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CORRELATION OF SELF-CONTAMINATION EXPERIMENTS IN ORBIT AND SCATTERING RETURN FLUX CALCULATIONS

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16. Abstract

Gaseous emissions from a spacecraft modify the orbital environment and degrade the observations of distant radiation sources. These emissions also provide contamination fluxes induced by self-scattering and scattering with ambient particles. These objectionable effects are especially important for a spacecraft with many large gaseous sources, orbiting at low altitudes and with surfaces which are critically affected by contamination (for example, the Space Transportation System).

Experiments were carried out on the orbiting Atmospheric Explorer-D satellite (AE-D) to verify the calculated return fluxes of a neon source. Known rates of neon were emitted in the direction of the velocity vector on command to the Molecular Return Measurement Unit (MRMU). At 250 km, the neutral mass spectrometer indicated a total neon return flux of 2.46×10^{-2} times the emitted flux. The calculated fraction was 1.23×10^{-2}, including 9.14×10^{-3} for the ambient scatter and 3.54×10^{-3} for the altitude independent self-scatter. The pressure gages indicated return pressures less than 9.33×10^{4} Pa (7×10^{-6} torr) at altitudes from 161 to 210 km. The maximum return pressure for 161-km orbit was calculated as 7.3×10^{-7} including a self scattering contribution of 2.4×10^{-6} Pa (1.8×10^{-8} torr).

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CORRELATION OF SELF-CONTAMINATION EXPERIMENTS IN ORBIT AND SCATTERING RETURN FLUX CALCULATIONS

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INTRODUCTION

The outgassing of protective materials, the leakage of cabins and systems, the venting and flashing of coolant fluids, and the gases from the propulsion system and chemical reactions modify the ambient atmosphere surrounding a spacecraft. These gases adsorb and condense on critical surfaces, changing the surfaces' optical and thermal characteristics. The gases create clouds which radiate with higher intensities than celestial objects and which absorb radiations from sources being observed. The column densities characterizing these clouds increase with the scattering of the emitted gases from ambient particles and among themselves. The evaluation of these two forms of scattering provides estimates on the number of molecules which return to the spacecraft. These return molecules add to the contamination of surfaces and increase the densities in the field of view of instruments. Several theoretical analyses have been made of the ambient scattering, and methods of calculation have been developed (References 1 through 6). The calculations are quite similar to each other. A graphical representation of this return flux as a function of both orbit altitude and size of the spacecraft is shown in figure 1 (Reference 1). Approximate relationships for the self-scattering have also been developed (References 4 and 7), giving conservative estimates of this parameter. Neither of these estimates, however, has ever been validated experimentally in either a chamber or in space. The scattered molecules cannot be differentiated from both the emitted and the chamber-reflected molecules during a test in a limited-size space chamber (References 8 and 9).

This paper reports on tests carried on the Atmospheric Explorer-D satellite (AE-D) that were designed to measure (with mass spectrometers) the scattering of a neon source emitted on command from the satellite. The Molecular Return Measurement Unit (MRMU) simulated a gas emission such as the outgassing of materials, the venting of a gas, or a propulsion jet issuing from the spacecraft. The return flux of this source due to ambient molecular scattering and intermolecular self-scattering was to be measured at various orbit altitudes and for various angular directions with respect to the orbit-velocity vector. The energies

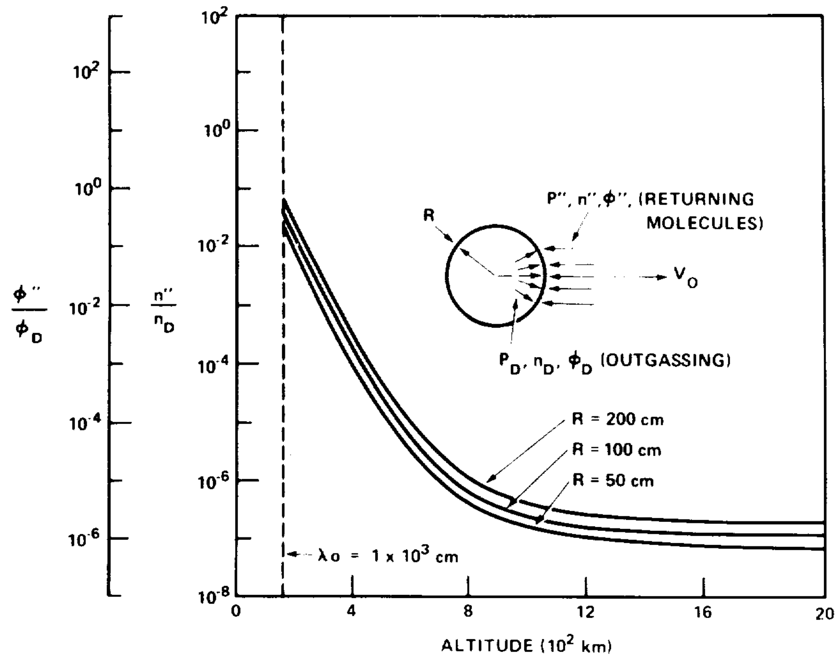


Figure 1. Density, pressure, and flux ratios at the spacecraft surface, produced by outgassed molecules returning to the satellite (for $\lambda_0 > 21$ R).

of the return molecules were also to be measured for both types of scattering. Unfortunately the premature failure of the spacecraft permitted only one test measurement at an altitude of 250 km and some exploratory tests at lower orbits. At 250 km, the Neutral Atmosphere Composition Experiment (NACE) mass spectrometer registered the density of the returned neon and indicated that the return flux amounted to 2.46×10^{-2} of the emitted molecules. This closely agrees with theoretical calculations indicating 1.26×10^{-2} for the total return fraction. The total ratio included 9.14×10^{-3} for the ambient scatter (as shown in figure 1) and 3.54×10^{-3} for the quasi-unchanging self-scatter. The ion gage, Pressure Sensor-A (PSA), and the capacitance manometer (PSB) used for exploratory tests indicated that the pressures resulting from the neon at altitudes varying from 161 to 210 km were, in all cases, less than 9.33×10^{-4} Pa (7×10^{-6} torr). The pressure calculated for 161 km should have been about 9.7×10^{-5} Pa (7.3×10^{-7} torr), including a self-scattering pressure of about 2.4×10^{-6} Pa (1.8×10^{-8} torr). These results give some assurance that the theoretical calculations can be used to estimate these parameters with a degree of confidence.

This document describes the AE-D spacecraft; the NACE spectrometer; the MRMU configuration and source characteristics; and the results of the experiment at 250 km. The experimental results are then compared with the expected theoretical results, followed by a summary with recommendations.

AE-D SPACECRAFT

The AE-D spacecraft (figure 2) was one of the three spacecraft of the Atmospheric Explorer program. The mission of this spacecraft, which was launched on October 6, 1975 from the Western Test Range by a two-stage Delta vehicle and which became silent on January 29, 1976, was to investigate the chemical process and energy transfer mechanisms that control the structure and behavior of the Earth's atmosphere and ionosphere. It carried 12 scientific instruments, including the NACE, MRMU, Bennett Ion Mass Spectrometer (BIMS), Open Source Neutral Mass Spectrometer (OSS), Neutral Atmosphere Temperature Experiment (NATE), Magnetic Ion Mass Spectrometer (MIMS), Atmospheric Density Accelerometer (MESA), Cold Cathode Pressure Gage (PSA), and Capacitance Manometer (PSB). These and other instruments are described in Reference 10.

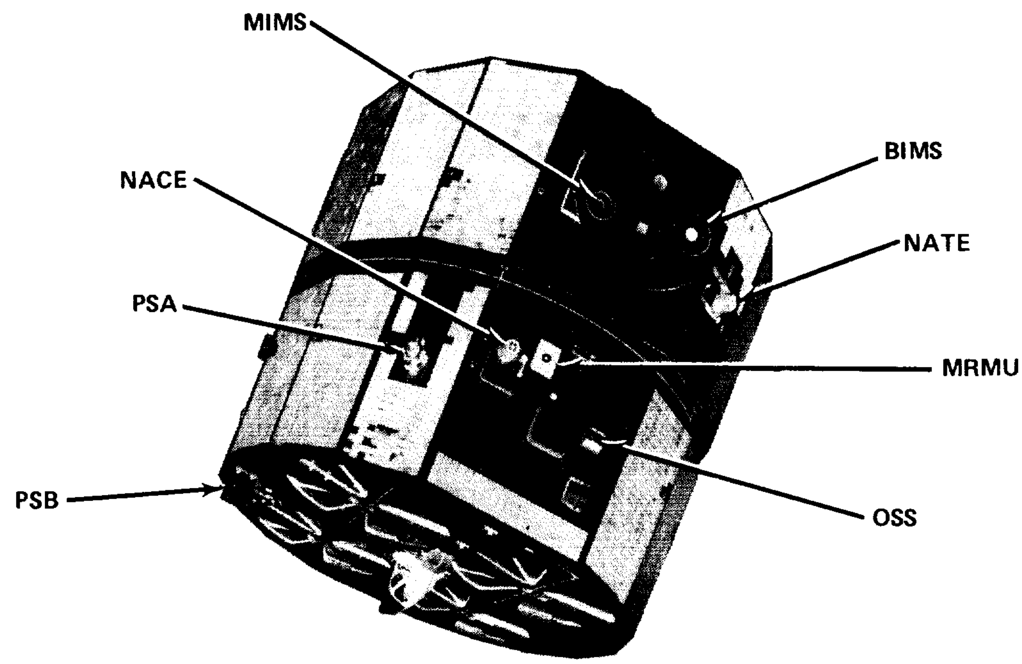


Figure 2. The AE-D spacecraft.

The AE-D spacecraft was a short 16-sided polyhedron approximating a right cylinder of 136 cm in outside diameter, 114 cm high, and weighing 679 kg. Its initial orbit had a perigee of 154.3 km and an apogee of 3804 km with an inclination of 90.1 degrees. As in the other AE spacecraft, the AE-D orbit-adjust propulsion system consisted of three hydrazine thrusters that provided the means to adjust the perigee and apogee altitudes, and the circularization of the orbit. The spacecraft could be operated in the despin and spin mode.

NEUTRAL ATMOSPHERE COMPOSITION EXPERIMENT (NACE)

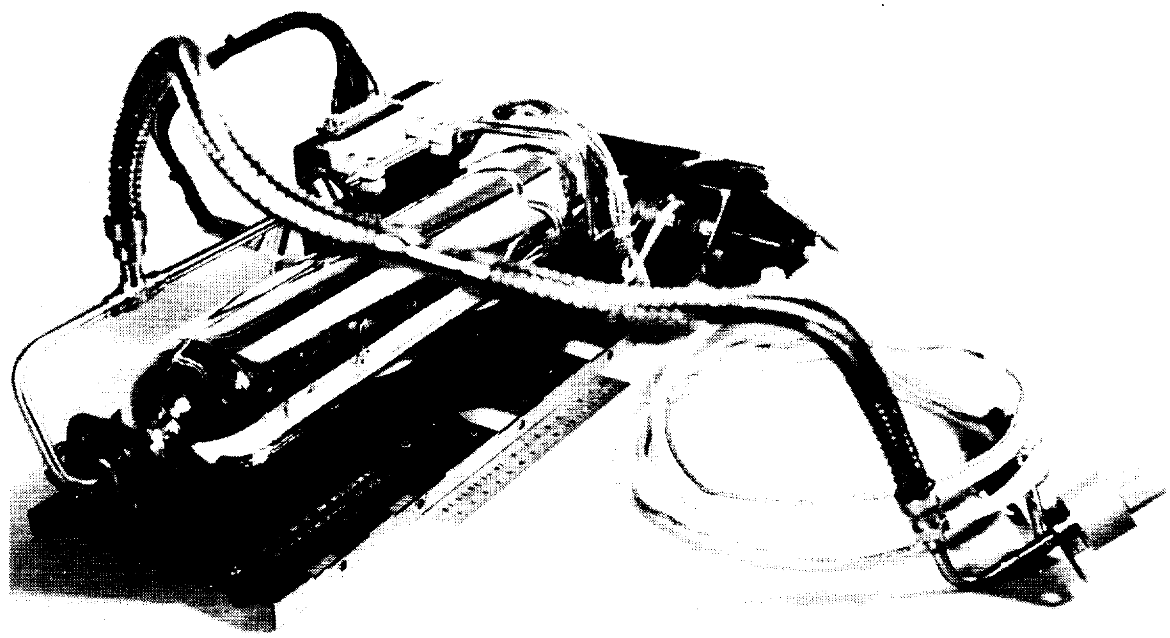
The sensor that measured the return neon was the closed-source neutral mass spectrometer described in Reference 10 that was used for the Neutral Atmosphere Composition Experiment (NACE). It was designed to obtain *in situ* measurements of the neutral thermosphere composition and was carried on all of the Atmospheric Explorer satellites. The mass-spectrometer sensor included a gold-plated thermalizing chamber and an ion source, a hyperbolic-rod quadrupole analyzer, and an off-axis electron multiplier. The automatic ion-source sensitivity control and the pulse-counting techniques provided density-measurement capability for an altitude of approximately 125 to 1000 km. The normal operating mode included measurements at all masses in the range of from 1 to 44 amu with emphasis on helium, oxygen, nitrogen, and argon. Additional operational modes could be optimized for studies of minor constituents of any gas in this mass range. The measurements made by this instrument have been correlated with measurements made by other spectrometers, spectrophotometers, and accelerometers on the AE. The knife-edge orifice of the NACE, which was exposed after the breaking of the cover by pyrotechnic actuators, was 14.35 cm away from the exit port of the MRMU. The orifice was about 1.9 cm away from the spacecraft panel; the MRMU port protruded 1.27 cm from the same panel. The spectrometer was not calibrated for neon, and therefore its sensitivity was estimated from cross-section ratios and calibrated sensitivities for neon and argon.*

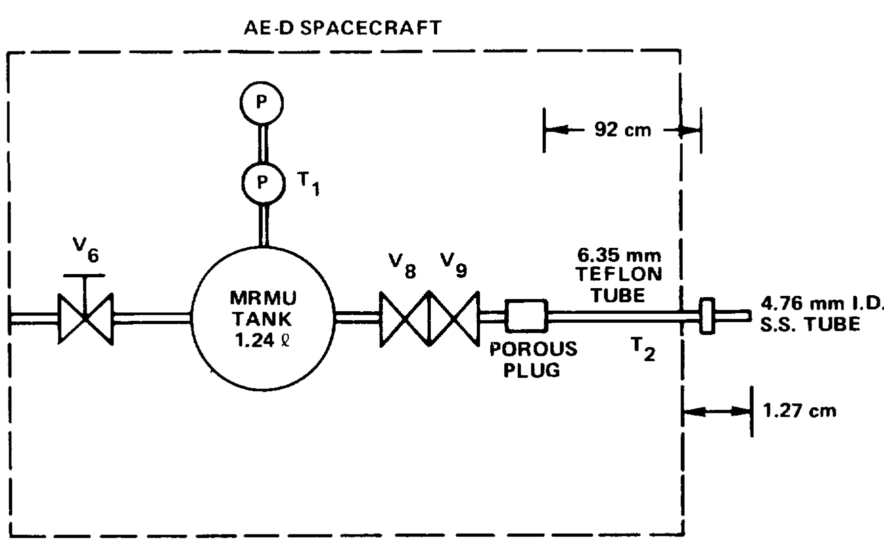
MOLECULAR RETURN MEASUREMENT UNIT (MRMU) NEON SOURCE

The neon source and metering system of the MRMU experiment is shown schematically and pictorially in figure 3. It consisted of a gas-filling valve, a 1.24-ℓ neon pressure tank, two pressure transducers, two series-redundant on-off valves, a porous metering plug located at the valves' exit, a 92-cm long section of 0.635-cm Teflon tubing, and a 0.476-cm ID stainless steel tube outlet that protruded from the spacecraft surface. Two temperature sensors measured the tank and tube exit temperatures. The total weight, including brackets and mounting hardware, was about 3.2 kg.

The neon source, based on a compromise which took into account restrictions on the space available on the spacecraft, the maximum allowable pressure, the availability of parts and other needs for a long blowdown time for extended operation, and large fluxes for high-altitude return-flux measurements, was designed to operate at an initial pressure of 37.19×10^5 Pa (36.7 atm). The flow-controlling porous leak used for the flight unit provided a neon flow of 4333 std cm^3/min that corresponded to a mass flow rate of 6.56×10^{-2} g/s and a molecular flow rate of 1.97×10^{21} s^{-1} for a neon density of 8.99×10^{-4} g/cm^3. The pressure-versus-time test of the unit is shown in figure 4. The pressure, the mass-flow rate, and the mass decay linearly with time in the high-pressure region. They have a time constant of about 830 s. The quantity of neon remaining after 3600 s of operation

*Personal communication, A. E. Hedin, March 3, 1976.





(V_6) MRMU FILL AND DRAIN VALVE
(V_8-V_9) THRUST VALVE (ELECTRICALLY OPERATED)
(T_1-T_2) PRESSURE TRANSDUCER (ELECTRICALLY OPERATED)

Figure 3. The MRMU gas-flow schematic diagram; photograph of the MRMU.

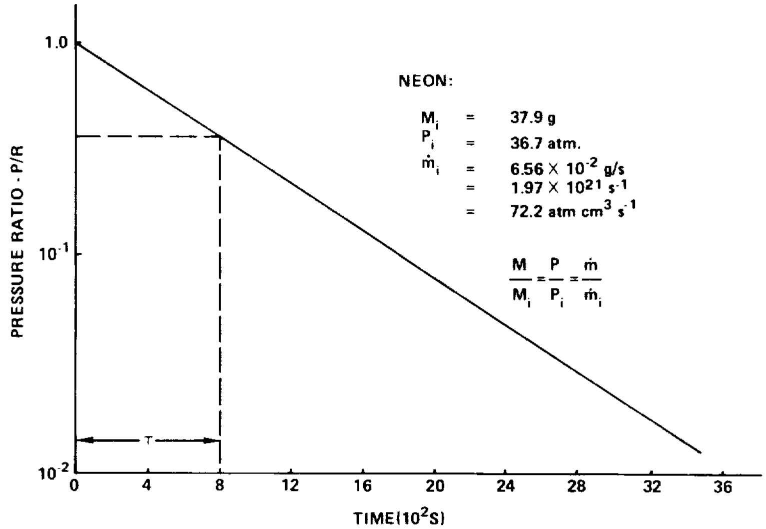


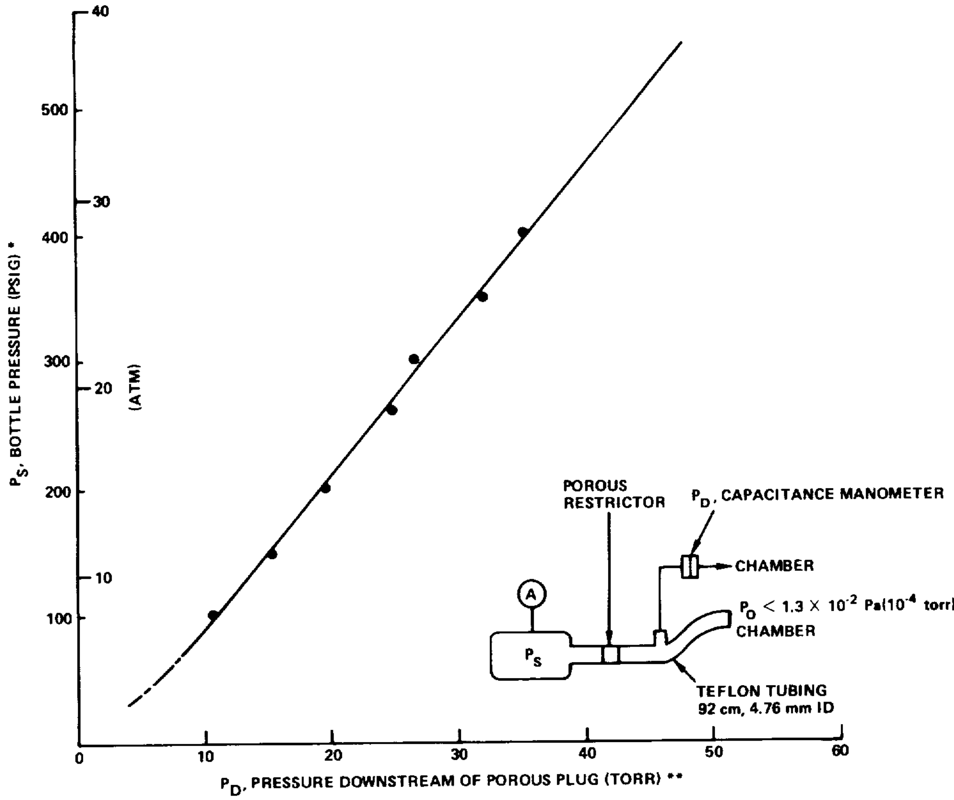
Figure 4. MRMU neon pressure, mass, and flow rate versus time.

is approximately 1 percent of the initial 37.9 g. The flow and pressure are at the same percentage after that time of operation.

Figure 5 shows the results of tests in a 3.65- by 4.57-m vacuum chamber to determine what were the pressures in the Teflon tubing at about 12 cm from the porous plug as a function of the upstream tank pressures. The pressure in this tubing is about 6.4×10^3 Pa (48 torr) for 36.48×10^5 Pa (36-atm) tank pressure. Another characteristic of this blowdown system is shown in figure 6. This shows the flux distribution as a function of the angle from the centerline of the exit port. The flow distribution was measured at 5.1 cm from the exit with a capacitance manometer rotating about the center of the exit port. The pressure in the tubing was held at 33.33×10^2 Pa (25 torr), corresponding to about 18×10^5 Pa (250 psig) (18 atm) in the tank. The reference pressure of the manometer was that of the large vacuum chamber that always remained below 1.33×10^{-2} Pa (10^{-4} torr). The curve shows that a 50-percent value of the flux (or pressure) corresponds to approximately a 47-degree half angle. The flow-distribution curve fitted a cosine function to the n = 1.75 power. Further, integrating this distribution flux over the hemisphere and equating it to the mass rate $\dot{m}$ gives the flux distribution as a function of distance r and angle θ,

$$\phi = \frac{n+1}{2\pi r^2} \dot{m} \cos^n \theta \qquad (1)$$

This indicates that at the edge of the spacecraft projected area (R = 68 cm) at a distance of 8.86×10^4 cm from the spacecraft corresponding to the mean-free path of the ambient atmosphere at 250-km altitude, the flux would be only 1 percent less than that at the center of the projected area.



* PSIG = 6894.757 newtons/meter^2 (pascals)
** torr = 133.32 newtons/meter^2 (pascals)

Figure 5. MRMU exit pressure versus tank pressure.

The critical velocity produced at the exit port is

$$C = \left(\frac{2\gamma}{\gamma + 1} \quad \frac{\mathcal{R}T}{M}\right)^{1/2} = 3.87 \times 10^4 \text{ cm s}^{-1} \tag{2}$$

where $\gamma = 1.66$, $T = 290$ K, $M = 20$ g mole, $\mathcal{R}$ is the gas constant. The adiabatic isoentropic velocity produced beyond the exit port can be estimated to be

$$V_E = \left(\frac{2\gamma}{\gamma - 1} \quad \frac{\mathcal{R}T}{M}\right)^{1/2} = 7.78 \times 10^4 \text{ cm s}^{-1} \tag{3}$$

This velocity, superposed to the spacecraft velocity of 8.5 km, would allow the neon molecule to collide with a stationary ambient particle in about 0.1 s when the ambient particle is at a distance of 8.86×10^4 cm, which is the ambient mean free path at 250 km (Reference 11). The collided neon could be reacquired by the spacecraft in approximately 10 ms. The operation of the MRMU, with the mass spectrometer (MS) scanning for neon, consisted of enabling

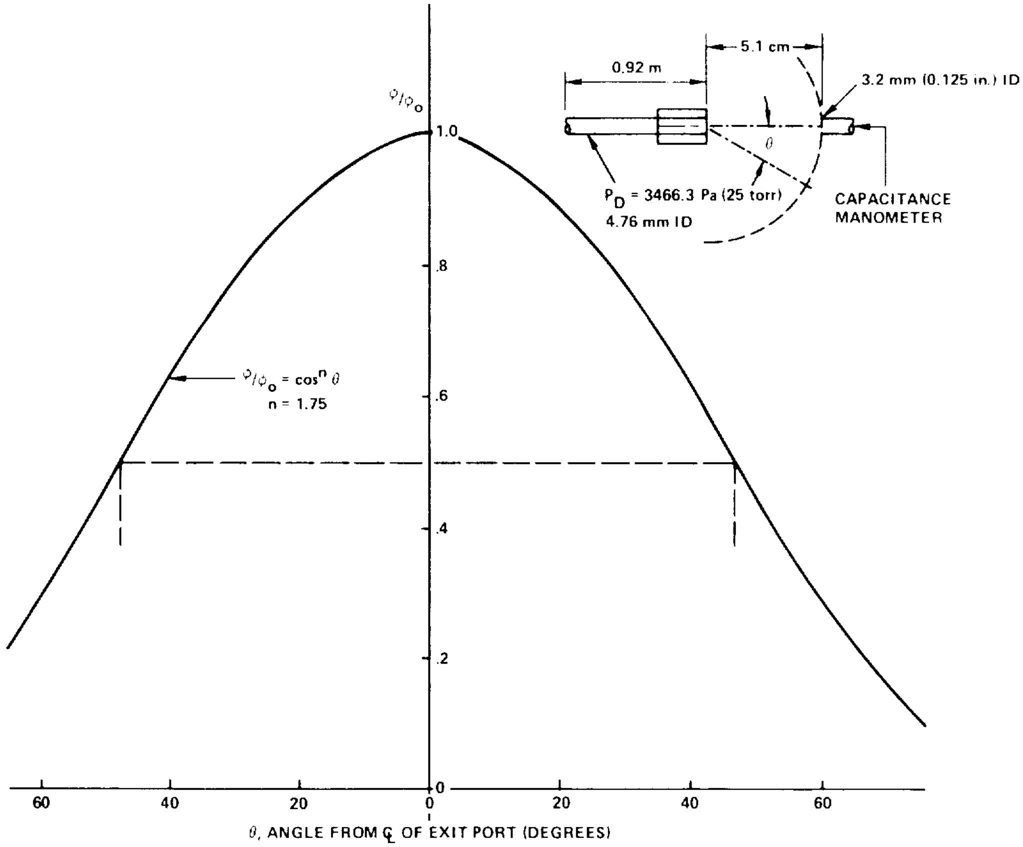


Figure 6. MRMU exit flow distribution at 5.1 cm.

the system, reading the initial pressure and temperature, and opening the valve. At completion of the experiment, the valve was commanded to close, and to read the final pressure and temperature. The minimum open and close cycle was 4 s.

THE EXPERIMENTS

Neon gas emissions were carried out at altitudes between 161 to 210 km previous to the 250-km experiment with the mass spectrometer. These exploratory tests were to ensure that densities around the spacecraft resulting from the neon emission would not be detrimental to other experiments. The PSA ion gage and the PSB capacitance manometer detected the neon and confirmed that the resulting densities would not pose a problem to other experiments.* They indicated that the response to the MRMU on-off was essentially instantaneous and proportional to the ambient pressure. The PSB manometer, limited in its low-pressure detection, indicated that the pressure produced by the neon was less than 9.33×10^{-4} Pa

*Personal communication, C. J. Rice, September 11, 1975.

(7 X 10^{-6} torr) for any of the altitudes. The PSA cold cathode ion gage showed the proportionality of the responses with ambient pressures, but it could not give unambiguous indications of the pressure increases because of its inability to separate the relative contribution to the signal from the increased neon and the decreased ambient gas pressure. The experiment, using the mass spectrometer as a detector, was carried out during orbit 94 at approximately 250 km while the AE-D was approaching the perigee of 150 km from an apogee altitude of 3755 km. The measured source densities for 20, 28, and 32 (total oxygen) are shown in figure 7. The date, latitude, longitude, and time of the test are also indicated in figure 7. The MRMU valve was opened on 54376.687 s at an altitude of 256.92 km and closed on 54348.687 s at an altitude of 251.22 km. The rate of emission was 5.24 X 10^{-2} g/s (1.58 X 10^{21} s^{-1}), corresponding to the measured neon tank pressure (29.3 atm).

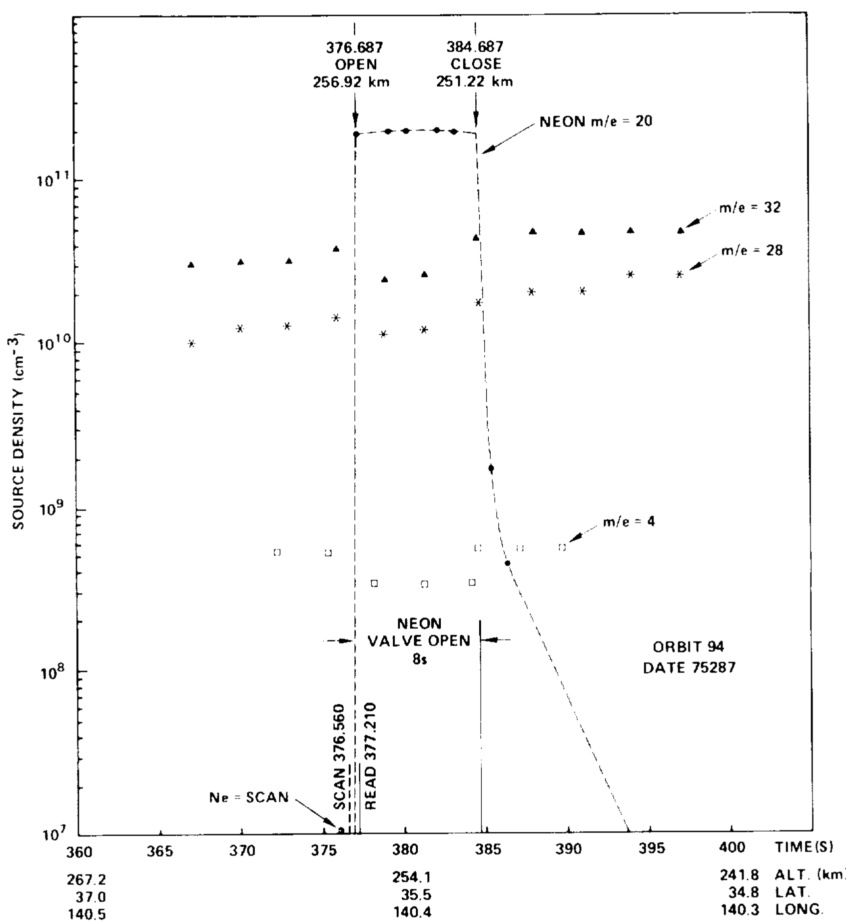


Figure 7. Source density versus time and altitude.

The corrected source densities for N_2, O_2, and A during the emission are also shown on this plot. It shows the neon density buildup and decay and that the maximum read neon density in the mass spectrometer was 1.92×10^{11} cm^{-3}.

ANALYSIS OF THE TEST RESULTS

Neon Detection Time and Density Drop

At t = 54376.2 s, before the neon emission, the mass spectrometer confirmed that there was no neon among the sources, as expected. The first reading of the neon occurred on t = 54377.210 s while the neon valve had opened 0.523 s earlier on 54376.687 s. The neon could not have been read earlier than 0.523 s because the mass spectrometer could scan neon at a rate of 0.650 per neon reading. It had begun to scan the various masses at 54376.560 s, that is, 376.687-376.560 = 0.127 s before the valve was open. The data, therefore, indicate that the neon was in the mass spectrometer within less than 0.523 s of its emission. From a previous discussion, the earliest time for neon capture, based on mean free path and gas velocity, could have been about 0.01 s after emission. PSA data during the 17 monitored neon tests confirm that the neon capture was within the 0.06 s time resolution of the instrument.*

In regard to the neon density drop following shut-off of neon at 54384.687 s, the first measurement was at 54385.167, 0.580 s later, and the density had dropped from 1.92×10^{11} to 1.71×10^{9} cm^{-3}. The density became 4.45×10^{8} and the noise level, 3.21×10^{6}, 1.515 s and 10.523 s, respectively, after valve closure.

Source Densities

As indicated in figure 7, the maximum neon source density was 1.92×10^{11} cm^{-3}, and it appears to be relatively constant as if the mass spectrometer were saturated. Also the density of mass 32 (really 0) dropped 35 percent, mass 28, 21.5 percent, and mass 4, 35 percent, during neon acquisition. However, the following observations** argue against the assumption that the instrument was saturated and suggest that the decrease in densities at mass 32, 28, and 4 resulted from the neon cloud reducing the flux of ambient molecules by scattering them away from the spacecraft. The total nominal density as measured was not unusually high and the ion-source voltage and current monitors showed no change at the time of neon burst. Contaminant gases generated within the source (masses 18 and 44) did not suffer same decrease. At the neon peak, the telemetry counts did show some fluctuations and the multiplier gain was normal. In addition, the PSA and PSB instruments confirmed that the neon density was well below the level needed to saturate the mass spectrometer.

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*Personal communication, C. J. Rice, September 11, 1975.

**Personal communication, A. E. Hedin, March 3, 1976.

Neon Return Flux, Density, Pressure, and Column Density

The neon flux entering the spectrometer under equilibrium conditions is balanced by the thermalized neon flux which leaves the mass spectrometer through the same port, so that the return flux is

$$\phi_R = \frac{1}{4} n_i V = \frac{1}{4} n_i \left(\frac{8 \mathcal{R} T}{\pi M}\right)^{1/2} = 1.40 \times 10^4 \, n_i = 2.69 \times 10^{15} \text{ cm}^{-2} \text{ s}^{-1} \tag{4}$$

where $n_i = 1.92 \times 10^{11}$ cm^{-3} is the measured neon density; V, the average neon velocity obtained using the gas constant $\mathcal{R} = 8.134 \times 10^7$ erg/K/g mole; M = 20 g mole; and T = 297 K, the temperature of the neon in the thermalizing chamber. The emitted flux for $\dot{m} = 1.58 \times 10^{21}$ s^{-1} and R = 68 cm at the time of the experiment was

$$\phi_E = \frac{\dot{m}}{\pi R^2} = 1.09 \times 10^{17} \text{ cm}^{-2} \text{ s}^{-1}. \tag{5}$$

Therefore, the ratio of the return flux to the emitted flux is

$$\frac{\phi_R}{\phi_E} = 2.46 \times 10^{-2} \tag{6}$$

The density at the surface of the spacecraft was approximately

$$n_R = \frac{\phi_R}{V_s} = 3.16 \times 10^9 \text{ cm}^{-3} \tag{7}$$

where $V_s = 8.5 \times 10^5$ cms^{-1} is the orbit velocity at 250 km. The equivalent pressure of this density, assuming a gas temperature of T = 293 K, was

$$P_R = n_R KT = 1.28 \times 10^{-5} \text{ Pa } (9.65 \times 10^{-8} \text{ torr}) \tag{8}$$

where $K = 1.38 \times 10^{-23}$ J K^{-1} (1.04×10^{-22} torr ℓ K^{-1}) is the Boltzmann constant. The column density neon can be calculated, as shown later, to be

$$N_C = \frac{\lambda_0}{V_s} \phi_R = \lambda_0 \, n_R = 2.8 \times 10^{14} \text{ cm}^{-2} \tag{9}$$

where $\lambda_0 = 8.86 \times 10^4$ cm is the mean free path at that altitude.

THEORY

Ambient Scatter

The analysis estimating the return flux due to ambient scattering (Reference 1) considers molecules radially leaving a spherical spacecraft of radius R being scattered and reacquired by the emitting surface. Molecules scattered out of the idealized emitted beam columns are disregarded under the assumption that they are replaced by molecules scattered in from other columns. With these assumptions, the return flux is given by

$$\phi_R = \phi_E \frac{R}{\lambda_0}\left(\frac{V_s}{V_E} + 1\right) \tag{10}$$

where λ_0 is the ambient mean free path, V_s, the spacecraft velocity, and V_E, the velocity of the emitted flux, ϕ_E. A more precise analysis, taking into account the contribution from other beams, should increase the return over the above results. Other authors, References 3 through 7, have studied the same problem and obtained expressions giving practically the same result. The above theoretical expression, applied to the condition of this test, for $\phi_E = 1.09 \times 10^{17}$ $cm^{-2}\ s^{-1}$, R = 68 cm, $\lambda_0 = 8.86 \times 10^4$ cm, V_s = 8.5 km/s, and for emission velocity $V_E = 7.78 \times 10^4$ cm/s, gives

$$\frac{\phi_R}{\phi_E} = 9.14 \times 10^{-3} \tag{11}$$

for the return ratio so that the return flux due to ambient scattering is

$$\phi_R = 1.0 \times 10^{15}\ cm^{-2}\ s^{-1} \tag{12}$$

According to Reference 1, one can estimate the density and pressure of this scatter from $n_R = \phi_R/v_s = 1.18 \times 10^9\ cm^{-3}$ by assuming that the return velocity is the spacecraft velocity.

Self-Scattering

In addition to ambient scatter, the self-scattering in the emitted flux should be considered. This scattering can be considerable and predominant at high altitudes, especially for large fluxes, as in the present experiment where a relatively dense beam of neon was ejected. Several investigators have provided estimates of the self-scattering. The most complete analysis has been provided by Robertson in Reference 7. This estimate employs a Krook model for self-scattering. This assumes a Maxwellian distribution superimposed on the radial component of the velocity. The following expression for the self-scattering is obtained using our present nomenclature:

$$\frac{\phi_S}{\phi_E} = 1.78 \times 10^{-2} \frac{\sigma R}{V_E} \phi_E \tag{13}$$

where σ is the molecular cross section, R the radius of the spherical spacecraft, and V_E the gas velocity. This expression, with a numerical coefficient about 4.68 to 6.42 times larger, can be obtained from a simple analysis (Reference 4 and author unpublished work).

Substituting the values given previously for R, V_E, and ϕ_E, and using $\sigma = \pi d^2 = \pi (2.59 \times 10^{-8})^2 = 2.10 \times 10^{-15}$ cm^2 for the neon cross section, one obtains

$$\frac{\phi_S}{\phi_E} = 3.23 \times 10^{-20}\, \phi_E = 3.54 \times 10^{-3} \tag{14}$$

for the fraction scattered and the scattered flux to be

$$\phi_S = 3.54 \times 10^{-3}\, \phi_E = 3.88 \times 10^{14} \text{ cm}^{-2}\text{ s}^{-1} \tag{15}$$

This indicates that the calculated self-scattering flux, which increases with the square of the emitted flux and is not a function of the altitude, was about 14 percent of the measured return or 38 percent of the ambient calculated return.

The density due to the scattering was about

$$n_S = \frac{\phi_S}{V_E} \approx 4.56 \times 10^8 \text{ cm}^{-3}$$

Ambient and Self-Scattering Return Flux

Ignoring the flux depletion due to scattering, we may add the ambient scattered flux obtained from equation 10 and the self-scattered flux from equation 13, so that the total expected return flux is

$$\begin{aligned} \phi_R &= \phi_E \left[\frac{R}{\lambda_0} \left(\frac{V_S}{V_E} + 1 \right) + 1.78 \times 10^{-2}\, \frac{\sigma R}{V_E}\, \phi_E \right] \\ &= 1.26 \times 10^{-2}\, \phi_E = 1.38 \times 10^{15} \text{ cm}^{-2}\text{ s}^{-1} \end{aligned} \tag{16}$$

This calculated total flux is 51 percent of that which was measured. The total density of these return molecules is 1.62×10^9 cm^{-3}.

As mentioned above, the ion gage and capacitance manometer indicated a pressure less than 9.33×10^{-4} Pa (7×10^{-6} torr) during exploratory tests at altitudes between 161 and 210 km. This is in agreement with theoretical calculations. In fact, using equation 10 with $\lambda_0 = 5.59 \times 10^3$ cm for the mean free path at 161 km (Reference 11) and an emitted flux $\phi_E = 1.35 \times 10^{17}$ cm^{-2} s^{-1} corresponding to the maximum initial neon pressure, the ambient return ratio is $\phi_R/\phi_E = 0.145$ and the ambient return flux $\phi_R = 1.96 \times 10^{16}$ cm^{-2} s^{-1}. This flux is equivalent to a density of 2.31×10^{10} cm^{-3} and a pressure of 9.52×10^{-5} Pa (7.14×10^{-7} torr). The self-scattering ratio is from equation 13, $\phi_s/\phi_E = 4.42 \times 10^{-3}$ and the scatter flux $\phi_S = 6 \times 10^{14}$ cm^{-2} s^{-1}. This corresponds to a density of 7.06×10^8 cm^{-3} and a pressure of 2.9×10^{-6} Pa (2.18×10^{-8} torr). These calculations show that under maximum flux and lowest altitude, the total pressure could have been about 9.87×10^{-5} Pa (7.4×10^{-7} torr) in agreement with the reported pressure of less than 9.33×10^{-4} Pa (7×10^{-6} torr).

Column Density

The column density is the integrated value of the density from the surface of the spacecraft sphere of radius, R to infinity. Its value for $\lambda >> R$ is as shown, in Reference 1 and for the parameters at 250 km.

$$N = \frac{\dot{m}}{4\pi V_E} \frac{1}{R} = \phi_E \frac{R}{V_E} = 9.56 \times 10^{13} \text{ cm}^{-2} \tag{17}$$

The second expression has been obtained by replacing $\dot{m} = 4\pi R^2 \phi_E$. The column density can be also expressed in terms of the return flux by replacing ϕ_E from equation 10. For the calculated ambient return, one gets $N \sim (\lambda_0/v_s)\phi_R \sim 1.04 \times 10^{14}$ cm^{-2} and for the total return, $N \sim 1.44 \times 10^{14}$ cm^{-2}.

COMPARISON OF THE EXPERIMENT RESULTS AND THEORY

The results of the experiment at an altitude of 250 km indicated a total neon return flux which was about two times the flux predicted by theoretical estimates. The ratio of the total measured return flux to the emitted flux was 2.46×10^{-2}. The same ratio from the calculations was 1.26×10^{-2}. If the self-scattering had not been included, the ratio of ambient scattering return flux to the emitted would have been estimated at 9.14×10^{-3}. The single experiment at 250 km did not allow separate measurements of the self-scattered and of the ambient-scattered return flux. The conservative analytical estimate of the self-scatter return indicates that this was 3.54×10^{-3} of the emitted flux or about 28 percent of the total scattered return for that altitude. With this magnitude, the self-scattered return would have been the major return contributor at altitudes above 300 to 350 km. On the other hand, at an altitude of 150 km, the self-scattering portion would have been only 1.4 percent of the ambient scattered flux. Table 1 shows the comparison between calculated and measured fluxes, densities, and column densities.

SUMMARY AND RECOMMENDATIONS

The MRMU experiment aboard the AE-D spacecraft did perform as intended; however, only a single measurement of neon scattering was made with a mass spectrometer and several exploratory measurements were made with pressure gages. The measurements which had been planned were: the scattering at various spacecraft altitudes, with the neon source pointed in various directions with respect to the orbit velocity vector; the ejection of neon while the spacecraft was spinning; the separation of scattering due to ambient and self-scattering; energy of the return flux; and finally, a complete validation of the theoretical calculations used to estimate the return fluxes of diffused and pointed gas sources from a spacecraft.

Table 1
AE-D Spacecraft, MRMU Neon Scattering Experiment:
Comparison Between Calculated and Measured
Results For 250-km Altitude

	Ambient Scattering		Self-Scattering		Total Scattering		Column Density (cm^{-2})		
	ϕ_R ($cm^{-2}\ s^{-1}$)	n_R (cm^{-3})	ϕ_S ($cm^{-2}\ s^{-1}$)	$n_{S'}$ (cm^{-3})	ϕ_R ($cm^{-2}\ s^{-1}$)	n_R (cm^{-3})	Ambient	Scattering	Total
Calculated Values	1.0×10^{15}	1.18×10^{9}	3.88×10^{14}	4.56×10^{8}	1.38×10^{15}	1.62×10^{14}	1.04×10^{14}		1.44×10^{14}
Measured Values	--	--	--	--	2.69×10^{15}	3.16×10^{9}		--	2.8×10^{14}
Ratio of Scattered to Emitted (Calculation)	9.14×10^{-3}	--	3.54×10^{-3}	--	1.26×10^{-2}	-	--	--	--
Ratio of Scattered to Emitted (Measured)	--	--	--	--	2.46×10^{-2}	--	--	--	--
Ratio of Calculated to Measured		--	--		5.12×10^{-1}	5.12×10^{-1}	--	--	5.1×10^{-1}

Notes

Orbit Velocity V_s = 8.5 km/s @ 250 km altitude
MFP λ_0 = 8.86×10^{4} cm @ 250 km altitude
ϕ_t = emitted flux = $1.09 \times 10^{17}\ cm^{-2}\ s^{-1}$ ($1.58 \times 10^{21}\ s^{-1}$)
V_t = emitted term velocity = 7.78×10^{4} cm/s
t = test time = 8 s
σ = cross section neon = $2.1 \times 10^{15}\ cm^2$
R = equivalent radius spacecraft = 68 cm

The experiment measured and detected the return flux of neon ejected in the direction of the velocity vector at a spacecraft altitude of 250 km. The results compare well with the predicted values and give some assurance that the theoretical calculations can be used for estimation of these parameters.

The measured fraction of the total return flux to the emitted was 2.46×10^{-2}, and the total calculated percent was 1.26×10^{-2}. A conservative estimation, based on the calculations, is that 28 percent of the total return flux was due to self-scatter in the neon plume. In the absence of measurements taken at very high altitudes, this cannot be confirmed, but the magnitude of the measured return fraction of the flux (2.46×10^{-2}), when compared with the fraction calculated for the ambient scatter (9.147×10^{-3}) and with the self-scattering (3.54×10^{-3}), appears to give credibility to this estimate. The self-scattered portion, which does not change with altitude, could have been the predominant return at altitudes over 350 km, but only 1.4 percent of the total scatter at 150 km. This implies that for high-altitude flights, the self-scattering may be the highest contributor to the return, especially for sources such as engines and ventings. The experiment has also indicated that the maximum return flux was detected within 0.5 s of the start of emission and that it dropped two orders of magnitude in less than 0.58 s and three orders 1.5 s after valve closure.

Tests at altitudes between 161 and 210 km using pressure gages as detectors gave additional validity to the theoretical calculations. The tests indicated pressures due to neon return of less than 9.33×10^{-4} Pa (7×10^{-6} torr). This agrees with calculations that showed that the pressure at the lowest altitude of 161 km and for the maximum neon emission should be about 9.87×10^{-5} Pa (7.4×10^{-7} torr).

Because of the importance of these parameters in the evaluation of the contamination and the environment of a spacecraft, it is recommended that the same or similar experiments be carried out in the future. They should confirm the theoretical calculations for other altitudes and directions of emission, obtain energy of the return molecules, and establish the effect of the gas molecular mass on the return fraction. Further, the return of ions injected in ambient plasma, in neutral atmosphere, and in electric and magnetic fields should be investigated.

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