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RESPONSE OF MODIFIED REDHEAD MAGNETRON AND BAYARD-ALPERT VACUUM GAUGES ABOARD EXPLORER XVII

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Goddard Space Flight Center
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SUMMARY

Two Redhead and two Bayard-Alpert gauges were used in the satellite Explorer XVII to measure the density, pressure, and temperature of the earth's upper atmosphere. Gauge pressures from 10^{-6} to 10^{-10} torr (a function of satellite attitude and velocity, and of certain atmospheric parameters) were measured over the altitude range from 260 to 900 kilometers. During the spin period of 0.67 second, the gauges recorded pressure changes as large as a factor of 30 (e.g. from 3×10^{-9} to 8×10^{-8} torr). Comparison of the independent gauge outputs yielded values in good agreement with kinetic theory predictions.

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INTRODUCTION

Knowledge of the neutral particle concentrations is important for an understanding of the physical and chemical processes occurring in the upper atmosphere. The Explorer XVII satellite (1963 9A), known prior to launch as "S-6"*, was placed into orbit to measure directly the neutral particle density, composition, temperature, and the electron density and temperature. The orbit attained had an inclination of 58 degrees, a perigee of 257 km, and an initial apogee of 920 km. The total of the previous direct measurements of the neutral particle atmosphere in the altitude region covered by Explorer XVII was so small that the first two days' output from the satellite significantly increased the amount of available data for study of this region.

The satellite was a pressure-sealed stainless steel sphere 0.875 m in diameter. Its experiment sensors—two Bayard-Alpert gauges (BAG), two Redhead gauges (RHG), two magnetic mass spectrometers and two electrostatic probes—were located as shown in Figure 1. The satellite was spin-stabilized at 1-1/2 cps, about an axis through the two mass spectrometers. The pressure gauges were mounted at the vertices of an equilateral tetrahedron, two of them being located on the satellite equator. Explorer XVII exceeded its expected 90-day operational lifetime by ten days, and considerable data were obtained from all experiments.

Some of the first observations of the gauge responses are discussed in this paper. As more data are analyzed, a more complete picture of the gauge performance will become available and will be presented in future papers.

THE GAUGE EXPERIMENT SYSTEM

To measure the neutral atmospheric density and temperature two Bayard-Alpert and two magnetron Redhead vacuum gauges were used. The reasons for these choices were:

1. These gauges are accepted as instruments for vacuum measurements.

*Horowitz, R., "S-6, An Aeronomy Satellite," *Advances in the Astronautical Sciences*, Volume 12, 1963. pp. 21 to 39.

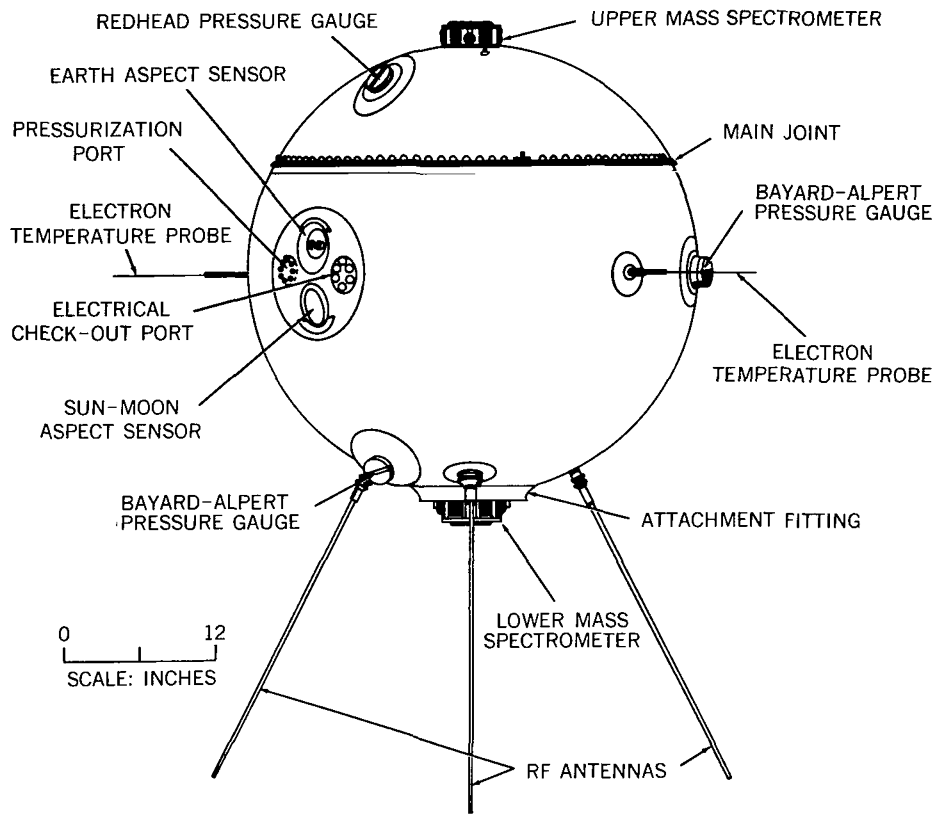

Figure 1—Lateral view of Explorer XVII.

2. The sensors complement one another and together cover the expected 10^{-6} to 10^{-11} torr pressure range.

3. The two types of detectors provided at least two decades of overlap in pressure range.

4. The gauges are being studied extensively in other laboratories as well as at GSFC.

Figure 2 shows a flight BAG (top) and a flight RHG (bottom). Both gauges have ion traps painted on the inside of the glass envelope, out of the ionization region, and have a volume of approximately 55 cm^3.

The Bayard-Alpert gauges were made by Westinghouse Electric Corporation, Electron Tube Division, and have been assigned the Westinghouse number WX 4250. They are 2.5 cm in outside diameter. Each detector has three filaments spaced symmetrically about the gauge axis, two of which were available during flight. If the first filament opened for any reason, the second filament would be switched automatically into use. However, both Bayard-Alpert gauges survived launch and the satellite operational life of more than 700 operations, on the primary filament.

The flight gauges differ from the normal laboratory Bayard-Alpert gauge in that:

1. The gauges have been miniaturized and ruggedized.

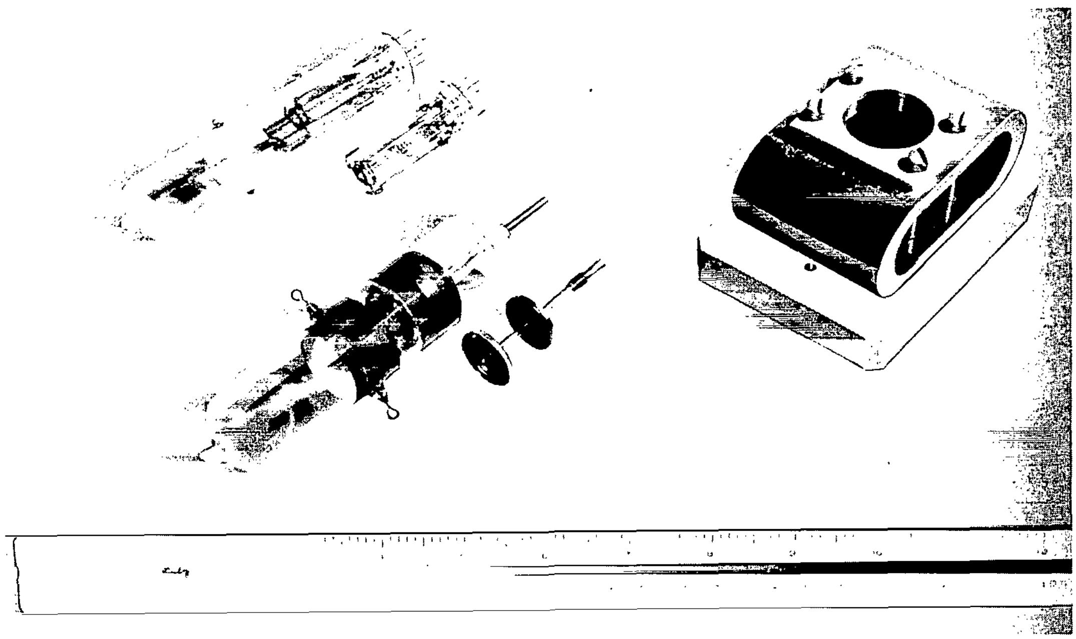

Figure 2—The flight Bayard-Alpert gauge (top), the flight Redhead gauge (bottom), and the Redhead magnet (right).

2. Ion traps have been added.
3. The tapered collector is brought through the same press as the other electrode connectors.
4. Each tube has three filaments.

The Redhead gauges, of 3.0 cm outside diameter, were made by NRC Equipment Corporation and carry the designation NRC 528. The cathode spool is mounted coaxially with the envelope, and a special magnet fits over the tube to provide an axial magnetic field. These detectors differ from the NRC 552 laboratory Redhead gauge in that:

1. The auxiliary cathodes are eliminated, and the tube is miniaturized and ruggedized.
2. The magnetic field is parallel to the gauge axis.
3. The anode is painted on the inside of the envelope.
4. Ion traps have been added.

The four gauge systems, which consisted of components similar to those shown in Figure 3, were electrically and otherwise independent of one another, and were programmed to operate automatically for 4 minutes when the satellite was commanded on. After turn-off, they were then inoperative until the next spacecraft turn-on.

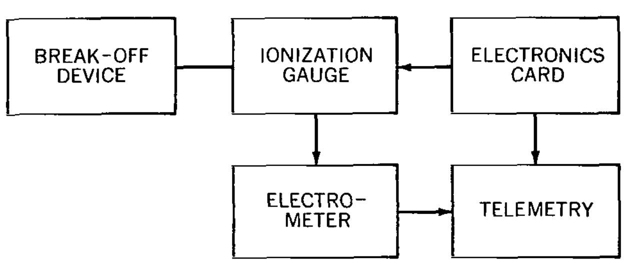

Figure 3—Representation of a pressure gauge experiment.

To maintain vacuum cleanliness, the gauges were sealed under vacuum prior to installation in the satellite. After the satellite was established in orbit, the sensors were opened by break-off devices, which exposed the gauges to the atmosphere through knife-edge kovar orifices 0.938 cm in diameter. These orifices have a calculated molecular conductance of 8.2 liters/second for nitrogen at room temperature. They protrude from the satellite shell a short distance and have 180 degree acceptance angles.

As is seen in Figure 2, the ion traps are cylindrical electrodes painted on the gauge walls between the ionization region and the orifice. For approximately 90 seconds during each 4 minute operating interval, a potential of 30 v was applied between traps to help evaluate the effect—if any—of entering, charged ambient particles. No significant effect was observed.

The electronics consisted of the power supplies to provide the gauge potentials and, for the Bayard-Alpert gauges, emission-current regulators, which held the grid currents constant to better than 2 percent. Logarithmic electrometers converted the gauge currents to voltages suitable for telemetry.

LABORATORY RESPONSES OF THE GAUGES

The laboratory responses of the gauges were obtained with the detectors energized as they would be during flight. For the Bayard-Alpert gauge the potential difference from filament to grid was 105 v, and from filament to collector, -27 v with the filament ground. The emission current was 5.0 ma.

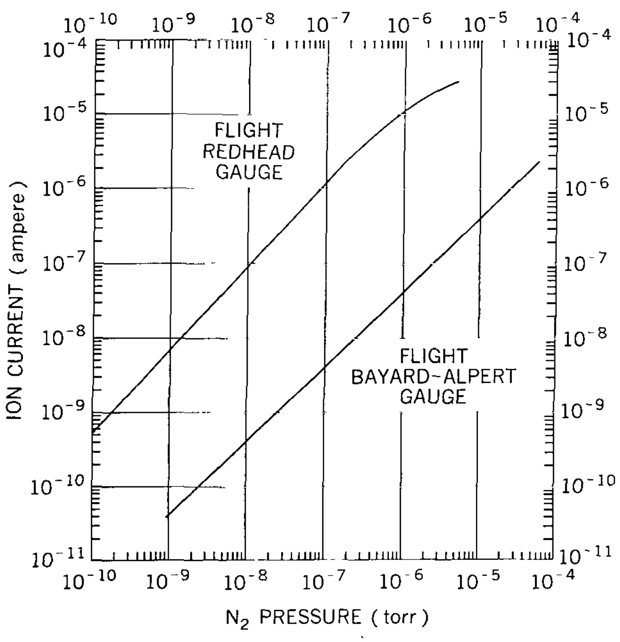

Figure 4—Ion current versus pressure characteristics of the flight Bayard-Alpert and Redhead gauges.

The Redhead gauge was operated with 4800 v between the anode and cathode, the latter being grounded through the electrometer. The magnetic field strength was 1000 gauss.

Figure 4 shows the output current of a flight Bayard-Alpert and a flight Redhead gauge plotted against nitrogen pressure*. The gauge residuals have been subtracted to obtain these curves. The flight BAG calibration was obtained by comparing its response to that of a Westinghouse 5966 tube operating at 0.1 ma. emission current, which previously had been compared to a Consolidated Vacuum Corporation GM 110 McLeod gauge over the pressure range from 10^{-3} to 10^{-6} torr. The flight BAG is linear from 10^{-9} to 10^{-4} torr and, for nitrogen at the flight emission current, the gauge has a sensitivity of $4.2 \times 10^{-2} \pm 25\%$ ampere/torr. The ratio of the helium sensitivity

*Hereafter all pressures are equivalent nitrogen pressures unless otherwise specified.

to that for nitrogen is 0.17. The precision of the measurements was better than 10% even though the data were taken on different days with intervening bake-outs of the system at 400 °C and outgassings of the sensors. Most of the tubes calibrated had sensitivities within 25% of each other. Normally, the use of different filaments in the same gauge changed the sensitivity by a few percent.

The response of the flight RHG is nonlinear in the pressure region from 2×10^{-10} to 2×10^{-7} torr, and the collector current i_+ follows an expression of the form $i_+ = kp^n$ where n is 1.15, k is a constant and p is the pressure. The calibration data supplied with the gauge was stated as being accurate to ±30%. At Goddard Space Flight Center (GSFC), the gauges were compared to a laboratory NRC 552 Redhead gauge which had been, in turn, compared to the McLeod-calibrated WH 5966, thus providing a calibration believed valid to ±30%. As a result of the comparisons, the NRC and the GSFC calibrations of the flight gauges were found to agree. The best-fit curve through the overlapping region of the two sets of data is used to analyze the flight measurements. The following observations can be made about the Redhead gauge:

1. The assigned gauge sensitivity in amperes/torr for a particular gas varies with pressure. For example, in nitrogen at a pressure between 10^{-10} and 10^{-9} torr the value is 7, and increases to 11 at the 10^{-7} to 10^{-6} torr range.
2. Preliminary analysis of laboratory measurements indicates that the ratio of the Redhead gauge sensitivity for nitrogen to that for helium at a particular pressure is the same as that of the Bayard-Alpert gauge.
3. The gauge is insensitive to pressure changes in the 10^{-5} torr region.
4. In the 10^{-9} to the 10^{-6} torr range, the gauges would generally strike a discharge in less than 30 seconds. The time to start varied from tube to tube and appeared to be a function of tube cleanliness. There was no starting problem in flight.
5. In certain regions of pressure the gauges are unstable, and the current consists of transients and noise, as well as a dc component. These pressure intervals are well defined and constitute a small part of the gauge response; thus they do not significantly interfere with the analysis of the flight data.

THE SATELLITE MEASUREMENT TECHNIQUE

In considering how the measurements were performed with the satellite, it is helpful to recall that the gauges are moving at a high speed compared to that of the atmospheric molecules.* Further, in the equivalent situation with the satellite at rest, the ambient molecules, in effect, are moving with the satellite speed in the opposite direction (as is illustrated in Figure 5, with the gauge facing into the "neutral beam"). In this case the gauge internal pressure will exceed the ambient. The trace on the right in Figure 5 shows the ratio of gauge pressure to ambient pressure as a function of the satellite spin angle, for a satellite speed of approximately 7.5 km/sec., with the gauge temperature equal to the ambient temperature. It is seen that the gauge pressure

*Spencer, N. W. et al., "On the Use of Ionization Gauge Devices at Very High Altitudes," *Amer. Rocket Soc. J.* April 1959, pp. 290-294.

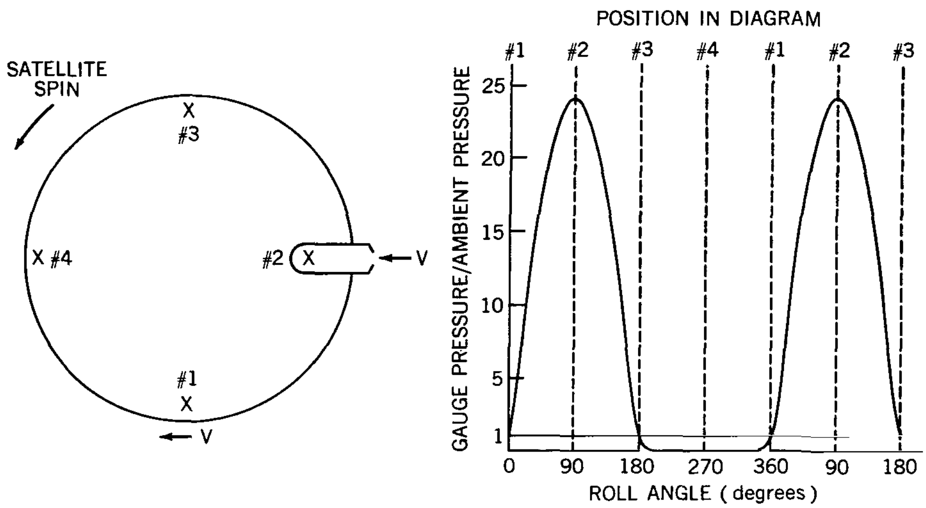

Figure 5—Plot of predicted gauge-pressure-to-ambient-pressure ratios versus satellite roll angle.

is a factor of 24.7 above the ambient when the gauge is in position 2. If the two temperatures were not equal, the ordinate would require adjustment by a thermal transpiration term. In position 3, the sensor does not "see" the beam and the pressure in the gauge is determined by the thermal transpiration equation or, for equal temperatures, equals the ambient pressure. In position 4, the pressure is essentially zero, since only particles in the high-energy tail of the thermal velocity distribution can overtake the satellite and enter the sensor. Position 1 is equivalent to position 3. Thus, over a spin cycle we would expect an ideal gauge response to exhibit this behavior. Since the four Explorer XVII gauges are mounted at the vertices of an equilateral tetrahedron, at least one will always experience a "ram" velocity and thus provide a detectable and known sample of the neutral-particle atmosphere.

THE GAUGES' FLIGHT RESPONSE

The satellite was operated during the first apogee pass, and the openings of the gauges were observed. Analysis of the data indicates that the gauges survived the launch vibration, and all indicated pressures after opening in the 10^{-9} torr range or lower, thus demonstrating their ability to indicate this low pressure in orbit.

Because of the satellite's attitude during the first few days in orbit, the operation of the lower BAG could not be immediately evaluated. The present evidence, however, is to the effect that it experienced a loss of sensitivity after opening. Related telemetry information indicates that proper operation should be expected. The apparent contradiction has not been resolved.

Figure 6 is a machine plot of the pressure gauge telemetry output for the orbit 118 pass over Blossom Point, Maryland. The period is 0.67 second corresponding to one rotational period of the satellite. The output of BAG I indicates that the sensor is in the rarefaction. The trace labeled BAG II is the output of the equatorial BAG, RHI is in turn the equatorial RHG signal and RHG II is the upper RHG response. The spin axis is 75 degrees from the velocity vector. The Redhead gauge output voltages are inverted, that is, a high voltage value corresponds to a low pressure. The peak-to-peak pressure values shown in Figure 6 are proportional to the atmospheric density at the time and location of measurement, and inversely proportional to a function of the satellite velocity. The analysis of the nonequatorial gauge data requires modified velocity considerations to obtain atmospheric density. The density obtained from these three detectors for this pass agree to better than 21% and is compatible with the expected densities. The phase relations between the gauges, which can easily be seen in Figure 6, are proper and in accord with the known satellite attitude.

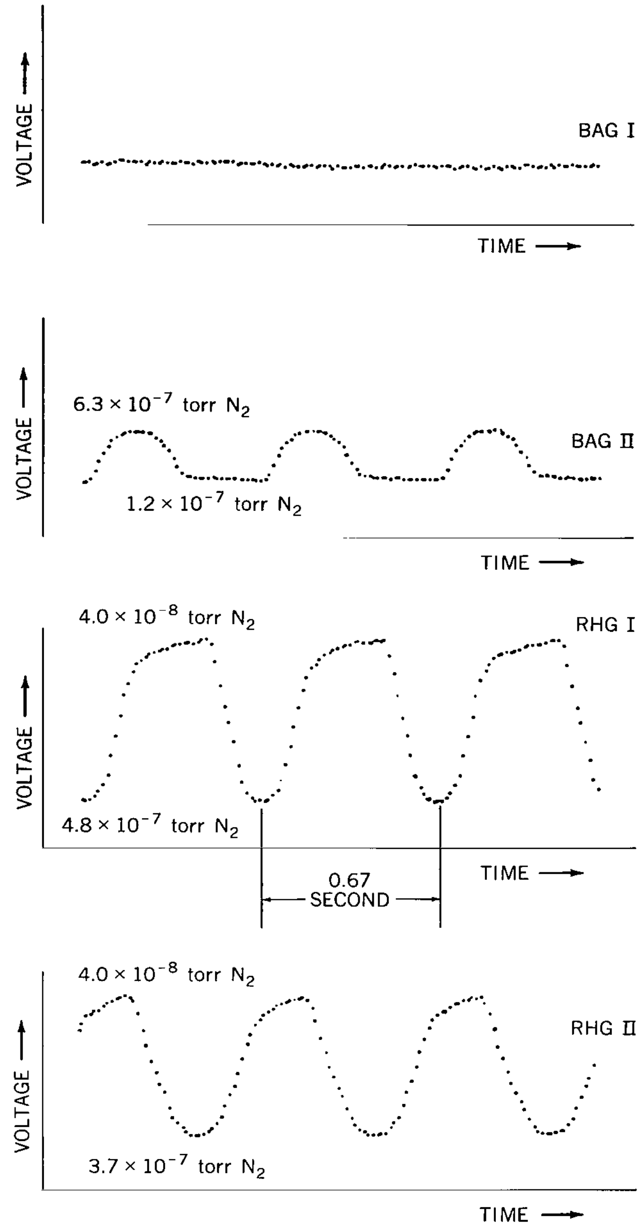

Figure 6—Pressure gauge telemetry output signal plots (Orbit 118, April 10, 1963, at 18:30 E.S.T. over Blossom Point, Maryland).

In Figure 7, the equatorial RHG pressure for the Blossom Point pass 118 is compared with its theoretical response as predicted from kinetic-theory considerations. The peak of the theoretical curve has been normalized to fit the maximum of the measured gauge pressure. The measured pressure agrees quite well with the theoretical curve shape. The resolution of the data is such that one pressure gauge output sample is obtained approximately each 9 degrees of satellite spin angle. It is seen that the measured maximum-to-minimum gauge pressure ratio for a spin cycle is 12, i.e., from 4.0×10^{-8} to 4.8×10^{-7} torr. Other passes have shown ratios as large as 30, e.g., from 3×10^{-9} to 8×10^{-8} torr. The theoretical gauge pressure, when the sensor is behind the satellite is a factor of more than 10^9 below the ambient value (0 and 180 degrees roll angle). The gauge, in this case, does not follow completely the theoretical response into the rarefaction region, but apparently has some effects of residual outgassing. Therefore we have the opportunity to observe and investigate the outgassing-residual of the sensors and its implications, each spin cycle.

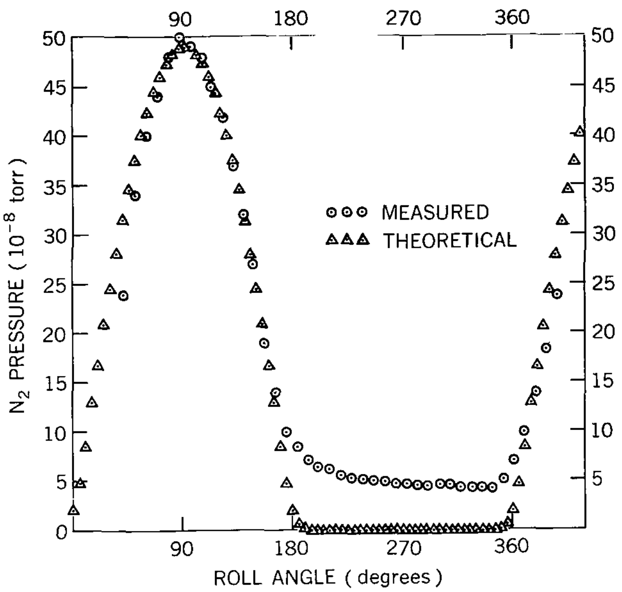

Figure 7—Plot of theoretical and measured equatorial Redhead gauge pressure versus satellite roll angle.

With respect to data analysis, the outgassing residual can only affect the density to the order of 10% in this case, since the minimum gauge pressure is less than 1/10 the maximum pressure. This same RHG has indicated gauge pressures at perigee in the 10^{-6} torr range and both RHGs have indicated gauge pressures at apogee in the 10^{-10} torr range which are spin modulated. When the ram velocity is less than that experienced during Blossom Point pass 118, which is a near-maximum ram velocity condition, the gauge response follows the theoretical response to lower pressures, and thus the gauge pressure at the 180 degree point is not dominated by the outgassing-residual.

At apogee, the equatorial BAG indicates a 10^{-8} torr pressure, which appears, in comparison with the RHG at apogee, to be due to residual gas in the BAG. The BAG as launched indicated a considerably higher pressure, i.e., in the 10^{-5} torr range, than the other sealed gauges, which were in the 10^{-9} torr range. It is not presently known whether this higher pressure contributed to the observed gauge residual.

As analysis of the data proceeds, atmospheric densities and temperatures, and in addition information regarding the following, will be obtained:

1. The behavior of the gauge residuals, both long term (day-to-day) and short term (orbit-to-orbit);
2. Gauge responses to particular satellite orientations and ram velocities;
3. Apparent outgassing rates of the gauges and their variations;
4. The effect, if any, of sustained exposure of the gauges to an atomic oxygen environment.

Sufficient data have been studied already, however, to show:

1. Very good agreement of the densities obtained from the two RHGs and the BAG, presently estimated to be generally better than 30%;
2. Agreement of measured densities with values obtained from theory and indirect measurements;
3. The ability of the gauges to follow large (several orders of magnitude) pressure variations, as experienced in an orbital period;
4. The ability of the gauges to follow large (factors of 12 to 30) pressure changes in a period of 0.670 second;

5. The agreement between the shape and phase of the gauges' responses to those expected from kinetic theory.

It is concluded that these gauges have made meaningful *in situ* direct measurements which can be interpreted easily in terms of the neutral atmospheric parameters—density, temperature, and pressure.

ACKNOWLEDGMENTS

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