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A SATELLITE ANEMOMETER

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FINAL REPORT

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FROM

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SUMMARY

This report describes the design, development, and testing of components of a satellite anemometer. UTD and the University of Rome are jointly developing an instrument for measuring neutral winds in the upper atmosphere from a satellite platform. The device, which uses four nearly identical pressure sensors, measures the angle of arrival of the bulk neutral flow in the satellite frame of reference. It could also be used in a feedback loop to control spacecraft attitude with respect to the ram velocity direction. We have now developed miniaturized ionization pressure gauges that will work well from the slip flow region near 115 km up to the base of the exosphere, which covers the entire altitude range currently being considered for Tether. Laboratory tests have demonstrated a very linear response to changes in ram angle out to ± 20 deg. (transverse wind component of 2.7 km s^{-1}) from the ram, and a monotonic response to out beyond 45 deg. Pitch (vertical wind) and yaw (horizontal wind) can be sampled simultaneously and meaningfully up to 10 Hz. Angular sensitivity of 30 arc seconds (~1 ms^{-1}) is readily attainable, but absolute accuracy for winds will be ~1 deg. (130 m/s) unless independent attitude knowledge is available. The critical elements of the design have all been tested in the laboratory.

BACKGROUND

The gas pressure in a chamber mounted on a satellite is determined by the angle that the normal to an orifice to the outside makes with the neutral ram direction, and on the external gas density. A comparison of the pressure in two chambers that have orifices symmetrically pointed to either side of the desired neutral ram direction gives information which can be fed to a spacecraft control system which could null the pressure differential and keep the spacecraft looking in the ram direction. Alternatively, if the spacecraft orientation is known, the pressure comparison gives a measurement of the transverse wind velocity component.

The traditional ionization gauge works well as a pressure sensor in this application. A hot filament provides a controlled electron flux which ionizes some of the neutral particles in the pressure chamber. The collected ion current is proportional to the chamber pressure.

Two pairs of ion gauges in their individual chambers are required to give directional information in two axes. Collector current from each gauge is measured using a logarithmic electrometer. Both pairs of outputs are fed into difference amplifiers which provide outputs proportional to the log of the ratio of the two pressures of a gauge pair. Polarity is determined by which chamber of a gauge pair has the highest pressure.

Ideally, the gauges and electrometers would be perfectly matched so that equal pressures in an axis pair would result in zero volts output from their difference amplifier. A sufficiently close match cannot be maintained over all operating conditions so an in-flight adjustment technique with a re-zero amplifier and nulling circuit is used. Re-zeroing begins when a pressure equalization (P. E.) valve is opened. The pressures in the chambers become equal and a nulling circuit drives the output to zero. The nulling signal is retained in memory and the P. E. valve is then closed. Pressures in the chambers regain their independent values and the angle of attack can then be determined from the difference amplifier outputs.

PROGRESS/RESULTS

Testing of a miniaturized pressure gauge continued during this period with much attention to the problem of nonlinearity at low pressures. Figure 1 shows collector current vs. pressure curves for an early gauge design. Nonlinearity of the curves below 10^{-6} torr can clearly be seen. This is in the expected range for the gauge operation and so it is unacceptable. This particular gauge design did not out-gas readily during normal operation. Many gauge geometries, grid potentials, and coated surfaces were investigated without adequate improvement. The gauge configuration in Figure 2, having a spiral grid with axial collector wire proved superior to all the others. It had lower x-ray effect and higher pressure sensitivity. Out-gassing at normal emissions improved its low pressure linearity and the out-gassing accelerated at high emission and elevated grid voltage. The characteristics shown in Figure 3 were observed following 28.5 hours of normal operation at 100uA filament emission and +120 V grid potential. Examination of the curves shows good linearity over nearly five decades of pressure with only a slight departure near 10^{-8} torr. This pressure range is a good match to the altitude range contemplated for Tether and many orbiting satellites.

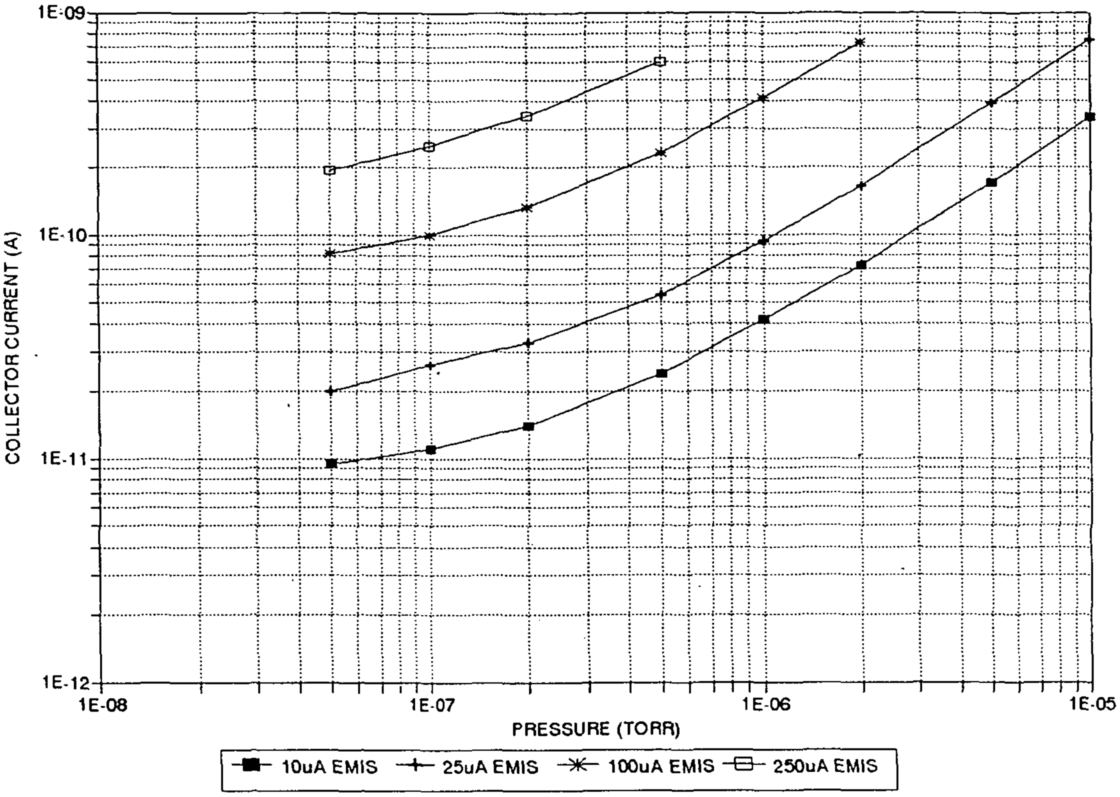


Figure 1. Collector current vs. pressure for an early gauge design.

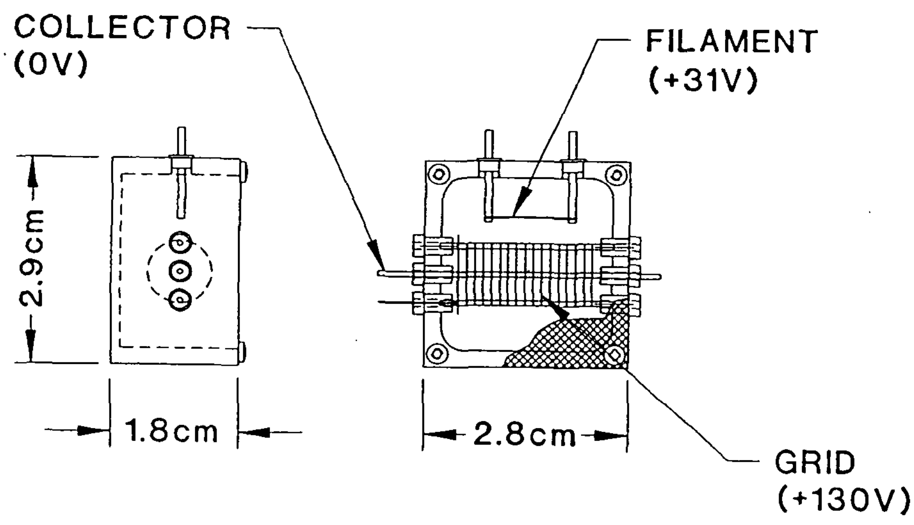


Figure 2. Redesigned miniature gauge with spiral grid and axial collector wire.

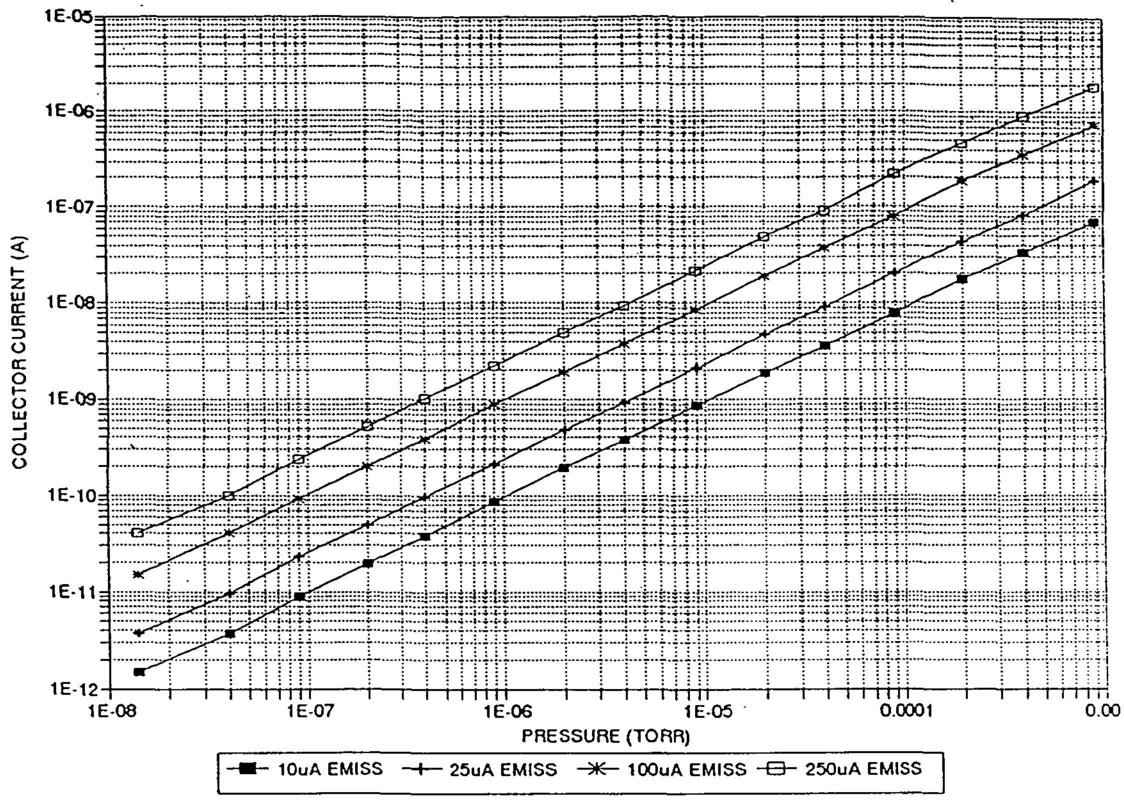


Figure 3. Collector current vs. pressure for the redesigned gauge.

The gauge pressure in orbit can be closely approximated by the expression:

$$P_g = \left[1.2 \times 10^{-15}\, n\ (O) + 2.3 \times 10_{-15}\ [n\ (O_2) + n\ (N_2)\ ]\right] \cos\alpha\ torr \qquad (1)$$

where n (O), n (O_2), and n (N_2) are the number densities (cm^{-3}) of the three principal atmospheric constituents below the base of the exosphere, and α is the angle between the velocity vector and the normal to the chamber orifice. The altitude range over which the device will function, based on the performance shown in Figure 3, can be seen in Figure 4. There the gauge pressure given by equation 1 is plotted versus altitude for noon and midnight atmospheric profile at both high ($F_{10.7}$ 150) and low ($F_{10.7}$ = 75) solar activity, with α taken as 30°. Even with the rarest atmosphere, the altitude range from below 125 km up to 400 km is operational, and for the denser atmosphere 500 km is within range.

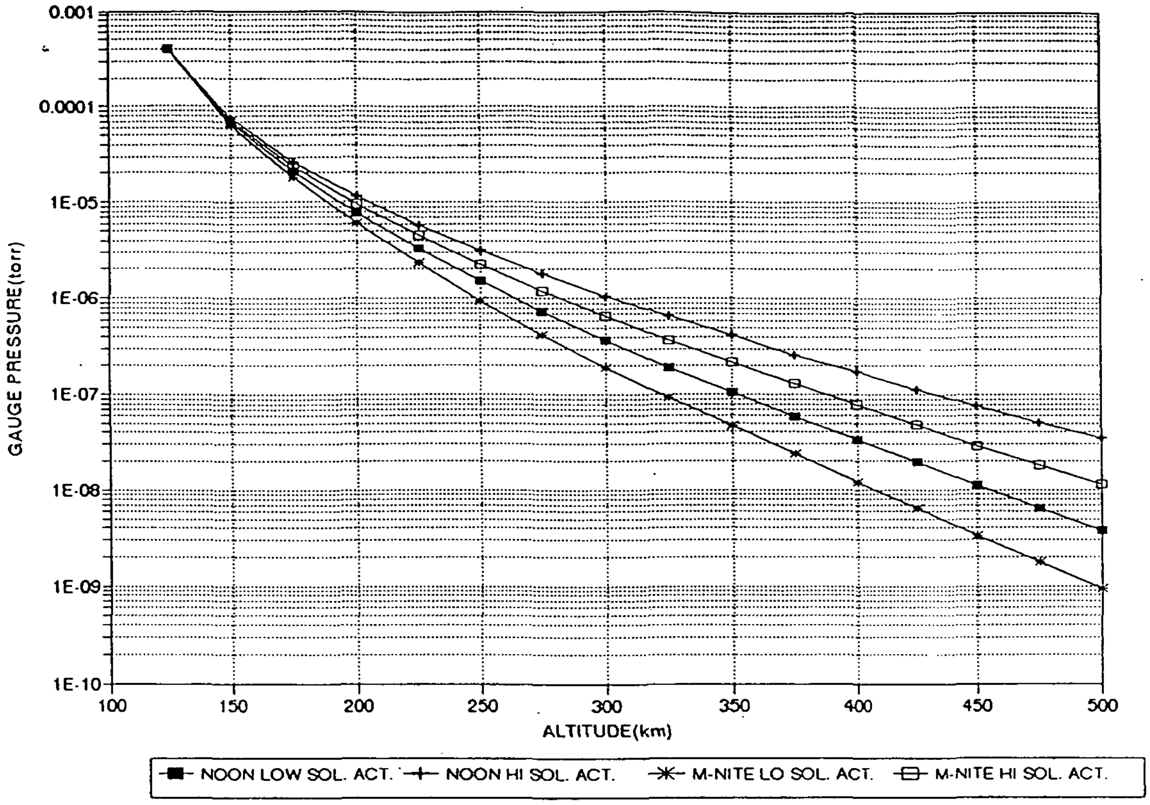


Figure 4. Gauge pressure vs. altitude.

Shown in Figure 5 are operating characteristics immediately after filament replacement (with the gauge exposed to atmosphere) and again after 4 hour of de-gas in the vacuum chamber at 250uA emission with +250 volts grid potential. The improvement in linearity after the de-gas procedure is apparent.

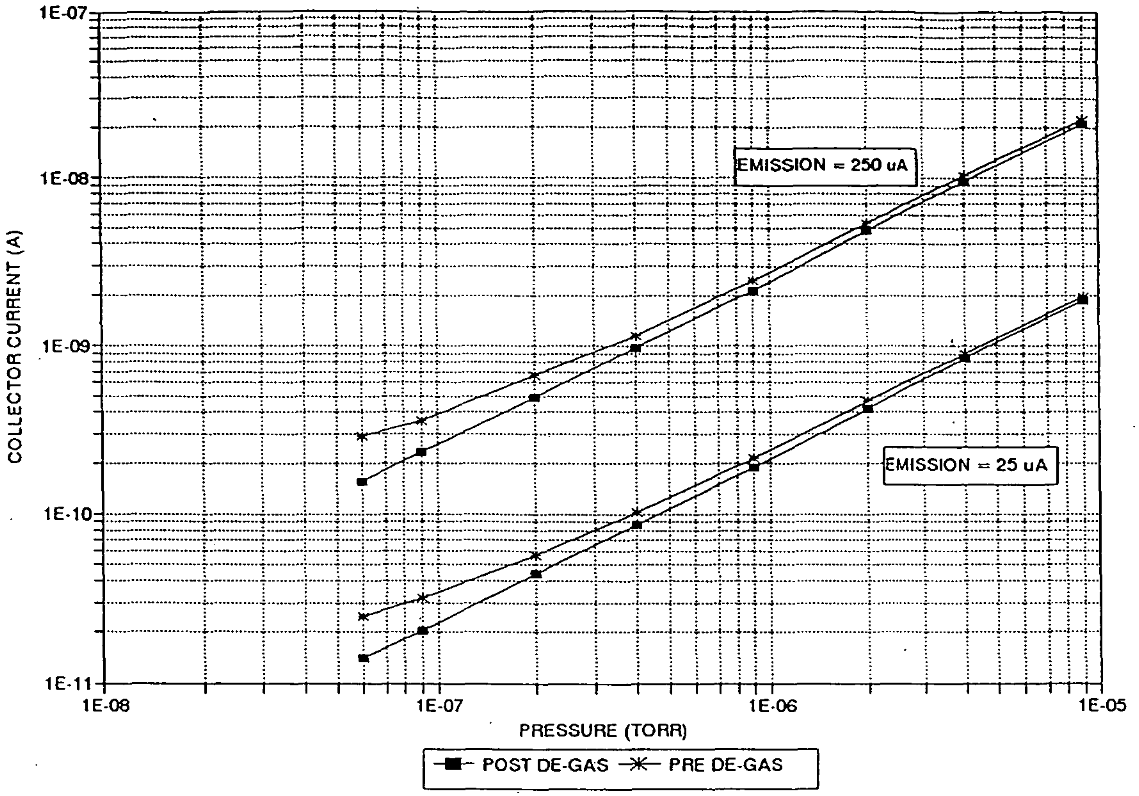


Figure 5. Gauge characteristics before and after de-gas.

Five candidate filament materials were tested for longevity and emission efficiency. Four filaments of each material were life tested at 10 microns pressure and two samples of each were tested for emission efficiency at three pressures. A summary of the results are shown in Table 1.

FILAMENT MATERIAL	2 × 3.7 MIL TUNGSTEN WITH 1% THORIUM	2 × 3.7 MIL TUNGSTEN WITH 3% RHENIUM	.003 DIA TUNGSTEN	.003 DIA RHENIUM	.003 DIA IRIDIUM
POWER (AVE. 2 FIL'S) $< 10^{-4}$ TORR 6×10^{-4} TORR 10^{-2} TORR	1.57 W 1.77 W 1.85 W	1.96 W 2.10 W 2.26 W	2.38 W 2.57 W 2.75 W	1.86 W 1.99 W 2.28 W	1.68 W 1.73 W 2.62 W
LIFE TEST (AVE. 4 FILS) 10^{-2} TORR	35.3 MIN	27.5 MIN	92.8 MIN	171.8 MIN	15.5 MIN

Table 1. Filament Test Results

Tungsten with 1% thorium had the best power profile. Two filaments of this material were life tested at an elevated pressure of 6×10^{-4} torr. One was emitting 250uA, the other 25uA. Both failed after 25 hours. Based on this test and the information in Table 1, filament lifetime is approximately proportional to the inverse of pressure. Therefore, a Tether spacecraft at an altitude of 120 km should expect a filament life of about one day but the lifetime rises dramatically at altitudes above 140 km.

A simple test that will demonstrate the first order relationship between the pressure in a chamber vs. the angle that an orifice to the outside makes with a neutral gas stream is to use a single chamber that can be rotated about an axis through its orifice and mount it in the gas stream as shown in Figure 6. With the gas flow rate adjusted for a background pressure of 9×10^{-6} torr and emission of 100ua, the collector current vs. angle was recorded as shown in Figure 7. A close correlation between the collector current and $K\cos\alpha$ can be seen despite a small error in angular alignment of the test fixture.

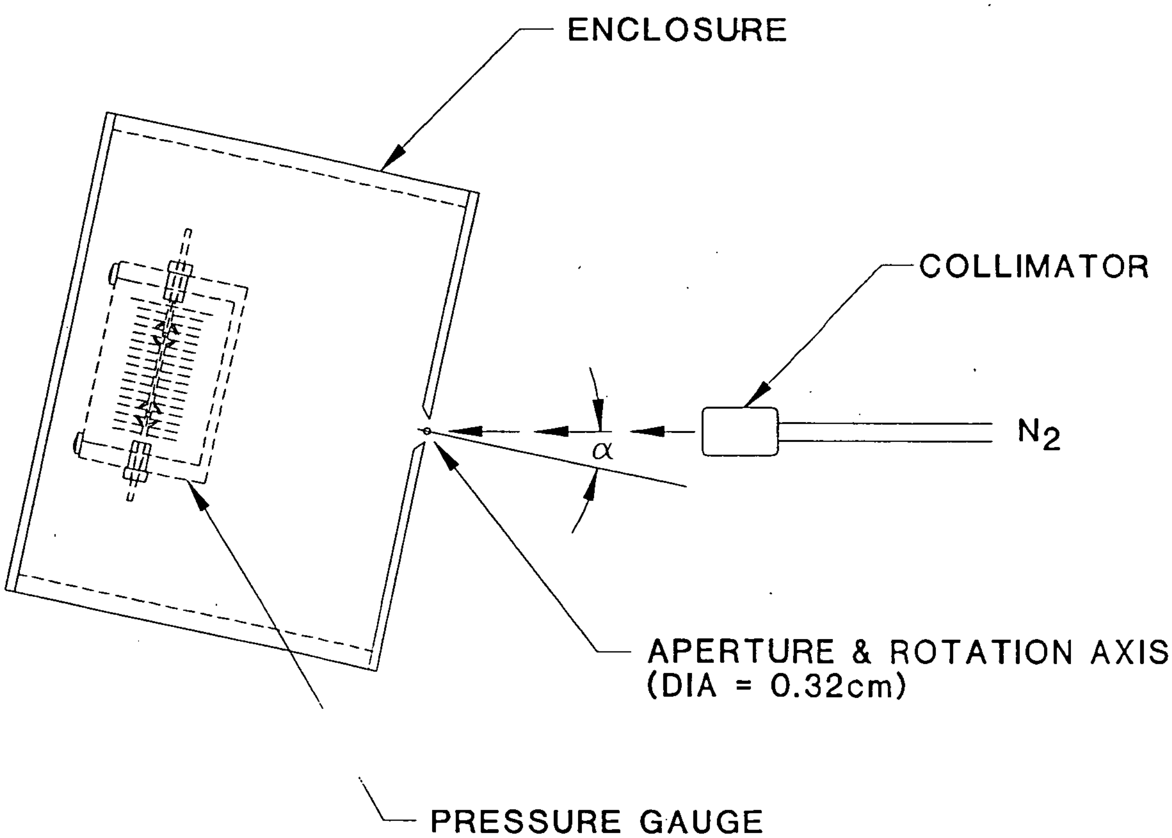


Figure 6. Single chamber angle test setup.

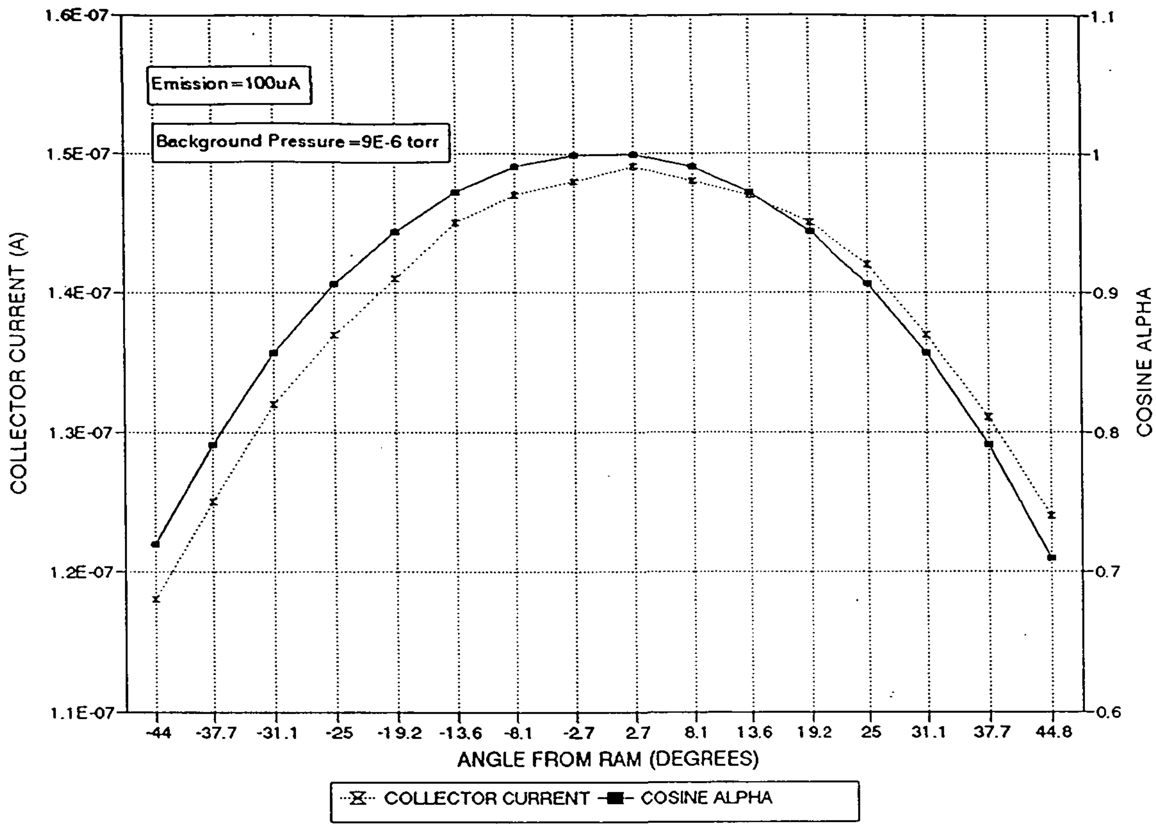


Figure 7. Collector current of a gauge in a single chamber vs. rotation angle (α) and $K \cos \alpha$.

In the angle tests described above it was desirable that a well defined, uniform gas stream be directed at the chamber aperture. A collimator with the following dimensions was attached to the gas tube outlet: length = 0.94 cm, diameter = .64 cm, 32 holes of 0.094 cm diameter the length of the collimator. The following test was conducted to determine the shape of the resulting neutral gas stream. The chamber with pressure gauge used in the angle tests described above was mounted on an X–Y table in the vacuum chamber. Collector current vs. horizontal displacement was recorded for 2.54 cm, and 5.1 cm spacings between the collimator and chamber aperture. The pressure in the gas supply line approximately 75 cm ahead of the collimator was 25 microns. Examples of the resulting curves are those in Figure 8 for the flow rate which raises the background pressure from 1.8×10^{-7} torr to 9×10^{-7} torr. The beam half angle at half maximum pressure from the plot in Figure 8 is approximately 0.25 radian for 2.54 cm separation and approximately 0.15 radian for 5.1 cm separation. The difference is attributable to the fact that the aperture diameter is comparable to the beam width at 2.5 cm separation, but the real beam half width must be approximately 0.15 radian. This is almost identical to the Mach angle for atomic oxygen in a LEO satellite, so these geometrical tests are very well scaled to flight conditions.

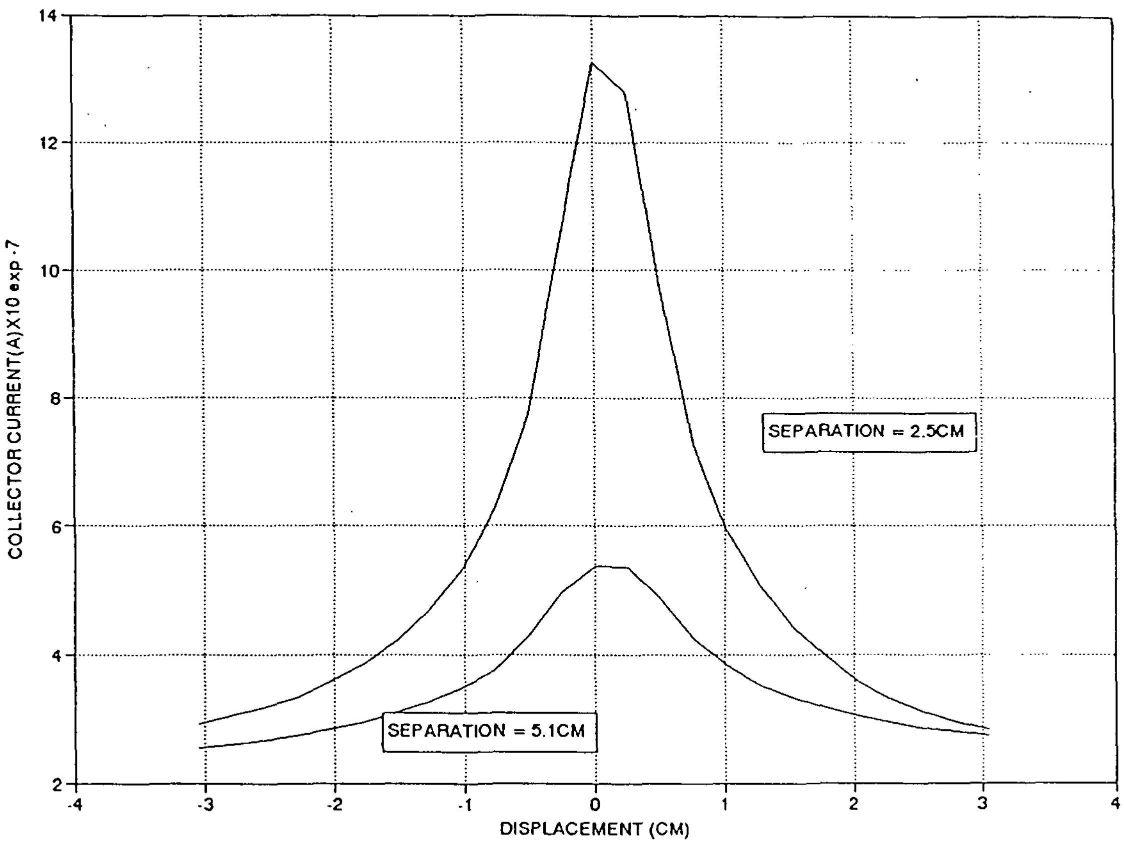


Figure 8. Gauge collector current (pressure) response in a chamber having 0.32 cm aperture moved laterally through a collimated gas stream.

A test which we believe proved the concept of the Anemometer is described below. A second pressure gauge of the design shown in Figure 2 was constructed. The two gauges were mounted in opposing chambers of a hemispherical detector housing provided by Centro Ricerche Aerospaziali (CRA) associated with the University of Rome, La Sapienze, Rome, Italy. A pressure equalization valve and motor were installed and the assembly was mounted in a vacuum chamber. A flexible gas manifold having two outlets along with a mechanism to control the gas flow direction was mounted in front of the detector assembly as shown in Figure 9. The two legs of the manifold were constructed to have equal throughput. The manifold outlets were controlled so that the gas streams were continuously directed at their respective apertures as the direction of flow was changed, i.e., the rotation axes for the collimators passed through the aperture centers. The curves in Figure 10 show the collector currents of the two gauges vs. gas flow direction. Note that the peak currents are at ± 30 degrees from ram as they should be since that is the angular displacement of the apertures on the detector hemisphere. Differences in collector currents for the gauge pair were minimized by adjusting their emission currents. Emission of gauge 1 was set at 25uA. Gauge 2 emission was adjusted for difference amplifier $e_{out} = 0$ at gas arrival angle of zero. Its resulting emission was 18.6uA. The two gauge collectors were then connected to logarithmic amplifiers whose outputs went to either side of a difference amplifier. The gain of this combination is one volt per current decade. Figure 11 shows the difference amplifier output vs. gas arrival angle with the pressure equalization valve open and closed. The data recorded with the pressure equalization valve closed show excellent linearity over the range of ±20 degrees. We believe this test sufficiently demonstrates the concept of the Anemometer. However, difference amplifier outputs for some angles with the equalization valve open are not zero and are significant enough to warrant further investigation. Figure 12 also shows the difference amplifier output vs. gas arrival angle with both gauge filaments emitting 10uA (no attempt to balance collector currents at zero angle). The curve for P. E. valve closed shows excellent linearity to ±20 degrees and is monotonic to ±45 degrees, well past the 30° aperture angles. This attribute is useful for a control system, which may need to acquire attitude information at very large angles.

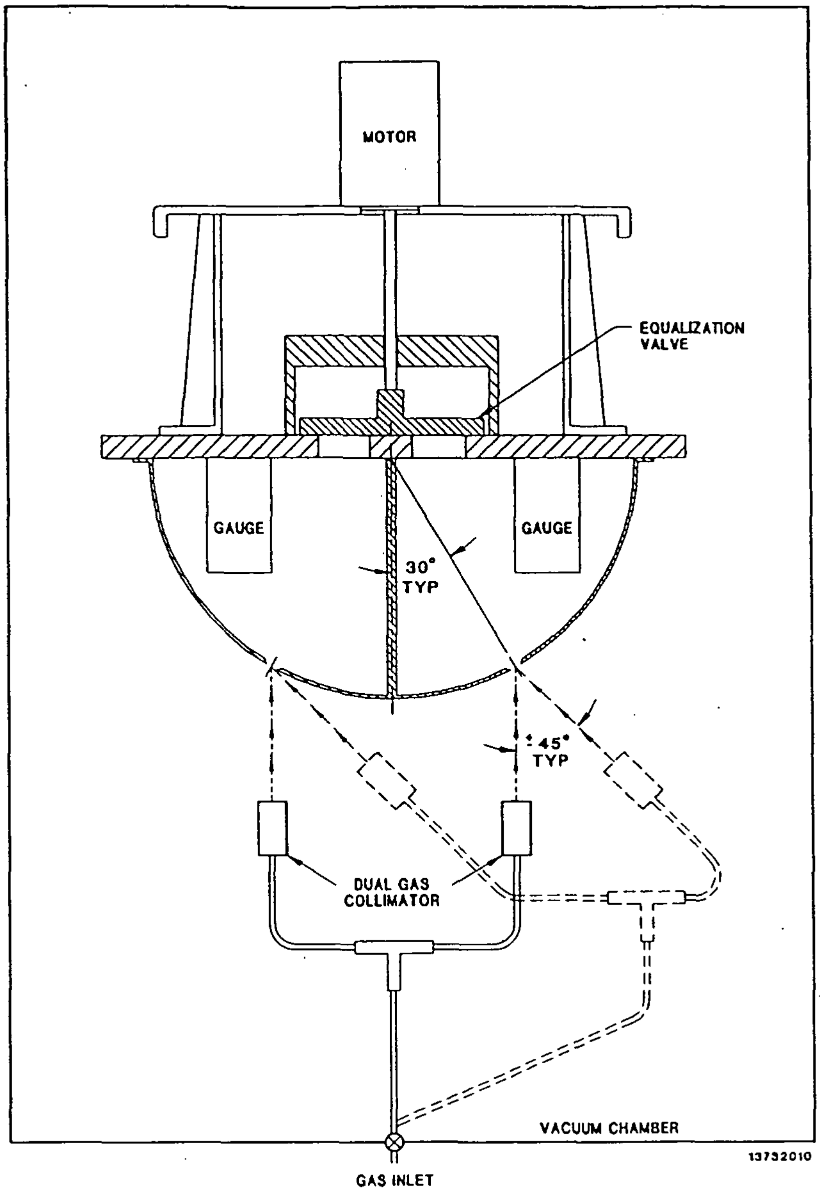


Figure 9. Two chamber angle test set-up.

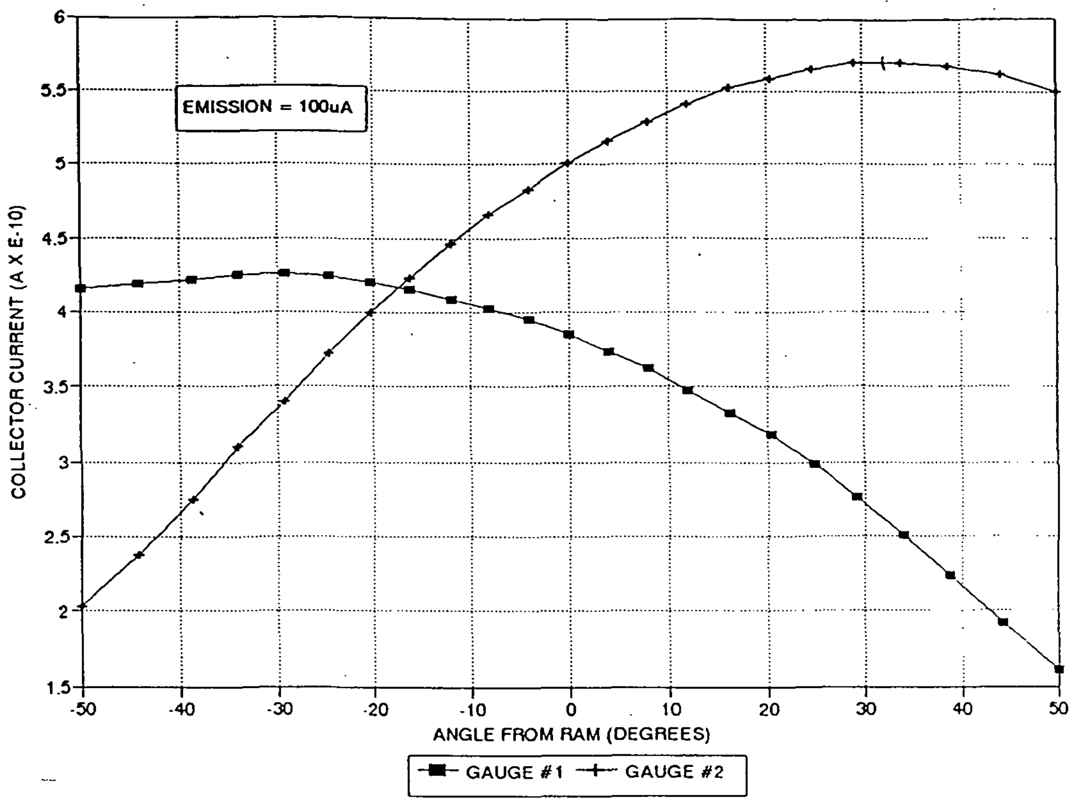


Figure 10. Collector current vs. gas flow direction.

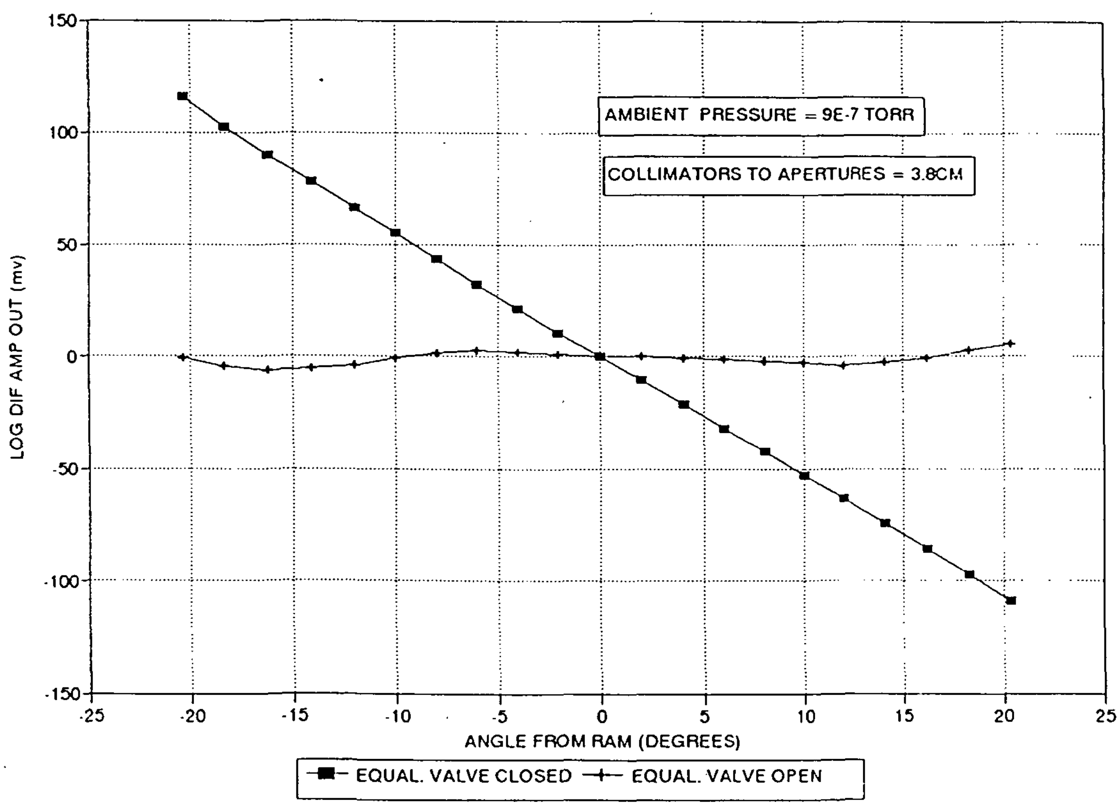


Figure 11. Difference amplifier output vs. gas flow direction.

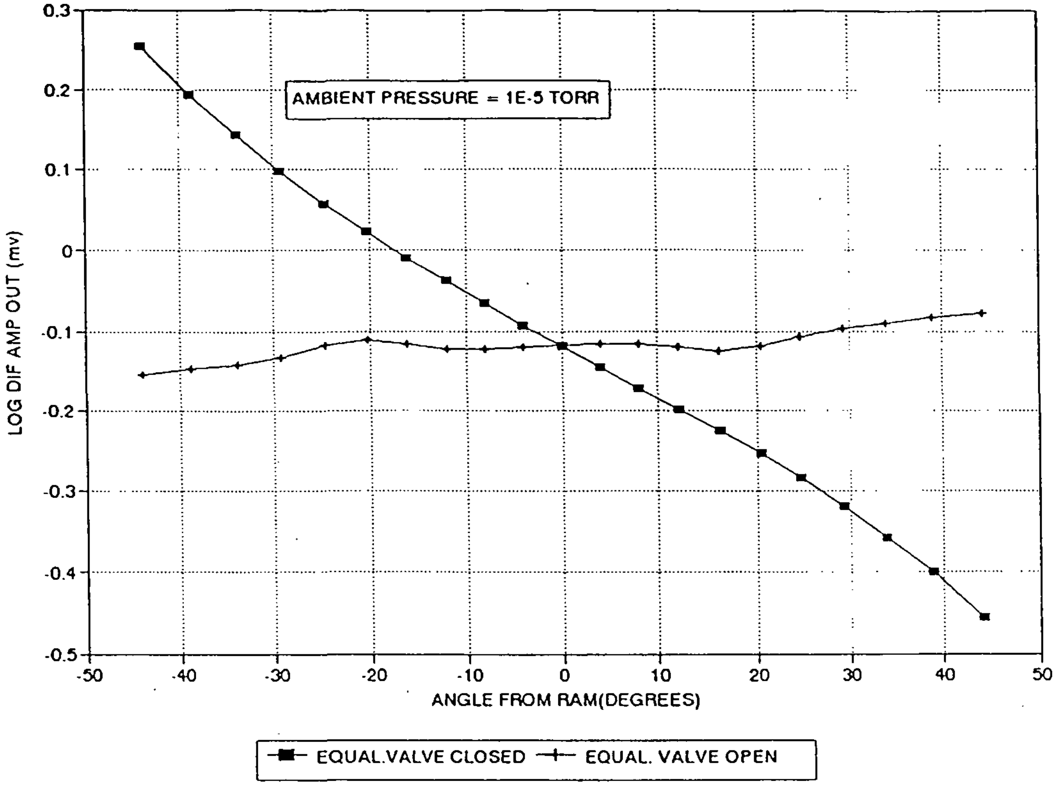


Figure 12. Difference amplifier output vs. gas flow direction.

A ruggedized version of the miniature pressure gauge has been designed. A drawing of it is shown in Figure 13. It has the spiral grid and axial collector wire of the test gauge described earlier and is designed to fit the detector baseplate supplied by CRA. This flight gauge design has redundant filaments and also includes a baffling arrangement designed to exclude ambient ionospheric plasma from the electrical elements of the gauge.

Two of the ruggadized gauges were constructed. Outgassing and sensitivity tests were conducted on both gauges. Following several hours of bake out and de-gas operation the response curves of the two were found to be very well matched. Non linearity in the lower 10^{-7} torr and 10^{-8} torr pressure ranges indicate less complete outgassing than was accomplished with the "breadboard" gauges (See Figure 3).

Filament mounting configurations were tested to optimize power efficiency.

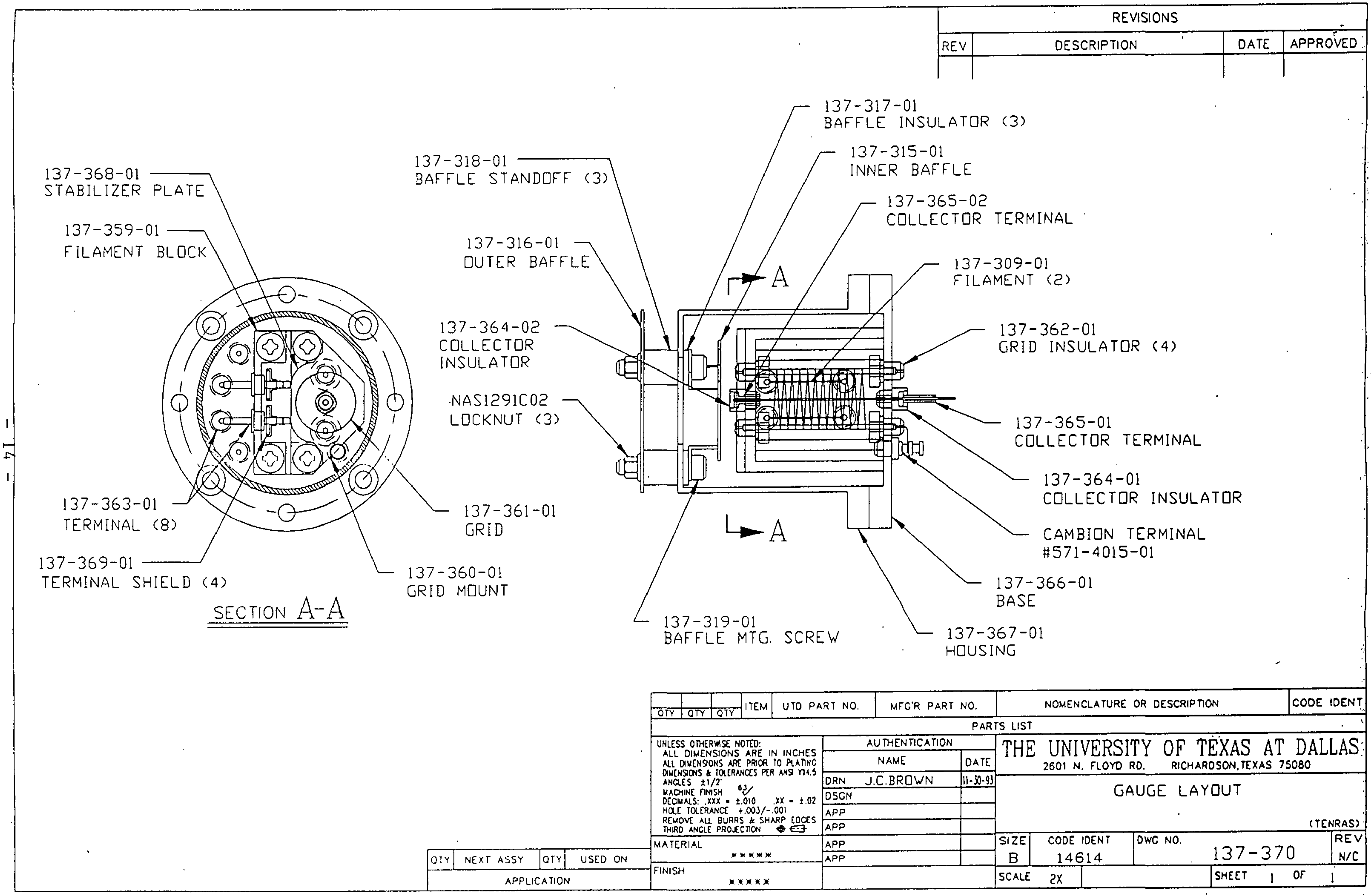


Figure 13. Ruggedized miniature pressure gauge.

The use of dual filaments increased the complexity of the emission regulators, resulting in two filament driver boards in the detector head and two emission regulator boards in the main electronics. With the logarithmic amplifier board included, four circuit boards would be required in the detector head assembly.

A fact sheet summarizing the pertinent parameters for an anemometer of this type is presented in Table 2. Since the spacecraft interface is unknown, the exact size and mass would have to be adjusted slightly to match a specific flight opportunity.

INSTRUMENT FACT SHEET

SATELLITE ANEMOMETER

GEOPHYSICAL FUNCTIONS:

A.) MEASURES HORIZONTAL CROSS WIND AND VERTICAL WIND COMPONENTS WITH A SENSITIVITY OF ~1 ms^{-1} AND ABSOLUTE ACCURACY OF ~15 ms^{-1}, DEPENDING ON ATTITUDE INFORMATION

B.) COULD BE USED IN ATTITUDE CONTROL LOOP TO PROVIDE ON BOARD PITCH AND YAW KNOWLEDGE WITH RESPECT TO NEUTRAL RAM OF ~0.1 DEG AT 10 Hz.

COVERAGE:

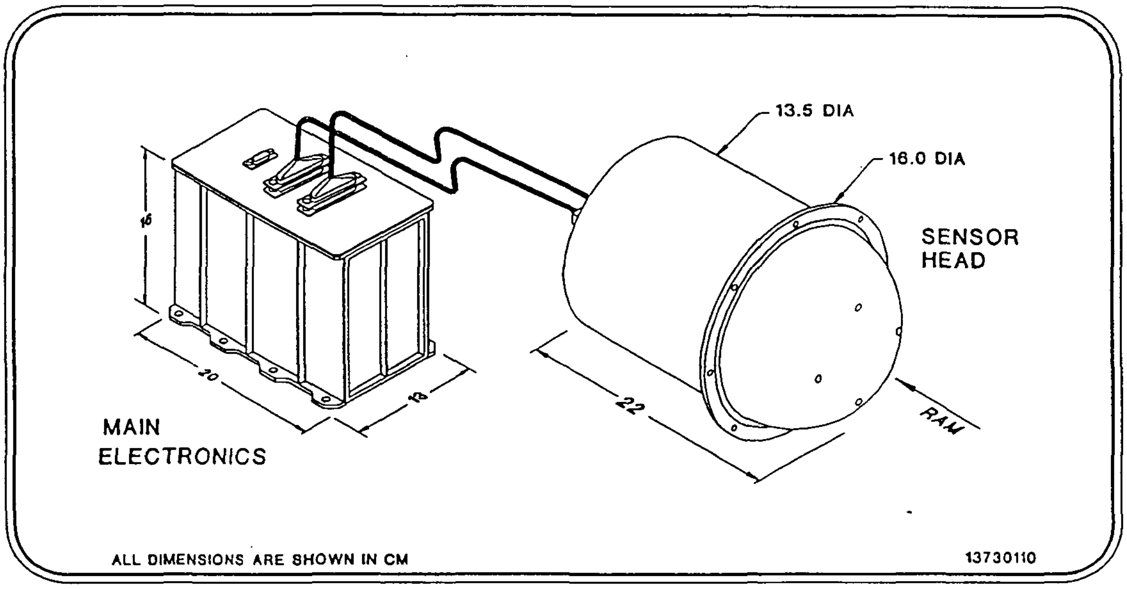
110 km ALTITUDE TO BASE OF EXOSPHERE ($N_n \sim 5 \times 10^7$ cm^{-3}, 450 ± 100 km ALT.)

ACCOMMODATION REQUIREMENTS:

A.) HEMISPHERICAL SENSOR TO VIEW ALONG S/C NOMINAL VELOCITY VECTOR (RAM)

B.) VIEW OF 2 Π STERADIANS DESIRABLE

C.) NEIGHBORING SURFACES THAT ARE IMPACTED BY RAM NEED TO MINIMIZE THE SOLID ANGLE SUBTENDED AND THE ASYMMETRY AS SEEN BY THE SENSOR APERTURES.



MASS:
SENSOR HEAD < 2 kg
MAIN ELECTRONICS < 2.3 kg

POINTING:
PLACEMENT <1 DEGREE
KNOWLEDGE <0.1 DEGREE

MOUNTING
SENSOR HEAD – 16 cm DIAMETER
MAIN ELECTRONICS – FOOT PRINT, 13 cm × 20 cm

POWER:
MAXIMUM < 13 W
TYPICAL < 11W

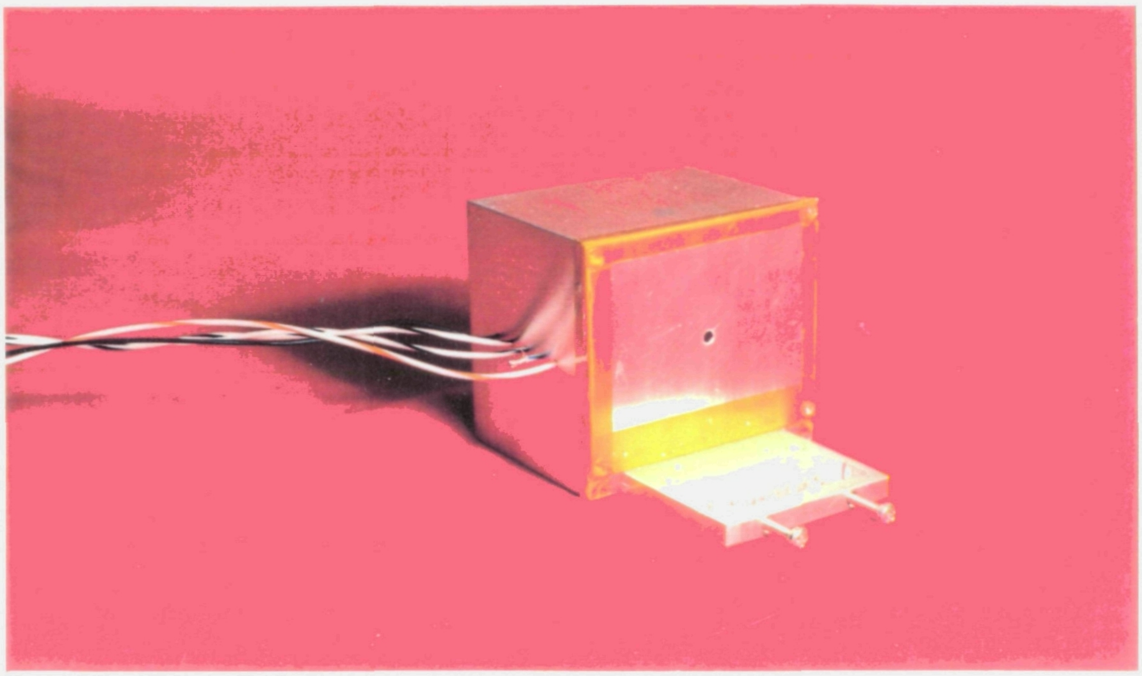
THERMAL:
OPERATING –20 DEG C TO +50 DEG C
NON-OPERATING –30 DEG C TO +60 DEG C

DATA RATE: <225 BITS PER SECOND

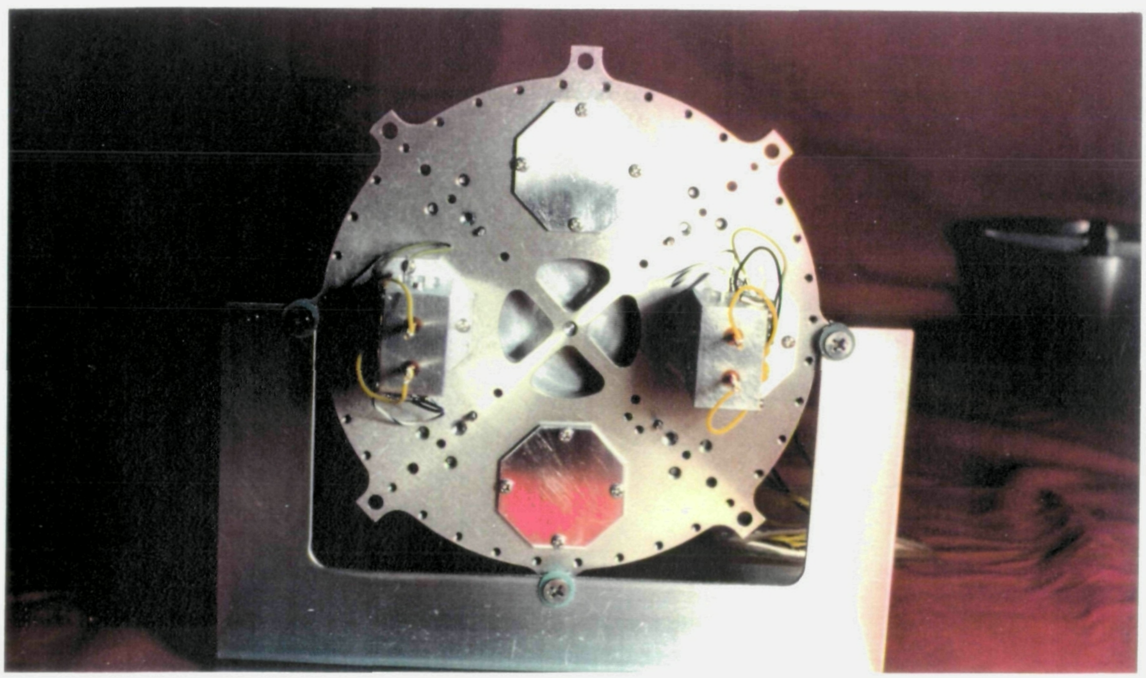
Table 2

APPENDIX A

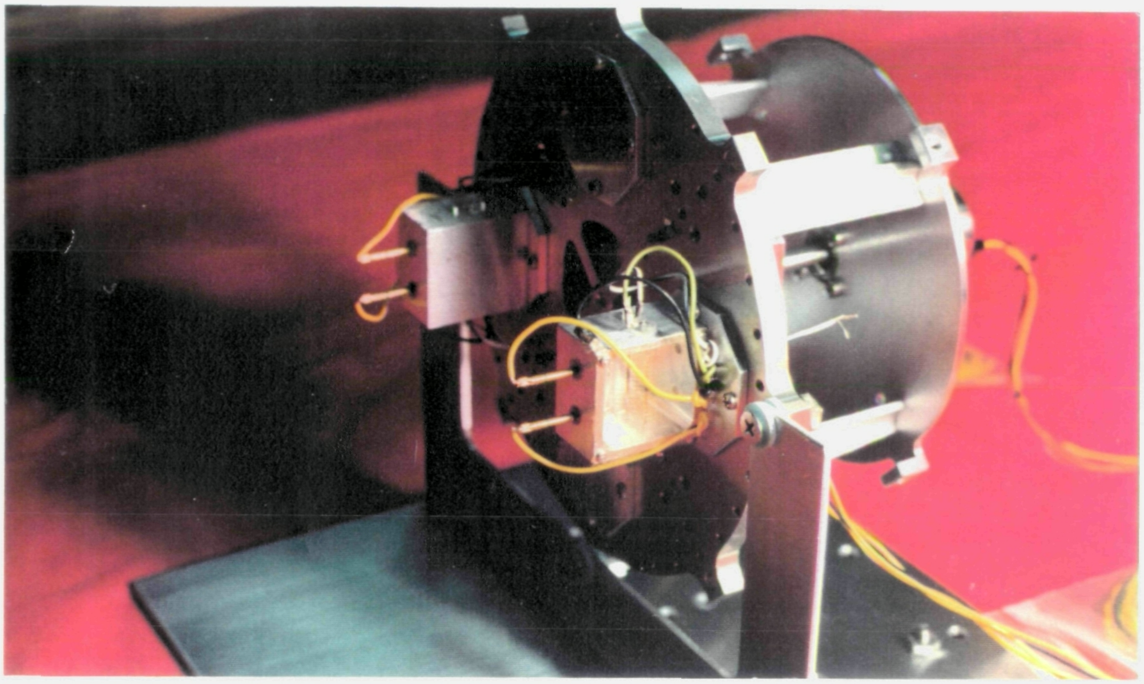
The following photographs show various hardware and test set-ups which were used during the tests described in the text.



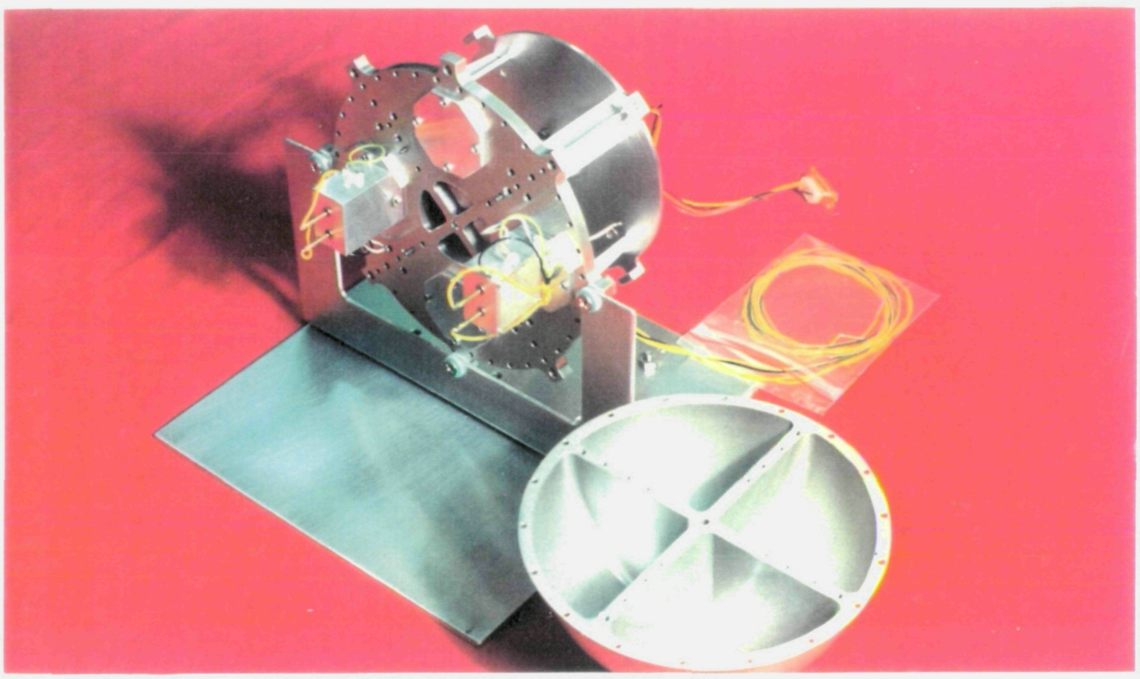
SINGLE CHAMBER ANGLE TEST FIXTURE.
(GAUGE INSIDE)



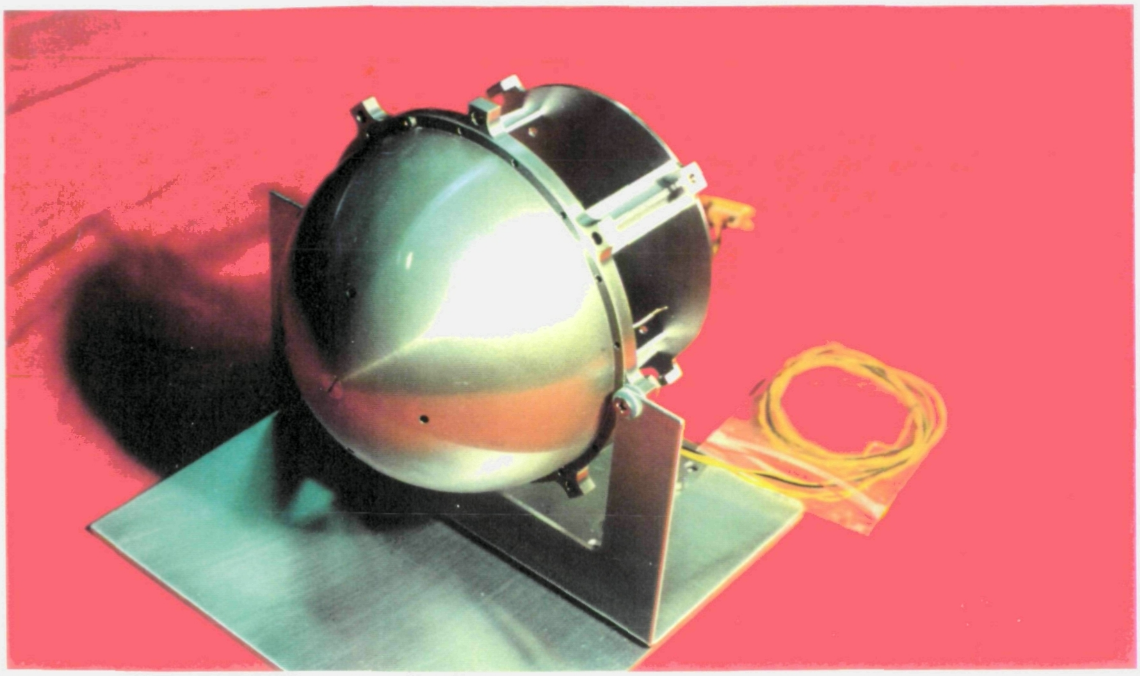
TEST GAUGES ON BASEPLATE.
BASEPLATE SUPPLIED BY C.R.A.



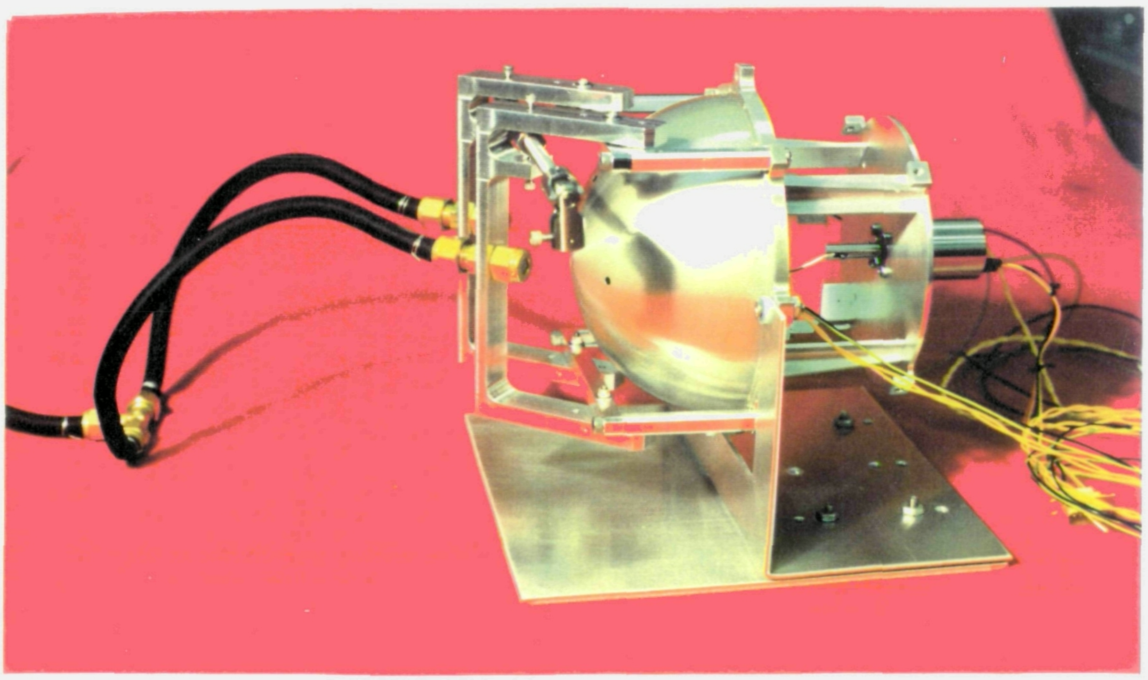
TEST GAUGES AND MOTOR SUPPORT.



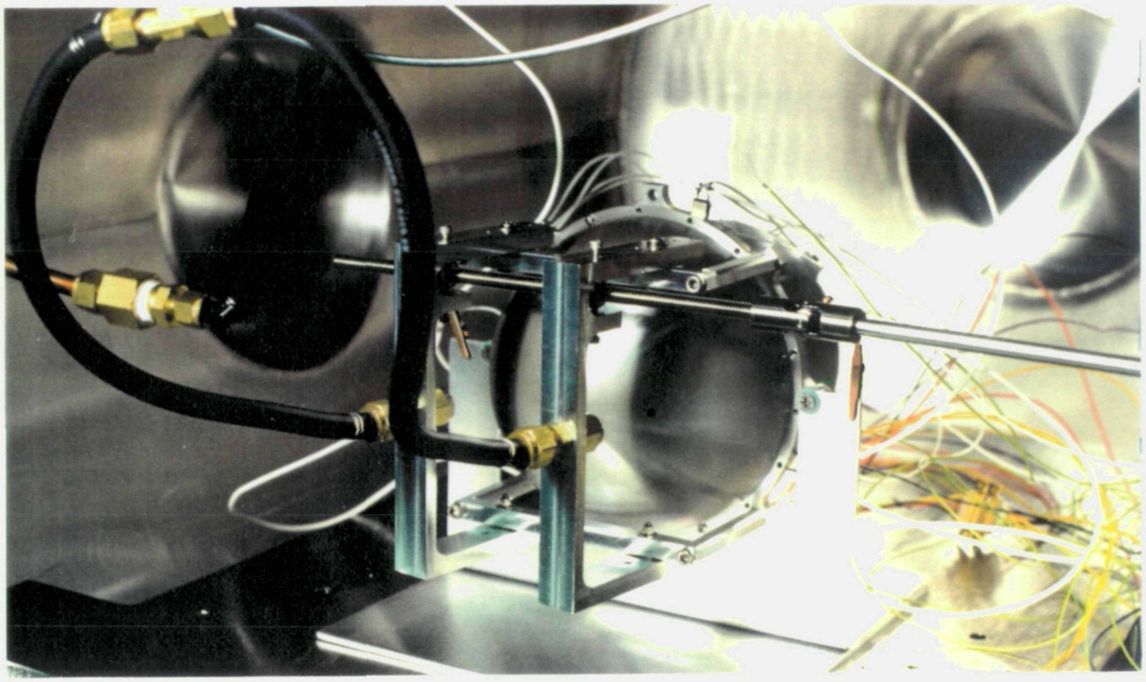
TEST GAUGES ON BASEPLATE WITH FOUR CHAMBER HOUSING SUPPLIED BY C.R.A.
(BEFORE HOUSING INSTALLATION)



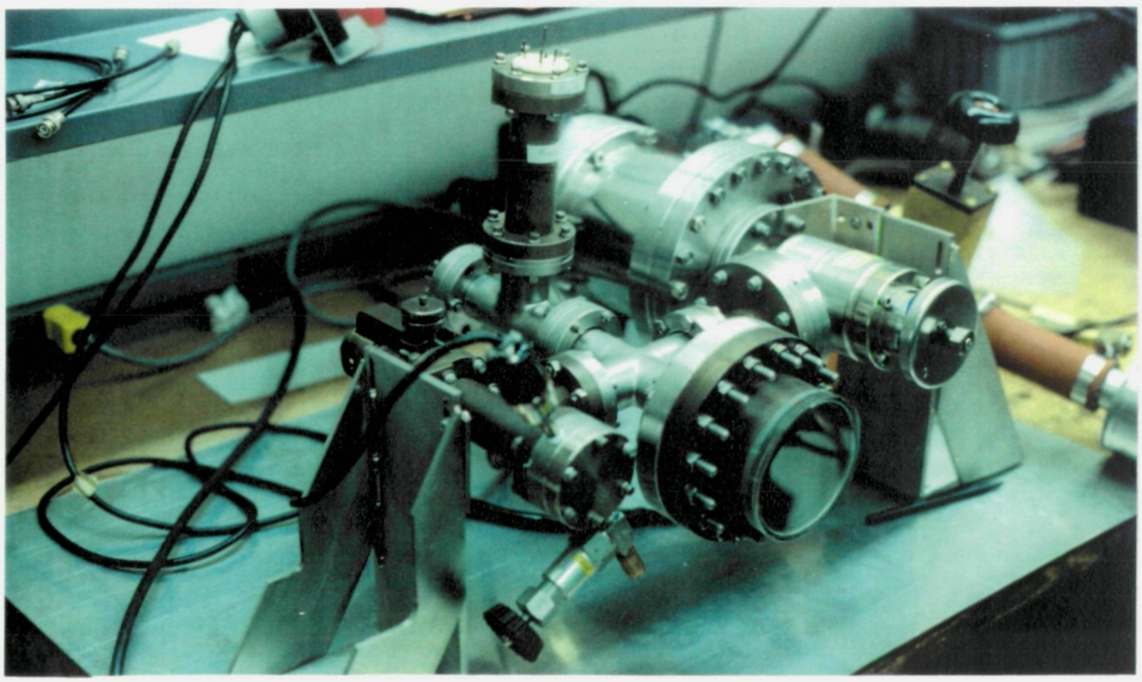
FOUR CHAMBER TEST ASSEMBLY WITH TWO GAUGES INSTALLED.



TEST ASSEMBLY SHOWING VALVE MOTOR WITH SUPPORT AND GAS FLOW CONTROL APPARATUS.



TEST ASSEMBLY IN VACUUM CHAMBER FOR TWO CHAMBER ANGLE TESTS.
HEATER RESISTORS FOR OUTGASSING ARE ATTACHED.



FILAMENT LIFE TEST APPARATUS.