these two pumps at the vacuum chamber through their attachment tubes is about equal to the pumping speed of a single pump at a normal straight section.

The material used in construction was 304 stainless steel. Inert (argon) atmosphere welding was employed in the fabrication of the system. All parts of the chamber were cleaned before welding according to the following "recipe." Ultrasonic cleaning in a solvent (Barcothene) followed by ultrasonic cleaning in hot (100° C) Oakite solution followed by a rinse in distilled water. After the parts were cleaned, personnel handling the parts wore nylon gloves, but no attempt was made to store the parts in any special atmosphere.

The vacuum chamber was assembled, pumped down and baked at 275°C for about 12 hours. Upon cooling, it was found that several small leaks had opened in the chamber. Thus, even after repairs, which were carried out with the system under vacuum, the pressure achieved after several days of pumping remained higher than 5×10^{-9} Torr. However, it is possible that the pressure would have gone lower had not one of the leaks been an intermittent leak in one of the vacuum pumps which could not be repaired until the system was let up to atmospheric pressure using dry nitrogen and disassembled.

After disassembly, the vacuum chamber was moved to the storage ring where it was reassembled two weeks later. During this period, it was impossible to completely exclude the normal laboratory atmosphere (cigarette smoke, dust, etc.) from the inner surfaces of the system.

Upon reassembly the chamber was pumped down. The steps during pump-down were as follows:

1. Evacuation to about 15 Torr by a graphite piston pump.
2. Evacuation to 10^{-3} Torr by sorption pump.
3. Evacuation to the 10^{-7} Torr range by a Boostivac pump. This unit combines both titanium sublimation and ion pumping. Use of this unit materially reduces the amount of water vapor and other condensables left in the storage ring pumps.
4. At 5×10^{-7} Torr in the Boostivac the ring pumps were turned on and the Boostivac valved off.

The total time required to reach 5×10^{-7} Torr from atmospheric pressure was about 90 minutes. Twenty-four hours later the system pressure as measured by a "nude" gauge in a straight section reached the low 10^{-8} range. At this time the pumps are given a mild bake (90^{o}C for 12 hours). The pressure then dropped to the low 10^{-9} range within two days. Left to its own devices, the pressure, in the course of about three months, reached 8×10^{-10} Torr. At this time a catastrophic failure occurred because of an arc in an air-cooled pulsed injection magnet, and the system filled with air from the laboratory air compressor.

A considerable amount of water vapor and some oil got into the system at this time. After repair, the system was again pumped down. This pump-down proceeded at about the same rate as the previous pump-down, and the pressure reached at the end of two months was again 8-9 x 10^{-10} Torr. It was thought, at the time, that this represented the ultimate pressure of the system without bake-out.

At this time, stored beam was achieved. It was found that the pressure in the system increased when there was stored beam. At first this increase in pressure was thought to be due to synchrotron radiation "scouring" the walls of the vacuum chamber. After several hours of operation with stored beam, a decrease in the pressure in the system both with and without beam was noted. However, according to experience at other laboratories (Stanford and Orsay), the number of "ampere hours" of stored beam had not been great enough for any appreciable "cleanup". Further, the pressure increase with stored beam was essentially independent of beam energy. In fact, the increase in pressure was found to occur without beam and to depend only on the rf voltage. It appears then that the pressure increase with stored beam was due to outgassing of the rf seal. The improvement in "base pressure" seems to be due to the "bake-out" of the rf seal.

After approximately ten hours of operation of the rf system, the pressure at the pumps with the rf system off had dropped to 3.5 x 10^{-10} Torr. No further decrease in this pressure has been noted and since this is close to the ultimate pressure of the

pumps, none is expected. On balance then, our conclusion based on the foregoing is that we are justified in using the present pressure in the system in making the following predictions of the outgassing rate in a clean "unbaked" system that has been under vacuum for several months.

Given the speed, S_p, of a pump and the pressure, P_p, at the pump, the total gas load, Q, on the pump is simply

$$Q = P_p S_p. \tag{1}$$

The effective outgassing rate, R, of the system is then

$$R = \frac{Q}{A} \tag{2}$$

Where A is the surface area of the system.

With an effective outgassing rate, the pressure anywhere in the system can be found if the conductance, C, from that point to the pump and quantity of gas, Q, flowing through the conductance can be found. The latter can be gotten from the outgassing rate while the former, in many cases of interest, can be computed from the geometry of the system. The pressure drop through a conductance, C is given by

$$P = \frac{Q}{C} . \tag{3}$$

Where several conductances occur in series, the overall conductance is given by

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots \tag{4}$$

Finally, where the conductances themselves produce the gas load, as is the case here, the difference in pressures between points x_2 and x_1 along such a conductance is given by

$$\Delta p = \int_{x_1}^{x_2} \frac{Q\ (x)}{C\ (x)}\ dx. \qquad (5)$$

If there are several such conductances in series, the individual pressure drops are simply added. Formulae for computing conductances of some of the more common shapes of vacuum plumbing are given at the end of this paper.

- Conductances of Various Things -

Lengths are in cm and conductances are in liters sec^{-1}.

1. Long pipe of circular cross section

$$C = 13.4\ \frac{d^3}{L}$$

where d is the diameter and L the length.

2. Long pipe, noncircular cross section

$$C = \frac{84.4\ A^2}{\pi L\ c}$$

Where A is cross-sectional area in cm^2 and c is the circumference.

3. Short pipe, circular cross section

$$C = \frac{11.6\ A}{1 + \frac{L}{12\ d}}\ .$$

4. Aperture, any reasonable cross section

$$C = 11.6\ A\ .$$

5. Effective length of an elbow

$$L_{eff} \leq L_{axial} + d\ .$$

Conductances are for nitrogen at $20^{\circ}C$.

The pressure is very nearly the same at all pumps in the PSL storage ring and is about 3.5×10^{-10} Torr. From this and (1) we have the quantity of gas being pumped by any pump as 3.5×10^{-8} Torr liters sec^{-1} under the assumption that the speed of the pumps is indeed 100 liters sec^{-1} at this pressure. This is probably a very conservative assumption since the ultimate pressure of these pumps is 10^{-10} Torr. The cross section of the vacuum chamber proper is a 5 x 10 cm ellipse with a 25-cm circumference. Then one quadrant of the chamber (2 m) has a surface area of 0.5 m^2. The clearing electrodes and probes in the chamber increase this by 50 percent. To this must be added the surface area of a straight section box which is 0.39 m^2. Thus the total outgassing area of one quadrant is 1.14 m^2. Then the effective outgassing rate of the system is 3.1×10^{-8} Torr liter $sec^{-1}\ m^{-2}$.

With this value for the outgassing rate we can compute the maximum pressure in the system. This will occur halfway between pumps or about 1.25 m from any pump. From (5) and the expression for the conductance of a long pipe with noncircular cross section we can derive the following expression for the pressure drop in

the vacuum chamber over a distance L:

$$\Delta P = \frac{\pi R\, c^2\, L^2}{168\, A^2} \qquad (6)$$

where P_p is the pump pressure and R is the outgassing rate. Taking L as 1.25 m and ignoring the conductance of the straight section which is large compared to the rest of the chamber we have

$$P_{max} = P + P_p = 3.7 \times 10^{-10} + 3.5 \times 10^{-10} = 7.2 \times 10^{-10} \text{ Torr.}$$

Since P goes quadratically with L, the average pressure in the system is $P = P_p + \frac{1}{3} \quad P = 4.75 \times 10^{-10}$. This is very respectable performance for an unbaked system.

Using these methods and assuming the outgassing rate of the PSL storage ring can be achieved in the 2 km of vacuum chamber on the NAL storage ring, we can make some predictions about the pressure that could be achieved there with vacuum chamber configurations currently being considered.

One possible configuration of the vacuum chamber for the NAL storage ring is a rectangular, or near rectangular, pipe with a 2.54 x 9 cm aperture. In the magnets, pump-outs might be at 1.87 m intervals or, more preferably, 3.75 m intervals. If 100 liter sec^{-1} pumps are assumed, the following results are obtained for the two possible pump spacings, taking the outgassing rate to be 3.1×10^{-8} Torr liter sec^{-1} m^{-2}.

Distance between Pumps	1.87 meters	3.75 meters
P_p	1.3×10^{-10}	2.7×10^{-10}

ΔP	1.7×10^{-10}	6.6×10^{-10}
P_{max}	3×10^{-10}	9.3×10^{-10}
$\bar{P}$	1.9×10^{-10}	4.9×10^{-10}

If 50 liter sec^{-1} pumps are assumed, the following results are obtained for the two pump spacings:

Distance between Pumps	1.87 meters	3.75 meters
P_p	2.7×10^{-10}	5.4×10^{-10}
ΔP	1.7×10^{-10}	6.6×10^{-10}
P_{max}	4.4×10^{-10}	1.2×10^{-9}
$\bar{P}$	3.2×10^{-10}	7.6×10^{-10}

It must be kept in mind that these very gratifying results depend on being able to achieve the assumed outgassing rate and on having the pumps as close as possible to the vacuum chamber. If the actual outgassing rates achieved were a factor of 5 higher and if engineering requirements resulting in less favorable pump placement decreased the conductance from the chamber to the pumps resulting in a reduction of pumping speed by a factor of 2, 100-liter pumps with the closest possible spacing would give barely acceptable performance. Furthermore, a 2 km circumference ISR would require some 2000 pumps. At an estimated $1500 per pumps, this would represent a sizable investment in pumps alone.

The use of internal pumps could solve most of the difficulties just mentioned. In this scheme, the pumping elements are mounted in the vacuum chamber and make use of the fringe field of the

bending magnets. Conventional pumps would have to be used in the straight sections. In the straight sections, the pumping problem can be made less difficult because while the surface area and therefore the gas load goes as the diameter, the conductance goes as the cube of the diameter.

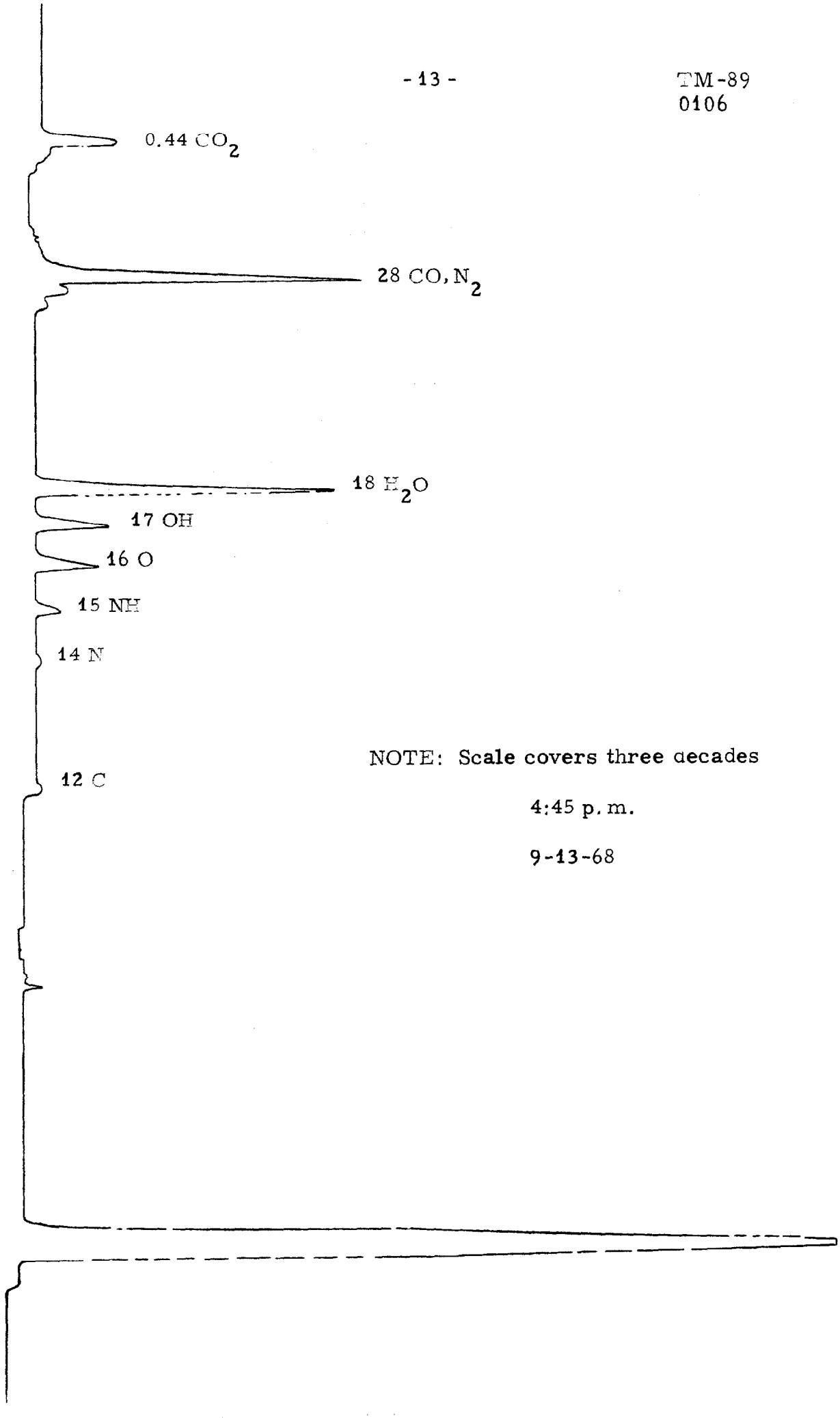
It is possible that long thin pumping elements running the length of the bending magnets could achieve a pumping speed as high as 100 liters sec^{-1} m^{-1}. This would give an average pressure in the bending magnets of 10^{-10} Torr at an outgassing rate of 3.2×10^{-8} Torr liters sec^{-1} m^{-2}. At an outgassing rate five times higher, the pressure would be 5×10^{-10} Torr. If pumping elements of, say, 50 liters sec^{-1} m^{-1} were installed, the performance would still be adequate. It was assumed in this calculation that the vacuum chamber was made 3 cm wider, that is, a 2.54 x 12 cm rectangle, to accommodate the pumping elements. These pumping elements should be considerably cheaper than complete pumps.

Earlier in these remarks, it was mentioned that the PSL storage ring vacuum chamber was given a fairly rigourous bake-out before it was let up to atmospheric pressure and installed. The question naturally arises as to whether the PSL vacuum chamber would have reached the pressure that it has had it never been baked out. On the basis of our experience with this vacuum chamber after the catastrophic failure, it is our opinion that it would have reached its present pressure without the original bake-out.

The answer to the question of whether or not to incorporate provisions for baking the NAL storage ring vacuum chamber in situ depends, it seems to us, on how often it is expected that the chamber will be opened and what an acceptable pump-down time is. There is no question that a mild bake(150^{o}C) would decrease the time required to remove a large part of the water absorbed on the chamber walls and make the system pressure less susceptible to changes in ambient temperature. However, making provisions for even such a mild bake on such a large system poses some impressive engineering problems. Further, the time required to accomplish this bake with reasonable safety may be just as great as the time required for the system to pump down naturally to the desired low 10^{-9} Torr range, especially after the system has once been pumped down. This is quite probable if internal pumps with their inherently large conductance to the source of gas are used. It will, of course, be necessary in any event to be able to heat the pumps themselves. With internal pumps heating could be accomplished by passing current through the pump elements.

A remark on the probable composition of the atmosphere remaining in the vacuum chamber after operating temperature has been reached is in order here. The "lore" has it that in an ultra high vacuum system the two most significant components will be hydrogen and carbon monoxide, with the hydrogen being ten or more times as plentiful as the carbon monoxide. We have

included here the results of a recent analysis of the gas remaining in the PSL storage ring vacuum chamber. This analysis shows that hydrogen is indeed an order of magnitude more plentiful than anything else, but that the anything else includes surprisingly high concentrations of oxygen, nitrogen, water vapor, and carbon dioxide as well as carbon monoxide. Accordingly, an experiment was performed in which a small portion of the vacuum chamber was heated sufficiently to cause the pressure in the whole system to increase by about a factor of 2. It was found that only the hydrogen and carbon monoxide increased relative to the original analysis. The hydrogen partial pressure increased by a factor of 2 while that of carbon monoxide increased by about 10 percent. The reason for the discrepancy appears to be that the residual gas analyzer (made by Veeco), which is permanently connected to the vacuum chamber through a rather small diameter pipe, was analyzing its own contamination as well as the gas in the system. This in spite of the fact that the analyzer itself had been baked at 225^{o}C for 12 hours before the analysis was made.



NOTE: Scale covers three decades

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