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FOURTH QUARTERLY PROGRESS REPORT

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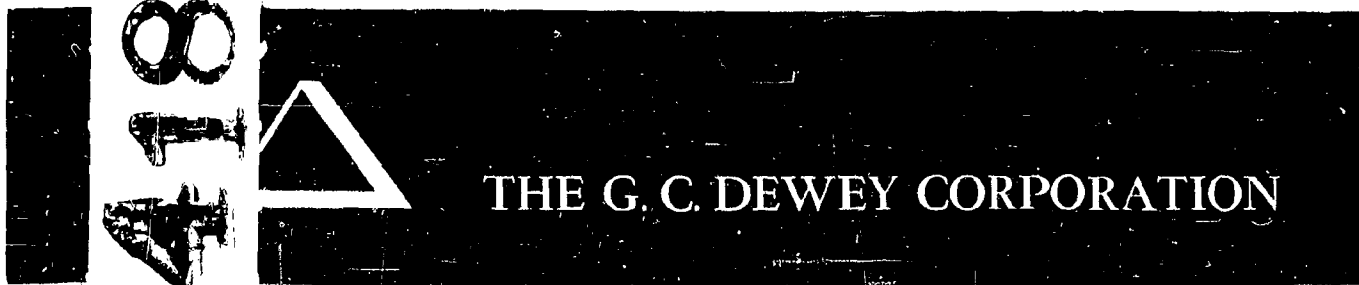
UNDER THE TECHNICAL SUPERVISION
OF THE ATOMICS BRANCH OF
THE APPLIED PHYSICS DIVISION
U. S. ARMY SIGNAL RESEARCH AND
DEVELOPMENT LABORATORIES
AT FORT MONMOUTH

by

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(6) AN EXPERIMENTAL INVESTIGATION OF
THE EFFECTS OF RADIATION ON THE PROPAGATION
OF ELECTROMAGNETIC SIGNALS IN AIR.

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I. INTRODUCTION

The present report covers work performed during the period 1 April to 30 June, 1962. During the period, the equipment was brought to a state of usability, and some very preliminary data were obtained, as anticipated in the earlier reports. As explained in Chapter III, the first measurements were performed on room air rather than oxygen, as originally anticipated.

It must again be emphasized that at this early stage in the program, the data are not yet reliable enough to provide insight into the physical processes occurring in ionized air. Rather, the measurements should be considered a test of the operation of the equipment and the reproducibility of the system and the phenomena.

Chapter II of this report describes the present status of the experimental equipment and the modifications still required. In Chapter III the results of the first measurements are shown, and some very general results drawn from them. The report closes with a discussion, in Chapter IV, of the plans for the next quarter.

II. EXPERIMENTAL EQUIPMENT

A. Introduction

The experimental effort in this quarter has been aimed at developing the whole system to a workable condition rapidly rather than perfecting any one piece of equipment. It was felt that flaws in the apparatus which might not otherwise be apparent would show up while running these first experiments. Therefore as soon as the major leaks in the welds were repaired, an aluminum foil was placed between the cavity and the beam tube and the cavity rf characteristics were checked.

The cavity's principle TE_{011} mode was found to lie at 390 Mc/sec in good agreement with theory. The rf bridge described in the third quarterly report was constructed for frequency shift measurements with the cavity under continuous electron bombardment. Although the Q of the cavity has not been measured accurately at this time owing to its very large value, an estimate of the loaded Q using a wavemeter and modulation markers (see E below) gives $Q_L \approx 11,000$.

With the two parts of the vacuum system separated by the aluminum foil, pressure readings in the beam tube were made on the Philips Gauge of the Van de Graaff. This gauge indicated a pressure of 8×10^{-6} mm of mercury. The pressure in the cavity was 6×10^{-6} mm of mercury, as measured on a nude ionization gauge mounted in the back of the cavity behind the internal backplate. With the cavity sealed off from the vacuum pumps by the 6" Cooke valve, its pressure rises by a factor of 10 in 30 minutes.

Dry air was let into the cavity through the glass filling system; the filling system has a liquid nitrogen cold trap at the valve to the air through which air can be admitted to the system. Enough air was let into the cavity to raise the pressure to about 1 mm of mercury. Then a 350 μ ampere beam of electrons at 1.5 MEV was projected down the beam tube, through 0.5 mil beryllium foil

mounted in an aluminum holder beyond the Van de Graaff generator, into the cone, through the aluminum foil, and finally into the air-filled cavity. A frequency shift in cavity resonance of 0.34 Mc/sec was observed.

This experiment demonstrated the feasibility of the experimental technique but also pointed out several difficulties in the apparatus. The vacuum in the cavity was not as good as it should have been; there was too much gamma radiation in the Van de Graaff control room, in the areas where the experimenters themselves are, and in the room overhead (radiation going up through the overhead hatch). In the next sections the solutions to these problems will be explained.

B. Vacuum

The construction of the vacuum vessels was completed early in the quarter. They were leak tested with a Veeco MS 9A Leak Detector, a permanent equipment in the laboratory; leaks were found at the welded joints to the tubulations holding the nude ionization gauge, 6" Cooke valve, and capacitance manometer. These were ground out and rewelded. Further testing revealed leaks in the bellows seal of the Cook valve, and at the weld holding this valve to the cavity where it had leaked before. The bellows assembly was sent back to the factory to be repaired and the weld was temporarily sealed on the outside with Apiezon Q wax.

At a pressure of about 6×10^{-6} mm of mercury electron bombardment of the empty cavity was attempted. It was found to increase the pressure in the cavity to about 5×10^{-5} mm Hg, thus holding out hope that this technique can be used to clean the walls as is done in some electron tube manufacturing.

When the first experiment, described in the introduction to this section, was completed, the cavity was taken apart, the walls cleaned with hydrochloric acid, water, and finally acetone. The weld to the Cooke valve was ground out and a new seal was welded on the outside

of the cavity where a better vacuum seal could be made. The zeolite was changed and it was determined that in all future zeolite bakeouts a lower bake temperature must be used, and the Chevron baffle immediately below the zeolite trap must be cooled.

A second series of experiments was then begun. The cavity was assembled and evacuated. A record was made of this pumpdown from which the effective speed of the roughing pump can be determined. Figure 1 is a plot of pressure versus time. Using this plot and the formula

$$-\frac{dP}{dt} = \frac{S}{V} (P - P_s) \quad (1)$$

where P is pressure, P_s the ultimate pressure of pump, S the speed of the pump, and V the volume of the system to be pumped (214 cu.ft.), a value of S can be obtained. Integrating equation (1) gives

$$\frac{\Delta \log (P - P_s)}{\Delta t} = \frac{S}{2.303V} \quad (2)$$

In our case Equation (2) yields S equal to 66 cu. ft./min. for the straight line portion of $\log P$ versus t in Figure (1). This may be compared to the manufacturer's rating for the pump alone of 80 cu. ft./min.

The roughing pump evacuated the system to a pressure of 40 microns of mercury in 50 minutes, at which time the zeolite trap was baked for 3 hours. While the zeolite cooled, the oil diffusion pumps were turned on. In one hour the pressure in the cavity was 2×10^{-5} mm of mercury.

To date, the lowest pressure reached in the cavity has been 4.5×10^{-6} mm Hg. Even admitting that the system has not yet been baked, this is still not a satisfactory pressure. For several reasons, it is felt that the pressure is limited by out gassing of zeolite in the pump baffle. First the rate of pressure rise in the cavity when shut off from the pump is of the order of 10^{-4} mm Hg/hour.

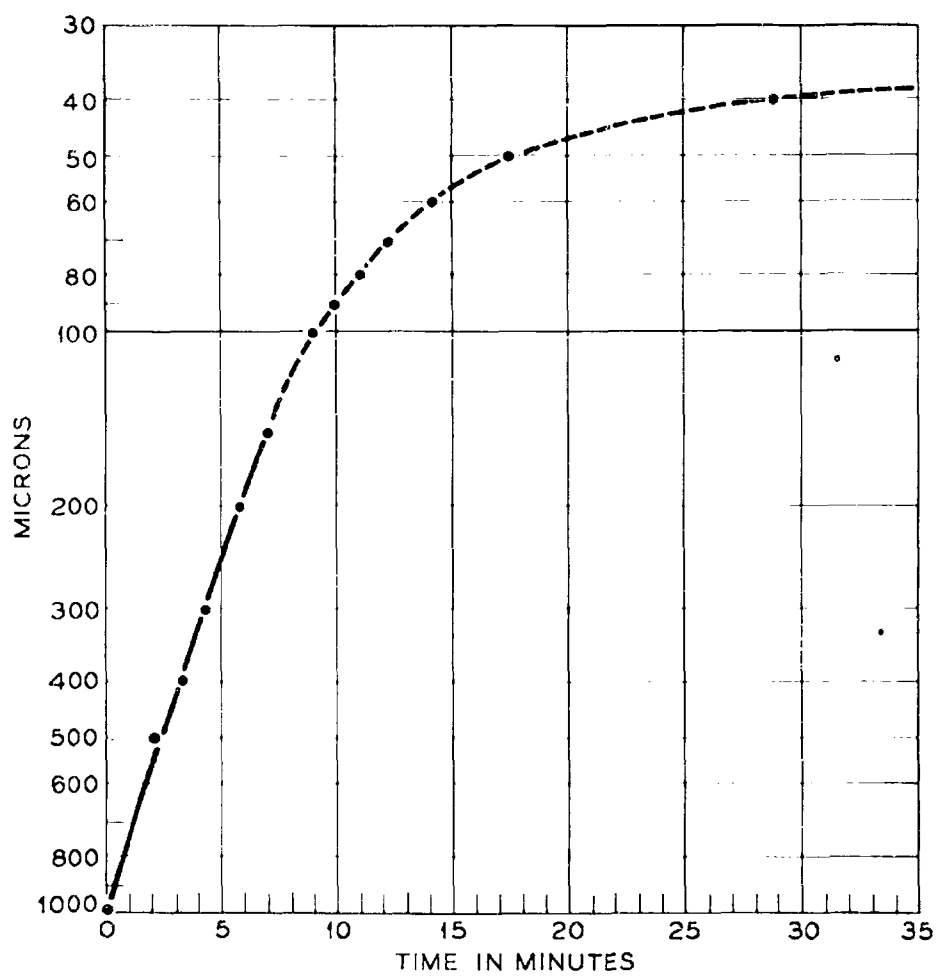


FIGURE 1
FOREPRESSURE VERSUS TIME FOR A TYPICAL PUMPDOWN

A simple calculation indicates that a pump speed of the order of 10 liters/sec would suffice to maintain the 700 liter cavity at 5×10^{-6} mm Hg if this were the only gas load. Our pump has an effective speed of about 500 liters/sec. During the rate-of-rise test, of course, the zeolite baffle is isolated from the cavity by the 6" valve, and its contribution to the gas load is not detectable in this test then. A careful search with the leak detector has failed to produce any signs of leaks in the cavity chamber. Finally, even during electron bombardment, the cavity pressure does not rise dramatically, although parts of the wall are still untouchably hot several minutes after the irradiation, which suggests that the walls are relatively clean.

We have not yet been able to process the zeolite correctly by baking it at 400°C in vacuum for 16 hours, as suggested by CVC, because of the resultant excessive heating of the chevron ring baffle. During the next report period, this baffle will be replaced by a water-cooled baffle, and the correct out gassing treatment will be performed. This should reduce the limiting pressure by about an order of magnitude.

Before significant reduction in ultimate system vacuum can be expected, it will be necessary to clean the walls of the system either by baking or electron beam bombardment. To date, all attempts to clean the walls with the electron beam have failed to produce a permanent reduction of pressure, which may however reflect the present ultimate vacuum limitation of the zeolite. After better bake-out of the zeolite we can determine the value of beam cleanup. Should it still prove necessary, an oven for baking the cavity will be designed. In any event, even with electron bombardment cleanup, baking of the pyrex gas-handling system will be necessary. The details of the baking procedures will appear in the next quarterly report.

One additional point should be noted in connection with the oven design. Measurements to be described in the next chapter suggest that the heating of the cavity by the electron beam at high currents causes thermal shifts of the resonant frequency even when the cavity is empty. It may prove necessary to wrap water cooling coils about the cavity to maintain some semblance of constant temperature during a high current bombardment. This refinement will not be necessary for either low-current experiments or afterglow studies with a pulsed beam.

C. Radiation Shielding

During the first experiment the level of gamma radiation was measured throughout the laboratory. Previously the electron beam had been stopped before the beam cone and cavity in a target which was well shielded with lead bricks. However, with the beam entering the beam cone and being stopped against the back wall of the cavity additional shielding had to be put in place behind the cavity in order to reduce the gamma level below 0.10 mr/hr in area where there are personnel. This shield is in the form of a 10-foot long concrete wall, two feet thick, extending to the ceiling behind the cavity, with wings running down toward the cavity on both sides. The wings are $1\frac{1}{2}$ ft. thick and 4 ft. long.

A beryllium foil .0004" thick is used to scatter the electron beam into a cone which completely fills the cavity. This foil and the collimator (Section D) produce some gamma rays and are shielded with lead bricks.

D. Optics of the Electron Beam

The cross section of the electron beam leaving the Van de Graaff accelerator is an ellipse 3 mm by $\frac{1}{2}$ mm; these dimensions are measured by burning spots into aluminum foils used to locate and define the

beam. In order to have the electron beam fill the 4-foot diameter cavity the beam must be spread or scattered. A thin beryllium foil has been chosen as the scatterer because of its very low $\frac{d\epsilon}{dx}$, low Z , high heat conductivity, high melting point, and availability in foil thickness which will produce close to the 4° scattering angle desired to cover the cavity. This foil is mounted on an aluminum plate in the 2" diameter beam pipe connecting the Van de Graaff with the beam cone. An aluminum collimator is also inserted after the Be foil to minimize gamma ray production at the walls of the beam tube (copper) and beam cone (stainless steel) and define the scattered cone which fills the cavity face.

While this system has worked well, there have been difficulties in alignment and centering of the electron beam. The results of experiments performed in this quarter have shown that the beam strikes the side wall of the cavity. Furthermore there appears to be an instability in the beam position about the central axis of the beam tube. Further studies of this instability will be required before remedial measures can be devised.

E. R.F. Circuit

The burden for the accuracy of the electron density measurements falls entirely on the discrimination of the transmission wavemeter in the usual circuits used for this purpose. The wavemeter, Hewlett-Packard Model 587-A, can be read only to a half megacycle, corresponding to an uncertainty of 5×10^6 electrons/cm³ (see First Quarterly Report). Actually, there is no need for an extremely accurate measurement of the cavity frequency itself, but only the free electron-induced changes in frequency. Thus, a scheme has been developed which will measure $\Delta\nu$ to within 10 keps, or 10^5 electrons/cm³.

The circuit, which has been used for the measurements reported in the following chapter, is shown in Figure 2. The cavity display

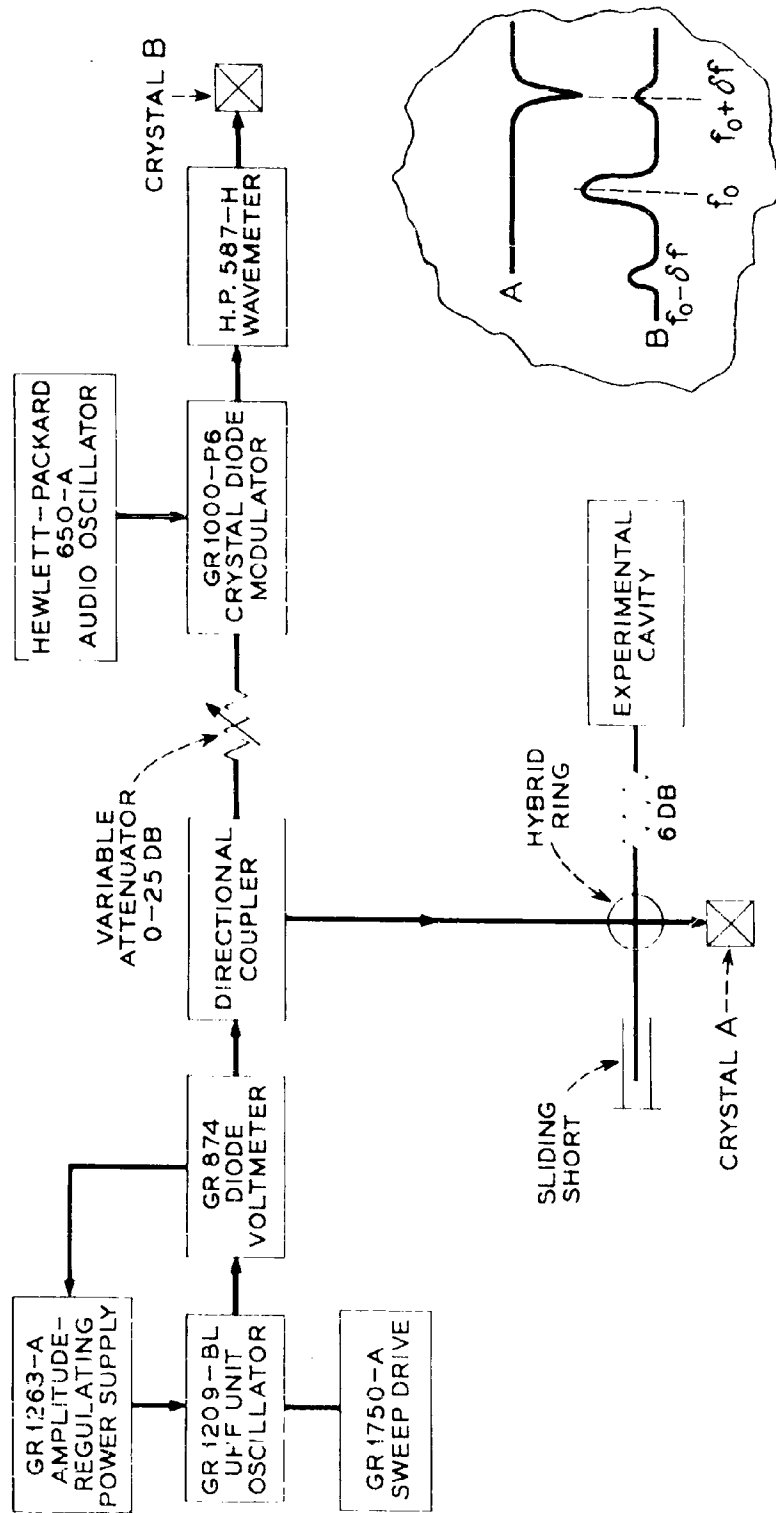


FIGURE 2
MICROWAVE CIRCUIT AND OSCILLOSCOPE DISPLAY

is taken off the 20db tap of a directional coupler, while essentially full oscillator power is sent to a General Radio Model 1000-P6 Crystal Diode Modulator, where the signal is mixed with the output of a 0-10 Mcps audio oscillator. The resultant signal is passed through the transmission wavemeter, purposely set about one-half megacycle below cavity resonance, where it remains throughout the experiment. All measurements are then made by aligning the high sideband with the cavity resonance curve, which can be done to an accuracy of 10 kilocycles under conditions of quiet signal (for a description of signal noise, see next chapter).

The circuit was then used to measure the loaded Q of the microwave cavity, in the following way. The cavity balance arm was adjusted to give a display of dispersion mode on the oscilloscope. The wavemeter was set to 390 Mc/sec, and the modulation frequency adjusted until the sideband coincided first with the low-frequency inflection point in the dispersion curve, then the high-frequency inflection point. The difference in these was 0.035 Mcps, corresponding to a loaded Q of about 11,000.

III. EXPERIMENTAL RESULTS

The preliminary experiment described in the previous chapter suggested the necessity of several equipment changes. The gamma shielding was increased, beam collimation improved, and the rf circuit modified to permit more accurate measurements of cavity frequency shifts. Following these changes, several other experiments were performed, which will be discussed in this chapter.

It should be pointed out that the measurements reported here cannot yet be depended on for insight into the physical processes occurring in air. Gas purity is not yet very good, and each gas load accumulates about 100 parts per million of system-contributed impurities during an irradiation. Also, there is no knowledge as yet of the intensity or the spatial distribution of electron beam flux across the cavity. Although the total beam current leaving the Van de Graaff is known, there is still no measurement of that fraction of the beam which gets stopped prior to entering the cavity. (This will be discussed below in more detail). Until more confidence can be placed in the data, and, of course, more data can be accumulated, the results of any measurements reported can be considered only as tests of equipment performance and reproducibility.

A. Beam Current Calibration

The Van de Graaff accelerator is equipped by the manufacturer with a Faraday cup for measuring the total beam current out of the drift tube, which is normally available at a front panel meter on the operating console of the accelerator. When a connection is made between the vacuum chamber and the accelerator and the Faraday cup is no longer in the beam path, this meter no longer can be used. The vacuum vessels could in principle be used as a Faraday cup but at present they are grounded through various pumping and electrical leads. It is doubtful at the moment that the kind of information

which we could obtain by ungrounding the vessels, i.e., the current stopped in both the cavity and beam cone, warrants the effort required in making the necessary changes.

To obtain quantitative information from the continuous beam (CB) experiments, we must know both the density and spatial distribution of beam current striking the cavity. As shown in the theoretical discussion in the First Quarterly Report of this project, evaluation of the destruction frequencies in the CB measurements requires a knowledge of both equilibrium electron density and incident beam current. In the "afterglow" of a pulse of radiation, the electron destruction frequencies are measured directly, and no knowledge of the beam current striking the gas is required beyond its being adequate to provide enough afterglow to be measured. Here, however, knowledge of the spatial distribution of the beam is still important. Also, we must be able to determine experimentally that the fall time of the beam is sufficiently short to avoid its affecting the measured decay frequencies. A practical system for accomplishing these various tasks will be developed during the next quarter.

For the present measurements, beam current was determined in the following way. The Faraday cup was connected to the accelerator, and a measurement of "Beam Current" meter reading I_B versus "Total Current" meter reading I_T , both from the panel meters on the accelerator console, was made. From this it was determined that $I_B = I_T - 75 \mu\text{amps}$ quite accurately above 200 μamps total current. It was then assumed that the actual current at the cavity is a fixed (although unknown) fraction of the beam current, so that even with this unknown factor we could at least measure relative changes in phenomena. The assumption proves to be a rather good one, as the data to be presented will indicate, within the following limitation. Following an internal arc-over in the accelerator (an infrequent but unavoidable occurrence) the beam position seems to shift permanently

before reaching the diffuser, so that some or all of the beam can be intercepted by the foil holder. Between arc-overs, however, the beam axis remains fixed and will pass through a properly positioned foil, and yield reproducible measurements. This situation will be remedied during the next quarter by the use of a larger foil. (The multiple scattering distribution for these foils is flat enough to permit small errors in beam centering, so long as the entire beam passes through the foil.) This will greatly improve the reproducibility of the measurements.

Again, it should be borne in mind that the measurements below are relative, and require calibration of the true beam current at the cavity before quantitative results can be obtained.

B Measurements

To search for any effects not originating in the experimental gases which might act as a background for the experiments, the empty cavity was irradiated with electrons while open to the pump. The results of this measurement are summarized in the table below.

TABLE: BOMBARDMENT OF EMPTY CAVITY

"BEAM CURRENT"	CAVITY PRESSURE	FREQUENCY SHIFT
(ma)	(mmHg)	(Mcps)
0	5.0×10^{-6}	0
.450	7.9×10^{-6}	
.800	1.1×10^{-5}	+ .300
1.2	1.6×10^{-5}	+ 1.25
1.4	2.0×10^{-5}	+ 1.70

Several features emerge. First, the beam increases the gas load in the cavity, apparently due to heating of the walls. Secondly, there is a non-negligible shift in cavity resonant frequency, due again to

thermal effects. That these effects were both thermal in origin appears from the fact that they persist for minutes after turning off the beam, during which time they disappear slowly. It is interesting to note that heating the cavity increases its resonant frequency, which might be due either to buckling of the backplate into the cavity or sagging of the foil. (Overall heating of the cavity would decrease the resonant frequency, or increase the resonant wavelength.) The latter explanation appears more valid at present in view of the results to be presented below in the gas-filled cavity.

Although the frequency shifts resulting from bombardment of the empty cavity were larger than anticipated, it was decided to try the gas filling experiment. It had been planned to use oxygen for these first measurements, and sealed-off flasks of oxygen were mounted in the gas-filling system. However, at this time it was discovered that the Granville-Phillips capacitance manometer, to be used for gas pressure measurement, was not behaving properly. (It was later discovered that moisture had condensed on the "dirty system" side of one of the insulators in the manometer sensing head, which was remedied by gentle flaming.) In order to perform some reproducible experiments, it was decided to use room air admitted to the system in the following way. A reentrant cold trap, of about 1/3 liter volume is connected to the gas handling manifold through a bakeable valve; the trap communicates with room air. This trap was filled through a silicone-greased stopcock with room air at atmospheric pressure. The stopcock was then closed, and the contents of the trap dumped into the cavity, resulting in a pressure of about 1/3 mmHg. (This was later repeated using the now-operating capacitance manometer, and found to be quite accurately 1/3 mmHg.) In this way the experiment can be reproduced at will at a later date.

A measurement was made of frequency shift versus "beam current", shown as Run 1 in Figure 3. Several things should be noted about

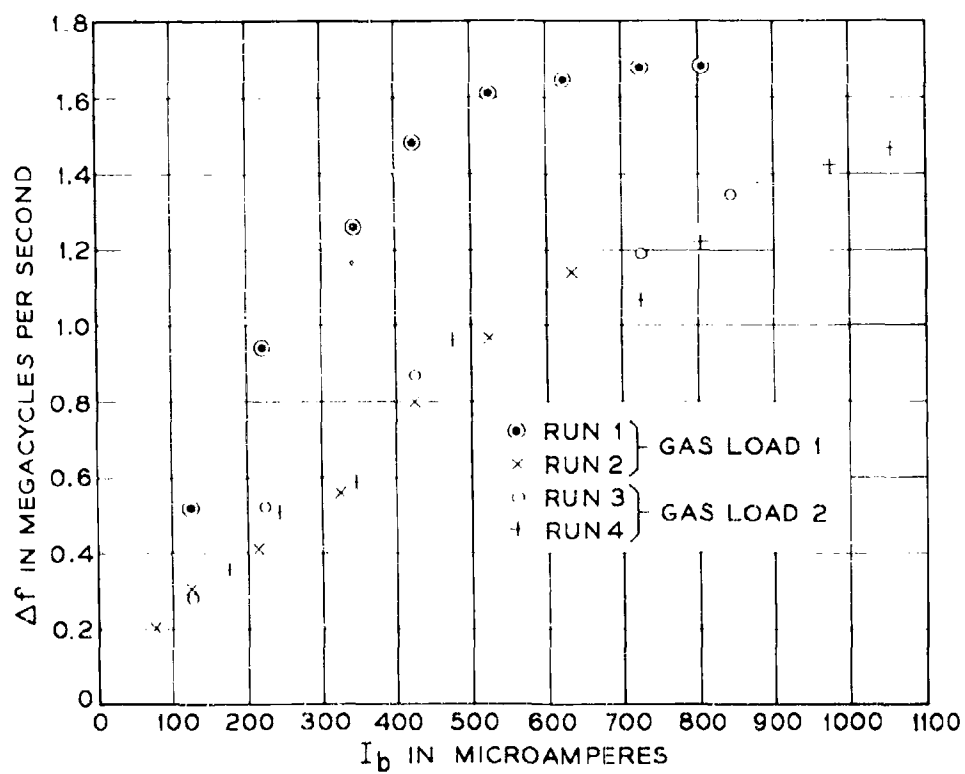


FIGURE 3
 CAVITY FREQUENCY SHIFT VERSUS ACCELERATOR
 BEAM CURRENT
 ROOM AIR, $p = \frac{1}{3}$ MM Hg

this measurement. First, at frequency shifts of the order of 1.2 megacycles, the curve flattens off with increasing beam current. Although this measurement alone does not show it convincingly, the curve seems to be linear with beam current to frequency shifts of about 0.9 Mcps. Second, the run was terminated by an arc in the Van de Graaff, and the data of this run were never reproduced numerically (see C below, however). Also, the zero-beam cavity frequency immediately after this run was 150 kilocycles lower than that prior to the measurement, which then drifted slowly back toward the original value.

Another measurement was attempted on the same load of gas following the arc-over. This is shown as Run 2 in Figure 3. The results appear substantially different than those of Run 1. With no indication of how much of the difference was due to beam position shift, how much to possible chemical changes in the gas, the first gas load was evacuated and a fresh filling was made, using the same filling procedure. Two measurements were then performed on this second gas load, shown as Runs 3 and 4 in Figure 3. It can be seen that the reproducibility of Runs 2, 3 and 4 is quite good. Among other things, this reproducibility between gas loads suggests the absence of chemical effects due to the beam. In fact, a five-minute irradiation of the second load with a beam current of 225 μ amps with apparently the same beam geometry as Runs 2, 3 and 4 failed to reveal any change in resonant frequency shift with irradiation time. In addition, the difference in zero-beam cavity resonance before and after the measurement is within 100 keps for Runs 2, 3 and 4.

C. Discussion of Results

The frequency shift due to thermal effects from the beam is much greater in the evacuated cavity than for the gas-filled cavity. This suggests that the main contribution to the empty-cavity shift

is due to sagging of the aluminum foil into the cavity under bombardment. The presence of gas in the cavity holds the foil against the rear supporting structure and prevents appreciable changes in shape of the foil. In all but Run 2, the empty cavity frequency was lower after the run than before, as would be expected from thermal expansion of the cavity dimensions. Further study is required to determine the seriousness of the remaining thermal effects, and to establish operating limits of beam current within which the thermal frequency shifts will be tolerable.

If the difference between Run 1 and the remaining runs is due only to a lower incident electron flux at the cavity because of beam misalignment following the arc-over, it should be possible to scale the "beam current" of Run 1 at one point, then fit this to the other three runs by applying this same scaling factor to the other points of Run 1. This has been done in Figure 4, which shows Runs 2, 3, 4 and the scaled Run 1. The agreement can be seen to be quite good. The results of four runs, on two different gas loads, all agree to within a reasonable variation. The experiment at least seems capable of providing consistent data.

The low frequency shift data seem to be linear with beam current, although this linear region extends over a very small range of variation in measured frequency shifts. The probable linear electron removal processes operating here are ambipolar diffusion and electron attachment to O_2 to form O_2^- . The departure from linearity at higher pressures may be due to electron-positive molecular ion recombination, or it may reflect the production of a short-lived electron-attaching molecular complex in the beam. On such meager data it is both foolish and dangerous to try to "explain" too much. Before any further discussion of processes is undertaken, much more data must be accumulated.

One further point of interest should be noted, however. As is well known, the relationship between electron collision frequency

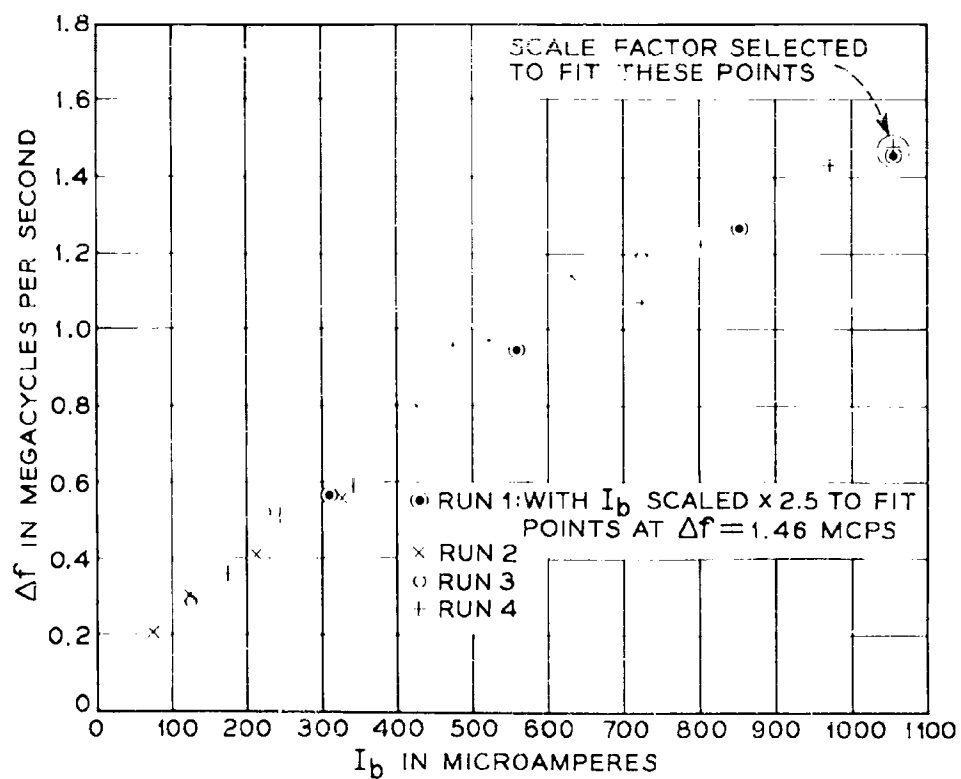


FIGURE 4
DATA OF FIGURE 3 REPLOTED WITH BEAM CURRENT
OF RUN 1 SCALED TO FIT AT $\Delta f = 1.46$ MCPS TO
SHOW REPRODUCIBILITY OF DATA

and change in cavity Q is given, for uniform spatial distribution of electrons in the cavity, by

$$\Delta \left(\frac{1}{Q} \right) = 2 \frac{\nu_c}{\omega} \frac{\Delta \nu}{\nu_0} ,$$

where ν_0 is cavity resonant frequency, $\omega = 2\pi\nu_0$, and $\Delta\nu$ is resonant frequency shift. Thus for $\Delta\nu = 1$ Mcps, $\nu_0 = 400$ Mcps, and assuming thermal electrons, for which ν_c in air is equal to $10^8 p$, one finds at $p = 1/3$ mmHg,

$$\Delta \left(\frac{1}{Q} \right) = \frac{2 \times \frac{1}{3} \times 10^8 \times 10^6}{2\pi \times 4 \times 10^8 \times 4 \times 10^8} \times \frac{1}{1.6 \times 10^4} ,$$

so that the cavity Q at this pressure is equal to about 6,500 when the frequency shift is 1 megacycle ($n = 10^7/\text{cm}^{-3}$). This is in good qualitative agreement with the visual observation that the cavity absorption signal was about half as large at $\Delta\nu = 1$ Mcps as for the empty cavity ($Q_L \sim 11,000$). This suggests that the knock-on electrons in the gas are essentially at thermal equilibrium at room temperature. The question of electron temperatures during the beam irradiation will be studied in more detail as a function of gas pressure during the next quarter.

IV. PLANS FOR NEXT QUARTER

Several equipment tasks must still be performed. During the next quarter the water-cooled pump baffle will be installed, the zeolite processing improved, and all efforts made to improve the vacuum in the cavity. If necessary, a bakeout oven will be designed at this time. The larger beam diffuser will be built and used, to try to eliminate the geometrical variations in the beam current due to position shifts. A monitoring system will be designed and installed during the quarter which will give information as to the spatial distribution of beam across the cavity face as well as absolute beam current.

The measurement program will continue to accumulate data, both on room air and on reagent grade oxygen. Particular attention will be paid to measurements, or at least estimates, of ν_c as a monitor of electron temperature. If the beam monitor is installed soon enough, some numerical results may be forthcoming during the quarter.

The theoretical program will have two goals during the next period. As measurements are made and more convincing data accumulated, it will be necessary to make at least tentative interpretations of the results. Also, a start will be made on the general problem of correlating the results obtained from these measurements with the situation in the upper atmosphere following a high-altitude nuclear detonation.

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