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REFURBISHMENT OF THE VACUUM SYSTEM OF THE BROOKHAVEN ALTERNATING GRADIENT SYNCHROTRON*

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INTRODUCTION

Three years ago a program was initiated at Brookhaven National Laboratory to upgrade the Alternating Gradient Synchrotron (AGS) vacuum system. The three objectives of this work are to: 1) improve the vacuum system reliability; 2) improve its maintainability; and, 3) improve its operating pressure from the present $2 - 3 \times 10^{-7}$ Torr to $< 10^{-8}$ Torr.

Figure 1 is a schematic representation of the AGS. The 250 m diameter accelerator is divided into 24 vacuum sectors. Each vacuum sector is subtended by isolation valves. Vacuum sectors are rough pumped with dedicated turbomolecular pump systems. Approximately 275 sputter-ion pumps are distributed about the AGS. These pumps subtend each of the 240 alternating gradient magnet chambers, and are also used to pump a variety of beam component apparatus located about the 'ring". The vacuum instrumentation and controls electronics are located in three equipment "houses" situated within the center of the accelerator.

At the start of this program, most of the vacuum system hardware and design technology were more than twenty years old. Improving the reliability and maintainability of the vacuum system have the obvious advantages of reducing operating costs and increasing experimental physics operating time. This is a fiscal trade-off. Better reliability and maintainability also result in reducing the radiation exposure of all maintenance personnel.

There appears to be a direct correlation between the reliability and maintainability of the accelerator vacuum system and it's operating pressure. The use of elastomers and plastics in vacuum applications is one example, worn out flange clamps and marginal seals, another. The reliability of the designs of beam components, such as magnetic and electrostatic septa, tune magnets, "kickers", flags, etc., all impact on the quality of the vacuum. Plastic insulator materials are used in many of these components, as well as in beam pick-up electrodes and current monitors. Many of these large beam component chambers are sealed with elastomers. The three improvement objectives require this be changed. In the interim period, when these components must be replaced or repaired, outgassing from the elastomers, on subsequent pumpdown, dominates the average pressure of the AGS for days.[1]

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A seemingly innocuous ele...rical circuit, external to the vacuum system, serves as another example of the correlation between the reliability of seemingly extraneous hardware and the system pressure. Because of eddy current effects in the alternating gradient magnet chambers, it is necessary to electrically isolate one chamber from another by use of porcelain enamel coated flanges (see Fig. 2). These enamel coated flanges present unique sealing requirements.[1] Without the use of beam image current "passing circuits", electrical isolation of the flange pairs would cause longitudinal beam impedance mismatches. In the past, one end of the flying leads of these passing circuits was secured to the flange clamps. The other end was attached, downstream of the flange, with finger stock which was jammed between the convolutions of the beam chamber bellows. This latter electrical connection was unreliable. After many years of use, some of the finger stock electrical discharge machined small leaks in the chamber bellows, resulting in serious problems. As part of the vacuum system improvement program, these external electrical circuits had to be replaced. A CERN PS passing circuit design was essentially copied, and new hybrid circuits were purchased and installed in 1988.[2]

PRESSURE REQUIREMENTS

The AGS is presently used to accelerate fully stripped oxygen and silicon, protons and polarized protons. On completion of construction of a new Booster accelerator, it will be possible to operate the AGS with much higher intensity proton beams, and accelerate heavier ions, including Au^{+33}.[3] The Booster operating pressure will be $< 10^{-10}$ Torr, comprising predominantly hydrogen. This low operating pressure is required because of the electron capture cross sections of the heavier, highly stripped, low energy ions. The Booster will inject Au^{+33} into the AGS at $\approx$ 300 MeV per nucleon. Some believe that at this energy, the electron capture cross section for Au^{+33} will be inconsequential, and the existing AGS operating pressure is adequate in this application. Others are less confident.

Current scaled data on electron-capture cross sections are given by Schlachter,[4] et al. These data are reported as valid for energies ≤ 8 MeV/nucleon. Cross section, σ_i, for species "i" target gas is given by the following equation:

$$\sigma_i = aq^{3.9} Z_i^{4.2}/E^{4.8}, \quad (1)$$

where
- a = is a constant of proportionality, 1.1×10^{-8},
- q = the charge state of the accelerated particle,
- Z_i = the atomic number of species "i" target gas,
- E = the kinetic energy of the accelerated particle (keV).

The electron-capture cross section varies as a function of the distance, x, which the particle travels in the accelerator. That is,

$$N_i\sigma_i = N_i Z_i^{4.2} q^{3.9} f(E(x)) \quad (2)$$
$$= \Psi_i f(E(x))$$
$$E(x) = E_0 - x(dP/dt) \quad (3)$$

and, E_0 = the initial kinetic energy of the beam particles,
dP/dt = the rate of change in momentum of the beam particles,
x = the distance traveled in the machine (cm),
N_i = the density of "i" gas (particles/cm^3).

Total beam intensity, I(x) as a function of x is found by solution of (4), which assumes "n" separate gas species in the AGS.

$$\int dI(x)/I(x) = -\int \sum_{i=1}^{n} \Psi_i f(x)dx \quad (4)$$

$$I(x) = I(0)\exp[-(\Psi_1 + \Psi_2 - ... + \Psi_n)\,\Phi(x)] \quad (5)$$

Equation (4) has the solution given in (5), assuming the exponents of both Z_i and "q" are <u>not</u> energy dependent. For gas species "i", $\Psi_i\Phi$ is simply:

$$\Psi_i\Phi(x) = \frac{a N_i q^{3.9} Z_i^{4.2}}{3.8\ dP/dt}\left[E_0^{-3.8} - (E_0 + x\,dP/dt)^{-3.8}\right]. \quad (6)$$

The invariance of "q" and Z_i with energy need not be assumed in evaluation of the integral leading to (5). That is I(x) could take the form:

$$I(x) = I(0)\exp[-(\Psi_1(x) + \Psi_2(x) + ... + \Psi_{n+1}(x))\Phi(x)], \quad (7)$$

where $\Psi_{n+1}(x)\Phi(x)$ is the capture cross section of, say, the test gas.

A cursory check was made of (7) for Si^{+14} on CO_2 at an average AGS pressure of $\approx 5 \times 10^{-8}$ Torr.[5] Energy at injection was $\approx$ 6.38 MeV/nucleon. The change in momentum with time, dP/dt, $\approx 2.5 \times 10^{-17}$ kg m/sec^2. Results of this test are given in Fig. 3, along with calculated beam intensity, assuming (1) applies at the higher energies. Calculated data are also given in this figure, assuming a cross section dependency of $q^{4.1}$ and $E^{-5.0}$. This change results in close agreement with measurement. It appears that the electron capture cross sections of Si^{+14} on CO_2 are slighyly less than predicted by (1). This simple test demonstrated that there are presently significant beam losses due to gas in the AGS, when injecting heavy ions. It is hoped that more refined measurements will be possible in the near future, using various gases and both silicon and oxygen beams. In the interim period, it is prudent to assume that pressures $< 10^{-8}$ Torr will be required during injection of the much heavier ions in the AGS.

METHODOLOGY AND DIAGNOSTIC TOOLS

The approach used to meet the three vacuum system improvement objectives was the simple, but arduous task of "bookkeeping"; that is, attempting to identify all of the "sources and sinks" of gas in the AGS, and then balancing the ledger to meet the new objectives. Materials used in all equipment within the vacuum envelope of the AGS are being assessed for outgassing, and designs implemented which remedy the uncovered problems.

A new vacuum Instrumentation and Control (I&C) system, commissioned in 1988, was used to diagnose sources of gas throughout the AGS.[6] This I&C system is schematically represented in Fig. 4. With the exception of local control chassis, all of the vacuum I&C system electronics are located in the three equipment "houses". The "devices" in the houses are essentially the power supplies which energize the sputter-ion pumps and gauging. A sputter-ion pump reports both the voltage and current upon interrogation by device controllers, also located in the houses. Penning and Pirani gauge power supplies likewise report pressure to the associated device controller. Other equipment, located within the ring, are binary on-off, open-closed type devices (e.g., valve actuation and position). These communicate directly with the device controllers through interface cards in "buckets".

The device controllers communicate with the "stations" located in each house. Both are microprocessor-based systems. The stations serve three purposes: 1) they set the time, relative to the AGS cycle, at which data are uploaded to the station from the associated device controllers; 2) they store data which are available if and only if they are interrogated; 3) they alert the Apollo computers with alarm messages identifying exceptional conditions. The stations make the comparison of the reported conditions vs. the standard condition. Data uploading by the stations is made asynchronous with the AGS cycle. Therefore, electromagnetic interference due to rf or active beam components may be "blanked out".

The Apollo computer only serves as the user/system interface. Apollo nodes are conveniently located about the AGS complex. From these nodes the user may monitor and control the status of any vacuum component. Alarm statuses, resident in the stations, may be compiled and reported by the Apollo. Additional features of this system include:

A. Logging of sputter-ion pump pressures at four levels - the highest level is one entry every 15 minutes for 48 entries; the lowest level is one entry per week for the last 52 weeks.
B. Real time data sheet displays of gauge and sputter-ion pump pressure, and the status of devices every AGS cycle.
C. Graphics displays of individual sputter-ion pump pressures for any combination, or all of the vacuum sectors of the AGS.
D. Graphics displays of logged pressure data.
E. Automatic vacuum sector roughing and sputter-ion pump starting.

This system has been used for diagnosis of active beam component problems. For example, Fig. 5 is a representation of a "real time" display of beam-induced heating of ferrite materials in a tune meter. As another example, multipactor in an rf cavity was verified by retrieving "logged" pressure data from a particular station (i.e., Fig. 6). The multipactor problem is easily remedied[7], as was the ferrite heating problem, once it was identified.

THE LEDGER OF GAS SOURCES AND REMEDIES

As mentioned, unreliable vacuum seals proved to be a major problem in the AGS. This problem is probably behind us.[1] The magnitude of the outgassing of the numerous beam components and instruments was quantified both in situ, using the new I&C system, and individually. With few exceptions, the major problem with these pieces of equipment has its origin in the use of plastic insulators within the chambers and the use of elastomers for the very large vacuum seals on many of these "boxes".

Outgassing rates for several materials were quantified in formulating technical arguments for the modifications of designs. These results are given in Table I. Without exception, the design fixes were simple to implement. For example, most of the Viton® seals are being replaced with metal vacuum seals. The plastics, are being replaced with Al_2O_3 materials.

Some equipment designs were not suited for use in a sputter-ion pumped system. For example, a beam "flag" drive shaft was sealed in one application using a double o-ring, grease packed seal. The fix merely involved the use of a welded bellows, sealed shaft. Another simple remedy involved the use of a curved "knife-edge" seal to attach large diameter, thin-foil "windows",[8] rather than using elastomer gaskets. A partial summary of the "bookkeeping" of the source findings, and estimated improved performance of the modified designs are summarized in Table II. Of course, system leaks and contamination levels are difficult to quantify. For example, the improper use of turbomolecular pumps caused considerable oil contamination of the AGS in the past. Features of the new I&C system now prevent this from happening.

PUMPING REQUIREMENTS

The pumping speed of an existing, baked AGS sputter-ion pump was determined to be negligible at 10^{-9} Torr, 25ℓ/sec at 10^{-8} Torr and 47ℓ/sec at 10^{-7} Torr, N_2. This rapid fall-off in pumping speed stems from the small, pump anode cell size. The drop in pump speed precludes achieving pressures much less than 10^{-7} Torr in the unbaked AGS system. New sputter-ion pumps are being purchased with cells of much larger diameter and length.[9] Noble diodes were selected for this application. It was specified that the speed of these pumps had to be ≥100ℓ/sec at 10^{-8} Torr. Speed data for the present AGS pumps and the new pumps are shown in Fig. 6.

Because of beam chamber eddy current effects, the sputter-ion pumps, operating at ground potential, must be electrically isolated from the beam chambers. Pumps are being purchased with Marmon-type flanges to facilitate quick installation or replacement in the AGS. The mating flanges on the beam chamber will be porcelain enamel coated. The pumps, when received from the vendor, will be under vacuum. They will have a welded flange joint which can be "pealed" off (see Fig. 7). After the weld bead is pealed off the flange, the edges of the flange will be "touched up" with a file. The pump will then be tested and installed in the AGS. Helicoflex Delta® vacuum seals are used with this enamel coated and conventional flange pair, and in most new sealing applications in the AGS.

RESULTS OF THE BOOK KEEPING

The data in Table II may be summarized into three datum for before and after the refurbishment program. If these are plotted on log-log paper, a very slight curvature of both functions is noted. This is to be expected, as the functions are the superposition of the outgassing of elastomers and metals. However, each set of data may be closely approximated by a straight line, when plotted. This results in the two functions representing the sum of the all of the outgassing, $\sum Q(t)$, which are crudely represented by:

$$\sum Q(t) = q_o (t/t_o)^m \qquad (8)$$

q_o = the outgassing rate at, say 10 hours,
t_o = 10 hrs.,
m = the slope of the given $\sum Q(t)$ on log-log paper.

Speeds as a function of pressure S(P), of both the present (subscript "b") and new (subscript "a") unbaked pumps may be approximated by two equations:

$$S_b(P) = k_1 \ln(P/P_1) + k_2 \ln(P/P_2) \qquad (9)$$

$$S_2(P) = k_3 \ln(P/P_3) + k_4 \ln(P/P_4) \qquad (10)$$

where, the k_i's are constants in ℓ/sec and the P_i's are two "blank-off" pressures for each function, in Torr. Values chosen for the constants, with increasing values of "i", are k_i is 1.37, 9.99, 7.24, and 8.68 ℓ/sec, respectively, and P_i is 10^{-9}, 10^{-8}, 10^{-9}, 10^{-10} Torr, respectively.

These assumptions, and the assumption that the outgassing rate is not pressure-dependent, suggests that in approximately one year, the present system, in the absence of contamination and leaks, would have a base pressure of $\approx 3.3 \times 10^{-8}$; the refurbished system, a pressure of $\approx 2.0 \times 10^{-9}$ Torr.

CONCLUSIONS

It has been shown that beam losses are significant due to electron capture during Si^{+14} injection into the AGS. The Booster will eventually inject heavy ions into the AGS at much higher energies. Improving the quality of the AGS vacuum will give added insurance of minimum beam losses. The objectives of higher reliability, better maintainability, and lower AGS operating pressures are being met by the systematic assessment and reconciliation of system sources and sinks. Because of the size and complexity of the system, there are no "quick fixes" in this process; just the use of more current technology and arduous "bookkeeping". Dividends are being realized in machine operating hours. For example, the AGS "down time" due to vacuum system failures in the last five years, starting with 1985, has been 188, 129, 33¼, 38 and 17¼ hrs., respectively. Neglecting possible electrical failures of components in the new I&C system, the machine "down time" should be negligible.

The first phase of refurbishment involved the design, construction and commissioning of the vacuum I&C system. The second phase was to establish reliable metal sealing technology, including seals and clamps, and implementation of a plan for the identification and elimination of most of the plastics and elastomers in the AGS. The third phase was to incorporate more current technology for vacuum penetrations and valving. The last emphasis will be on refurbishing all alternating gradient magnet beam chambers and installing new sputter-ion pumps with higher speed at the lower pressures.

ACKNOWLEDGMENTS

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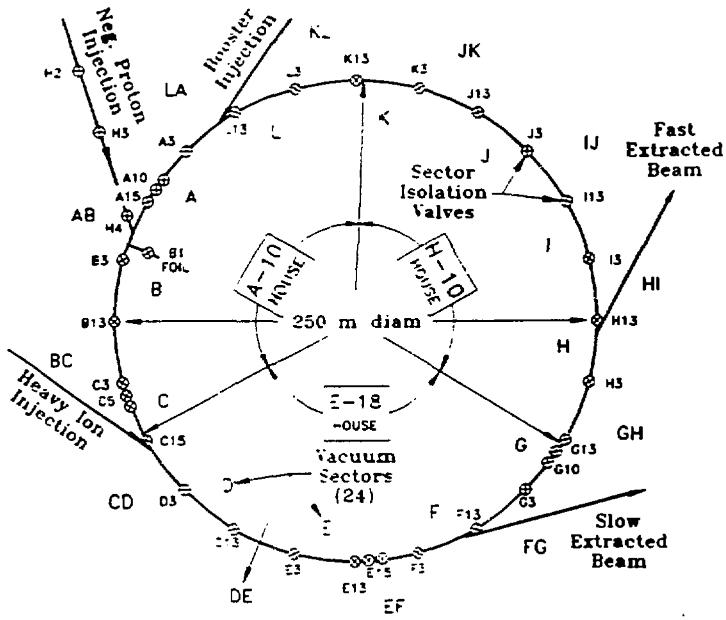

Figure 1. Schematic Representation of the AGS Vacuum System.

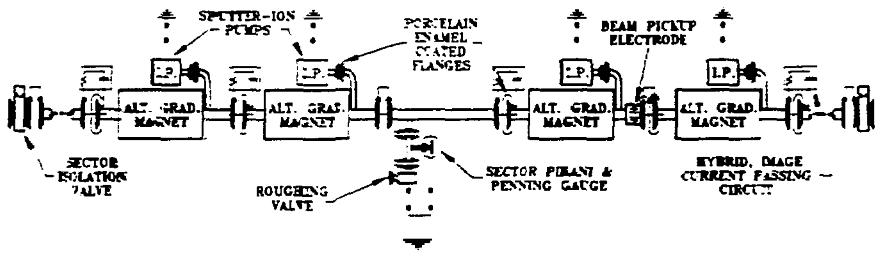

Figure 2. Schematic Representation of One Variety of AGS Vacuum Sector.

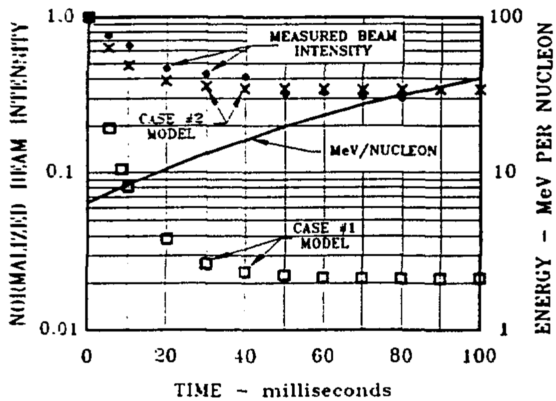

Figure 3. Measured and Calculated Si^{+14} Beam Intensity vs. Time.
Measured Intensity for CO_2 Pressure of 5×10^{-8} Torr.
Case #1: Calculated Assuming Cross Section Varies with $q^{3.9}$ & $E^{-4.8}$.
Cast #2: Calculated Assuming Cross Section Varies with $q^{4.1}$ & $E^{-5.0}$.

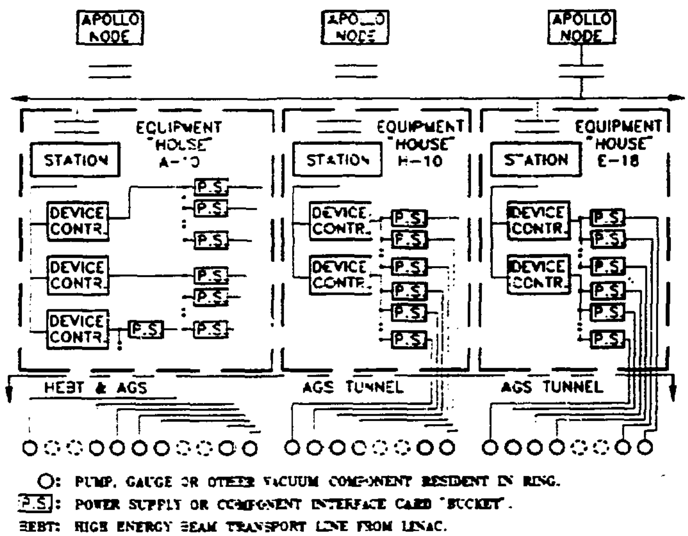

Figure 4. Schematic Representation of the AGS Vacuum Instrumentation and Control System.

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2, 2

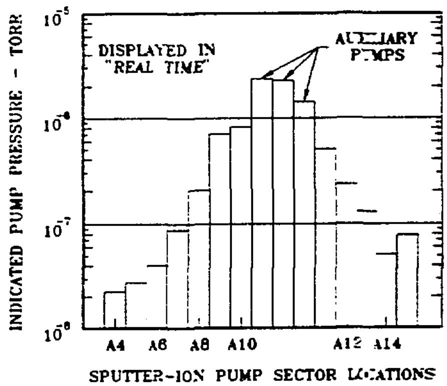

Figure 5. Example of AGS Vacuum Sector Pressure Profile Stemming From Beam Induced Heating of Ferrite Materials and Elastomer Seal Outgassing.

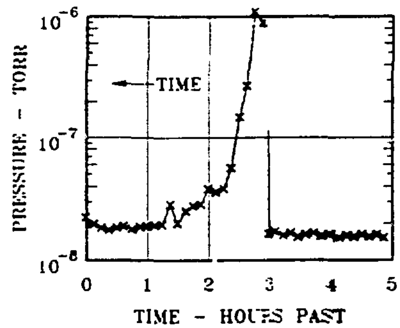

Figure 6. Data, Automatically Logged by the I&C Ststem, of RF Cavity Multipactor Effects on the Proximate Sputter-ion Pump Pressure.

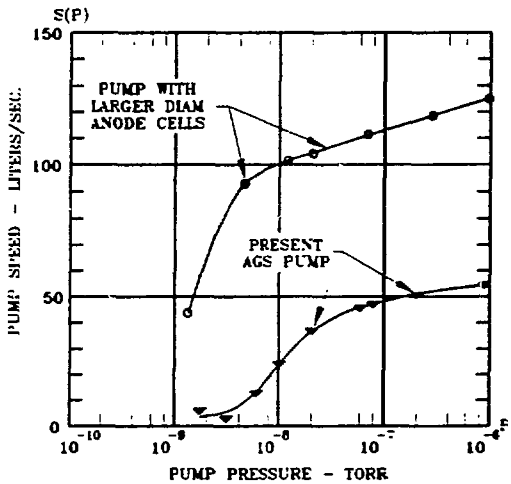

Figure 7. Nitrogen Speed as a Function of Pressure for the Present and Newly Specified AGS Sputter-ion Pumps.

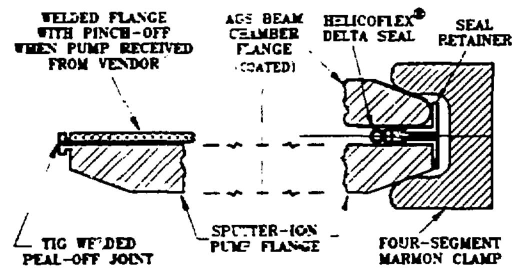

Figure 6. Pump and Flange as Provided by Vendor With Peal-off Flange, and Later Shown Adapted to AGS.

Table 1. Summary of Outgassing Rates as a Function of Time of a Number of Materials Used in Beam Components Apparatus.

MATERIAL	OUTGASSING RATE FOR HOURS PUMPING – TORR-L/sec cm^2			NOTES
	10 hr	100 hr	1000 hr	
VITON-A® O-RINGS	5.0×10^{-7}	1.3×10^{-7}	3.5×10^{-8}	1
BUNA-N® O-RINGS	2.8×10^{-6}	3.5×10^{-7}	4.0×10^{-8}	1
GRAPHITE BLOCK	3.0×10^{-8}	2.5×10^{-9}	2.0×10^{-10}	1
Al_2O_3 FLAG MATERIAL	1.3×10^{-6}	2.5×10^{-10}	6.5×10^{-12}	1
CERAMIC RESISTORS	2.5×10^{-8}	2.1×10^{-9}	1.0×10^{-10}	1
RADELIN FLAG MAT'RL	2.2×10^{-6}	8.0×10^{-8}	2.4×10^{-8}	1,2
RADELIN FLAG MAT'RL	1.2×10^{-7}	6.0×10^{-9}	2.4×10^{-10}	3
REXOLITE® INSULATOR	8.7×10^{-7}	2.2×10^{-7}	4.5×10^{-8}	1,4
VESPEL® INSULATOR	1.7×10^{-6}	4.0×10^{-7}	5.3×10^{-8}	1,5

NOTES: 1) As received; wiped with methanol and dried.

2) A plastic-like material, of unknown composition, with CdS activator.

3) Vacuum baked at 100 C for 24 hr, vented to atmosphere for several hours; then tested.

4) A form of polystyrene.

5) Fabricated from a polyimide resin.

Table II. Examples of Component Outgassing Rates Before and After the Refurbishment of the AGS Vacuum System.

SOME ACCELERATOR COMPONENTS AND EQUIPMENT QUANTIFIED	FORMER OUTGASSING RATES Torr Liters per Second			PREDICTED OUTGASSING RATES Torr Liters per Second		
	10 hr	100 hr	1000 hr	10 hr	100 hr	1000 hr
FERRITE TUNE-METER	7.1×10^{-4}	1.9×10^{-4}	4.1×10^{-5}	3.3×10^{-6}	6.5×10^{-7}	6.5×10^{-8}
BEAM SCRAPER	4.2×10^{-4}	1.1×10^{-4}	2.6×10^{-5}	6.2×10^{-5}	6.4×10^{-6}	5.4×10^{-7}
ION PROFILE MONITOR	2.7×10^{-4}	7.0×10^{-5}	1.6×10^{-5}	1.2×10^{-4}	2.0×10^{-5}	4.2×10^{-6}
POLARIMETER "BOX"	4.7×10^{-4}	1.2×10^{-4}	3.2×10^{-5}	7.6×10^{-5}	2.0×10^{-5}	4.6×10^{-6}
MAGNETIC SEPTUM	2.7×10^{-4}	7.3×10^{-5}	1.5×10^{-5}	8.3×10^{-6}	1.5×10^{-6}	1.5×10^{-7}
ELECTROSTATIC SEPTUM	2.0×10^{-4}	5.8×10^{-5}	1.4×10^{-5}	5.8×10^{-6}	1.1×10^{-6}	1.0×10^{-7}
"SECTOR" VALVE (32)*	3.8×10^{-4}	6.2×10^{-5}	1.4×10^{-5}	1.6×10^{-4}	1.9×10^{-5}	2.7×10^{-6}
HEAVY ION INFLECTOR	2.4×10^{-4}	6.0×10^{-5}	1.4×10^{-5}	7.2×10^{-6}	1.1×10^{-6}	1.0×10^{-7}
AGM CHAMBER (168)*	2.2×10^{-6}	2.7×10^{-7}	3.5×10^{-8}	2.2×10^{-6}	2.7×10^{-7}	3.5×10^{-8}
AGM CHAM w/PUE (72)*	8.8×10^{-6}	1.1×10^{-6}	1.4×10^{-7}	4.4×10^{-6}	5.5×10^{-7}	6.7×10^{-8}

*Outgassing rate of one component. Total number of components in parentheses.