Plasma Diagnostics Package Initial Assessment of the Shuttle Orbiter Plasma Environment

Stanley D. Shawhan,* Gerald B. Murphy,† and Jolene S. Pickett†
University of Iowa, Iowa City, Iowa

A primary objective of the Plasma Diagonostics Package (PDP) on the third Space Shuttle flight (STS-3) was to assess aspects of the Orbiter's induced gaseous, plasma and electrical environment with respect to the conduct of scientific investigations. Instrumentation temperatures were found to be within predicted limits, payload bay pressure varied from ambient (10^{-7} Torr) up to almost 10^{-3} Torr with thruster firings, electromagnetic interference (EMI) levels were found to be below worst-case estimates but included Orbiter-induced electrostatic noise, and Orbiter potential was consistent to first order with $V \times B$ motional potentials varying ± 5 V with respect to the plasma. Electrostatic noise, neutral pressure and potential all exhibited orbit-period modulation. Payload bay plasma varied in density and composition from ambient to a rarefied mixture with Orbiter-produced H_2O^+. Energetic electrons and ions with energies up to 10's of electron volts were observed occasionally. Primary and vernier thrusters typically induce a momentary perturbation to the electron density, to the pressure, and to the electric field and spacecraft potential with low-energy ions and electrons occasionally observed. With the PDP on the remote manipulator system (RMS), both automode and manual modes were used to seek sources of EMI, to characterize the Orbiter's plasma wake, and to measure beam-plasma phenomena.

Introduction

DURING March 22-30, 1982, PDP was flown on STS-3 as part of the Office of Space Science first science payload (OSS-1).[1] A photograph taken of the OSS-1 pallet configuration during the STS-3 mission can be found in Ref. 8 also in this issue.

The purpose of this paper is to report the initial results of one of the principal technical objectives of the PDP which was to measure the thermal, pressure, electromagnetic, and plasma environment found on-orbit both in and near the Orbiter bay. A summary of results from the science objectives can be found in Ref. 2.

Sensors for measurement of these environmental parameters are identified on the PDP in Fig. 1. Detailed measurement parameters and measurement ranges for the various PDP instruments are listed in Table 1. Most of these instruments and sensors were either flight spare units from previous NASA programs such as IMP, HELIOS, and ISEE or were built from spare parts with modified designs from earlier sounding rocket programs, ISEE and SCATHA.

Thermal Environment

The STS-3 flight test mission was designed as a mission of thermal extremes in order to evaluate the operation of the Orbiter. A 23-h tail-to-sun and an 80-h nose-to-sun attitude exposed the payload bay to continuous dark conditions and cold extremes. The hottest possible conditions were obtained from the top-to-sun attitude which was sustained for 26 h.

Since the PDP unit was not coupled to a coldplate, part of the freon cooling loop, it responded to these temperature extremes in a manner representative of a large payload element. Thermal control of the PDP was carried out with internal thermostatically controlled heaters, external multilayer thermal blankets, and external radiating (taped and painted) surfaces.[3]

Even with the thermal environment extremes, the minimum and maximum temperature values stayed within the desired operating limits. Operating limits and observed temperature values for a few monitoring points, including an interface electronics box which was on a coldplate, are given in Table 2. The release/engagement mechanism (REM) allows the PDP to be separated from the pallet.

Pressure Environment

Included as part of the PDP instrument complement is a colimated and baffled cold cathode ionization pressure gage with a dynamic range of 10^{-3} to 10^{-7} Torr. The pressure gage operated any time the PDP was activated so that the pressure environment was monitored during most of the STS-3 mission. At OSS-1 pallet turn-on at MET 00:04:45 (days: hours:minutes) the pressure was 10^{-5} Torr; it took nearly 24 h to outgas to the ambient level for 240 km altitude of 10^{-7} Torr.

On MET days 2, 3, 4, and part of 5, the most prominent feature is the modulation of the apparent pressure between the ambient level for 240 km altitude of 10^{-7} Torr up to 10^{-5} Torr. This distinct modulation which is shown in Fig. 2 for part of MET days 2 and 3, occurs during the nose-to-sun attitude with the Orbiter rolling at two rolls per one orbit ($2 \times$ orb rate). However, the modulation is at the orbit rate and not at the roll rate. A sketch of the STS-3 nose-to-sun orbit configuration is given in Fig. 3. The ascending node occurs when the Orbiter crosses the equator going toward the north. At this point, the Orbiter attitude is such that the atmospheric gases are ramming into the Orbiter bay. As the Orbiter continues to high latitude and then toward the descending node at night, the Orbiter completely blocks the flow into the bay and a wake attitude predominates. This ram-to-wake-to-ram sequence is cyclic at the orbit period. Note in Fig. 2 that the maximum apparent pressures occur at the ascending node under maximum ram conditions. Even during the periods when the PDP is deployed on the RMS (see periods of "periodic FPEG emissions" on day 03) the pressure modulation trend persists. Perturbations are caused by the fast pulse electron generator (FPEG) electron beam

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*Professor of Physics, Department of Physics and Astronomy; presently, Branch Chief, Space Plasma Physics and the Earth Science and Applications Division, NASA Headquarters, Washington, D.C.

†Staff Research Assistant, Department of Physics and Astronomy.

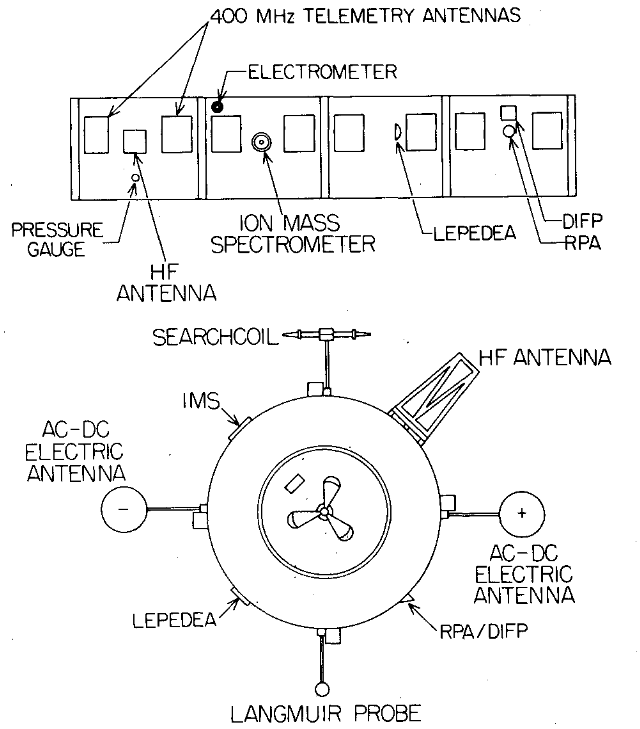

Fig. 1 Identification of the various sensors and instruments carried by the PDP.

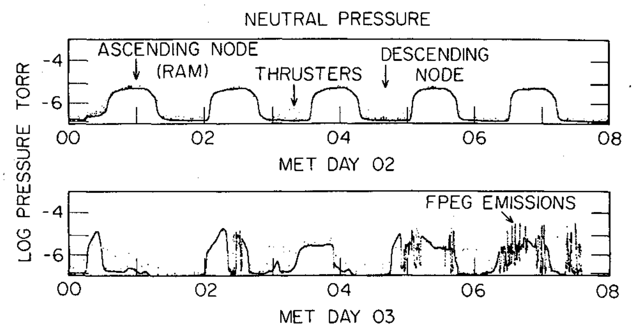

Fig. 2 Sample pressure data for the STS-3 mission both in bay (day 02) and on RMS (day 03).

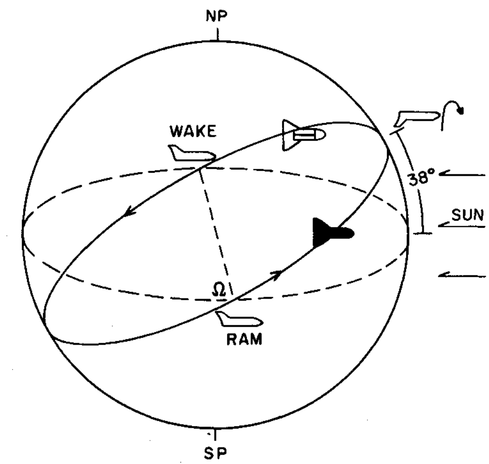

Fig. 3 STS-3 nose-to-sun attitude with the Orbiter roll at 2× orbit rate.

Table 1 OSS-1 PDP instrumentation and measurements

Low-energy proton and electron differential energy analyzer (LEPEDEA)
  Nonthermal electron and ion energy spectra and pitch angle distributions for particle energies between 2 and 50 36 keV.
ac magnetic wave searchcoil sensor
  Magnetic fields with a frequency range of 10 Hz to 178 kHz.
Total energetic electron fluxemeter
  Electron flux 10^9-10^{14} electrons/cm^2 s.
ac electric and electrostatic wave analyzers
  Spectra with a frequency range of 10 Hz to 1 GHz.
  Electric field strength at S-band, 2.2 GHz.
Wideband receiver
  Analog electric and magnetic fields in three 10 kHz bands to 30 kHz.
dc electrostatic double probe with spherical sensors
  Electric fields in one axis from 4 mV/m to 4 V/m.
  Spacecraft potential ± 8 V.
dc triaxial fluxgate magnetometer
  Vector magnetic fields from 12-mG to 1.5 G.
Langmuir probe
  Thermal electron densities between 10^3 and 10^7 cm^{-3}.
  Density irregularities with frequencies of 1 Hz to 178 kHz.
Retarding potential analyzer/differential ion flux probe
  Ion number density from 10^2 to 10^7 cm^{-3}.
  Energy distribution function below 16 eV.
  Directed ion velocities up to 15 km/s.
Ion mass spectrometer
  Mass ranges of 1-64 amu.
  Ion densities from 20 to 2×10^7 ions cm^{-3}.
Pressure gage
  Ambient pressure from 10^{-3} to 10^{-7} Torr.

Table 2 Operating limits vs observed temperature values

Location	Desired limits low/high, °C	Observed low/high, °C
PDP instrument deck	$-30/+50$	$-2^a/+51$
EGF connector housing	$-65/+135$	$-38^a/+53$
REM structure	$-75/+150$	$-13/+40$
Electronics box on coldplate	$-30/+40$	$+7/+15$

[a] Low values controlled by thermostatic heaters in the -32 to -37°C range.

operations and by attitude changes of the PDP by the RMS. Figure 2 also illustrates that attitude control thruster firings produce short-duration pressure increases of typically an order of magnitude.

More detailed pressure plots for selected hours are shown in Fig. 4. For Figs. 4a and 4b the PDP is deployed on the RMS and is being rotated through 360 deg so that the pressure gage is alternatively directed close to the incoming gas flow (ram condition) and away from the flow (wake condition). A general increase in pressure is seen near the ascending node point but the pressure is modulated by the gage rotation. Consequently, the 10^{-5} Torr value cannot be due to a pervasive bay pressure of 10^{-5} Torr. The gage is baffled so that it is not subject directly to ram effects of neutrals or ions. In a ram condition, it is possible for the dynamic pressure near the gage surface on the PDP to be a factor of 20 to 50 above the ambient value,[4] but a factor of up to 200 is observed (see Fig. 4a or 4b).

It is believed that the measured pressure must be indicative of a surface chemical effect due to atomic oxygen reacting at the spacecraft surface near the pressure gage, thus causing a higher density gas layer. When the PDP is pointed away from the ram direction or when the Orbiter blocks the oxygen flow to the surface near the gage, the gas layer is not formed and ambient pressure is measured. This hypothesis is supported by the TV and photographs taken during dark periods. Surfaces of the Orbiter subject to the atmospheric ram are observed to glow. This resultant glow layer appears to be 20-50 cm thick.[5-10] Papadopoulos[6] theorizes that this thickness will be approximately 10-20 cm, which is fairly consistent with the

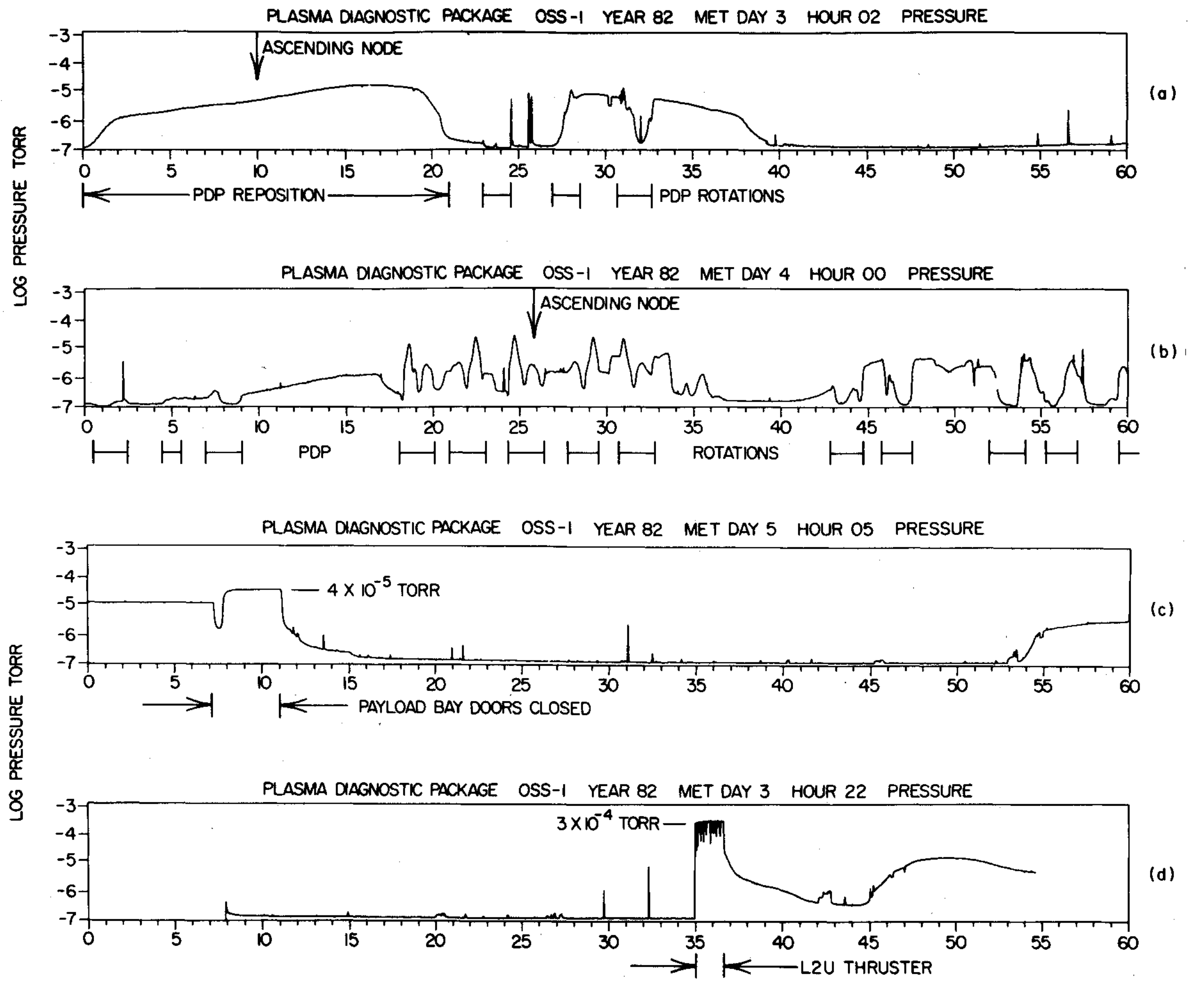

Fig. 4 Detailed 1-h pressure plots: a) and b) PDP deployed and rotated near ascending node; c) payload bay doors closed; d) L2U PRCS thruster firing.

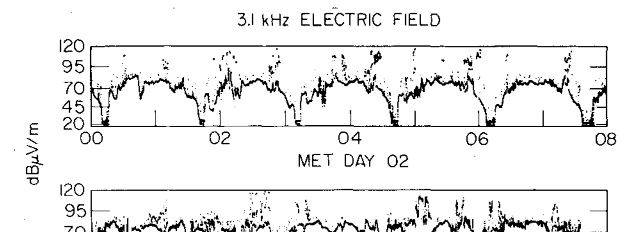

Fig. 5 Intensity of 3.1 KHz broadband electrostatic noise both in bay (day 02) and on RMS (day 03).

observations. Also, the electron beam from the FPEG is not distinctly visible except within about 50 cm of the FPEG aperture—again suggesting a low ambient bay pressure but an enhanced pressure (gas layer) near the surface at the FPEG aperture.

Atomic oxygen ram surface effects are definitely not the cause of the pressure increases shown in Figs. 4c and 4d. Figure 4c includes a period on MET day 5 at 05:08 h when the bay doors are completely closed. In this case, the bay pressure rises to 4×10^{-5} Torr probably due to outgassing of the payload elements and gas leaks into the bay itself. This value is consistent with that measured by the neutral mass spectrometer which was included in the induced environment contamination monitor (IECM). During a sustained test firing of primary reaction control system (PRCS) thrusters, Fig. 4d shows a pressure rise to 3×10^{-4} Torr for the 1.5-min firing period. Evidence of the short vernier thruster control system (VRCS) firings are also seen at 22:30 and 22:32. Additional effects of thruster firings are discussed in the section on thruster perturbations and Ref. 7.

Orbiter Electromagnetic Wave Environment

The PDP is equipped with wave receivers which measure electric field emissions from a few hertz through S-Band and magnetic field emissions from a few hertz to 200 kHz. Emissions are due to Orbiter and payload subsystems, Orbiter-induced plasma perturbations, natural ionospheric plasma waves, and operation of the FPEG electron beam.

Details of the performance characteristics for the PDP receiver systems are given in two companion papers.[8,9] Measurements of the Orbiter and payload background EMI levels indicated that the upper Orbiter limits were not exceeded at any frequency for the broadband electric field or narrowband magnetic field.

A ubiquitous electrostatic background noise dominates the electric field spectrum from 30 Hz to 178 kHz with a peak in the spectrum at 300-500 Hz of 130 dB μV/m/MHz. The noise is thought to be Orbiter-induced due to the motion of the Orbiter through the ionospheric plasma since the noise variability exhibits a marked orbit periodicity. Figure 5 illustrates this variability at a frequency of 3.1 kHz chosen because of its representative nature. The brief dropouts of the noise occurred when the payload bay was most nearly in the wake attitude near the descending node of the orbit. This noise is observed to be enhanced by ~20 dB during thruster

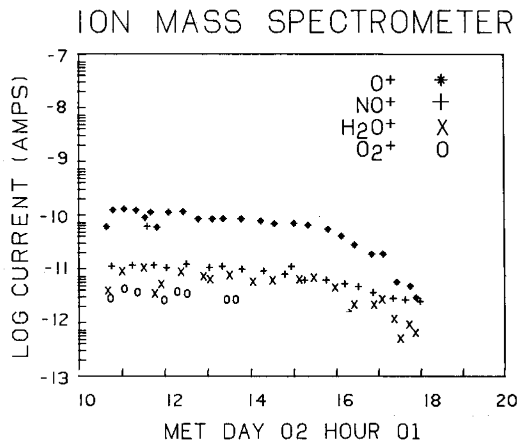

Fig. 6a Ion currents collected while the PDP was in the Orbiter cargo bay.

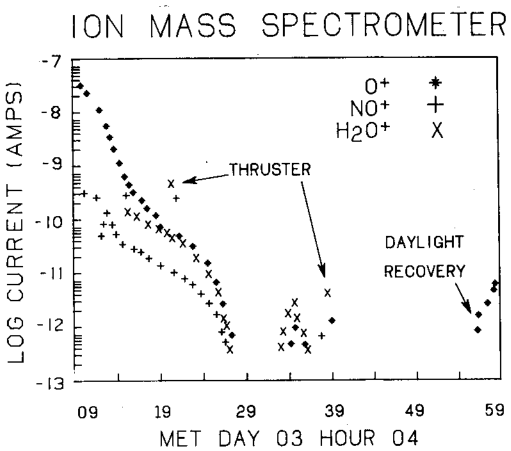

Fig. 6b Ion currents collected while the PDP was on the extended RMS.

firings and by ~40 dB during operation of the FPEG and to be increased by water dumps at night. No theory for the source of this noise has yet been confirmed. More details of the electromagnetic environment are found in Refs. 8 and 9.

Plasma Environment

The plasma environment of the Orbiter is monitored using three instruments—the ion mass spectrometer (IMS) which gives the thermal ion composition and density, the combined retarding potential analyzer/differential ion flux probe (RPA/DIFP) which measures ion energy and analyzes directional ion flow, and the low-energy proton and electron differential energy analyzer (LEPEDEA) which detects the pitch angle and flux of energetic suprathermal electrons and ions.[2]

Measurements of the thermal ion composition are given in Figs. 6a and 6b for the cases of the PDP in the payload bay and on the RMS, respectively. The log current scale is directly proportional to density. In both cases the expected ambient ionospheric components of O^+, NO^+ are observed. However, the H_2O^+ must be produced by the Orbiter since it is not naturally present in the ionosphere. It could be that H_2O^+ is ionized H_2O from water dumps and flash evaporator operations, that it comes from water absorbed by the Orbiter's surface tiles, or that it is produced with the atomic oxygen surface reaction. There is some evidence of increased H_2O^+ concentrations after the flash evaporators have been operating for some extended period of time or during water dumps on the dark side of the orbit. Although NO^+ is expected as a natural ionospheric constituent, it appears to be

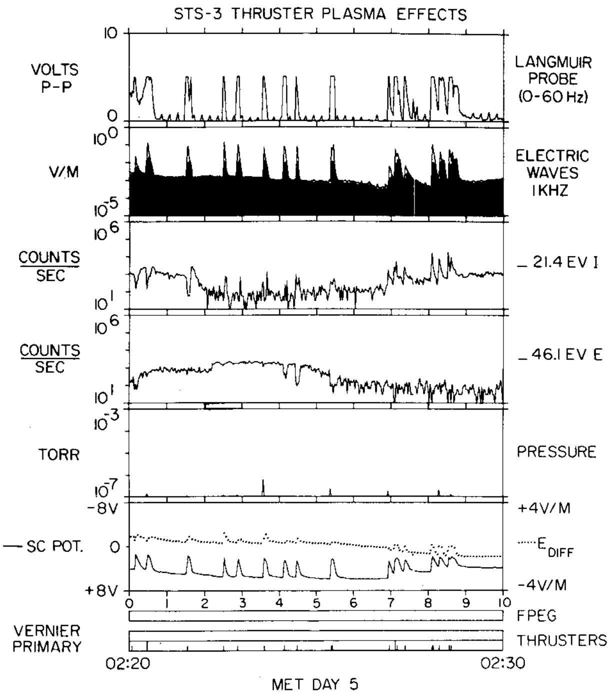

Fig. 7 Sample of PDP measurements indicating the pressure and plasma effects of thruster firings.

enhanced during and just after thruster firings (Fig. 6b). This is expected since NO^+ is a primary ion constituent of the plume.[7]

The marked decrease in density seen in Fig. 6b (greater than or equal to five orders of magnitude) occurs as the Orbiter moves into darkness and into the wake condition. Measurements with the RPA and Langmuir probe on the PDP and the spherical retarding potential analyzer and Langmuir probe of the vehicle charging and potential (VCAP) investigation confirm this marked decrease in plasma density within the payload bay.[10] Since the Orbiter is large compared to a thermal ion or electron gyroradius and is moving at a speed of Mach 5 to 7, a very significant plasma wake is expected behind the Orbiter.

When the PDP is deployed on the RMS, the direction of ion flows are detected by the DIFP instrument. In some cases the DIFP detects two flows of ions coming from different directions.[12] One beam seems to come from the velocity vector as expected, the other, at an angle of typically 30 deg to the first, is as yet unexplained. The RPA observes mean energies of the bserves mean energies of the ions of 10 eV. Assuming that the predominant ion is O^+ as seen by the IMS, only 5 eV of the 10 eV would be due to the kinetic energy of the O^+ ion as it flows into the Orbiter; the other 5 eV gives further evidence that the PDP and Orbiter are charged negatively with respect to the ambient plasma by at least 5 V (see next section).

On occasion energetic plasma is observed with the LEPEDEA (without electron gun operation). Ions are observed with energies up to 30 eV which are sometimes concurrent with the ion beams. More frequently, energized electrons are observed with energies up to 80 eV on the dayside of the orbit. The energetic electrons may be photoelectrons emitted from the Orbiter and PDP surfaces since they are observed predominately on the sunlit parts of the orbit. However, the energy spectrum is not that expected for photoelectrons and is not yet explained. Current work seeks evidence for a significant plasma sheath or evidence to support a beam-plasma interaction.

Orbiter Potential

On the PDP a measurement is made between the average potential of the two 20-cm-diam spheres and the PDP circuit common which is the same as the Orbiter circuit common. This potential is found to vary up to ± 5 V with the orbit period.[11] This potential variation is observed even when the presence of energetic plasma (see previous sections) suggests that the Orbiter may be surrounded by a large potential sheath. Therefore the variation must be caused locally.

All of the Orbiter is covered primarily with thermal insulating tiles or other nonconducting material except for 30 m^2 conducting area on the main engine farings. Therefore, the potential variation has been compared with $\boldsymbol{V}\times\boldsymbol{B}\cdot\boldsymbol{L}$ motional potential due to the Orbiter velocity $\boldsymbol{V}$ (modeled from the Fig. 3 orbit geometry) through the Earth's magnetic field $\boldsymbol{B}$. The distance $\boldsymbol{L}$ is taken to be from the engine farings to the PDP. This simplistic model explains to first order the potential variation observed. Significant deviations from this model occur duing electron gun operations (causing a positive potential) and during thruster firings.

Thruster Perturbations

Thruster firings are necessary to change the Orbiter attitude as well as to maintain a specified attitude within a deadband. On the STS-3 mission there were more than 40,000 thruster firings. Thirty-eight 870-lb thrusters make up the PRCS and six 25-lb thrusters make up the VRCS. Effects of the thruster firings can be seen with several of the PDP detectors. A sample of these effects is given in Fig. 7 for a 10-min period during which time several PRCS thrusters fired. Note that the PDP provides a resolution of 1.6 s for most measurements which is longer than the typical 80 ms thruster firing period.

The Langmuir probe, which responds to variations in the electron density in the vicinity of the PDP, sees a significant perturbation with frequency components in the 0-40 Hz range when thrusters fire. Coincident with the thruster firing is an increase in the intensity of the electric field from 30 Hz to above 10 kHz—the 1 kHz response is representative in Fig. 7. Increases by two orders of magnitude up to 0.1 V/m are observed. Frequently low-energy ions or electrons or both are observed to change fluxes with the LEPEDEA. For example, in Fig. 7 both decreases and increases in the 21 eV ion flux are observed although the 46 eV electron flux shows only occasional decreases. Pressure spikes with peak values up to 10^{-4} Torr are occasionally observed associated with some of the thruster firings (see also Figs. 2 and 4). The spacecraft potential (SC POT) shows a 2-V change with each thruster sequence and the electric field in the vicinity of the PDP indicates perturbation up to 1 V/m. Similar effects are associated with some of the VRCS thruster operations.

The mechanism or mechanisms which produce these effects have not yet been determined. A more detailed investigation of thruster effects and an examination of their causes are presented in Ref. 7.

Summary

Operation of the PDP at its pallet location and on the RMS provides a reasonably comprehensive set of measurements on the thermal, pressure, electromagnetic, and plasma environment that is experienced by a payload element on the Orbiter. Thermal extremes are moderate. The payload bay reaches the 10^{-7} Torr ambient pressure of the atmosphere only with the payload bay in wake condition. A gas layer of pressure up to 10^{-5} Torr seems to be associated with surfaces that are bombarded with the atmospheric gases. Pressure increases well above ambient are observed with the payload bay doors closed and during thruster operations. Orbiter-generated EMI is below the Orbiter specification limits. However, an intense electrostatic broadband noise is observed which may be the result of an Orbiter-plasma interaction. Orbiter-produced H_2O^+ ions are observed with densities comparable to the ambient ions. Energetic ions and electrons with energies up to 10's of electron volts are seen occasionally; it is suggested that under some conditions the Orbiter is surrounded by a plasma sheath. With or without the sheath, the Orbiter exhibits a motional potential which varies ± 5 V over an orbit. Thruster firings perturb the electron density, electrical, and energetic particle environment of the Orbiter but the mechanisms for these effects have not yet been determined.

In general, the Orbiter provides a friendly platform from which to carry out plasma-related experiments and in fact its motion through the ionosphere is itself an interesting plasma experiment. To minimize some perturbing effects during sensitive experiments the attitude and orbit location needs to be specified and the thruster system disabled. Awareness of the operation of the flash evaporator system and/or water dump cycles may also be important for some experiments.

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References

[1] Neupert, W. M. et al., "Science on the Space Shuttle," *Nature,* Vol. 296, No. 5854, March 18, 1982, pp. 193-197.

[2] Shawhan, S.D. and Murphy, G.B., "STS-3/OSS-1 Plasma Diagnostics Package (PDP) 90-Day Science Report," University of Iowa, Iowa City, Iowa, Rept. OSS-1/PDP 82-07, July 1982.

[3] Kerl, M.E., Clark, T.W., and Shawhan, S.D., "STS-3/PDP Thermal History and Time Constants," University of Iowa, Iowa City, Iowa, Rept. OSS-1/PDP 82-09, Sept. 1982.

[4] Carrigan, G., Private communication, University of Michigan, Ann Arbor, Mich., Oct. 1982.

[5] Banks, P.M., Williamson, P.R., and Raitt, W.J., "Space Shuttle Glow Observations," *Geophysics Research Letters,* Vol. 10, No. 2, Feb. 1983, pp. 118-121.

[6] Papadopoulos, K., "On the Shuttle Glow (The Plasma Alternative)," *Radio Science,* Vol. 19, No. 2, March-April 1984, pp. 571-577.

[7] Murphy, G.B., Shawhan, S.D., and Pickett, J.S., "Perturbations to the Plasma Environment Induced by the Orbiter's Maneuvering Thrusters," AIAA Paper 83-2599, Oct. 1983.

[8] Shawhan, S.D., Murphy, G.B., and Fortna, D.L., "Measurements of Electromagnetic Interference on OV102 Columbia Using the Plasma Diagnostics Package," *Journal of Spacecraft and Rockets,* Vol. 21, July-Aug. 1984, pp. 392-397.

[9] Murphy, G.B. and Shawhan, S.D., "Radio Frequency Fields Generated by the S-Band Communication Link on OV102," *Journal of Spacecraft and Rockets,* Vol. 21, July-Aug. 1984, pp. 398-399.

[10] Murphy, G.B. et al., "Interaction of the Space Shuttle Orbiter with the Ionospheric Plasma," *Proceedings of the 17th ESLAB Symposium,* Noordwijk, The Netherlands, 1983, pp. 73-78.

[11] Shawhan, S.D. and Murphy, G.B., "STS-3/OSS-1 Plasma Diagnostics Package (PDP) Measurements of Orbiter-Generated $V\times B$ Potentials and Electrostatic Noise," *Proceedings: Workshop on Charging of Large Space Structures in Near Earth Polar Orbit,* Sept. 14-15, 1982, pp. 119-123.

[12] Stone, N.H. et al., "Multiple Ion Streams in the Near Vicinity of the Space Shuttle," *Geophysics Research Letters,* Vol. 10, Dec. 1983, pp. 1215-1218.