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MEASUREMENTS OF ATMOSPHERIC PRESSURE, TEMPERATURE, DENSITY, AND COMPOSITION AT VERY HIGH ALTITUDES

Prepared for the project by

N. W. Spencer

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INDIVIDUALS CONTRIBUTING DURING THE REPORT PERIOD

Black, J. R.*	Engineer
Boyd, R. L.	Engineer
Brace, L. H.	Engineer
Burdette, G. L.	Engineer
Grover, L. L.	Technician
Kanal, M.	Mathematician
Nary, D. B.	Secretary
Spencer, N. W.	Project Supervisor

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*Tube shop personnel.

1. INTRODUCTION

This is one of a series of reports on a research effort whose objective is the determination of the ambient pressure, temperature, density, and composition of the earth's atmosphere at altitudes above the level where the mean free path of the various particles is appreciably greater than the dimensions of the measuring object.

The research effort is devoted to several tasks:

(a) a theoretical study of the general measurement problem, and several associated problems;
(b) development of suitable sensors;
(c) development of associated instrumentation to permit fruitful employment of the sensors; and
(d) the development of an ultra-high vacuum system capable of achieving pressures as low as the state of the art permits, with the final objective of sensor calibration and testing.

2. THEORETICAL STUDY

Theoretical studies of various aspects of the general measurement problem, which is the subject of the research under this contract, are being carried out as has been indicated above and outlined in previous reports. Present efforts in this regard concern consideration of (a) the time constant of possible sensor chambers in relation to motion of the instrumentation package, (b) the problem of achieving the desired orientation of the instrumentation with respect to the trajectory, and (c) the orifice flow problem.

3. SENSOR DEVELOPMENT

During the period covered by this report, considerable progress has been made, it is felt, in the direction of (a) attaining workable omegatrons, and (b) gaining a better understanding of the operating mechanism of the omegatron, and thus of the reasons why the device may or may not be suitable for use as intended for the desired measurements.

In regard to (a), two tubes have been built and operated, which are similar except in one respect. The first tube[*] (tube serial number 3, Fig. 1) was cubical in shape, fabricated from sheet molybdenum, and was patterned roughly after one described in the literature.[2][**] It was operated for many hours on a standard laboratory vacuum system at a total pressure of approximately 5×10^{-6} mm. Some trouble was experienced initially in detecting ions; however, it was determined rather early why this occurred and subsequently proper operation was effected. In considering the cause of the difficulty that was being experienced, it was suspected that the ions were being deflected by pernicious electric field effects resulting from localized surface charge on the inner wall of the tube envelope. To understand how this might be possible, it should be pointed out in reference to Fig. 1, that two sides of the tube structure were left open.

Digressing for the moment, Fig. 2 shows a functional drawing of an omegatron and the experimental circuit arrangement that has been utilized in most tests conducted to date. The various tube elements are as follows:

1,2	end plates, through and normal to which the ionizing electron beam passes.
3,4	side plates to which an rf potential is applied.
5,6	side plates which are, in general, at ground potential, as are 1 and 2.
7	heat shield behind the filament which serves also to prevent scattering of electrons from the back of the filament. It is connected (electrically) to the filament which is biased to some potential such as -90 volts.
8	electron beam collector which is biased similarly but +90 volts.

Returning to the discussion of the operation of tube number 3, and referring to the above, side plates 5 and 6 were those omitted. This meant that the electric field in these local regions of the tube, a significant factor, would be determined by the other plates, the glass envelope and any charge it might accumulate, and finally, by metallic surfaces external to the tube such as the electro-magnet employed to establish the necessary magnetic field.

In an effort to alter the field in the region of the open sides, electrodes in the form of wires at ground potential were placed external to the tube envelope and moved around until a position was found for which ion current was detected. This arrangement was obviously makeshift but sufficed to prove the point, and led eventually to some conclusions regarding the general usefulness of the omegatron, which will be discussed later.

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[*] Serial no. 2 was not vacuum-tight and was destroyed during attempted repair.

[**] Numbers refer to items of a list of references which is included in each quarterly report and which represents all applicable and suitable references known to the writer. As new references become known, they are included.

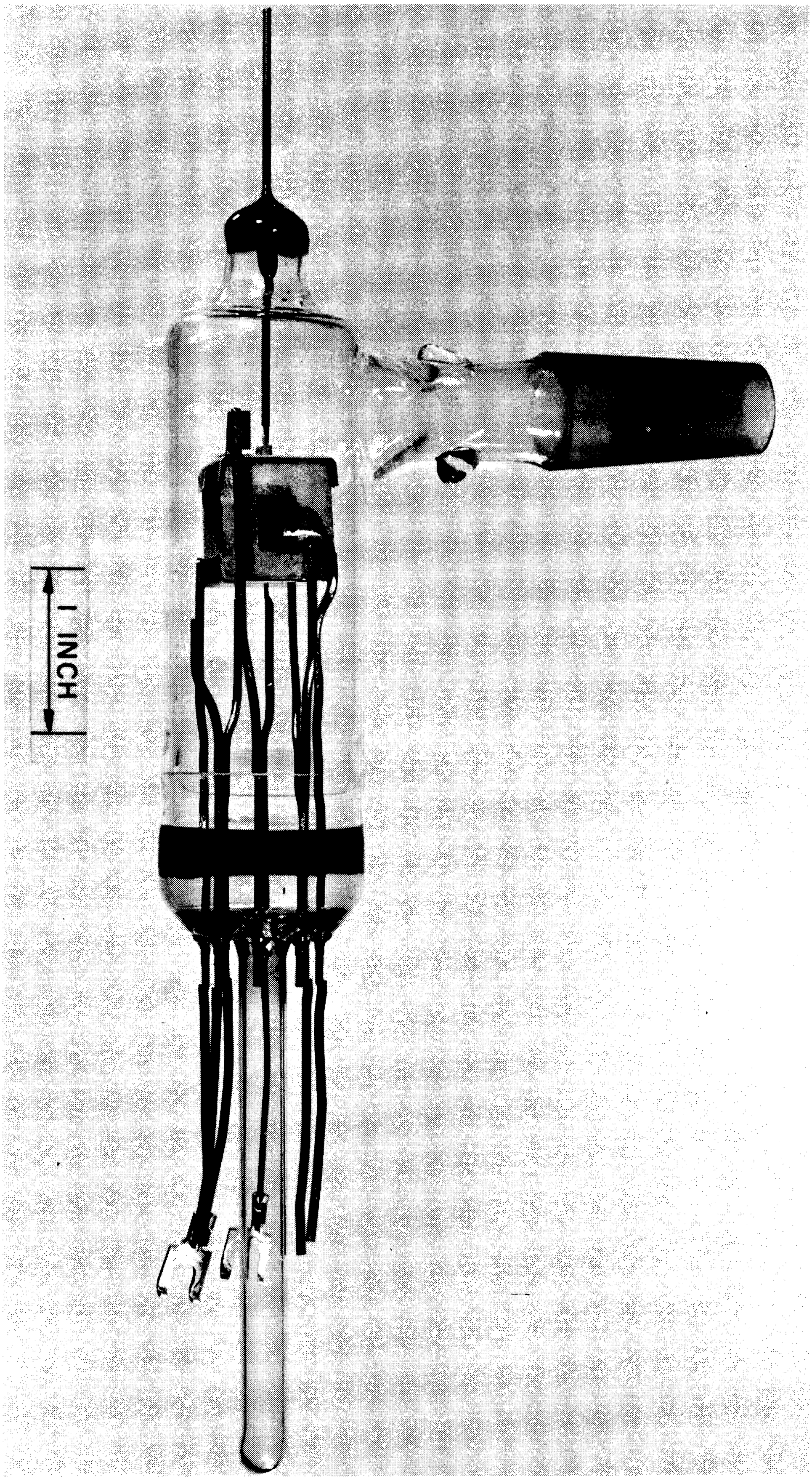

Fig. 1. Omegatron, Serial No. 3.

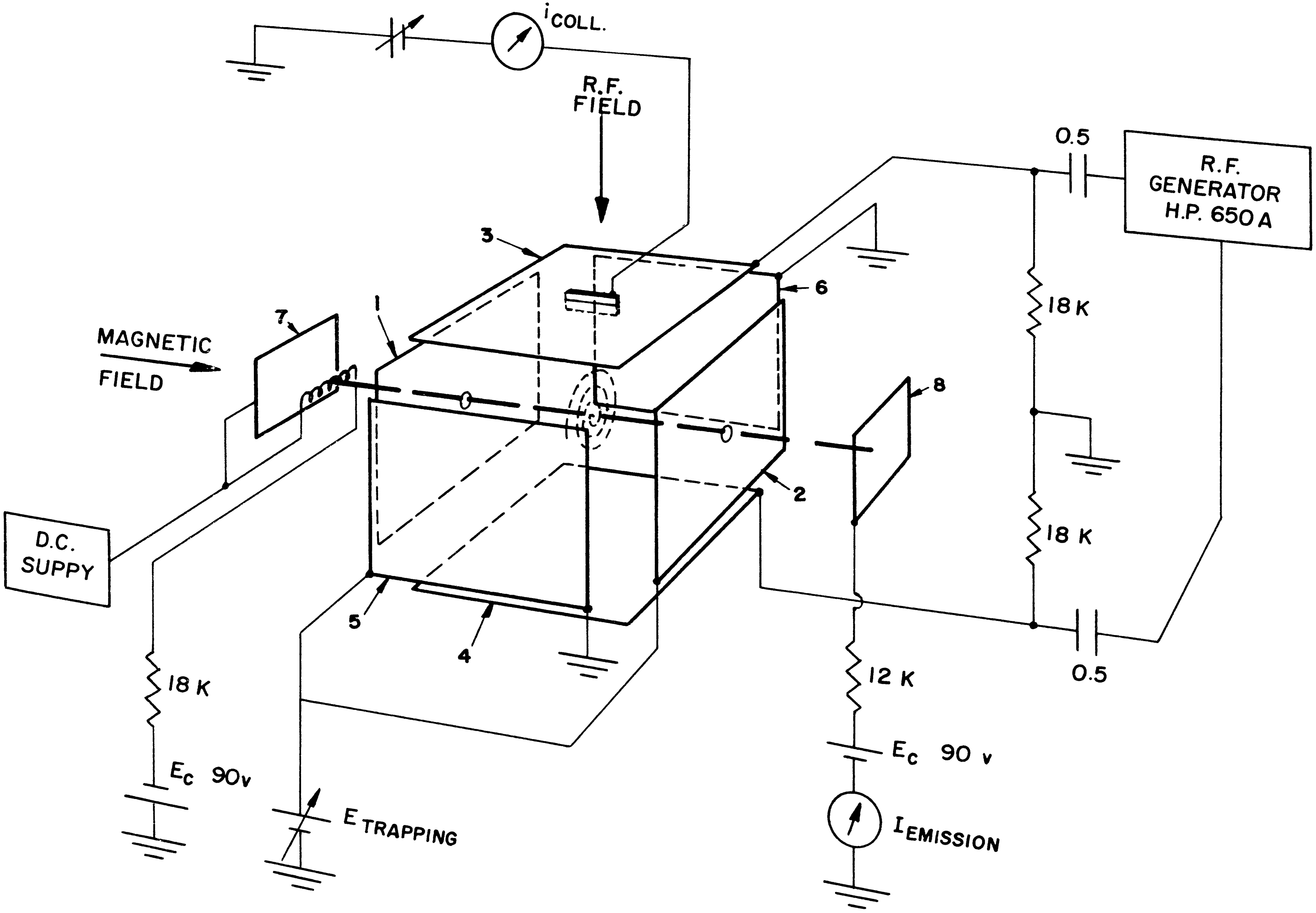

Fig. 2. Functional diagram and experimental setup.

Following these tests during which several gases were detected qualitatively, a new and essentially identical tube was built, the chief difference being the addition of the side plates omitted in tube number 3. The new tube, serial number 4, is shown in Fig. 3. The experimental setup employed in testing this tube was nearly identical to that employed for tube number 3 and thus Fig. 2 again is appropriate.

Tube number 3 functioned in the expected manner without difficulty. Various electrode potentials, magnetic field strengths, beam currents, and total pressures were employed in carrying out experimental studies and acquiring experience with the device. Various gases from atomic hydrogen up through AMU 50 have been detected and observed. Some anomalies have been observed which are not entirely explained. Figure 4 is a crude spectrum observed on one occasion. It is a plot of raw data taken under general conditions of no particular significance. The cause of the large peak that occurs near a frequency of 1.5 Mc is not completely understood. It may be a consequence of malfunction of some type or may be valid, or what seems more likely, may be a combination of the two. In order to determine the reason, a different, commercially built spectrometer tube will be employed and comparisons made to assess the true composition of the gas.

4. EXPRESSIONS PERTAINING TO PARTICLE MOTION

Particle motion under idealized conditions can be predicted rather easily. Following are some expressions useful in this regard.

The angular velocity of the ions is constant assuming all applied voltages and fields constant; thus from the cyclotron equation,

$$\omega_c = \frac{eB}{m} \tag{4.1}$$

where

ω_c = $2\pi f$ = angular frequency
e = charge of the ion
B = magnetic field
m = mass of ion

and

$$\omega_c = v/r \tag{4.2}$$

where

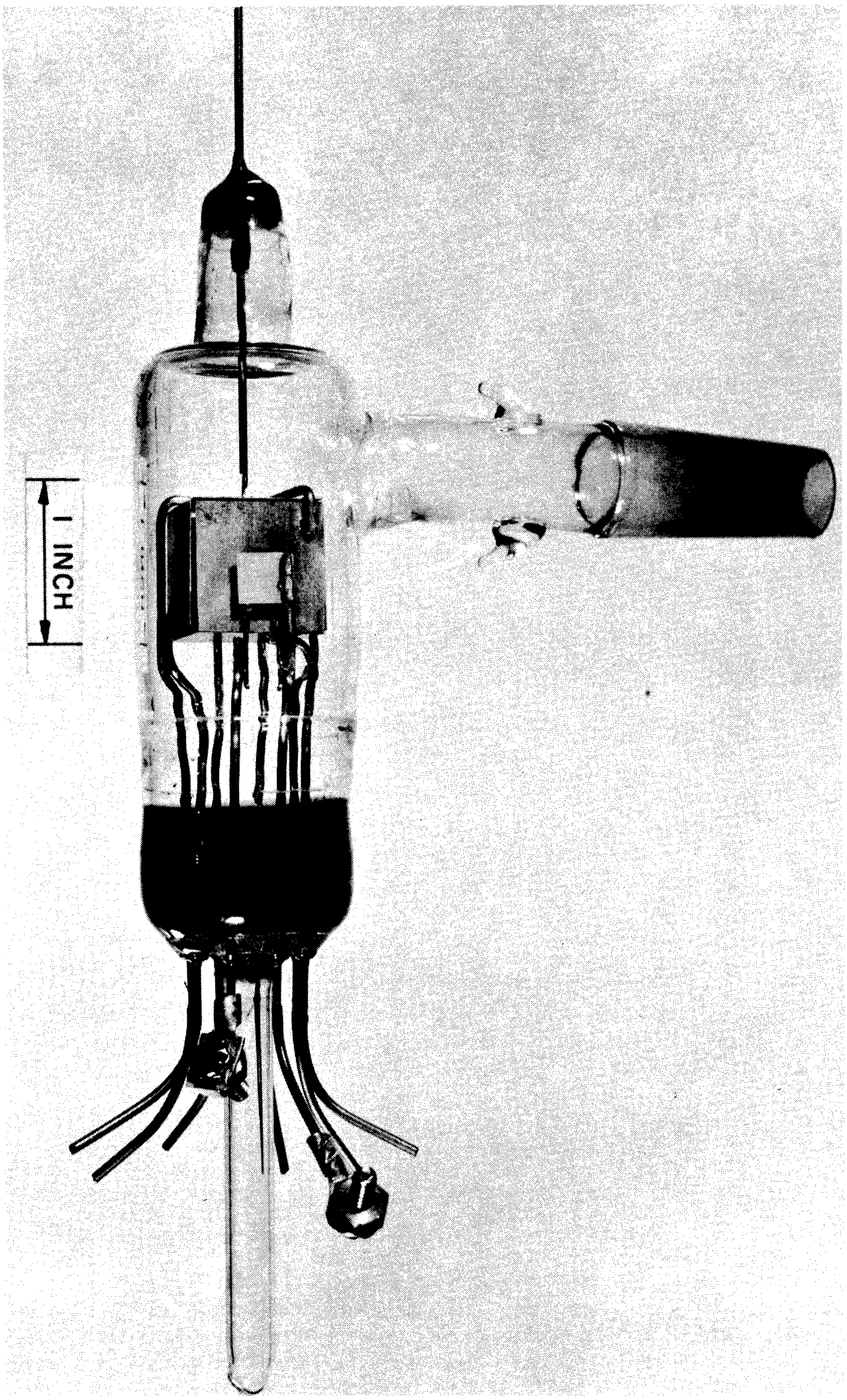

Fig. 3. Omegatron, Serial No. 4.

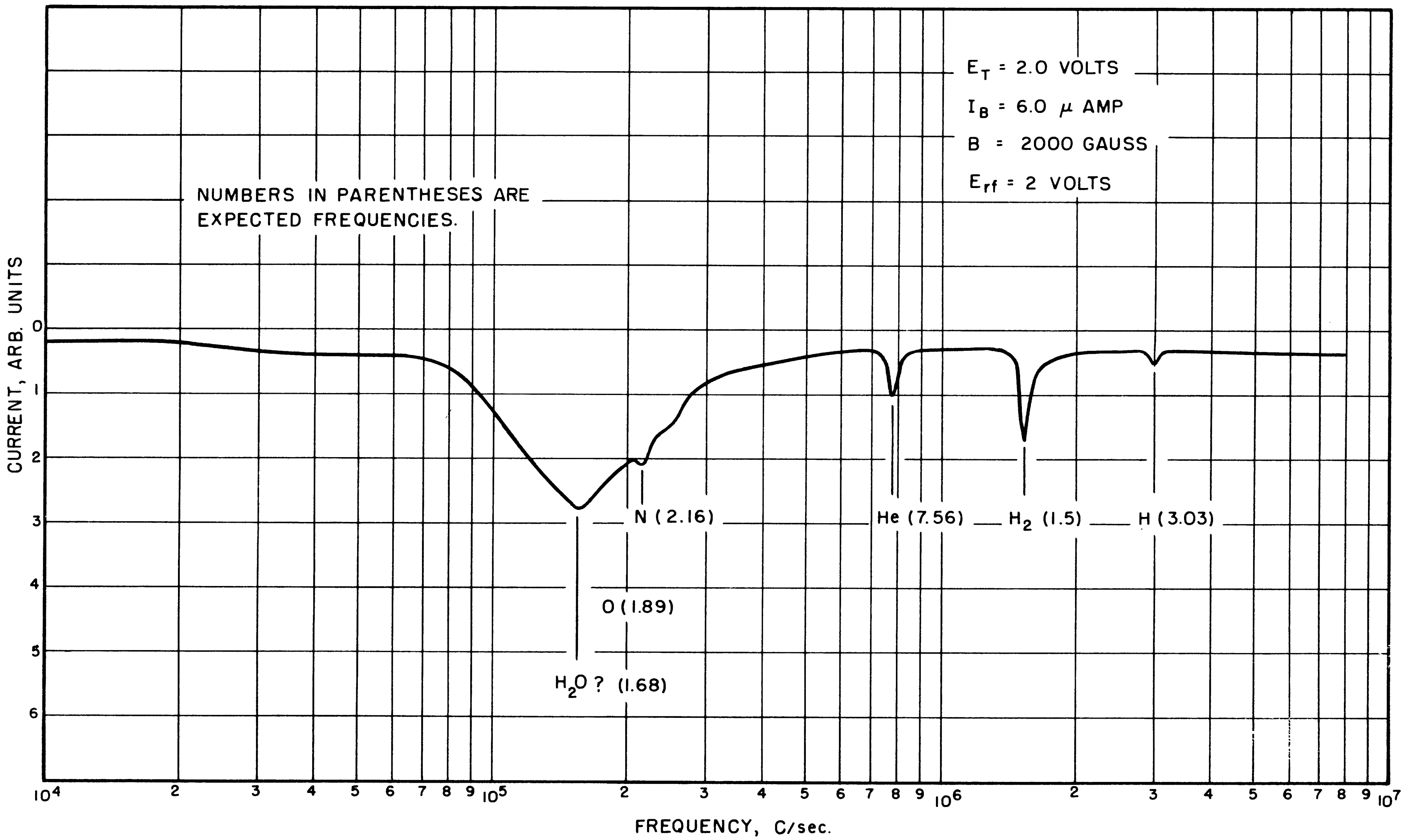

Fig. 4. Experimental spectrum.

v = tangential velocity
r = radius of path

The force on a particle in the field B is constant. Thus one may equate the centripetal force to the force on a particle:

$$f = mv^2/r = Bev \tag{4.3}$$

and, from this,

$$r = mv/eB \tag{4.4}$$

or

$$v = rBe/m \quad \text{(velocity at radius r)} \tag{4.5}$$

To find the energy per particle, substitute Eq. (4.5) in $W = 1/2\ mv^2$; thus,

$$W = \frac{r^2B^2e^2}{2m} \quad , \tag{4.6}$$

or, since

$$1/2\ mv^2 = Ee \quad , \tag{4.7}$$

the energy in electron volts is

$$E = \frac{r^2B^2e}{2m} \quad . \tag{4.8}$$

Since the angular velocity is constant, and

$$\omega_c = eB/m = 2\pi f \tag{4.9}$$

$$t = 2\pi m/eB \quad \text{(seconds per revolution)} \quad . \tag{4.10}$$

The time to arrive at a radius r is

$$t_r = 2Br/E_o \tag{4.11}$$

where E_o is the rms value of the applied rf voltage.[1] If now the time per revolution is divided into the time to arrive at a given radius, the number of revolutions results:

$$n = \frac{e\ B^2\ r_o}{\pi\ m\ E_o} \ \text{revolutions} \quad . \tag{4.12}$$

The total path length is the mean path length times the total number of revolutions. Thus,

$$L = \frac{e B^2 r_o^2}{m E_o} \quad . \tag{4.13}$$

In general, the sensitivity of the device is proportional to the number of ions collected in comparison with the number of gas particles available in an arbitrary region available to the beam. If one employs the scheme of measuring the energy absorbed[6] by the ions as an indication of the number of ions, then clearly the sensitivity is a function of the ion energy.

Since the energy is proportional, for an ion of a given charge-to-mass ratio, to the square of the product rB [Eq. (4.8)], then one can evaluate those factors important in sensitivity considerations. Thus, the sensitivity:

$$S \approx f\,(r^2 B^2 \ell_b) \tag{4.14}$$

where ℓ_b represents the length of the beam, assuming constant ionization per unit length of beam.

The number of ions is also proportional to the beam current on the average; thus

$$S \approx f\,(r^2 B^2 \ell_b I_b) \quad . \tag{4.15}$$

One of the limitations that becomes apparent is the mass of metal or power required to provide the magnetic field. Thus it is helpful to interpret B in these terms and express the field in terms of NI. Let

$$B = \mu NI/\ell_g \tag{4.16}$$

where NI (ampere turns) is proportional to the magnetic capability available (in regard to size and weight), whether permanent- or electro-magnet, and ℓ_g is the magnetic circuit air gap length. Since the circuit reluctance is determined primarily by the air gap, μ may be neglected. Thus substituting this expression in Eq. (4.15),

$$S \sim f\left[\frac{r^2 (NI)^2 I_b \ell_b}{\ell_g^2}\right] \quad . \tag{4.17}$$

In most cases, and for illustrative purposes, the beam length will be nearly the same as the gap length. Thus taking the liberty

$$\ell_b \cong \ell_g = \ell \tag{4.18}$$

the expression becomes

$$S \sim f\left[\frac{r^2(NI)^2 I_b}{\ell}\right] \qquad (4.19)$$

which shows that the ultimate sensitivity of the omegatron is proportional to the radius squared, the magnetic field capability squared, the ionizing beam current, and inversely proportional to the length of the air gap. This latter point really says that for a given NI one is better off to reduce the length of the device.* This is a consequence, naturally, of the significance of air gaps in magnetic circuits.

These statements, particularly those relative to length change, are applicable to systems which determine the number of ions by measuring the energy absorbed. They are not, in general, applicable to systems which depend upon counting, in effect, the number of ions. Although the relative merits of the two techniques have not been assessed by the writer, it is believed that the energy measurement holds the greatest promise, at least at present.

5. PRESENT EVALUATION OF GENERAL APPLICABILITY OF AN OMEGATRON TO STRUCTURE MEASUREMENTS

Adequate experience has been acquired with the omegatron, through theoretical and experimental studies, to enable at least a preliminary evaluation of its general usefulness as an instrument for making measurements in the earth's atmosphere. It appears at this time to possess the following merits:

(a) its relatively small size indicates that chambers which would enclose it would not pose unusual gas response problems;
(b) it is a simple device, easily constructed, and thus does not require extreme precision in manufacture;
(c) associated circuits, with the possible exception of the collector current electrometer, can be simple, require low power, and may be easily assembled using semiconductor devices, thus enabling low-volume implementation; and
(d) the device is well, perhaps even best suited to the detection of low mass number ions, or putting it more precisely, to the detection of ions of high charge-to-mass ratio.

The omegatron has, on the other hand, several drawbacks.

(a) In general, it does not have adequate resolution to be generally useful for detection of singly ionized ions of mass number greater than about 75.

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*Until Eq. (4.18) is no longer reasonably valid.

Simple sheet-metal tubes as opposed to tubes assembled from carefully machined elements are probably not useful above mass 50. This is not necessarily disadvantageous for atmospheric measurements. The general statement that can be made, however, is that the tube is most useful at low mass numbers.

(b) The general sensitivity level, that is, in practical terms, the collector current or its equivalent that must be measured as the information signal, is low by thermionic ionization gage standards. At a total pressure of the order of 10^{-6}, which is about an order of magnitude below the useful high-pressure threshold of the omegatron, the currents corresponding to normal atmospheric constituents under normal operating conditions are of the order of 10^{-11} amperes. With increasing altitude, this value will fall rapidly, posing serious problems. There is at least one possible solution which will be discussed later.

(c) The tube in its present form does not appear to be as promising for use where the initial or thermal velocities of the gases or ions is very high compared with that at normal room temperatures.

(d) Operation of the device can be easily affected by low potentials that may result, for example, from the accumulation of surface charge on various insulators, or surfaces near the action space.

Points (c) and (d) above, and other possible notable drawbacks, all stem from a common fundamental fact, which warrants discussion.

The omegatron depends, for its operation and consequent properties which afford discrimination between ions of various gases, basically upon the fact that the ions of a particular charge-to-mass ratio move through very long paths at low velocity from their origin to their collection. Because they gain energy slowly, or to put it another way, because they are orbiting a relatively long time, low potentials, the order of a volt or so, are required for operation. The velocity (tangential) of a typical ion upon emergence from a hypothetical beam of 1-mm radius is about 10^5 cm/sec (atomic nitrogen). Velocities of particles entering the beam to be ionized, if comparable or greater than this velocity, may well be lost by being carried out of the active region before collection.

Initial velocity may be of thermal origin (N at 1200°K will be about 2×10^4 cm/sec) or an apparent velocity due to vehicle motion. In the case of a satellite, 10^5 cm/sec is typical for atomic nitrogen. Thus, whatever the cause of initial velocity, if it is appreciable in comparison to ion velocity at beam emergence, it can cause ion loss, for it can act over the total orbiting time of the ion. A considerable deviation of the ion from the desired path, axially can result. Higher temperatures mean greater loss of ions and thus an alteration of the normally anticipated collector current is observed.

Loss of ions axially to the end plates, which are perpendicular to the beam (1 and 2 in Fig. 2), can be compensated for to a degree by proper choice of a decelerating potential applied to these plates known as the "trapping" voltage. However, because the incoming gases will have a distribution of velocities, trapping is only effective to a degree and cannot be a "clear-cut" effect. If the omegatron can be operated at voltages the order of several volts or more rather than at voltages of the order of 1 volt, adequate for relatively low initial velocity conditions, it can be made more independent of the local conditions. This possibility is being investigated.

It is fortunate that the thermal velocity of the gases increases only as the square root of the temperature. Otherwise there would be a serious and rapidly reached altitude limit to usefulness of the omegatron. Thus it appears at this time that for reasons of thermal velocity effects, the omegatron can be effective for gas temperatures up to, say, several thousand degrees corresponding to altitudes of a few hundred miles.

In regard to present altitude limits, there is another consideration. At the present time, if one were to use collector current as the information signal, the useful upper limit of the omegatron (altitude-wise) is probably set by the state of the art of measuring low d-c currents in a rocket or satellite. This corresponds to altitudes of something like 150 to 200 miles; however, the use of an electron multiplier may be helpful to increase this limit.

6. CIRCUIT DEVELOPMENT

The use of an omegatron or a similar device in the upper atmosphere naturally requires supporting circuitry. In connection with these requirements, and other work in progress in the laboratory, a significant effort has been devoted to the development of techniques and circuits applicable to the measurement of d-c currents. Similarly, development of telemetry subcarrier oscillators, various small power supplies, and timing devices has been in progress. When possible, the development has been limited to arrangements which would employ semiconductor devices. The only case in which a vacuum tube appears at this time to be necessary is for the measurement of d-c current less than approximately 10^{-11} to 10^{-12} amperes.

A separate report is being prepared which will detail the devices whose development is reasonably complete.

7. ULTRA-HIGH VACUUM SYSTEM

The U-H vacuum system is now in operation. Pressures less than 10^{-10} mm Hg as indicated by an Alpert ion gage are attainable with relative ease.

8. FUTURE WORK

Investigation of the omegatron is continuing, with emphasis on exploration of characteristics which effect the apparent spectrum. A "Diatron" (180° orbit) tube is being obtained (commercially available) for use as a basis of comparison in further studies, and also for consideration of its applicability as an alternate device. Because of its mode of operation, that is, 180° orbit instead of multi-turn orbit, higher voltages are required for its operation. However, there is correspondingly less sensitivity to disturbing potentials, resulting, for one thing, in better resolution.

Two new omegatron tubes are being built. One is similar to tube number 4 except that it is being arranged to permit accommodation of an electron multiplier. Successful combination of this device with the omegatron can assist greatly in solution of the sensitivity problem.

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