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M. Bernardini and L. Malter: VACUUM PROBLEMS OF
ELECTRON STORAGE RINGS. -

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ABSTRACT.

The problem of gas evolution in electron-positron storage rings due to synchrotron radiation was explored. The spectral distribution of the radiation was first computed. From this and data on quantum efficiency it was possible to determine an upper limit to the resultant photoemission from the ring walls. Measurements of the desorption efficiency from stainless steel n. 304 then made possible a determination of the maximum gas load which could be expected as a result of the synchrotron radiation.

This treatment was applied to a planned storage ring to be built at Frascati. From this it appeared that with modest processing the ring walls could be put into a condition such that the gas evolution would have completely acceptable values.

The effects of wall temperature and of processing in hydrogen and oxygen upon the desorption efficiency were determined. It was shown that allowing the ring to rest with no circulating beam present creates no problems due to the formation of sorbed films, at least for the material studied.

On the basis of the results obtained it is concluded that optimum results would be obtained by the use of materials which are gas free and on which tightly bound layers are formed from the ambient atmosphere.

I. INTRODUCTION.

The use of stored electron beams for studies of the interaction of colliding beams was originally proposed by O'Neill⁽¹⁾. This concept was extended to the study of colliding positron and electron beams, by a group at the Frascati Laboratories and reduced to practice in the ring designated as ADA⁽²⁾.

In order to perform experiments with colliding beams which will yield the most meaningful data, it is essential that the half-life of the stored beams be as great as possible, certainly of the order of many hours. One factor which contributes to decay of a stored beam is scattering of the electrons by collisions with gas molecules. The magnitude of this effect is dependent upon the gas pressure, the nature of the residual gas and upon the beam dynamics (energy, path curvature and length). In general however it can be said⁽³⁾ that the pressure should not exceed 1×10^{-9} torr and should preferably be at least 2 to 3 times smaller.

It should be mentioned that higher pressures are undesirable not only because of their adverse effect the beam lifetime but because they are responsible for beam scattering with its consequent increase in background thus reducing experimental sensitivity.

In the light of modern vacuum techniques involving the use of fluidless pumps such as sputter-ion pumps, cryogenic pumps, sorption pumps, and the complete elimination of all organic materials the attainment of such low pressures-in fact even in the 10^{-11} torr range-is now straightforward and routine.

It develops however, that the vacuum problem is made more severe by the presence of synchrotron radiation within the storage rings. For Adone, (the Frascati $e^+ e^-$ ring), this will amount to 17 KW extending from about 1 A thru the ultra-violet, visible and into the microwave region. This radiation is effective in generating gas thru the following 2 step process (that has been first suggested by Garwin⁽¹²⁾):

- 1) Photons effect electron emission from the walls;
- 2) These electrons bombard the walls with appreciable energy, resulting in gas desorption with consequent increase in the gas load. This gas load may greatly exceed that due to other sources and must thus be taken into consideration in the determination of the pump requirements as well as of the system design.

II. OUTGASSING PROBLEMS IN STORAGE RINGS.

Our problems fall into two principal categories. In the first place we wish to determine the outgassing which would occur under operating conditions when synchrotron radiation is present. With this as a background, we then seek means for minimizing the gas load under operating conditions so as to lessen the pump requirements and to operate at adequately low pressures at all points in the system, whether near or far from the pump outlets.

The most straightforward and unequivocal results would be obtained by actually measuring the outgassing under the influence of synchrotron radiation. To do this within existing synchrotrons appears nearly impossible since these operate at relatively high pressures of 10^{-7} torr and greater. The power dissipated in these synchrotrons in the form of radiation is too low to produce measurable changes in the system pressure. A modified approach would involve permitting some of the radiation to leave the synchrotron and to enter a low pressure region ($\sim 10^{-10}$ torr) and observing the pressure rise when this radiation impinges on a target. Such an approach is not simple since it requires the use of very thin, essentially non-absorbent windows, or of differential pumping techniques along slitted structures. In either case outgassing of the window or in the differential pumping structure, is bound to produce a background which must be distinguished from the sought-after information. Nevertheless, there is no fundamental objection to this approach and in fact it would have the advantage of yielding unequivocal data. Nevertheless it

was decided not to pursue this approach at Frascati (where an electron synchrotron is available) since it was felt that the necessary data might not be obtained in time for the actual storage ring design. We understand however that this approach is being taken by the Cambridge Electron Accelerator group.

The approach taken in these laboratories was a less direct one, consisting of three steps as follows:

- 1) Determination of the radiation spectrum;
- 2) Evaluation of the quantum efficiency of the radiation, i. e. the electron emission consequent upon the impingement of the radiation upon the storage ring walls;
- 3) Measurement of the Desorption Efficiency i. e. the gas desorption resulting from the self-bombardment of the ring walls by the photo-electrons emitted therefrom.

Combining the results of 1, 2, and 3 above should yield a measure of the degassing during operation. The means for doing this are presented in section III immediately following. From this result and the desired upper limit to be attained by the pressure, it becomes possible to design a vacuum pumping system to yield the desired minimum half life of the stored beams.

III. DETERMINATION OF OUTGASSING RATE.

We shall now discuss how the contributions of 1, 2 and 3, of the preceding section, "cooperate" in determining the gas evolution during storage ring operation.

Let the number of quanta radiated per second in a wavelength interval $d\lambda$ by a single electron circulating in a storage ring be denoted by $f(\lambda) d\lambda$.

Let $N_\lambda(v) dv$ be the number of photoelectrons with velocity v in velocity range dv produced by a photon of wavelength λ when the radiation falls on the storage ring walls. Then the quantum efficiency of the radiation of wavelength λ is given by:

$$(1) \quad q(\lambda) = \int_0^{\infty} N_\lambda(v) dv$$

The total number of electrons emitted per second in velocity range dv by the total radiation from a single circulating electron is then given by:

$$(2) \quad N_v dv = \left[\int_0^{\infty} f(\lambda) N_\lambda(v) d\lambda \right] dv$$

6.

The total number of electrons of all velocities emitted by the radiation from a single electron is given by: $\int_0^{\infty} N_v dv$.

We define Desorption Efficiency (hereinafter designed as DE) as the number of gas atoms or molecules desorbed from a surface when it is struck by a single electron. Let the DE for electron of velocity v be denoted by $(DE)_v$.

Then the gas desorption per second due to all the photoelectrons produced by the radiation from a single electron is given by:

$$(3) \quad N_a = \int_0^{\infty} (DE)_v N_v dv$$

$$(4) \quad = \int_0^{\infty} (DE)_v \int_0^{\infty} f(\lambda) N_\lambda(v) d\lambda dv$$

In fact eq. (4) does not correspond exactly to reality since both $N_\lambda(v)$ and $(DE)_v$ are functions of the angle of incidence of photons and electrons respectively. We could try to feed these factors into a determination of an improved form of eq. (4), but, as will be seen shortly, we shall actually operate with a greatly simplified form of eq. (4) which will allow for the "angle of incidence" effects just mentioned.

Now $f(\lambda)$ can be computed by theory (see Section IV). In principle $N_\lambda(v)$ and $(DE)_v$ can be determined experimentally, thus permitting a full evaluation of N_a . In fact however, a thorough literature search indicated that the available data for these two quantities are not really useful for the following reasons.

- 1) The data are extremely scanty and are largely restricted to narrow wavelength regions around 10 Å and between 400 and 700 Å.
- 2) The surfaces studied are not those of interest to us.
- 3) The surface treatments are either very different from those of interest to us or are so poorly defined as to make the relevant data virtually valueless.
- 4) The vacuum conditions are generally very poor as compared with those which will prevail in storage rings. This results in uncontrolled and indeterminate surface conditions which markedly affect quantum and desorption efficiencies.

The fact is, that for our purposes we do not necessarily need to determine N_a accurately. Suppose we could set an upper limit on N_a and then note that this upper limit is a completely acceptable one for the vacuum techniques available to us. Certainly from the standpoint of storage

ring design we would have done an adequate job. We shall now investigate this possibility.

We consider first the matter of the velocity of the photo-electrons ($N\lambda$ (v)). Experimental studies by Heroux and Hinteregger down to 250 Å, show that the large majority of the photo-electrons have energy less than 4 electron volts and that very few possess energies above 10 electron volts. Rudberg⁽⁵⁾ has shown that at 44 Å, have energies of 20-30 eV. In addition retarding field curves by Lukirskii, Rumsh, and Smirnow⁽⁶⁾ at wavelengths of 67 and 113 Å indicate that here too the vast majority of the photoelectrons have energies below 20 volts.

We shall now arbitrarily assume that all the photo-electrons have a single energy namely that of 20 eV. We feel that this is a conservative value since:

- 1) The preponderant fraction of observed photo-electrons have energies of below this value.
- 2) The measured Desorption Efficiencies, as will be shown, change quite slowly between 10 and 50 eV.

On the basis of this assumption $(DE)_v$ is now a constant viz: the measured value at 20 eV and will be represented by $(DE)_{20}$.

Eq. (4) and eq. (1) now combine to yield

$$(5) \quad N_a = (DE)_{20} \int_0^{\infty} q(\lambda) f(\lambda) d\lambda$$

$q(\lambda)$ has been measured in the far ultra-violet by Walker, Wainfan and Weissler⁽⁷⁾, and in the soft X-ray region (around 10 Å) by Rumsh, Lukirskii and Shchemelev⁽⁸⁾. Results vary widely depending upon material, treatment, wavelength and angle of incidence. However, as before, we find that we can set an upper limit to $q(\lambda)$, which is larger than the vast majority of the observed values. We choose as this upper limit the value 0.1. Eq. (5) now becomes

$$(6) \quad N_a = 0.1 (DE)_{20} \int_0^{\infty} f(\lambda) d\lambda$$

We introduce one further modification and that is to limit the integration to 1200 Å as an upper limit. This is based on the observations that the quantum efficiency above that wavelength of all surfaces (except those specially treated to have low work functions), are of the order of 10^{-3} or less. Furthermore since this wavelength corresponds to a photon energy of about 10 eV the vast majority of the photoelectrons will have

8.

very low energies and will thus be relatively ineffective in producing desorption. We thus finally write:

$$(7) \quad N_a = 0,1 (DE)_{20} \int_0^{1200} f(\lambda) d\lambda$$

This then is an upper bound on the desorption rate (molecules per second) due to a single circulating electron in a storage ring. The integral can be computed; $(DE)_{20}$ can be measured.

IV. SPECTRUM COMPUTATIONS.

IV. a - General Formula for Number of Photons.

The radiation spectrum can be computed by starting with eq. (5) of Tomboulian and Hartman⁽⁹⁾:

$$(8) \quad P_\lambda = \frac{3^{5/2}}{16 \pi^2} \left(\frac{e^2 c}{R^3} \right) \left(\frac{E}{m_0 c^2} \right)^7 G(y)$$

$$(9) \quad \text{where } G(y) = y^3 \int_y^\infty K_{5/3}(\eta) d\eta$$

P_λ is the instantaneous power flow per electron into all angles per unit wavelength centered about the radiated wavelength R . E is the energy of the electron and R its orbital radius. Since storage rings are generally composed of straight as well as circular sections, the average power radiated is reduced in the ratio R/R_M where R_M is the mean radius of the ring.

We can obtain N_ϕ , the number of quanta per second per electron per Angstrom by dividing P_λ by $\epsilon = [(19,9 \times 10^{-9})/\lambda]$ ergs, where ϵ is the energy in a quantum and λ is measured in Angstroms.

$$(10) \quad \text{Then } N_\phi = 5,02 \times 10^7 P_\lambda \lambda \quad \text{photons/sec/electron/Angstrom}$$

$$(11) \quad \text{In eq. (9)} \quad y = \lambda_c/\lambda \quad \text{where } \lambda_c = \left(\frac{4\pi R}{3} \right) \left(\frac{m_0 c^2}{E} \right)^3$$

λ_c is a so-called critical wavelength, slightly in excess of that corresponding to the maximum energy point in the spectrum. $G(y)$ was deter-

mined with a computer and is plotted in Fig. 1. From eq. (8) and (10) and from Fig. 1, N_{ϕ} was computed for three storage rings:

- 1) Adone, the proposed 1.5 GeV Frascati electron-positron storage ring.
- 2) AdA, the experimental Frascati 200 MeV electron positron storage ring.
- 3) The existing Stanford Electron Storage Ring (at $E = 300$ MeV and with a circulating current of 1 ma).

The results are plotted in Fig. 2.

From this figure it is possible to determine the total number of quanta between any two wavelengths. Such was done for each of the cases of Fig. 2 for the range between the cut off wavelength and 1200 \AA .

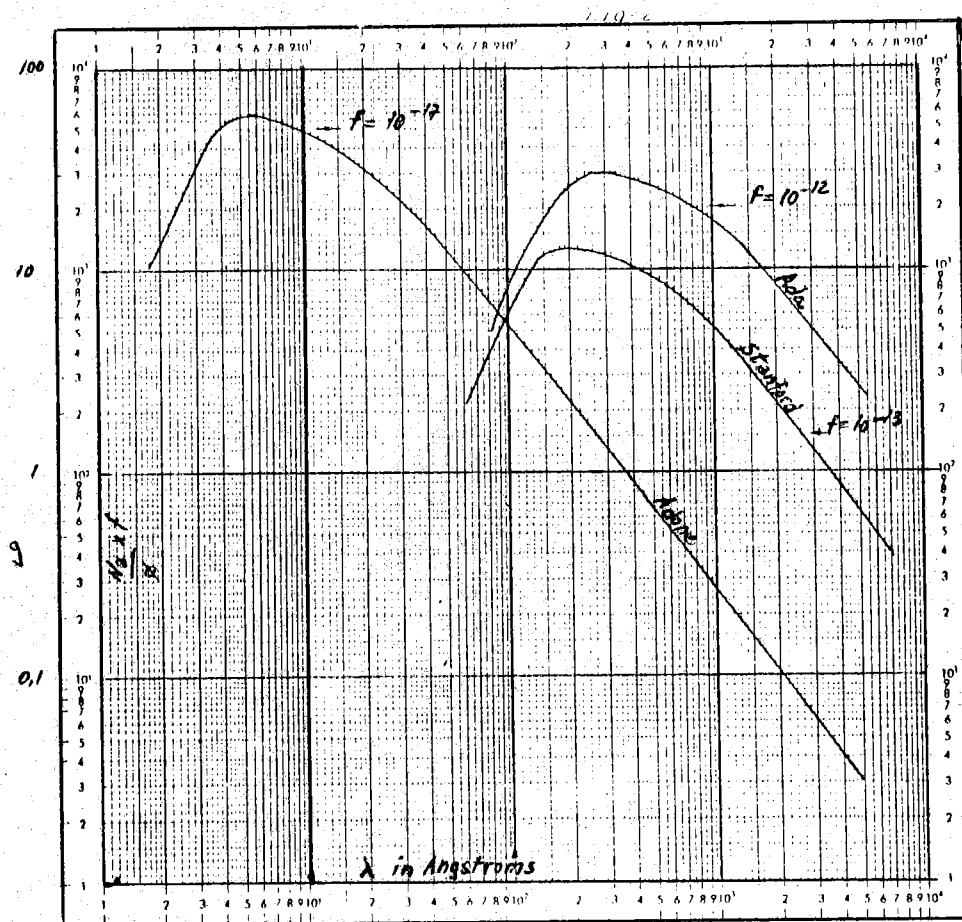


FIG. 2

10.

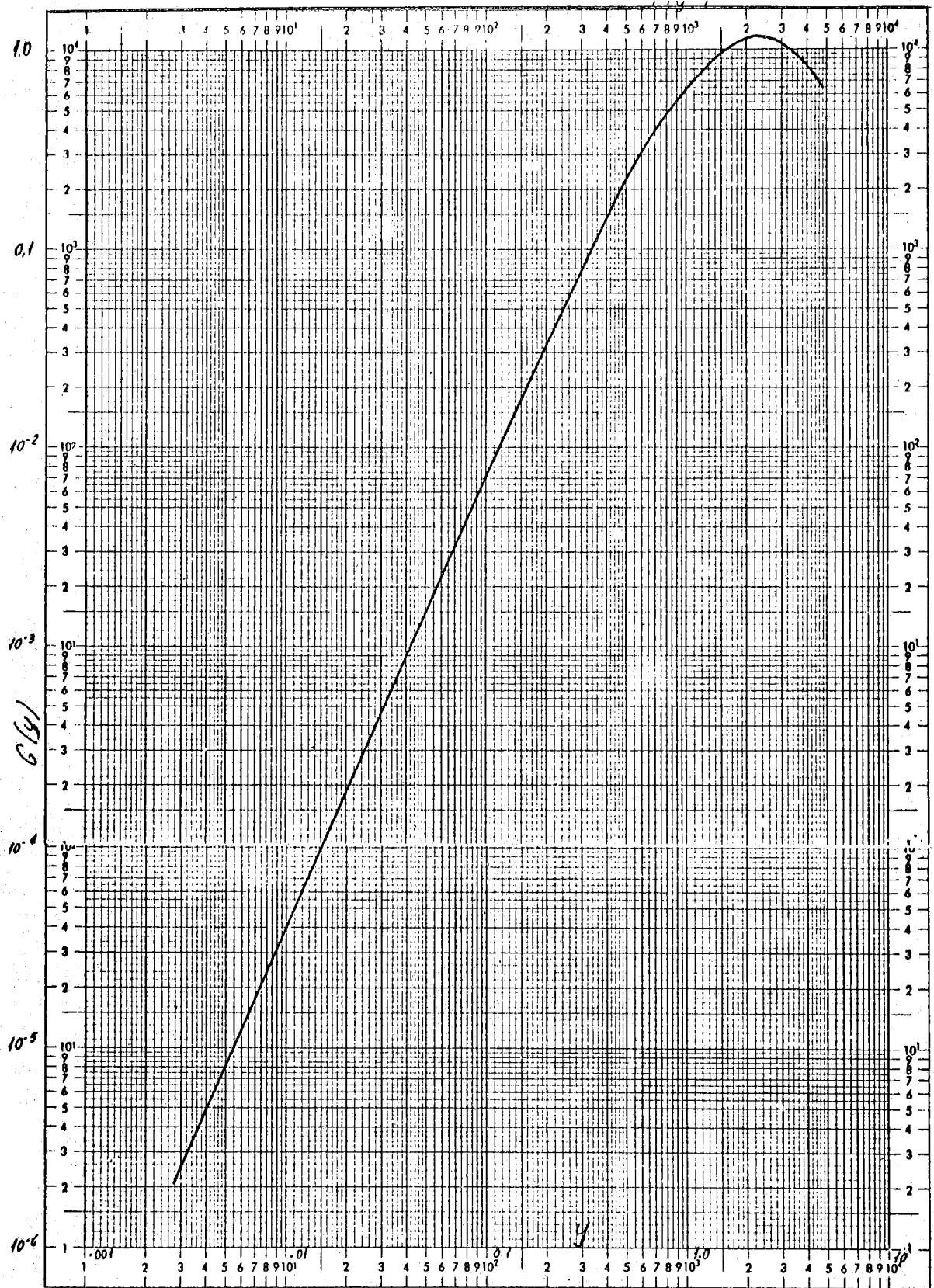


FIG. 1

The data of interest for these three rings are collected in Table I below.

TABLE I

	Adone	AdA	Stanford Storage Ring	Remarks
R_O (meters)	5.0	0.60	1.40	
R_M (meters)	16.2	0.65	1.83	
E (MeV)	1500	200	300	
I	94 ma	0.58 ma	1 ma	$I = 7.60 \times 10^{-12} \frac{N_e}{R_M}$
N_e	2×10^{11}	5×10^7	2.4×10^8	N_e is the number of stored electrons
N_ϕ	8.2×10^{19}	2.1×10^{16}	6.7×10^{16}	Between cutoff and 1200 \AA
λ_c	8.4 \AA	424 \AA	294 \AA	
$(\Delta E)_R$	89.5 KeV	0.236 KeV	0.511 KeV	$= \frac{88.5 (E_{\text{Bev}})^4}{R_M}$ in KeV
P_R	8.5 KW	0.14 w	0.516 w	

$(\Delta E)_R$ is the energy radiated per electron per revolution P_R is the total power radiation within the storage ring (in watts or kilowatts) at the designated current value.

IV. b - Approximate formula for number of photons.

From Schwinger basic paper on synchrotron radiation⁽¹⁰⁾ it can be shown that the spectral distribution of synchrotron radiation can be expressed quite closely by:

$$(12) \quad N(\omega) d\omega = \left[3.56 \times 10^{-3} \left(\frac{\omega_0}{\omega} \right)^{2/3} d\omega \right] \frac{R_O}{R_M}$$

where N is the number of photons in frequency band $d\omega$. ω_0 is given by c/R_O . It is related to ω_c , the critical frequency by the relation:

$$(13) \quad \omega_0 = \frac{2}{3} \omega_c \gamma^{-3}$$

12.

$$(14) \quad \text{where} \quad \gamma = \frac{E}{m_0 c^2}$$

The number of photons/sec/electron cut off and some frequency ω_α [provided $(\omega_c/\omega_\alpha) > 3$], is given approximately by:

$$(15) \quad \begin{aligned} N_\phi &= \int_{\omega_\alpha}^{\omega_c} N(\omega) d\omega = [3.56 \times 10^{-3} \omega_0^{2/3} \int_{\omega_\alpha}^{\omega_c} \frac{d\omega}{\omega^{2/3}}] \frac{R_0}{R_M} \\ &= 3 \times 3.56 \times 10^{-3} \omega_0^{2/3} \left| \omega^{1/3} \right|_{\omega_\alpha}^{\omega_c} \left(\frac{R_0}{R_M} \right) \\ &= 1.07 \times 10^{-3} \omega_0^{2/3} \omega_c^{1/3} \left[1 - \left(\frac{\omega_\alpha}{\omega_c} \right)^{1/3} \right] \frac{R_0}{R_M} \\ &= 1.07 \times 10^{-3} \left(\frac{3}{2} \right)^{1/3} \omega_0 \left(\frac{E}{m_0 c^2} \right) \left[1 - \left(\frac{\omega_\alpha}{\omega_c} \right)^{1/3} \right] \frac{R_0}{R_M} \end{aligned}$$

$$(16) \quad N_\phi = 7.3 \times 10^6 \frac{E \text{ MeV}}{R_M} \left[1 - \left(\frac{\omega_\alpha}{\omega_c} \right)^{1/3} \right]$$

We recast this into a more convenient form employing λ

$$(17) \quad N_\phi = 7.3 \times 10^6 \frac{E \text{ MeV}}{R_M} \left[1 - \left(\frac{\lambda_c}{\lambda_\alpha} \right)^{1/3} \right]$$

We shall now compute N_ϕ by the approximate formula of eq. (16) using the value of 1200 Å for λ_α . This rather arbitrary choice is based on the following considerations:

The value of the quantum efficiency above this wavelength has values of less than 10^{-3} for all common metals and their oxides. As will be seen below, significant values of quantum efficiency (in contributing to gas desorption) will be taken as being 100 times greater. Furthermore, this value of wavelength corresponds to a quantum energy of about 10 ev. A quantum of this energy will not produce electrons, any appreciable fraction of which, will have energies in excess of one electron volt. Such electrons will be relatively ineffective in producing gas desorption, as compared with those produced by more energetic photons with energies measured in hundreds and thousands electron volts. The combined effect of low quantum efficiency and of low energy photoelectrons is such that we exclude from further consideration in this treatment

the contribution to the gas load of radiation with wavelength in excess of 1200 Å.

From eq. (16) we compute N_{ϕ} between 1200 Å and cut-off. These (approximate) values are presented in Table II in comparison with those of Table I which were obtained by numerical integration:

TABLE II

Photons/sec	Between	Cut off and 1200 Å	
	Adone	AdA	Stanford Storage Ring at 1 ma
N_{ϕ} from eq (16) Photons per second	11.0×10^{19}	3.3×10^{16}	10.5×10^{16}
N_{ϕ} by numerical integration Photons per second	8.2×10^{19}	2.1×10^{16}	6.7×10^{16}

Note. -

Garwin⁽¹²⁾, in an unpublished memorandum computes N_{ϕ} by dividing P_R (the total power radiated) by the energy of the quantum corresponding to the critical wavelength. The basis for this choice is not presented. This choice is continued in a later unsigned and undated memorandum from the Cambridge Electron Accelerator Group entitled "Scaling Law for Gas Production". -

V. PERMISSIBLE VALUES FOR DESORPTION EFFICIENCY.

We are now in a position to determine what values of DE will be acceptable in the light of the requirement that the gas evolution within the storage ring due to the synchrotron radiation, should not cause a pressure rise greater than 1×10^{-9} torr. This presupposes that the effective pumping speed has already been established. A figure for that quantity is generally determined by other considerations, specifically by the system base pressure desired.

We shall limit ourselves to a consideration of Adone. It is planned that as a minimum, Adone will be provided with a sputter-ion pump capacity of 4000 liters/sec at 10^{-9} torr. (This may be supplemented with sublimation pumping, the decision to be based on tests now underway). This pumping system should maintain Adone in the low 10^{-10} torr range when no stored beam is present.

From Table II, we have (for Adone) $N = 8,2 \times 10^{19}$ photons/sec between cut off and 1200 Å. Over this range we postulate that the quantum efficiency q is 0,1 (In effect, we set $q=0$ at longer wavelengths). Then N_e the number of electrons produced by $N\phi$ is:

$$N_e = q N\phi = 8,2 \times 10^{18} \text{ electrons/sec.}$$

We now further postulate that, effectively, these photoelectrons have a uniform energy of 20 electron volts. Then the gas desorption is given by:

$$(18) \quad N_a = (DE)_{20} q N\phi = 8,2 \times 10^{18} (DE)_{20} \text{ molecules/sec.}$$

To transform into torr liters/sec we note that one torr liter contains $3,6 \times 10^{19}$ molecules. Eq (18) then becomes:

$$(19) \quad Q = \frac{8,2 \times 10^{18}}{3,6 \times 10^{19}} (DE)_{20} \text{ torr liters}$$

$$= 0,23 (DE)_{20} \text{ torr liters}$$

Now the pressure rise in a system due to gas load Q is given by:

$$\Delta P = \frac{Q}{S}$$

where S is the pumping speed. For Adone we set $S = 4000$ liters/sec. Then:

$$(20) \quad Q \leq \Delta P S$$

and we set $\Delta P = 10^{-9}$ torr, we obtain:

$$Q \leq 0,23 (DE)_{20} \text{ torr liters} = 4 \times 10^{-6} \text{ torr liters}$$

or:

$$(21) \quad (DE)_{20} \leq 17 \times 10^{-6}$$

As will be seen later, this is in fact a much larger value for $(DE)_{20}$ than can be obtained quite easily. We shall choose however, to use a still smaller value by virtue of a factor which has not been taken into consideration thus far and which has not been studied to date. We refer to the possibility that the photoelectrons cause gas desorption not only when they return to and strike the ring walls, but in fact also as they emerge. In the absence of any data on this point, we shall (we believe conservatively) assume that the gas evolved at electron emergence is about twice that upon return. The limiting expression (eq. 20) then becomes:

$$(DE)_{20} \leq 6 \times 10^{-6}$$

We proceed now to experimental studies of this quantity under a variety of experimental conditions.

VI. EXPERIMENTAL SETUP AND PROCEDURES.

All the experiments were carried out in systems as shown in Fig. 3. The apertured disc (with limited conductance), between the sputter-on pump and the remainder of the system, was employed in order that the system be exhausted at an essentially uniform pumping speed. (At the lower pressures attained, the pumping speed of the older pumps employed falls off from their higher pressure values). The tantalum filament (0.4 mm diameter) was heated with A. C.

Electrons emitted therefrom were permitted to strike the inner surface of the target cylinder under the influence of an applied

voltage. Studies showed that the variation of test results with cylinder voltage was sufficiently slow so that no corrections for the A. C. variations in filament potential were necessary under saturated conditions which almost always prevailed the bombarded surface comprised about 40 cm^2 . The target cylinder was water-cooled during tests except when effects of temperature variation were being studied.

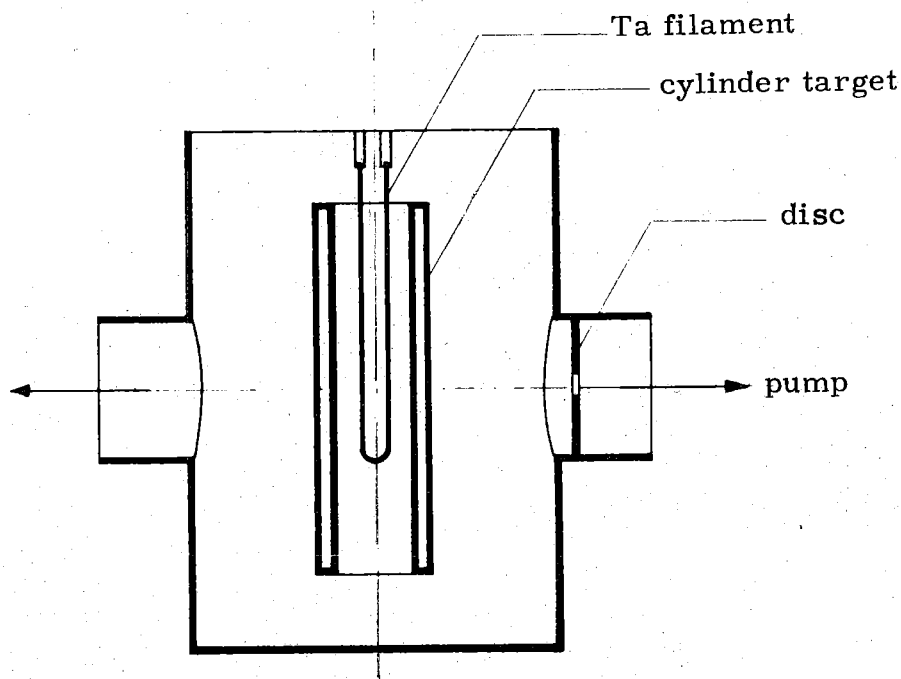


Fig. 3 - Schematic experimental set-up.

The target itself was made of stainless steel N. 304, obtained from laboratory stock.

As will be seen, rather wide differences in desorption efficiency of different samples suggest that commercial samples may differ considerably among themselves. At the time of writing this report, analyses of the various samples had not been made.

Before assembly the system parts were chemically cleaned: this consisted of an initial degreasing with organic solvents followed by a processing in a hot alkaline bath of a commercial material "Eflcolene". The detailed procedures were in accordance with instructions supplied with the material. Following the alkaline bath, the parts were repeatedly rinsed in distilled water.

In all cases, the system was first baked for from 30 to 72 hours at temperatures in the neighbourhood of 300°C . Initial exhaust was with a turbomolecular pump. Subsequent pumping was with the Vac Ion pump,

(except as will be seen in a few instances, where pumping was carried out the ionization gauge only). Pressure measurements were made with a Varian ionization gauge whose X-ray limit was sufficiently low (less than 2×10^{-11} torr) so that no corrections to the observed readings were necessary. Towards the end of the bake (and extending beyond its close) the tantalum filament was heated to a temperature at last 200°C above its maximum operating temperature for a length of time sufficient to result in a system pressure in the low 10^{-9} torr range. Except for the first run, care was taken to insure that not over one monolayer of Ta. would be evaporated into the test surface. (In the first run, the evaporated material was equivalent to four monolayers).

With growth of understanding, it was realized (during the course of the experimental investigations) that a different course of the studies would have been rewarding.

VII. EFFECT OF TIME AND MAGNITUDE OF BOMBARDMENT VOLTAGE UPON DESORPTION EFFICIENCY.

In the preceding discussions, we have indicated that we shall concern ourselves with values of DE taken at 20 volts. This limitation was made when the experimental studies were well under way. As a consequence considerable data were taken, (and are presented here) at other voltages. However, in the light of comparative studies of the effect of different voltages upon DE, it appears that all these data are useful.

The studies of time and voltage dependence of DE were made in a succession of systems. The results will be presented in sequential order of the systems employed.

VII. a - System N. 1.

This initial study was directed primarily towards determining the effect of prolonged bombardment upon the DE. (Due to inadvertence the test surface of this system was bombarded at 100 volts at unknown current densities for unknown periods of time and without recording of data). Consequently the studies did not begin with a completely fresh surface. (This "mistake" was not repeated).

Recorded data were first taken at 55 volts and 44 ma. Since the surface being bombarded was estimated as having an area of about 40 cm^2 it is seen that the current density was approximately 1 ma/cm^2 . DE as a function of time is plotted in Fig. 4.

We have already concluded that an observed value of $(\text{DE})_{20}$ of

less than 6×10^{-6} will be acceptable. It is thus seen at once (since DE is a monotonic function of voltage) that in this case an acceptable value of DE was readily obtained. To see the effect of higher voltage bombardment tests were made as follows:

200 volt bombardment (at 44 ma) yielded an initial value of DE = $1,53 \times 10^{-6}$. After 66 minutes this fell to $1,33 \times 10^{-6}$. This was followed by a brief (4 minute) test at 300 volts which yielded $DE \approx 2,5 \times 10^{-6}$. This was immediately followed by a run at 100 volts which yielded (after 35 minutes) a value of $0,70 \times 10^{-6}$.

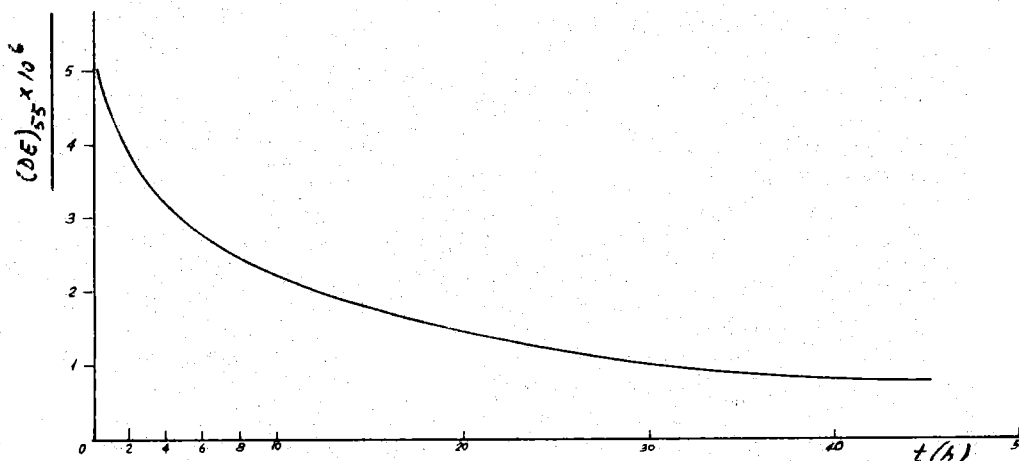


FIG. 4

A check at 55 volts now gave $DE = 0,63 \times 10^{-6}$. Thus the brief bombardments at 100 to 300 volts had further lowered the $(DE)_{55}$ value.

From these results it may be concluded that for Stainless Steel N. 304 (designated here after as SS 304), a modest electron bombardment at 55 volts and 1 ma/cm^2 (or higher) will put that surface into an acceptable condition in much less than one day. It may also be inferred that with simple operation with a stored beam only, which we believe, yields electrons with energies largely below 20 volts, acceptable performance would also be achieved in less than a day. This inference is supported by studies to be reported below.

Data were then taken to determine the effect of electron energy on DE. These were obtained by rapid shifts up and down between various voltages. The results are plotted in Fig. 5 relative to DE at 100 volts as unity. A study of that figure reveals that:

a) DE is a monotonic function of electron energy for an SS 304 surface.

b) It appears that DE varies only slowly below 100 volts (this was studied in more detail later and will be described below).

These observations must, at least for the present be restricted

to the surface under study which was close to room temperature and which was exposed to an ambient pressure (of unknown composition) in the 10^{-9} torr range.

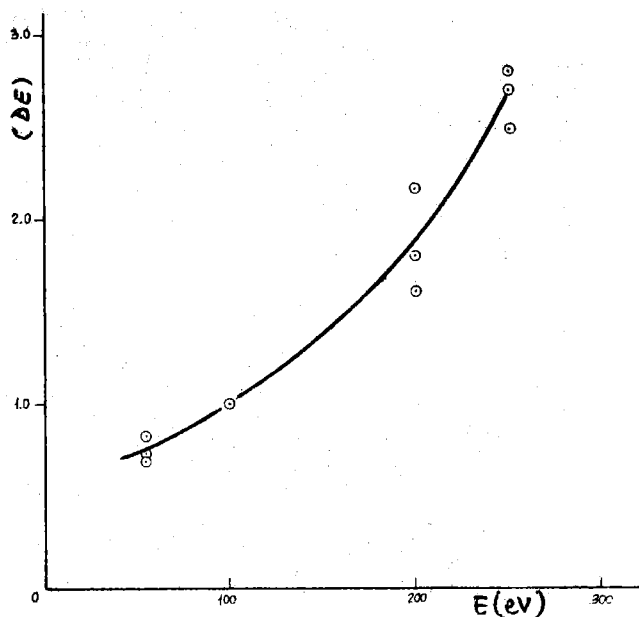


FIG. 5

An effort was finally made to determine the composition of the gas evolved under electron bombardment by means of the omegatron. Unfortunately, as it developed, the omegatron itself was so profuse a source of gas that, under operation, it provided a severe pressure background. Nevertheless, while an accurate analysis was impossible, the following positive observations were made.

- 1 - No water vapor was released under bombardment.
- 2 - No hydrogen was released under bombardment.
- 3 - Considerable mass 16 and 28 were released, but their identification was not possible.

These conclusions apply, of course, to the SS 304 surface with the history as described when bombarded with electrons in the low hundreds of volts range. Since it was hard to see what essential use could be made of the omegatron data, and because of its high outgassing rate, no further omegatron data were taken.

VII. b - System N. 1A.

An accidental burn out of the Ta filament of system N. 1 required its replacement. The same test cylinder was reemployed but was chemically recleaned using the procedure previously described. It was baked at 300°C for 48 hrs and the filament then outgassed with care so as not to evaporate more than a monolayer of Ta into the test cylinder.

A run taken at 300 volts yielded the astonishingly low DE results shown in Fig. 6. These results were essentially repeated 1 and 3 days later. Unfortunately before further studies could be made, this system

developed such severe gasket leak problems that it was torn down and rebuilt with varian seals. (Conflat).

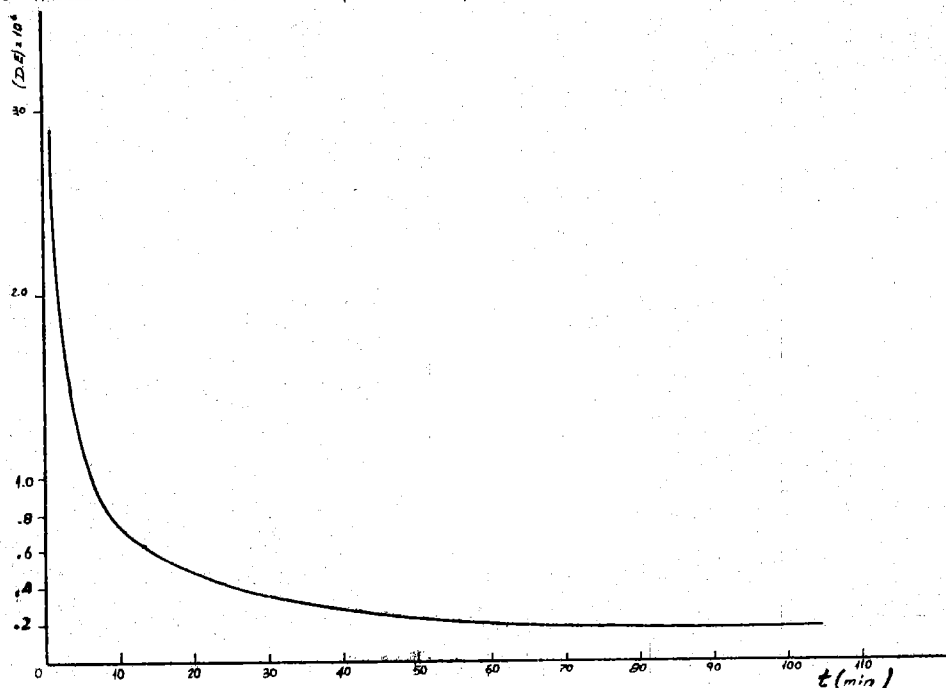


FIG. 6

These low figures were never reattained. Could they be due to a heavy coat of Ta? Presumably the chemical cleaning removed that. Could the surface now have been pure stainless steel as against Ta coated stainless in System N. 1. But in later systems in which care was also taken to prevent excessive evaporation of Ta much higher values of DE values were observed. The explanation eludes us. Nevertheless the results must be presented to indicate how low a value of DE has been observed, (and at 300 volts).

VII. c - System N. 2.

This was essentially a duplicate of system N. 1 but with improved flanges. It was baked at 330°C for 65 hours and then the filament was outgassed. The surface was bombarded for 90 minute at 100 volts and 0,3 ma/cm². Following this a 20 volt 0,2 ma/cm² run for 1 hour resulted in DE = 1,7 x 10⁻⁶.

This system was then used previously for a study of the effect upon DE of heating in Hydrogen. Following the end of these studies (which are reported in Section XI) (DE)₂₀ was less than 0,7 x 10⁻⁶.

In the following three days this surface was subjected to a varied bombardment history (including 24 hours at 300 volts and 2,5

ma/cm²) in order to study reabsorption with the beam off. These studies will not be reported here since more carefully taken data will be presented later. At the end of these studies DE at 20 volts was down to $0,22 \times 10^{-6}$ thus showing how low a value can be achieved after moderate electron bombardment. (The intervening hydrogen treatment did not appear to contribute to a lowering of DE).

VIII. EFFECT OF TEMPERATURE ON DESORPTION EFFICIENCY.

Studies was made to determine the effect of the temperature of the surface being bombarded upon the desorption efficiency. These studies were made in System N. 2, following those described in the preceding Section.

DE was measured initially at 20 volts, $0,2 \text{ ma/cm}^2$ and found to be $0,22 \times 10^{-6}$. The system was then heated up to 300°C and DE readings were taken at that time at 20 and 100 volts and after 20 hours at 300°C . Since the ambient pressure (and gas composition, no doubt) changed along with temperature and time, it is not possible to state with certainty that the results obtained are purely a temperature effect. The results are compiled in the following table.

Temp	Room temp	300°C	after 20 hours at 300°C
V = 20 volts			
I/cm ²	$0,20 \text{ ma/cm}^2$		$0,24 \text{ ma/cm}^2$
P in torr	5×10^{-9}	$2,1 \times 10^{-7}$	7×10^{-8}
DE	$0,22 \times 10^{-6}$	$5,0 \times 10^{-6}$	$2,5 \times 10^{-6}$
V = 100 volts			
I/cm ²		$0,55 \text{ ma/cm}^2$	$0,50 \text{ ma/cm}^2$
P in torr		$2,1 \times 10^{-7}$	7×10^{-8}
DE		$15,0 \times 10^{-6}$	7×10^{-6}

It is seen that the operation at 300°C resulted in an initial increase of DE by over 20. This diminished to a about 10 in less than one day. The value of $2,5 \times 10^{-6}$ at 20 volts is of course, an acceptable value. Since in most cases operation well below 300°C will be pos-

sible (and at pressures much lower than employed here) it would seem that a rise in the temperature of the bombarded surfaces in storage rings need not be of great concern, provided that the temperature effect upon system pressure is not itself excessive,

IX. STUDIES OF READSORPTION.

In our previous studies we have determined that the Desorption Efficiency as a function of time, voltage, temperature and processing. From these, it appears that with relatively simple processing and following short periods of operation completely acceptable values of Desorption Efficiency are obtained.

It appears further, that once a surface has been brought into a satisfactory state, a subsequent exposure to the atmosphere would require a reprocessing not too different from that required originally.

Another important question presents itself, however, and that is the following one:

Suppose the surface of storage ring is in a good state with the beam on, what will happen to that surface if the beam is turned off? Will the surface build up a heavy adsorbed layer so that when the beam is restored, an extended reprocessing will be necessary to restore the desorption efficiency to its original low value. This question has been answered in the negative, at least for SS 304.

A series of experiments to investigate this point was carried out. A typical one will now be described.

The test structure of system N. 2 was bombarded at 100 volts and $0,6 \text{ ma/cm}^2$ for 1 hour and the final system pressure was observed to be $2,95 \times 10^{-9}$ torr. The applied voltage was removed for 1 hour at which time the pressure had fallen to $1,55 \times 10^{-9}$ torr. The 100 volts was reapplied and the pressure behaviour measured with time.

It was seen that in one hour the pressure had returned to its value of $2,95 \times 10^{-9}$ torr held before the period with voltage off. Thus, by integrating over the period between the instant when the voltage is reapplied and the time when the pressure returns to its former value of $2,95 \times 10^{-9}$ torr we can determine the quantity of matter sorbed during the rest period. This is found to be $2,3 \times 10^{-6}$ torr liters. This is equivalent to $8,3 \times 10^{-13}$ atoms, if we assume that a monolayer contains 10^{15} atoms. It turns out that in the return to equilibrium, 2×10^{-3} monolayers was desorbed. Since during the rest period the average pressure was about $1,6 \times 10^{-9}$ torr, the equivalent of six atomic layers arrived at the test surface during the rest period of one hour.

From this we conclude that the average sticking probability of gas arriving at the surface during the rest period is in the 10^{-4} range. This is about 3 orders of magnitude smaller than that generally observed for clean surface e. g. tungsten flashed to high temperatures. From these results we can only conclude that the stainless steel surfaces here studied are not clean in the sense of being only the metals of which the alloy is composed. The surface must in fact be in the form of tightly bound compounds, most likely oxides, nitrides and carbides, whose binding energy is great. At room temperature the sticking probability of these complex surfaces has the low values measured. The percentage coverage of the originally sorbed layer is close to 100%. The coverage is no doubt not "static" but represents an equilibrium between arrival with some sticking and of desorption under the influence of the forces which promote desorption. Normally these forces are those due to temperature only, and as can be seen, these are quite ineffective at room temperature, so that an essential complete monolayer is present. The addition of the electron beam adds to the desorbing forces but only to a small degree as is seen by the fact that the change in the sorbed layer is by only several parts in 10^4 . That the low energy electron beams should be ineffective in the removal of chemisorbed layers is not at all surprising in the light of results obtained in low energy electron diffraction studies of surface structures⁽¹¹⁾.

We thus arrive at a picture of a "good" surface for storage rings which is not atomically clean, but which, on the contrary possesses a sorbed monolayer which is tightly bound. In fact it would appear undesirable to operate with surfaces which do not form tightly bound sorbed layers (perhaps gold) since such surfaces would degas strongly following a period with the beam off. It is thus not surprising that stainless steel should possess such good properties. One visualizes a surface consisting largely of chromium compounds which are possessed of large binding energies. It would be interesting to study materials such as titanium or zirconium which are quite outstanding in forming compounds which are not readily decomposed.

Questions which suggest themselves are:

1) On the basis of the preceding picture why does not the DE attain an equilibrium value under electron bombardment rather than diminish steadily.

(x) - The conclusions above which are based on measurements with 100 volt beams and 1 hour rest periods, are changed not at all qualitatively by the use of beams at other voltages or with rest periods of as much as 3 days. Studies at 20 and 100 volts lead to results which differ from those already reported by factors of less than two.

2) Why does the DE increase with increasing temperature of the surface?

3) Why does DE increase with ambient pressure? (see Section X).

These and other questions will be considered in a later section.

X. EFFECTS OF HEATING IN HYDROGEN UPON DESORPTION EFFICIENCY.

The original concepts had led us to the belief that the most desirable surface was that of a pure metal. This suggested the desirability of such treatments as heating in hydrogen in order to reduce surface compounds.

The effect of heating in hydrogen was first studied in system N. 2. Tank hydrogen was continually flushed through the system while the pressure was maintained at 1×10^{-6} torr. The system temperature was maintained at 280°C for 1 hour.

Prior to the above described hydrogen treatment $(\text{DE})_{20}$ was about $2,5 \times 10^{-6}$. Following the treatment the value was $2,0 \times 10^{-6}$. This reduction could be explained as being due to the normal decrease following further bombardment. A further study was made by operating with the test cylinder under electron bombardment at 300 volts for 90 minutes. The cylinder temperature was above 300°C during this run; the ambient hydrogen pressure was about 3×10^{-6} torr.

Since bombardment during this heating contributed to the decrease in DE it is not possible to separate the bombardment effect from the temperature effect. However, the decrease in $(\text{DE})_{20}$ from $1,9 \times 10^{-6}$, to $0,7 \times 10^{-6}$ as a result of this treatment, indicates that it has a useful effect.

The preceding tests were considered to be inconclusive for the following reasons.

1) Tank hydrogen was employed, this is known to be generally impure.

2) The surface studied, having been previously used for other studies, started at low DE values, so that further decreases were not only small but could not have their cause isolated between bombardment and heating in hydrogen: As a consequence, it was decided to start with a fresh surface and to proceed as follows:

1) Bake and process system as usual.

2) Make a 10 minute run at 20 volts in order to establish a reference, but without excessively reducing DE by bombardment.

3) Heat in pure hydrogen and then make a check run at 20 volts.

A flow of pure hydrogen was maintained through this system (N. 3) at a pressure of 3×10^{-6} torr. The system temperature was about 350°C . The measurements of $(\text{DE})_{20}$ before and after the hydrogen treatment are presented in Fig. 7. From this figure it appears that the hydrogen treatment most likely has a modest beneficial effect beyond that obtained with a simple vacuum bake. For such a system it is doubtful whether the added complexity of a further hydrogen bake is justified. However, as will be seen in the next section for highly contaminated systems the hydrogen treatment is highly beneficial.

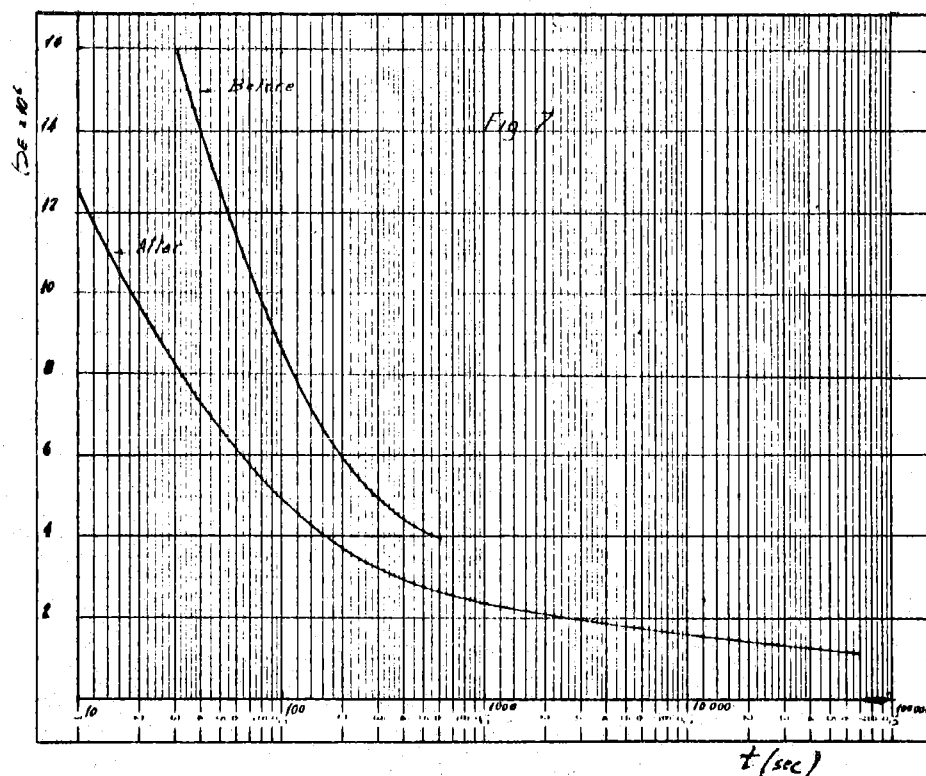


FIG. 7

XI. SURFACES WITH HIGH VALUES OF DESORPTION EFFICIENCY.

In the experiments with SS 304 described thus far for values of $(\text{DE})_{20}$ of the order of 1×10^{-6} were obtained fairly readily. However, much higher values have been reported by Garwin⁽¹²⁾. It appears that such high values may exist at this time in the Stanford Storage Ring. In one case such high values were observed by us. It will be of interest to relate how this surface came about and how it was restored to low DE values.

System N. 3 had been brought into a state where its DE value at 20 volts was about 2×10^{-6} . It was now planned to see whether exposure of the system to hydrogen at high pressure and subsequent pumpdown

and mild processing would restore the system to its former "good" state. Hydrogen at about 100 torr was admitted to the system for 2 hours. At this time it was found that the tantalum filament was burned out. Its replacement required opening the system to air. Immediately following pumpdown $(DE)_{20}$ was 5000×10^{-6} , decreasing to 900×10^{-6} in 5 minutes (the system pressure was high- 10^{-6} torr).

The system was now baked at 150°C for 4 hours. This procedure was based on reported observations that a system first exposed to hydrogen, and then air, could be restored to low pressure values (obtained previously after rigorous processing) by a low temperature bake of about 150°C .

The $(DE)_{20}$ now began at 5300×10^{-6} and diminished to 100×10^{-6} in 11 minutes. (Concurrently the pressure moved from the 10^{-6} torr to the 10^{-7} torr range). The system was now baked at 300°C for 3 days and the filament was well outgassed. Initial $(DE)_{20}$ was 200×10^{-6} (pressure in the 10^{-8} range). The values of $(DE)_{20}$ remained about ten times higher than that of the same surface after its original bake.

An examination of the history of this system now revealed that during its latest processing, it had been permitted to operate for some time with only a mechanical oil pump. (The turbomolecular pump should have been running during this period, but was not). It was speculated that oil may have gotten to the test surface and was responsible for the high DE values. It was then decided to subject the system to a treatment which, as reported privately by Garwin, was highly effective in reducing DE. This consisted of a 1 hour bake at about 300°C in hydrogen at about 10^{-6} torr followed by a similar treatment with oxygen.

Following the hydrogen treatment $(DE)_{20}$ (10 minutes after turning on the beam) was about 7×10^{-6} . This represented a decrease from the value before the hydrogen treatment by a factor of close to ten. The oxygen treatment now lowered $(DE)_{20}$ to below 2×10^{-6} , thus effecting a further reduction by a factor of about four.

It thus appears that contaminated stainless steel surfaces with high values of DE can be considerably improved by a modest bake in hydrogen and still further considerably improved by a modest bake in oxygen. It also appears that surfaces are adversely affected by oil contamination. Insurance against accidents involving possible contamination by pumping fluids can be effected by restricting oneself to pumps which do not employ fluids (such as sputter-ion pumps, cryopumps, sublimation pumps and sorption pumps).

XII. CONSIDERATIONS REGARDING THE PROCESSES OF GAS DESORPTION AND MEANS FOR ITS DEMINUTION.

From the preceding studies we can draw some conclusions regarding the processes of gas desorption.

It appears quite conclusive that with materials such as SS 304 we are dealing with an impure surface, very likely in the form largely of an oxide layer of the material constituents. Following the described processing, this impure layer is in the form of a monolayer whose impurity atoms are so tightly bound that they are not dislodged under the influence of the beam.

The bulk of the material contains impurity gas atoms. Under the influence of the thermal ambient, these atoms diffuse to the surface. When the beam is absent, these atoms largely evaporate at once, but a small fraction contribute to a slight increase in the coverage of the underlying metal. With the beam present, some of the atoms which contribute to the increase in coverage with the beam off, are desorbed. Thus we have a picture of a tightly bound surface layer which contributes little if anything to gas desorption under electron bombardment. Under electron bombardment, an equilibrium distribution of impurity gas atoms close to the surface is disturbed in that some of these atoms which are close to the surface are desorbed. Diffusion now brings new atoms to the surface which are now subject to desorption under electron bombardment. Under continuous bombardment, the density of impurity gas atoms near the surface falls off, thus accounting for the fall off in Desorption Efficiency with time of bombardment. The depletion of the surface layers is a nearly permanent process as is evidenced by the fact that, once a low value of DE has been achieved (after prolonged bombardment) it is easily reattained, even after long rest periods.

The increase of DE with temperature is now easily accounted for as being a result of accelerated diffusion towards the surface of the impurity gas content of the base material.

From these considerations we infer that the optimum surface is one which is covered by a monolayer of very high binding energy. This suggests the use of such materials as Chromium (as in Stainless steel), Titanium,^(x) Zirconium or Magnesium, all of which form strong oxides. In addition we wish to deplete the layers near the surface of their gas content. This suggests high temperature vacuum firing. It would appear to be least desirable to employ materials which do not

(x) - (Note at following page).

form strong compounds, and on which sorbed layers are weakly held. Such materials would behave badly following "rest" periods during which sorbed monolayers would form. Gold may be an example of such an undesirable base material.

XIII. SUMMARY AND CONCLUSIONS.

Studies were made for the purpose of determining the gas load which would be generated by the presence of a circulating electron (or positron) beam in a storage ring. The gas evolution is by a three step process involving first radiation by the accelerated beam, then photoemission by this radiation, and finally gas desorption when the photoelectrons strike the ring walls.

The radiation was computed; an upper limit was set upon the photoemission (quantum efficiency); and finally the gas evolution under electron bombardment was measured experimentally (Desorption Efficiency). The effects of prolonged bombardment, energy of electrons, and surface temperature upon the Desorption Efficiency were studied.

The following conclusions have been drawn.

1) Stainless steel N. 304 is a satisfactory base material for storage ring fabrication. It can be readily processed by combination of chemical cleaning and subsequent moderate bakeout to result in acceptable characteristics in so far as gas evolution in the presence of a stored beam is concerned.

2) Desorption Efficiency (DE) of SS 304 diminishes rapidly under electron bombardment at electron voltage of 20 volts or higher, to yield values within one day, which are several times lower than is needed for stored beam operation.

(Note added in proof)

(x) - Tests in a new system (n.4) appear to confirm these speculations. This stainless steel system was built so that titanium could be sputtered upon the test surface. Results on the stainless steel prior to sputtering were in substantial agreement with those previously reported. Following the sputtering there was a dramatic drop in DE. Due to faulty design the currents were severely space charge limited. As a consequence the DE at 20 volts was below the measurable limit. It was certainly less than 3×10^{-7} and may have been as low as 1×10^{-7} . The DE was measured at 100 volts and found to be 3×10^{-7} . The system is being rebuilt to make possible more accurate data.

3) Increase of surface temperature results in increase of DE but not to an extent which will be troublesome with readily maintainable temperatures.

4) Hydrogen cleaning has little effect in reducing DE for SS 304 which has previously been cleaned chemically followed by a vacuum bake.

5) Exposure to oil in the vacuum system causes a very large increase in DE. This contaminated surface is not improved enough by the bakeout found adequate for a chemically cleaned surface. It can be put into an acceptable state by heating first in hydrogen and then in oxygen.

6) The most desirable surfaces appear to be ones which form strongly bound compounds very likely in the form of monolayers. Such surfaces appear to those of compounds of Chromium, Titanium and Zirconium are also very likely good base materials.

8) It is very likely desirable to vacuum fire the ring material at elevated temperatures (say 1000°C) in order to deplete the regions near the surface of contained gas.

APPENDIX I

RECOMMENDED EXPERIMENTS.

The work described in the body of this report while most likely sufficient to permit the design of the Adone storage ring to go forward, should be supplemented by a number of other experiments. Aside from clarifying some of the doubtful points in the work to data, they will contribute to more sophisticated designs of future storage rings. These suggested experiments will now be presented seriatim.

1. Desorption at Electron Exit.

Studies should be made of the gas desorption when the photoelectrons emerge from their source material. This should be done at several wavelengths between 5 and 500 Å.

2. DE of Different Materials.

Materials other than SS 304 should be studied. This can include materials other than those suitable for vacuum chamber walls, since it is not necessary that the photoemission and gas desorption take place from the storage ring walls. Possible study materials of interest are titanium, chromium, magnesium, aluminium, gold, platinum, copper, nickel, nichrome, tungsten, molybdenum, tantalum, and carbon. In some cases the studies should be made with evaporated or sputtered layers.

3. Cleaning by Gas Discharge.

Studies should be made in which surface layers of the material to be studied are sputtered away.

4. Hydrogen and Vacuum Firing.

Studies of hydrogen and vacuum firing and combinations thereof should be carried out, particularly at elevated temperatures.

5. Exhaust Procedures.

Effect of length and temperature of exhaust should be studied.

6. Formation of "Strong" Compounds.

Studies should be made of tightly bound surface layers. Thus, for example, a test could be made of the properties of a film formed by

first evaporating titanium and then oxidizing it.

7. Temperature and Pressure Effects.

Further studies of the effects of these two parameters should be carried out.

8. Angle Effects.

The effect of angle of incidence of the radiation upon quantum efficiency and of the angle of incidence of the incident electrons upon the Desorption Efficiency should be studied.

APPENDIX II

RECOMMENDED PROCESSING FOR ADONE STORAGE RING.

On the basis of experiments to date it is recommended that the Adone storage ring be processed as follows:

- 1) Chemical cleaning by present Frascati Laboratory techniques.
- 2) Firing in hydrogen at 1000°C.
- 3) Vacuum firing at 1000°C.
- 4) Fill with Argon

APPENDIX III

DEPENDENCE OF THE OUTGASSING-RATE ON THE STORED BEAM ENERGY.

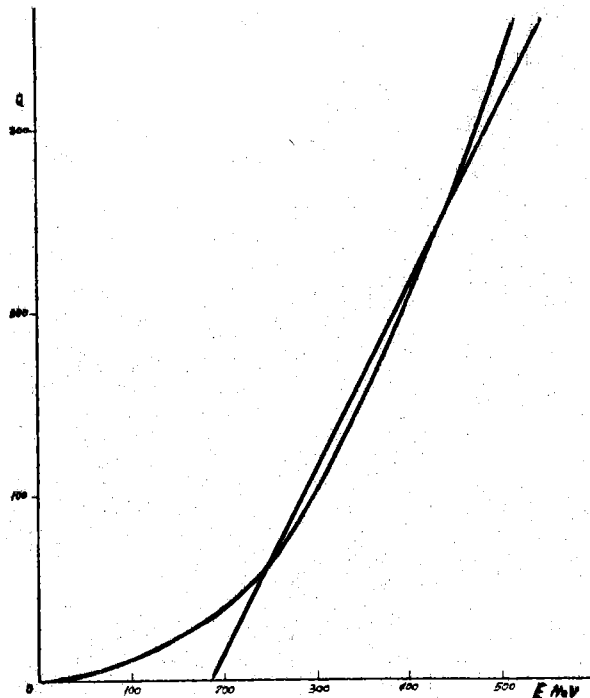
Some experiments performed with the Stanford Ring indicate that, between 300 and 500 MeV circulating beam energies, the outgassing-rate versus beam energy can be fitted with a $E^{2.5}$ law.

According to the calculation we give in this report, the main energy dependence is contained in the photon number formula. If we consider for instance the approximate formula (eq. 17) we obtain for the outgassing-rate

$$(22) \quad Q \propto E_{\text{MeV}} \left[1 - \left(\frac{\lambda_c}{\lambda_\alpha} \right)^{1/3} \right]$$

This last equation, conveniently rewritten, becomes

$$(23) \quad Q \propto (E_{\text{MeV}} - 165 R_0)^{1/3}$$



with R_0 radius of curvature of electron path in meters (at Stanford $R_0 = 1,4$ m).

Fig. 8 shows that in the range $300 \div 500$ MeV, the $E^{2,5}$ law and the law given by eq. (23) (arbitrary units) are very similar; our conclusion, supported by the results here reported on the energy dependence of DE, is that the outgassing-rate should have small deviations, if any, from a linear dependence upon beam energy.

FIG. 8

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