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Omegatron Mass Spectrometer for Partial Pressure Measurements in Upper Atmosphere[*]

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A simple Omegatron mass analyzer used for measuring density and temperature of nitrogen in the 100 to 350 km region of the upper atmosphere has been developed. The mechanical and electrical configurations have been designed for rocket flight application, and the operating parameters optimized for the upper atmosphere measurement. This Omegatron is calibrated and flown as part of a sounding rocket experiment known as the Thermosphere Probe, which also contains an electron temperature probe for determining electron temperature and density. Several successful flights have shown that the Omegatron is a reliable device for this application.

INTRODUCTION

A SERIES of eight rocket flights of the Thermosphere Probe have been conducted in an aeronomy program to determine the structure of the earth's atmosphere at altitudes above 100 km.[1] Each of these probes has included an Omegatron mass analyzer which was designed to measure the number density of molecular nitrogen. This paper describes the Omegatron developed for this flight program. Many papers describing Omegatrons and their applications have been published. The basic principles were originally described by Sommer *et al.*[2] Berry[3] made a detailed mathematical analysis of an idealized Omegatron. Brubaker and Perkins[4] considered the effects of nonhomogeneous electric and magnetic fields. A simplified Omegatron used as a partial pressure analyzer was built and described by Alpert and Buritz.[5] Several others have also contributed.[6–8]

The Omegatron employs the cyclotron principle to effect mass separation. In the action region a constant magnetic field is crossed with an rf electric field. A narrow electron beam ionizes neutral gas particles in the center of the action region. If the frequency of the rf electric field is equal to the cyclotron frequency of a particular species of ions, these ions are accelerated in trajectories which are approximately Archimedes' spirals. As they gain energy, they move outward and can be collected by an appropriately placed collector. Nonresonant ions do not gain enough energy to reach the collector. The gas density of a resonant species in the gauge and the ion current reaching the collector are linearly related over several decades of density; thus a measurement of the ion current provides a useful and simple means of analyzing the gas in the gauge.

DESIGN CRITERIA

At the outset of the development program, it was intended to develop an Omegatron to measure the density of neutral N_2 within a volume that is open to the earth's atmosphere through a knife edge orifice. The main purpose of the measurement was to determine the vertical profile of atmospheric temperature above 100 km. This modest objective permitted the choice of a relatively simple device with operating parameters optimized for the measurement of molecular nitrogen.

The application of devices on rockets dictates several design criteria. The device must withstand the acceleration and vibration during the rocket's thrust, and subsequently operate in the environment of space. Size, weight, and power consumption are to be minimized; and the requirement for reliability in a device destined for a single application is paramount.

CONSTRUCTION

An exploded view of the Omegatron assembly is shown in Fig. 1. The envelope, which is an integral part of the Thermosphere Probe, is made of nonmagnetic stainless steel (type 304). This envelope, with a volume of 65 cm^3, is coupled to the region of measurement by a knife edge orifice with a diameter of 1.11 cm providing a gas conductance of about 10 liters/sec. The opposite end of the envelope provides the mounting surface for the baseplate of the gauge. A copper gasket is compressed between two knife edges, providing a bakeable vacuum seal at the baseplate-envelope interface. The gauge, mounted to its baseplate, is located in the envelope between the two pole pieces of the magnet assembly. The magnet assembly combines two U shaped Alnico magnets (G. E. No. 5N238) mounted face to face against a soft iron adapter which butts against the two 3.3 cm diam soft iron pole pieces. The pole pieces

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[1] N. W. Spencer, L. H. Brace, G. R. Carignan, D. R. Taeusch, and N. Nienann, J. Geophys. Res. **70**, 2665 (1965).

[2] H. Sommer, H. A. Thomas, and J. A. Hipple, Phys. Rev. **82**, 697 (1951).

[3] C. E. Berry, J. Appl. Phys. **25**, 28 (1954).

[4] W. M. Brubaker and G. D. Perkins, Rev. Sci. Instr. **27**, 720 (1956).

[5] D. Alpert and R. S. Buritz, J. Appl. Phys. **25**, 202 (1964).

[6] A. G. Edwards, Brit. J. Appl. Phys. **6**, 44 (1955).

[7] A. Klopfer and W. Schmidt, Vacuum **10**, 363 (1960).

[8] G. Schuchhardt, Vacuum **10**, 373 (1960).

are threaded into the envelope wall to minimize the gap and to provide a fixed orientation of the magnet assembly. The magnet assembly weighs 3.63 kg; the weight of the total Omegatron assembly is 4.54 kg.

The Omegatron cage, a cube 1.75 cm on a side, is shown in more detail in Fig. 2. Four of its sides are made of nonmagnetic stainless sheet metal 0.254 mm thick. The other two sides are screen of the same material with 75% optical transparency to permit a good particle flow between the inside and the outside of the cage. Twelve ruby rods, kept in place by the friction of wire loops which are spot welded to the plates, constitute the frame of the assembly. A nine pin stainless steel ceramic header is Heliarc welded into the baseplate. The cage and the ion collector are spot welded directly to the pins of the header. The ion collector is 1.17 cm wide and extends 0.151 cm into the cage. The filament is a ten turn spiral of 0.0762 mm diam rhenium wire wound on a mandrel 0.1 mm in diameter with a separation between turns of 0.05 mm. It is welded onto two 0.533 mm diam molybdenum wires, which are mounted in a glass insulator and clamped onto the first trapping plate. The electron beam collector, a small stainless steel plate, is similarly mounted on the second trapping plate. The electron beam passes through focusing holes in plates 1 and 2. The diameters of the holes are 0.635 and 1.0 mm, respectively.

A great deal of care is taken in construction to hold tight tolerances on most dimensions. It is important that opposing sides of the cube be parallel, and that the alignment of the electron beam with the magnetic vector be held to within $\frac{1}{2}°$ for optimum operation. The materials and techniques used throughout are such that the assembled, evacuated Omegatron is bakeable to 400°C.

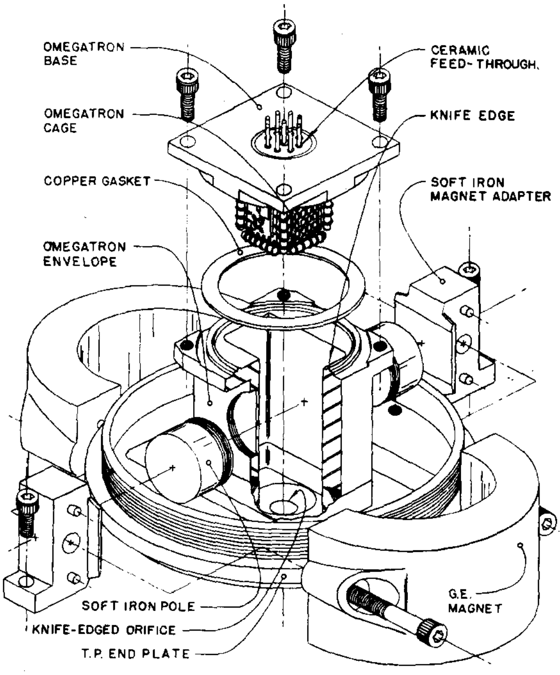

FIG. 1. Exploded view of the Omegatron assembly.

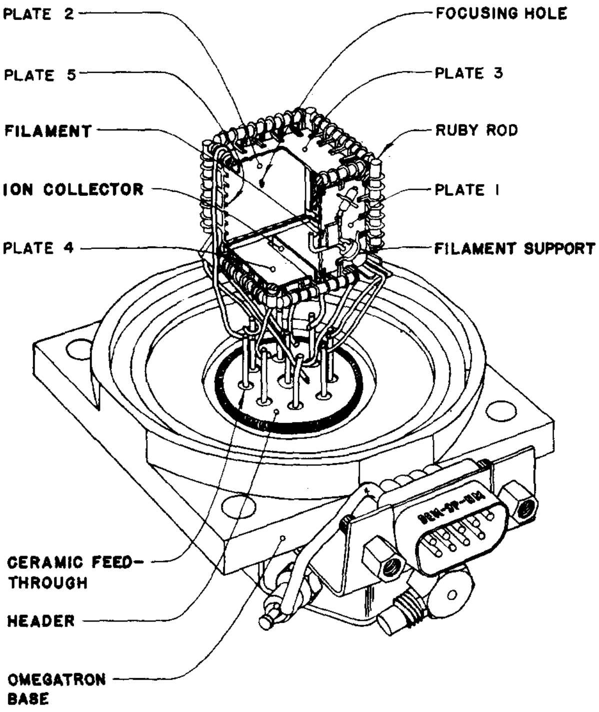

FIG. 2. Omegatron cage and baseplate.

OPERATING PARAMETERS

Many variations in the operating parameters are possible. The choices, given in Table I and in the diagram in Fig. 3, were arrived at analytically and empirically as best suited to provide the combination of mass resolution, background current level, linearity, and sensitivity desirable for this experiment. The only inflexible parameter in the design was the magnetic field strength, which has a value of 2200 G. Its upper limit is based on weight and size considerations.

The ionizing beam, generated at the filament, is focused by the magnetic field. The electrons in the beam are accelerated before entering the action chamber, which they traverse at an essentially constant 90 eV energy. This is near the peak value of the ionization cross section for N_2, and it is used to maximize sensitivity and minimize sen-

TABLE I. A summary of the values of the Omegatron parameters.

Parameter	Value
Ionizing current	4 μA
Electron energy	90 eV
rf voltage	1.25 V (peak)
V_{dc}	−0.2 V
V_c	−0.4 V
Magnetic field strength	2200 G

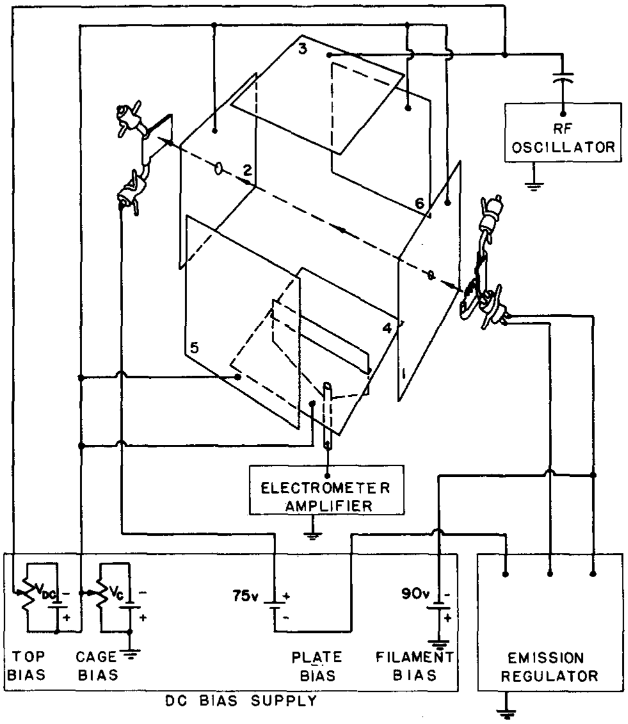

FIG. 3. Block diagram of circuit arrangement for a simple Omegatron used as partial pressure sensor for molecular nitrogen and oxygen.

sitivity dependence on small changes in electron energy. The electrons leave the action region through a small hole in plate 2 and are neutralized at the collector. The collector is biased positively with respect to plate 2 to ensure collection of all electrons. The beam current value is based on considerations of gauge sensitivity and undesirable space charge effects. Values in excess of 4 μA generate a space charge which causes the resonant frequency to be density dependent and the density-ion current relationship to become nonlinear.

Once the ionizing current magnitude and energy have been chosen, the sensitivity of the gauge becomes a function of the percentage of ionized particles reaching the collector. To evaluate the ion collection efficiency, plates 3, 4, 5, and 6 are connected to the collector and plates 1 and 2 are biased about 5 V positive. Thus total ion current is measured, which when compared with the current reaching the collector, provides a measure of ion collection efficiency. The total available current is used as a normalizing factor in operational analyses, since the collection efficiency has been found to be pressure independent below about 2×10^{-6} Torr.

The rf excitation voltage and a small dc voltage V_{dc} are applied between plate 3 and the other five sides of the cage. Also, all plates are raised by a fixed potential V_c above ground; the effect of this is to produce a small potential difference between the ion collector and the cage. The ion collector is connected to the input of an electrometer amplifier and is at quasiground potential. The value of the rf voltage is chosen on the basis of a compromise between collection efficiency and mass separation. Figure 4 shows the ion collection efficiency dependence on the rf voltage magnitude, and Fig. 5 shows plots of mass 28 peaks for three different rf voltages. The ordinate in Fig. 5 is normalized to the peak current. The rf voltage value chosen is near the optimum for collection efficiency and also provides adequate mass resolution since, in its application, the Omegatron does not encounter masses in significant amounts nearer than mass 32. The radio frequency of reso-

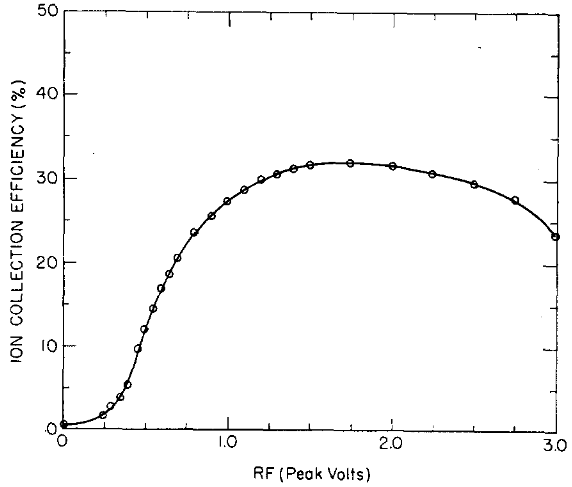

FIG. 4. Ion collection efficiency vs rf voltage for molecular nitrogen.

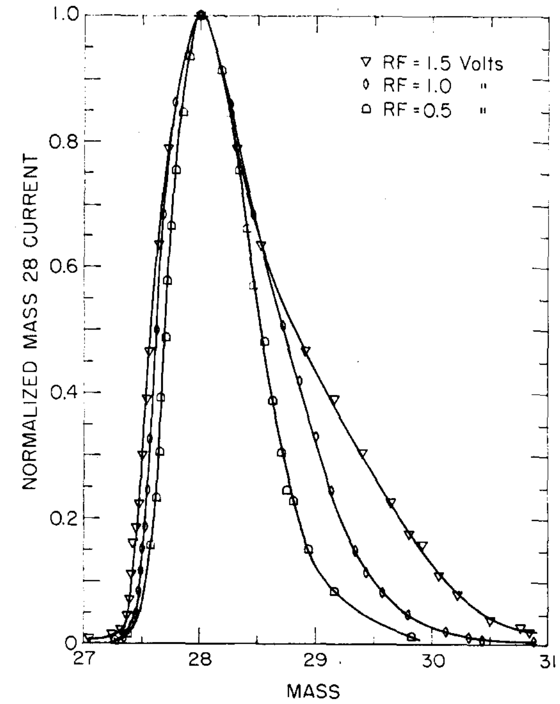

FIG. 5. Normalized mass 28 current vs mass about atomic mass 28 (molecular nitrogen) with rf voltage as parameter.

nance is inversely proportional to mass, and its values are essentially set by the magnetic field strength. The resonant frequency for mass 28 with the 2200 G field is approximately 110 kHz.

Because of the rf field component in the magnetic field direction and the thermal motion of the ions, a fraction of the available ions are able to escape to plates 1 and 2 and hence are not collected. By biasing plate 3 negative with respect to the rest of the cage and thus trapping the ions in the magnetic field direction, the loss of ions can be reduced. Figure 6 shows the ion collection efficiency as a function of this bias voltage V_{dc}. The shape of the curve is mass independent, but its horizontal position is shifted to the left for lighter gases; i.e., a larger negative bias voltage is required to optimize ion collection for lighter gases such as helium. This is reasonable since the lighter ions have greater mobility in the direction for which the bias is effective in providing trapping; i.e., parallel to the magnetic field lines. The mass dependence of the optimum bias value, shown in Fig. 7, is inconvenient if spectra are to be obtained; but in the fixed tuned mode, this presents little problem.

From Fig. 6, it can be seen that when the bias voltage reaches about half of the peak value of the rf voltage no ions reach the collector. When it is past this point, the net field causes the ions to drift away from the collector, since the radial drift velocity is proportional to E_{dc}/B and the gain in radius due to the cyclotron action is proportional to $E_{rf}/2B$. E_{dc} and E_{rf} are the electric field components in the plane perpendicular to the magnetic field vector, and B is the field strength.

A small fraction of the nonresonant ions in the action region drift to the ion collector and cause a background ion current. The size of this fraction depends on the mass of the nonresonant ions but is essentially independent of pressure. A negative bias voltage of 0.2 V between the cage and the collector reduces the background current by a factor of two without changing the resonant ion current. About 2% of the nonresonant nitrogen and oxygen ions and 0.2% of helium ions reach the ion collector regardless of rf voltage and frequency.

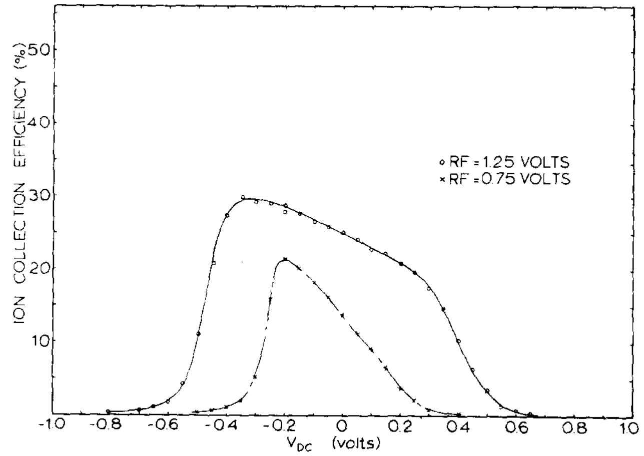

FIG. 6. Ion collection efficiency vs dc bias voltage for molecular nitrogen.

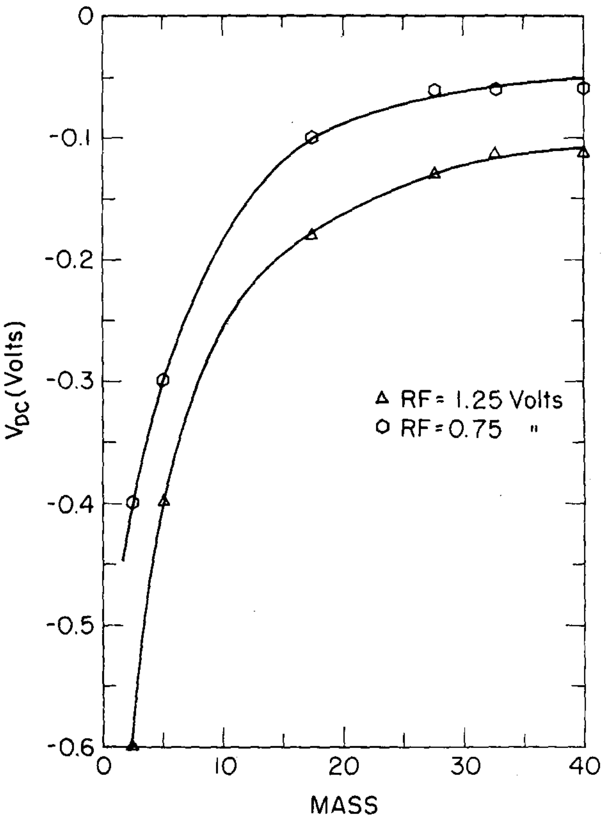

FIG. 7. Dependence of optimum dc bias voltage on the atomic mass number.

ELECTRONICS

The principal electronic subsystems required to operate the gauge are the filament regulator, the bias voltage supply, the rf oscillator, and the electrometer amplifier. Each of these are standard circuits but especially adapted for the Omegatron use. The filament regulator controls the current through the filament to maintain a constant ionizing beam. The bias supply, packaged with the filament regulator, provides the several bias voltages needed. The rf oscillator is a Colpitts type. The frequency determining components are so chosen that the frequency drift is less than 1 part in $10^5/\mathrm{C}^\circ$ over the temperature range indicated below.

The ion current detector is a 100% feedback linear electrometer amplifier with eight ranges. Range is changed automatically in both directions by sampling the output for the switching criterion. The eight ranges provide adequate resolution over four decades of ion current, from 5×10^{-14} to 5×10^{-10} A, which corresponds to a pressure range of approximately 1.5×10^{-9} to 1.5×10^{-5} Torr.

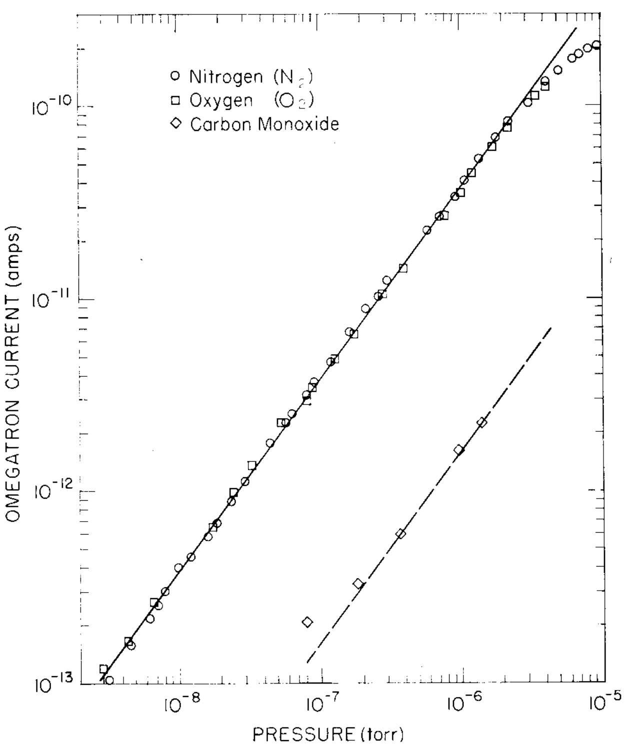

FIG. 8. Pressure calibration curves for the Omegatron for molecular nitrogen and oxygen. The dashed curve shows the collector current caused by mass 28 ions when oxygen was introduced into the calibration system.

The circuits are temperature compensated to operate over a temperature range of 0 to +60°C and are constructed to withstand the effects of vibration and acceleration. Components with the highest available reliability factors are used throughout, and each subsystem is subjected to extensive environmental testing before flight application.

CALIBRATION

To obtain the necessary correlation between the measured ion current and the pressure in the chamber, the Omegatron is calibrated against several reference gauges. The calibration is performed on a vacuum calibration system at Goddard Space Flight Center, which uses a conductance determined pressure division as described by Roehig and Simons.[9] In this system, several manifolds are used to provide an accurately known pressure ratio of several orders of magnitude between the highest and lowest pressure chambers. This permits calibration of gauges in the low pressure manifold against a McLeod gauge in the high pressure manifold. Several Bayard-Alpert and Redhead gauges are calibrated in the manner described and then used as "secondary" standards against which the Omegatron is calibrated. This procedure, rather than direct calibration of the Omegatron against the McLeod guage, is used to save time and to permit evaluation of dynamic effects such as hysteresis and time response. Before the Omegatron is calibrated, the vacuum system is baked, and the Bayard-Alpert gauges are electronically degassed. With this preparation, a base pressure of about 10^{-9} Torr is obtained. The instrument is then calibrated by leaking in a purified gas and thus increasing the pressure in small increments. After the pressure has reached about 10^{-5} Torr, it is incrementally decreased to the base pressure. This procedure provides data on both increasing and decreasing pressure, for evaluation of hysteresis.

Figure 8 shows a typical set of calibration data for molecular nitrogen and oxygen. The Omegatron ion current is plotted against the Bayard-Alpert gauge pressure after correction for background. It can be seen that the Omegatron's sensitivity is about 3.5×10^{-5} A/Torr in its linear region. At high pressure, the gauge becomes nonlinear because of an increase in space charge in the action region. Its linear region can be extended, at the expense of sensitivity, by reducing the beam current, but only to about 2×10^{-5} Torr, at which point the mean free path of the molecules approaches the path length of the resonant ions. For nitrogen, the increasing and decreasing pressure data agree to 5%. A hysteresis effect is observed in the oxygen calibration. This is attributed to a memory in the Bayard-Alpert gauges, a phenomenon which has been described by Schuemann *et al.*[10] The data in Fig. 8 were taken

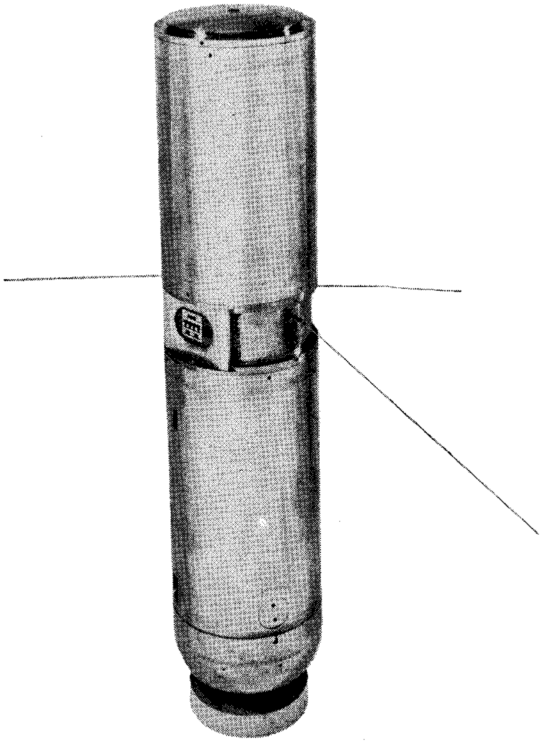

FIG. 9. The Thermosphere Probe.

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[9] J. R. Roehrig and J. C. Simons, Jr., *Trans. 8th Natl. Vacuum Symp.* (American Vacuum Society, 1961), Vol. 1, p. 511.

[10] W. C. Schuemann, J. L. de Segovia, and D. Alpert, *Trans. 10th Natl. Vacuum Symp.* (American Vacuum Society, 1963), p. 223.

during increasing pressure runs only. The dashed curve in Fig. 8 represents measurements of the ion current, as measured when the Omegatron is tuned to mass 28 and oxygen is used as a test gas. It is believed to be CO formed by the hot filaments of the gauges and on the metal walls. To determine the contribution to the mass 28 current by the ionization gauges, their filaments were turned off temporarily while the Omegatron was measuring mass 28. The ion current decreased only a few percent; this indicates the possibility that a significant amount of CO is being produced in the Omegatron itself. In flight, when the molecular nitrogen concentration of the upper atmosphere is to be measured, a correction is required for the CO produced in the gauge chamber by atmospheric oxygen. Above 100 km, where oxygen begins to dissociate, even more CO may be produced. Work is going on to evaluate this effect in a vacuum system where atomic oxygen can be introduced.

After initial calibration, the Omegatron is exposed to atmospheric pressure, baked, and recalibrated. It is then subjected to a vibration test at levels similar to those expected in flight, and again recalibrated. The sensitivity of several gauges, subjected to these tests changed by less than 5%. The sensitivity from gauge to gauge has varied as much as 15%. This effect is believed to be at least partially due to small design changes introduced from time to time to simplify the gauge construction. For any given Omegatron the absolute calibration accuracy is believed to be about 25%, but the relative accuracy from gauge to gauge is probably better than 10%.

PERFORMANCE

The Omegatron described is used in a rocket program of aeronomy research which employs the Thermosphere Probe instrument package. The probe, shown in Fig. 9, has been especially developed to carry a variety of measuring devices into the thermosphere. The Omegatron, with its electronics, occupies about 25.4 cm of the length of a 15 cm diam stainless steel cylinder. Sharing the instrument package are other aeronomy experiments and the power supplies, telemetry, and auxiliary subsystems needed to make the probe completely self-contained.

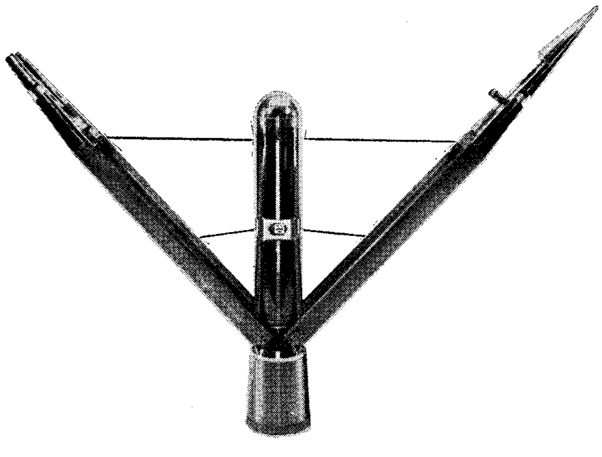

FIG. 10. Photograph of Thermosphere Probe as it rests on the plunger in the clamshell nose cone.

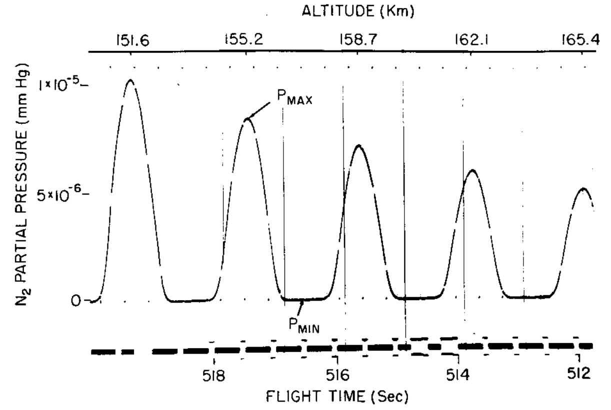

FIG. 11. Photograph of a section of Omegatron telemetry (labeled in terms of N_2 partial pressure) recorded during five consecutive tumble cycles as the instrument descended through the atmosphere.

The cylinder, vacuum sealed, is carried aloft inside a nose cone (see Fig. 10) and ejected at about 100 km. The Omegatron is evacuated before launch and is flown in vacuum. At ejection, the probe is caused to tumble so that the orifice of the Omegatron is oriented cyclically into and away from the direction of motion. If the velocity of the probe, the orientation of the orifice with respect to the velocity vector, and the density and temperature inside the gauge are known, the ambient particle density can be calculated.[11,12] A section of the telemetry record from one of the flights is shown in Fig. 11. The pressure variations from the tumble motion are clearly visible, having a period of about 2 sec. The decrease in pressure with altitude is also obvious in the 14 km interval shown.

The geophysical data obtained from the first four flights of the Omegatron in the Thermosphere Probe have been reported in the literature.[1] The success of the gauge in measuring the latitude density profiles of molecular nitrogen has led the experimenters to try to increase the scope of its utility to include measurements of other gases. The Omegatron's principal value remains, however, in its ability to measure the partial pressure of a nonreactive gas whose abundance is 10% or more of the total. Its simplicity of construction, ruggedness, and reliability make it ideal for application in rockets and satellites.

ACKNOWLEDGMENTS

We thank G. R. Carignan, who directed the Thermosphere Probe Program, and the engineers and technicians

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[11] F. V. Schultz, N. W. Spencer, and A. Reifman, "Upper Air Research Program," Engineering Research Institute, The University of Michigan, Ann Arbor, Michigan, Report No. 2 (July 1948).

[12] R. Horowitz and H. E. LaGrow, J. Geophys. Res. **62**, 57 (1957).

of Space Physics Research Laboratory, The University of Michigan, who assisted with the experiment; the Goddard Space Flight Center personnel, who assisted with the calibration; and particularly W. G. Kartlick of The University of Michigan, who constructed the gauges. We are indebted to N. W. Spencer of the Goddard Space Flight Center, who initiated the Omegatron project and whose suggestions contributed to its success.

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Construction of Precision Glass Cell for Hall Coefficient Measurements of Liquids

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The construction of a glass cell with rectangular cross section for measuring Hall coefficients of liquids is described. The cell can be hermetically sealed and is bakeable under vacuum. Probes for the detection of the Hall voltage have been accurately aligned by alternately grinding the holes through the cell wall and measuring their misalignment. In this way, it has been possible to reduce the misalignment of the voltage probes to half a micron or less.

INTRODUCTION

HALL coefficient measurements of liquids are subjected to the difficulty of containing the specimen in a cell provided with electrodes for the specimen current and for measurement of the Hall voltage. The cell geometry determines the spatial variation of the current density. In order to simplify the evaluation of measurements, it is advantageous to contain the specimen in a cell having a rectangular cross section of accurately known dimensions.

Glass is a desirable cell material because of its chemical resistance and the relatively simple cleaning procedures for its surfaces. However, the accuracy of glass blowing techniques is limited and the alignment of the voltage probes represents a serious problem. Although experimental methods[1,2] have been developed to eliminate the misalignment voltage of displaced probes, difficulties arise, for the measurements of small Hall coefficients in the order of 10^{-4} cm^3/C if the probe misalignment is appreciable. The success of Hall effect measurements of liquids depends greatly on the construction of the cell.[3] For this reason, an attempt has been made to construct precision glass cells with rectangular cross sections and to reduce the probe misalignment beyond the limits achievable by conventional glass blowing.

CONSTRUCTION OF CELLS

The cells are constructed of four flat glass plates. The bottom and the top plates have a thickness of 2 mm, and the side plates a thickness of 1 mm. The greater thickness of top and bottom plates gives the cell the mechanical strength to withstand bakeout under vacuum as well as to withstand a few atmospheres of excess internal pressure under operational conditions. All four plates have a length of 75 mm. The width of top and bottom plates is 7.50 mm. This dimension determines the inside width of the cell and, therefore, it is kept within close tolerances by grinding the plates.

In the first step of the cell construction, the ends of top and bottom plates are sealed to glass tubes with a metal spacer between the plates. The spacer determines the inside height of the cell and is removed when this sealing operation is finished. The glass tubes at the ends of the plates assure the correct spacing of 0.50 mm during the following phases of the construction. A schematic drawing of the assembly at the completion of the first step is shown in Fig. 1.

The most critical operation in the construction of cells with rectangular cross section is the sealing of the side plates to the top and bottom plates. The reduced thickness of the side plates is of great importance for obtaining flat inside surfaces with rectangular edges at the joints of two plates because it permits sealing of the side plates without heating the inside surfaces of the cell to the softening point of the glass. The side plates are fused to the outer edges

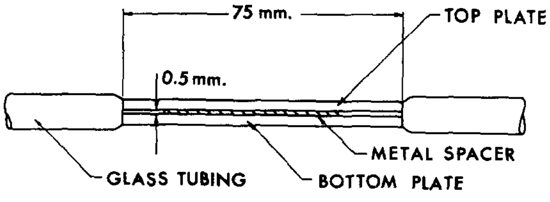

FIG. 1. Glass cell after first stage of construction.

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[1] H. Fritzsche, "The Hall Effect" in *Methods of Experimental Physics, Solid State Physics*, K. Lark-Horovitz and V. A. Johnson, Eds. (Academic Press, Inc., New York, 1959), Vol. 6, Pt. B.

[2] B. R. Russell and G. Whalig, Rev. Sci. Instr. **21**, 1028 (1950).

[3] N. E. Cusack, Rept. Progr. Phys. **26**, 361 (1963).