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# Payload Environment and Gas Release Effects on Sounding Rocket Neutral Pressure Measurements

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**The Space Physics Experiments Aboard Rockets-3 sounding rocket carried a payload that performed active experiments to diagnose the physical mechanisms and test the effectiveness of several grounding schemes, to study high-voltage bias effects on the performance of solar cells, and to monitor the undisturbed plasma and neutral gas environment of the payload. As a part of that payload, the neutral pressure gauge obtained measurements of the pressure surrounding the payload both during and between the various active experiments. Neutral pressure results show a pressure elevated by as much as two orders of magnitude over atmospheric model-derived pressures for the entire flight. Neutral pressure measurements indicate that gas released during neutral gas (argon) releases, which was one of the mechanisms for grounding the payload, and attitude control system thruster firings (nitrogen) may be displacing the ambient gas, at least from the vantage point of the neutral pressure gauge. The prerelease ambient pressure appears to be the determining factor for whether a gas release causes an increase or decrease in the ambient pressure. Also, the decay time associated with these gas releases, or the time it takes for the measured pressure to return to ambient, is on the order of a few tenths to a few hundredths of a second once the gas valves are shut.**



## Introduction

THE Space Physics Experiments Aboard Rockets (SPEAR) program was a multiseries sounding rocket program initiated in the mid-1980s. The stated purpose of the SPEAR program was to determine the feasibility of operating high-voltage and high-current systems in space by using theoretical studies, computer modeling, and ground-based vacuum chamber experiments in conjunction with sounding rockets carrying relevant experiments into the low Earth orbit space environment.[1,2]

The third rocket in the series, SPEAR-3, was successfully launched on the night of March 15, 1993, from Wallops Island, Virginia. It reached an apogee of 289 km during its nearly 9-min flight over the Atlantic Ocean. The major objectives of SPEAR-3 were to further the work that was begun on the first flight, SPEAR-1 (Refs. 1 and 2), and to answer some of the questions resulting from that earlier flight. These objectives included testing the effectiveness of various grounding schemes and monitoring the undisturbed plasma and neutral gas environment.

In this paper we are primarily concerned with presenting and discussing the results of the neutral pressure gauge (NPG) that was flown as a part of the SPEAR-3 payload. The scientific objectives of the SPEAR-3 NPG were to monitor the undisturbed neutral gas environment of the payload and the effects of various gas releases on neutral pressure. Both of these objectives were met as evidenced by the data presented in the Observations section.

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## Instrumentation

The SPEAR-3 NPG was a cold cathode ionization gauge similar in design to the magnetron designed and constructed in the late 1950s.[3] Its principle of operation is that a discharge current in a transverse magnetic field is linearly dependent on the density, and hence pressure, of the neutral gas. The SPEAR-3 NPG was calibrated over the range $10^{-7}$–$10^{-3}$ torr using $N_2$ as the reference gas. The sensitivity of the NPG varies according to the gas being measured.[4] Its sensitivity to $N_2$ is 1.00 (by definition) and to argon is 1.13. The NPG utilized an internal power converter operating at 30 kHz to convert a 28-V dc input supply to −2300 V dc, which was the potential applied to the cathode of the sensor. A complete description of the operation of the gauge and its electronics is provided by Adrian.[5] An optical baffle was placed inside the gauge aperture tube. The purpose of this baffle was to prevent the weakly ionized component of the atmosphere from affecting the measurement of ion current by the gauge. A motor-driven butterfly valve was used to seal the gauge sensor cavity until the rocket payload attained an altitude of about 120 km, 81 s into the flight. Sealing the gauge cavity ensured that the cavity remained clean during testing and that an instantaneous startup occurred once an adequate altitude was achieved. The gauge cavity was filled with a clean gas, dry nitrogen at 1 atm, and had not been exposed to air at atmospheric pressure for several months. Because of this and the fact that during this time the gauge tube had been open only while under vacuum ($P < 10^{-3}$ torr), it is highly unlikely that water or any substance other than nitrogen was adsorbed on the tube walls. When the valve was opened at an atmospheric pressure $<10^{-3}$ torr, the dry nitrogen rushed out and the pressure in the cavity passed down through the Paschen region, thus striking the necessary discharge to start the gauge while keeping the cathode clean.

Two crucial tests were conducted with the NPG in the laboratory prior to launch (see Adrian[5] for the complete details of these tests). The first concerned measuring the time required for the NPG sensor cavity to outgas. Based on the results of this test, we would expect that, in the worst case, the gauge cavity would have outgassed within 1 min after the sensor cavity was opened in flight. A second test was performed to experimentally determine the time response of the

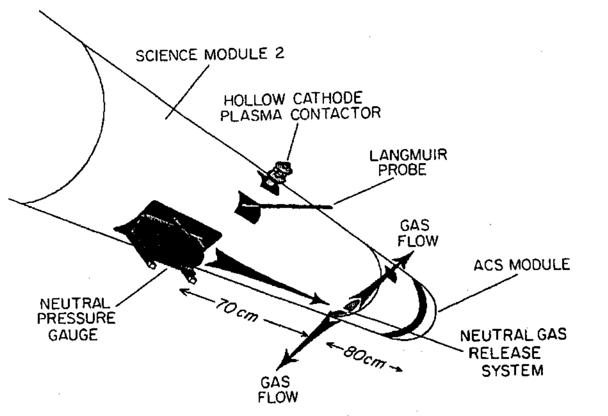


**Fig. 1 Aft end of the SPEAR-3 rocket payload, showing location of the NPG with respect to the NGRS and ACS.**

NPG. It is clear from this test that in flight the NPG could resolve gas pressure pulses occurring on a time scale of 10 ms or greater. It was necessary for the NPG to be able to distinguish between individual thruster firings and gas releases that occurred on those time scales to meet its objectives.

The NPG was located on the second of two science modules at the aft end of the SPEAR-3 rocket payload. Only the attitude control system (ACS) module was located beneath the Science-2 module (see Fig. 1). At launch the NPG was positioned inside the rocket skin. At 73.7-s mission elapsed time (MET) the door directly over the NPG was blown away and the NPG was deployed outside the rocket skin with the aperture pointing aft, as shown in Fig. 1. The center of the aperture of the NPG was positioned about 4 cm from the plane of the rocket skin. At 81.0-s MET the NPG butterfly valve was opened and the gauge ionized within a second. As can be seen in Fig. 1, the NPG was strategically positioned such that it was looking directly down at one pair of the neutral gas release system (NGRS) jets and in the general direction of the ACS thrusters.

There were two pairs of NGRS jets located on the rocket payload. As already mentioned, one set was located directly in the line of sight of the NPG (approximately 70 cm away), and the other set was located 180 deg from this. The direction of the gas flow from these jets was tangential, as shown in Fig. 1. The argon gas was expelled from the four NGRS Mach-4 nozzles at a rate of approximately 2 g/s/nozzle for the high rate releases and 0.2 g/s/nozzle for the low rate releases. Five groups of scheduled releases took place throughout the flight as part of an experiment to test the effectiveness of neutral gas emissions for vehicle grounding.

The ACS consisted of a set of eight thrusters positioned around the ACS module. There were four pitch nozzles, namely, nozzles 1, 2, 3, and 4, located at spacecraft azimuths 0, 180, 90, and 270 deg, respectively, and two pairs of roll nozzles, namely, nozzles 5, 6 and 7, 8 located near 90 and 270 deg. The NPG was located at 274 deg. ACS nozzles 5 and 8 acted to roll the spacecraft counterclockwise, and nozzles 6 and 7 acted to roll the spacecraft clockwise. The pitch nozzles directed the nitrogen gas radially from the rocket cylinder while the roll nozzles directed it tangentially. The rate of release of these nozzles was approximately 12 g/s/nozzle for the roll nozzles and 29 g/s/nozzle for the pitch-yaw nozzles. The ACS was used to perform two major attitude maneuvers and to maintain those attitudes with a fairly loose deadband so that the thruster firings would not interfere with other experiments.

## Observations

The NPG was turned on and produced good, clean measurements from approximately 91-s MET to 510-s MET. Figure 2 is plot of all of the neutral pressure measurements made during the flight, along with a plot of the predicted atmospheric model pressures for the SPEAR-3 trajectory (MSIS-86 model[6] based on mass spectrometer and incoherent scatter data). NPG data were sampled at the rate of 1054 samples/s throughout the entire flight. Evident at 81 s is the initial ionization of the gauge with a full-scale output pressure of about $1 \times 10^{-3}$ torr. As discussed earlier, a few tens of seconds are required for the sensor cavity of the gauge to outgas. Thus, too much importance should not be placed on events that took place during this time period. The lowest pressure measured by the NPG was $2.3 \times 10^{-5}$ torr at 399.2-s MET, at which time the pressure began to rise and continued to do so for the remainder of the flight. Since apogee was reached at about 280-s MET, it is apparent that the pressure measured by the NPG was elevated above that predicted by the MSIS model. At about 475-s MET the upper limit of the NPG measuring range was reached and remained that way through the end of the flight. Also shown in Fig. 2 for comparison is a plot of the predicted pressures taking into account the effect of the NPG aperture being exposed to ram conditions (labeled MSIS86 with ram).

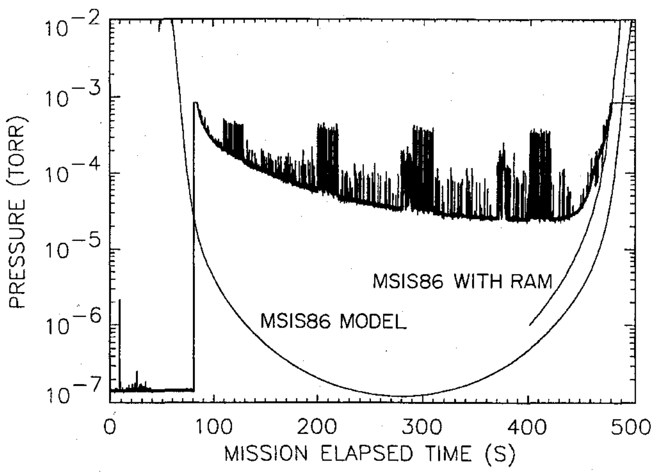


**Fig. 2 SPEAR-3 pressure profiles, including measured pressure.**

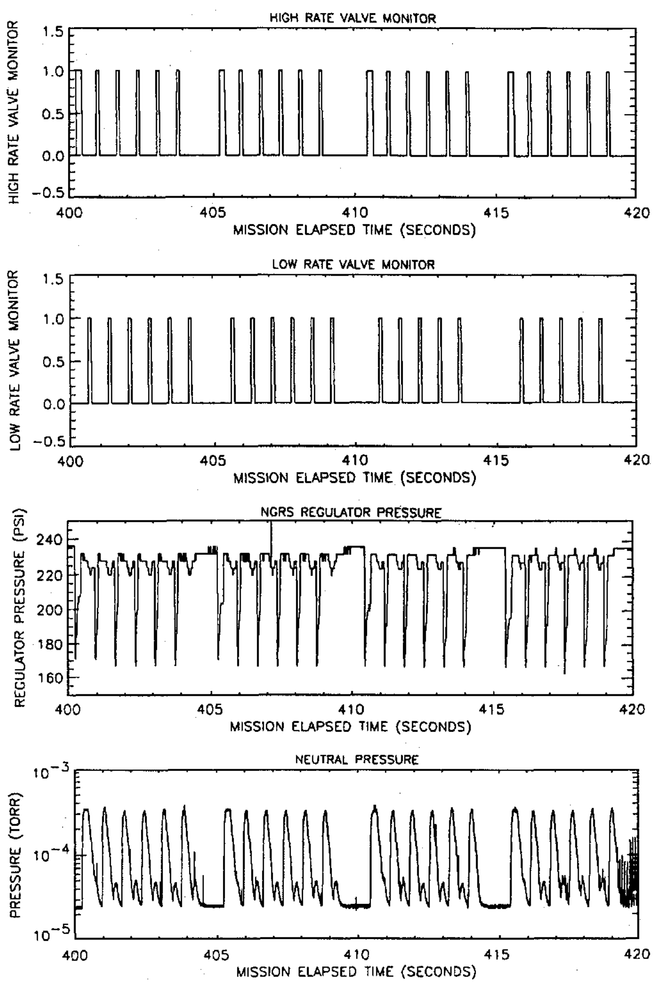


**Fig. 3 Effects of neutral gas releases on pressure during a period of low ambient pressure.**

Figures 3 and 4 show data from two of the five groups of NGRS gas releases. An NGRS group consists of four sets of releases. The

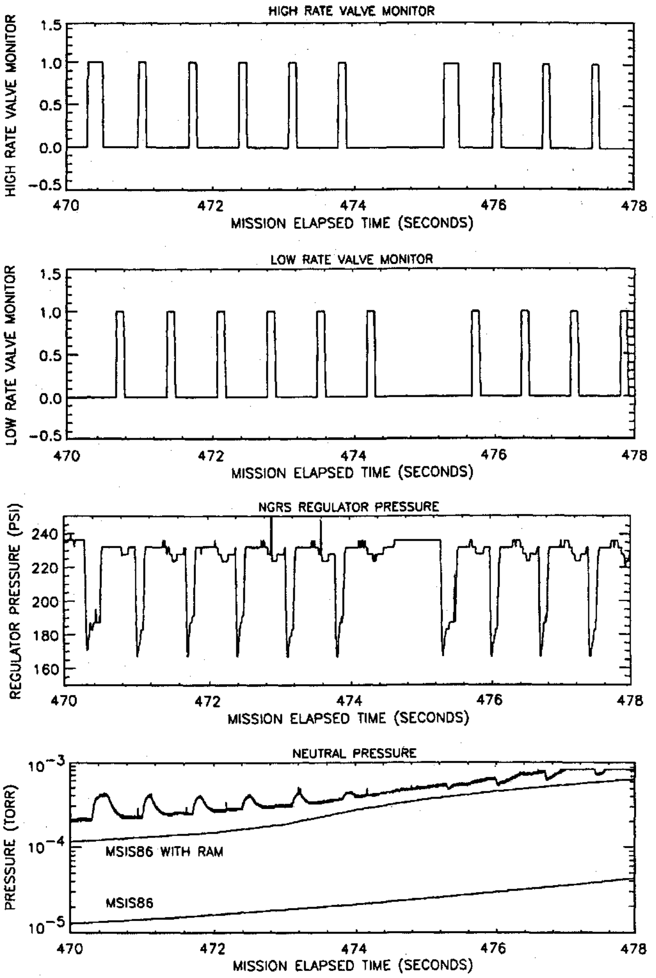


**Fig. 4 Effects of neutral gas releases on pressure during a period of high ambient pressure.**

first two sets contain a high rate release followed by a low rate release repeated six times. The last two sets contain a high rate release followed by a low rate release repeated five times with a single high rate release at the end. The time between sets of releases is approximately 1 s. In Figs. 3 and 4 each diagram consists of four panels. The first panel (from the top) indicates when the high rate valve is open (1) or closed (0). The second panel shows the same quantity for the low rate valve. The third panel shows the regulator pressure in the neutral gas release pressure tank. The fourth panel shows the response of the Iowa NPG. The MET in seconds is shown on the abscissa. The first four groups of NGRS releases are clearly visible in Fig. 2 beginning at about 110-, 200-, 290-, and 400-s MET. These responses are qualitatively similar to each other. Peak values tend to be slightly higher when the ambient pressure (hereinafter defined as the measured pressure in the absence of NGRS, ACS, or hollow cathode gas releases) is high. Figure 3 presents NPG data taken during NGRS releases when the ambient pressure was near the low for the flight. Figure 4 shows the first two sets of the final group of NGRS releases beginning at about 470-s MET. This group of releases is distinct from the others because the ambient is changing rapidly while the peaks maintain a near constant level, which is an interesting and unexpected result. After 475-s MET, gas releases are manifested as pressure reductions (decreases) from the ambient baseline. Note that these pressure reductions do not reach down to the peak level defined by the first six pulses in the group.

Pressure changes were also noted during ACS firings throughout the entire SPEAR-3 flight. In fact, most of the pressure pulse increases noted in Fig. 2 at times other than the NGRS releases are as a result of ACS firings. The two attitude maneuvers took place beginning at about 279- and 369-s MET. Figure 5 is a 14-s plot that shows NPG data in greater time resolution for the second of the two attitude maneuvers. NPG data are plotted in the top panel with ACS data being plotted in the bottom eight panels designated by ACS nozzle

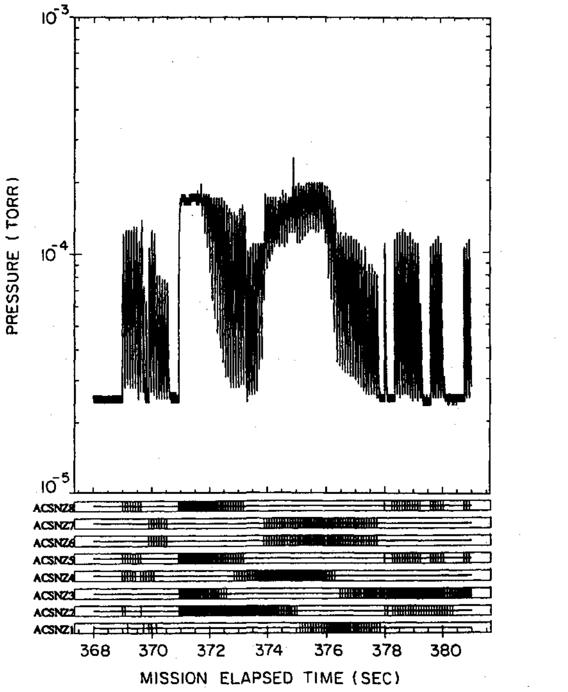


**Fig. 5 Neutral pressure measurements made during a SPEAR-3 attitude control maneuver with identification of which thrusters fired.**

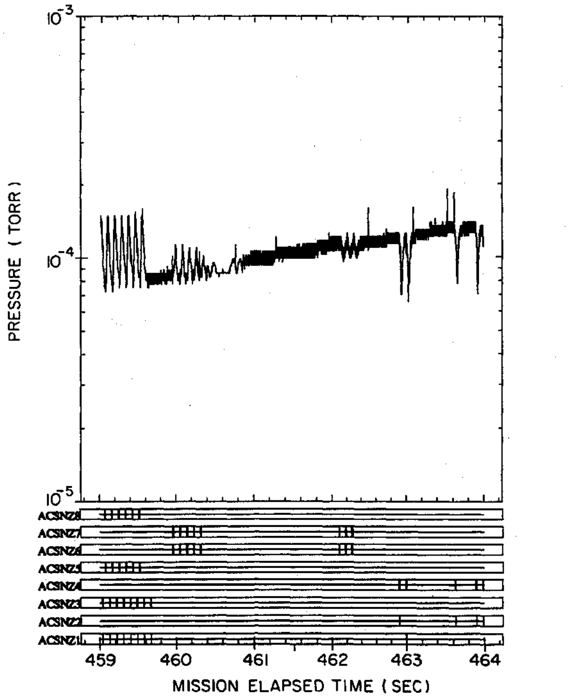


**Fig. 6 Neutral pressure measurements made during high ambient pressure showing effects from attitude control thrusters.**

number. The eight ACS panels indicate when the various ACS jets were firing. Several things should be noted in Fig. 5. Of the pitch nozzles (1–4), only nozzle 4 has any effect on the pressure. Nozzle 4 is located almost 150 cm directly beneath the pressure gauge. Of the roll nozzles (5–8), it is believed that only those located almost directly below the NPG had any effect, but this cannot be proven because the roll nozzles always fire in pairs, one at 90 deg with one at 270 deg. When the thrusters fire almost continuously, either pitch or roll, the pressure increase over ambient remains high. As the time between firings decreases, the pressure cannot completely recover to ambient. Of the ACS jets for which the NPG sees effects, roll nozzles 5 and 8 appear to affect the pressure the greatest. Figure 6 also presents pressure data taken during ACS firings near the end of the flight. As was the case with the NGRS releases, we see decreases in pressure during ACS firings after about 462-s MET. Figure 6 clearly shows the transition from pressure increases to pressure decreases for ACS firings of nozzles 6 and 7.

## Discussion and Comparison with Previous Results

From Fig. 2, it is clear that the ambient pressure, that is, the baseline from which deflections are measured, does not conform to the MSIS-86 (Ref. 6) atmospheric model pressures. One contribution to this difference is outgassing from the rocket. It is evident that this outgassing component dominates the ambient pressure up to 400-s MET. Up to that time the ambient pressure decreases with time, even though the MSIS-86 pressure increases after reaching apogee. Such a decreasing pressure signature is exactly what would be expected from an outgassing payload, where the amount of outgassing decreases with time. Similar outgassing profiles were seen in the pressure data from the SPEAR-1 (Ref. 1) and Viking 7 (Ref. 7) sounding rockets. We have estimated the level of the contribution from water vapor to this outgassing to be on the order of $10^{-5}$ torr based on the method described in Narcisi[8] for determining such a quantity for a rocket flight. When lesser amounts of other outgassed molecules such as $H_2$ and $CO_2$ are added to this, levels consistent with our measurements are plausible.

If the only deviation of the measured ambient pressure from the MSIS-86 model was because of outgassing, we would expect the measured pressure to approximately track the model pressure once outgassing ceased to dominate, i.e., after about 450 s. However, Fig. 2 shows that this is clearly not the case. Instead, the measured pressure remains significantly higher than the model pressure to the end of the mission. Thus, some additional effect is causing the measured pressure to deviate from the true pressure. At about 370-s MET, the rocket rotated to an attitude in which the NPG aperture was being exposed to an ever increasing ram velocity. Gas ramming into the NPG causes the density, and hence pressure, inside the gauge to be larger than the density outside the gauge. Horowitz and LaGow[7] derived an expression for determining the pressure inside a pressure gauge on sounding rockets. The curve labeled MSIS86 with ram in Fig. 2 is the result of scaling the MSIS-86 model pressure according to that expression. It uses the recorded attitude data to calculate orientation of the NPG aperture with respect to ram. The agreement between the measured pressure and this ram model just prior to NPG saturation is remarkable and gives confidence in both the quality of the measurement and the validity of the ram model. Most of the decreasing discrepancy between the measurement and the ram model can be attributed to the continuing contribution of the outgassing component.

Pressure measurements from the earlier flight, SPEAR-1, were made with a gauge nearly identical to that of SPEAR-3. The ambient pressure measurements from that flight[1] are very similar to SPEAR-3 up to the time at which the pressure began to rise at the end of flight. When ambient pressure began to exceed the pressure associated with payload outgassing, the model pressure and measured pressure nearly tracked each other. The measured pressure was always greater than the model pressure and any differences certainly fell within the accuracy of the measurements. Unlike SPEAR-3, the SPEAR-1 NPG aperture was not exposed to ram conditions near the end of its flight.

The first four groups of SPEAR-3 NGRS releases seem to indicate that regardless of the ambient pressure, a high rate release raised the measured pressure to around $3–4 \times 10^{-4}$ torr. The low rate releases appear to have raised the pressure to different values depending on the ambient pressure: when the ambient was high, the measured pressure from the low rate releases was higher than when the ambient was low, as in Fig. 3, and the measured pressure was lower. However, when the pressure was extremely high, as in Fig. 4, no effect whatsoever was seen from the low rate releases. It is significant that in Fig. 4 a region was traversed in which the effect of the high rate releases went from an increase in pressure to a decrease in pressure. The tendency seems to be that these releases either increase or decrease the pressure to a near constant value associated with the expelled gas, regardless of the ambient pressure.

To better understand this tendency toward near constant pressures during high rate neutral gas releases, we consider collisions between oxygen and argon. Particularly, we are interested in how the NGRS (argon) affects the atmosphere (oxygen) in the vicinity of the NPG, and so we choose $4 \times 10^{-4}$ torr as the pressure of the argon, representative of the peak pressures observed by the NPG during the NGRS high flow. At this pressure, the mean free path for oxygen–argon collisions would have been approximately 0.2 m based on a cross section for argon–oxygen collisions of about $3 \times 10^{-19}$ m$^2$, which was computed using radii data contained in Ref. 9. A mean free path of this length is considerably less than the separation between the NGRS and the NPG (0.7 m). Near the NGRS nozzles the mean free path would have been much smaller. This analysis shows that the oxygen would have been significantly reduced by collisions with the argon during NGRS releases. The reduction in ramming oxygen could thus lead to depletions with respect to the pressure measurement because the NPG is substantially shielded from the impinging atmospheric molecules. These are only depletions with respect to the NPG measurement, not the true pressure, approximated by the MSIS-86 model.

Similar pressure increases and decreases as those seen during NGRS releases were observed for ACS firings from nozzle 4 and nozzle pair 6, 7. Figure 6 shows the transition for nozzle pair 6, 7. As noted earlier, the level to which the pressure was raised is somewhat dependent on which jets fired, how long they fired, and how many were firing at once. Most peaks fell somewhere between $9 \times 10^{-5}$ and $2 \times 10^{-4}$ torr. As seen in Fig. 6, after 462-s MET the deflections from ambient were negative. Pressure decreases may have occurred earlier in time with the ACS than the NGRS releases because the ACS firings gave a smaller pressure enhancement than the NGRS. Hence, the ambient measurement exceeded the ACS peak level earlier than the NGRS enhancement level.

A nearly identical ACS system to that of SPEAR-3 was flown on SPEAR-1, which had two attitude maneuvers. The SPEAR-1 ACS firings had no noticeable effect on the pressure measured by the neutral pressure gauge on that flight.[1] This difference from SPEAR-3 implies that the effect of gas releases on a pressure measurement depends greatly on the location and orientation of the gauge. The pressure gauge flown on SPEAR-1 was located in the nose cone of the rocket about 300 cm from the ACS nozzles with its aperture pointed 180 deg from the direction to the nozzles. The SPEAR-3 NPG was located about 150 cm from the nozzles in the ACS module with its aperture pointing toward the nozzles. Moreover, the SPEAR-3 NPG nearly coincided in azimuth with three of the nozzles. An effect on pressure during jet firings was also noted by Horowitz and LaGow,[7] who point out a pressure plateau during rocket ascent that was associated with the continuous firing of spin jets on Viking 7. The pressure gauge on that flight was located on the side of the nose cone of the rocket with the small spin jets being located on the rocket tail fins.

A neutral pressure gauge flown on Spacelab-2 in 1985 was in a position to measure pressure changes resulting from the Space Shuttle attitude maneuvering thrusters and the orbital maneuvering system (OMS) engines.[10] No pressure decreases were seen on that flight from the releases, and the pressure increases that were seen were very small. Only the OMS burn made any significant change. Denig[11] reports seeing effects on pressure from a cold cathode gauge flown on the space transportation system STS-39 mission in 1991 as part of the critical ionization velocity experiment on the Shuttle pallet satellite (SPAS). On that flight he reports pressure increases from firing of the orbiter's attitude maneuvering thrusters and from the SPAS jets when SPAS was a free flyer.

We also examine the shape of the high rate gas release spikes as detected by the NPG. Figure 7 shows the detail of a high rate pulse detected at low ambient pressure. We have chosen a high rate pulse that is not followed by a low rate pulse to observe the form of the pulse without interference. At the command to open the high rate valves, the measured pressure rose by a factor of ten almost immediately. Simultaneously, the neutral gas pressure in the line between the regulator and the nozzles dropped by about 70 psi. This drop occurs as the line empties prior to the opening of the regulator. The regulator acts as an additional valve, which opens or closes depending on the demand downstream, allowing gas to flow from the tank into the line. While the high rate valve remained open, the

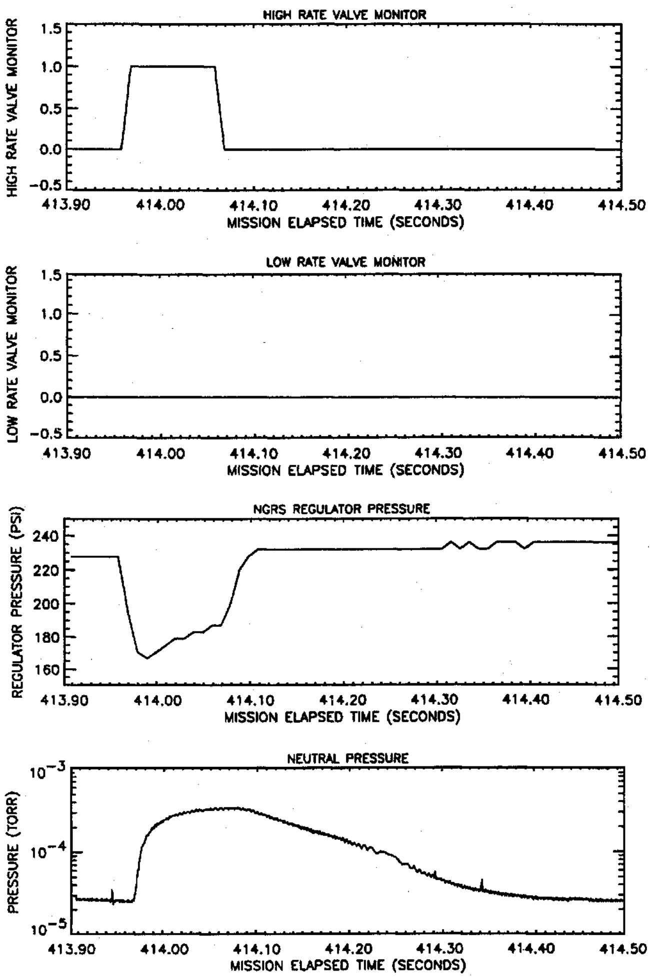


**Fig. 7 High time resolution profile of a high rate neutral gas release showing the long decay time after the gas valve has been closed.**

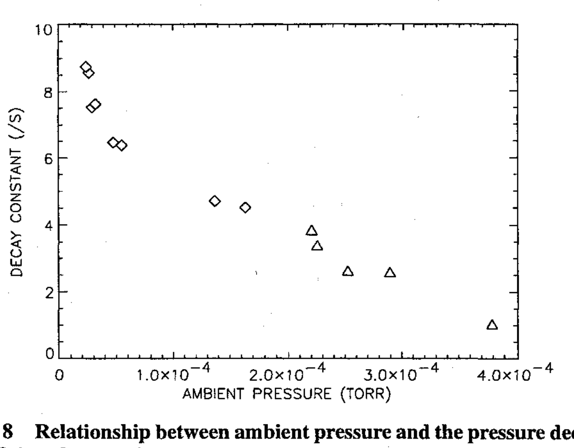


**Fig. 8 Relationship between ambient pressure and the pressure decay coefficient for certain neutral gas releases.**

NPG measurement continued to climb slowly and the pressure in the line recovered slightly. Within 0.02 s after the command to close the high rate valves was issued, the pressure in the NGRS line began to rise, indicating that the high rate valves had closed and the line was filling with gas until the regulator stopped flow from the tank. The characteristics of the line pressure clearly indicate that NGRS two-way solenoid valves closed quickly and completely. Coinciding with the rise in line pressure, the NPG measurement began to fall off nearly exponentially over a period of up to 0.3 s. The only deviation from a steady decline is a slight shoulder part way down.

To study this exponential decline in detail, we have plotted in Fig. 8 the exponential decay constant against the value of the ambient for the 18th and 24th NGRS releases in the first four groups of releases, represented by diamonds, and the first five releases of the fifth group, represented by triangles, in which later releases produced decreases in pressure. We did not plot the measurements for the gas releases associated with pressure decreases since the form of these pressure signals is qualitatively different from that of the increases. Figure 8 reveals the decay constant as a linear function of the ambient for all except the lowest pressures, for which the decay constant shoots up abruptly. The five measurements just prior to the negative pressure deflections appear to form a linear relation continuous with the points during the previous groups of gas releases.

A plot of the decay coefficient vs ambient pressure for the ACS nozzle pair 5, 8 gives a similar result to that presented for the NGRS in Fig. 8. Again, there is an approximately linear relationship between the decay coefficient and ambient pressure, which holds quite well for the higher pressures down to about $1 \times 10^{-5}$ torr. The same plots for nozzle 4 and nozzles 6, 7 look similar except that the slope for nozzle 4, a pitch nozzle, is much steeper. The difference in the slope of the lines, which relate the decay coefficient to the ambient pressure for each nozzle or nozzle pair, suggests that the decay coefficient depends strongly on whether flow from the nozzles impacts the vehicle. Whereas gas flows radially from the pitch nozzles with virtually no collisions with the vehicle, much of the gas flowing from the roll nozzles impacts the vehicle. This difference is probably also why only the pitch nozzle directly below the NPG gave rise to a pressure modification at the NPG. Apparently, collisions with the vehicle play a major role in containing the gas within the vicinity of the payload. This result is consistent with the observations from Shuttle flights that thrusters that impact surfaces greatly enhance the pressure in the payload bay, whereas thrusters that do not impact surfaces show no effect.[12]

It is also helpful to consider collisions between argon and outgassing water vapor in understanding why the pressure does not immediately recover to ambient once the NGRS valves are closed. The average cross section for these collisions is approximately $5 \times 10^{-19}$ m$^2$ based on radii data contained in Refs. 9 and 13. Using the NPG as the measurement of water vapor pressure, the mean free path at the time of the first NGRS release (110 s) is about 0.35 m, which is less than the distance between the NGRS nozzles and the NPG. If the outgassing water represents a comparable pressure at comparable or greater distances from the payload than this mean free path, we can expect the outgassing water to greatly impact the argon flow. By 400 s the mean free path has increased to 3.1 m, where we would expect the effect on the argon flow to be small but measurable by the NPG. It seems clear from this analysis that the dependence of the decay constants on ambient pressure in Fig. 8 and in similar plots for the ACS arises mainly from collisions with the outgassing population, with larger outgassing pressures scattering a larger fraction of the argon. The sharp break at low pressures likely occurs roughly where the mean free path equals the thickness of the outgassing blanket. In support of the assumption that the decay time is associated with the dynamics external to the NPG rather than any effects within the gauge, Berg et al.[14] report that the high-flow NGRS releases were able to ground the vehicle and that the ion sheath around the vehicle remained collapsed for more than 100 ms after the NGRS valve was closed. They also report that many ACS firings (presumably those of sufficient duration) grounded the vehicle and that the effect persisted beyond closure of the ACS valves.

## Summary and Conclusions

The neutral pressure gauge on SPEAR-3 provided valuable results, some of which were directly related to furthering the mission science objectives and some of which were unexpected. In particular, the following information was gained:

1) Ambient neutral pressure at the point of measurement near the aft of the rocket payload never got below $1 \times 10^{-5}$ torr even though the atmospheric model predicted pressures as low as $1 \times 10^{-7}$ torr. We strongly believe that the reason for this is that the payload was outgassing heavily throughout the flight. A major constituent of this outgassing would have been water vapor desorbed from payload surfaces, which is estimated to be at a level of about $10^{-5}$ torr for most of the flight.

2) On the down leg portion of the flight, the measured pressure was expected to track the predicted pressure. These pressures most likely did not track because the aperture of the NPG was subject to ramming of atmospheric gases, which we have shown tends to increase the measured pressure.

3) Controlled neutral gas releases, both high rate and low rate, and ACS firings affected the pressure and were usually seen as increases over the ambient pressure. Near the end of the mission, however, both high rate NGRS releases and ACS firings tended to produce decreases from the ambient pressure. These decreases are probably a result of a shielding of the NPG from the impinging atmospheric oxygen because of collisions between the released gas and the oxygen.

4) The decay time associated with both kinds of gas releases is on the order of a few tenths to a few hundredths of a second and appears to change with ambient pressure—the higher the pressure, the longer the decay time. Note that decay times are much shorter for ACS firings. This decay time is most likely associated with a containment of the released gas around the vehicle because of surface collisions, and with collisions between the released gas and the outgassing water vapor. This is a significant result in terms of vehicle grounding.

5) The magnitude of the measured effect, if any, on pressure because of gas releases depends on the position (distance) of the source of the gas release with respect to the NPG and the orientation of the NPG aperture to the source, as well as the type of gas released and its flow rate.

An accurate description of the dynamics of gas releases requires a detailed model. Such a model must include a full three-dimensional pressure tensor including the ram effect and the pressure gradient and diffusion of the outgassing cloud. In this context the competition between fluid expansion and diffusion of the residual release cloud could be evaluated.

## Acknowledgments

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## References

[1]Allred, D. C., Benson, J. D., Cohen, H. A., Raitt, W. J., Burt, D. A., Katz, I., Jongeward, G. A., Antoniades, J., Alport, M., Boyd, D., Nunnally, W. C., Dillon, W., Pickett, J., and Torbert, R. B., "The SPEAR-1 Experiment: High Voltage Effects on Space Charging in the Ionosphere," *IEEE Transactions on Nuclear Science*, Vol. 35, No. 6, 1988, pp. 1386–1393.

[2]Raitt, W. J., Burt, D. A., Berkey, F. T., Torbert, R. B., Kelley, M., Pickett, J., and Jost, J., "Current Collection by Electrodes at High Voltages Exposed to the Ionospheric F-Region," *Advances in Space Research*, Vol. 10, No. 7, 1990, pp. (7)143–(7)146.

[3]Redhead, P. A., "The Magnetron Gauge: A Cold-Cathode Vacuum Gauge," *Canadian Journal of Physics*, Vol. 37, No. 11, 1959, pp. 1260–1271.

[4]Summers, R. L., "Gas Sensitivity Tables," NASA TN D-5285, June 1969.

[5]Adrian, M. L., "Cold Cathode Neutral Pressure Gauge for the SPEAR III Spacecraft," M.S. Thesis, Dept. of Physics and Astronomy, Univ. of Iowa, Iowa City, IA, Aug. 1993.

[6]Hedin, A. E., "MSIS-86 Thermospheric Model," *Journal of Geophysical Research*, Vol. 92, No. A5, 1987, pp. 4649–4662.

[7]Horowitz, R., and LaGow, H. E., "Upper Air Pressure and Density Measurements from 90 to 220 Kilometers with the Viking 7 Rocket," *Journal of Geophysical Research*, Vol. 62, No. 1, 1957, pp. 57–78.

[8]Narcisi, R. S., "Quantitative Determination of the Outgassing Water Vapor Concentrations Surrounding Space vehicles from Ion Mass Spectrometer Measurements," *Advances in Space Research*, Vol. 2, No. 10, 1983, pp. 283–286.

[9]Dean, J. A. (ed.), *Lange's Handbook of Chemistry*, 12th ed., McGraw–Hill, New York, 1979, pp. 3-120–3-125.

[10]Pickett, J. S., Murphy, G. B., and Kurth, W. S., "Gaseous Environment of the Shuttle Early in the Spacelab 2 Mission," *Journal of Spacecraft and Rockets*, Vol. 25, No. 2, 1988, pp. 169–174.

[11]Denig, W. F., private communication, Phillips Lab. (U.S. Air Force Systems Command), Geophysics Directorate, Hanscom AFB, MA, June 1993.

[12]Wulf, E., and von Zahn, U., "The Shuttle Environment: Effects of Thruster Firings on Gas Density and Composition in the Payload Bay," *Journal of Geophysical Research*, Vol. 91, No. A3, 1986, pp. 3270–3278.

[13]Lide, D. (ed.), *Handbook of Physics and Chemistry*, 75th ed., CRC Press, Boca Raton, FL, 1994, p. 9-19.

[14]Berg, G. A., Raitt, W. J., Thompson, D. C., Gilchrist, B. E., Myers, N. B., Rodriguez, P., Siefring, C. L., Anderson, H. R., and Potter, D. W., "Overview of the Effects of Neutral Gas Releases on High-Voltage Sounding Rocket Platforms," *Advances in Space Research*, Vol. 15, No. 12, 1995, pp. (12)83–(12)86.

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