N85-22495

# PLASMA INTERACTION EXPERIMENT II (PIX II): LABORATORY AND FLIGHT RESULTS

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The Plasma Interaction Experiments I and II (PIX I and II) were designed as first steps toward understanding interactions between high-voltage solar arrays and the surrounding plasma. PIX II consisted of an approximately 2000-$cm^2$ array divided into four equal segments. Each of the segments could be biased independently and the current measured separately. PIX II was tested in the laboratory and in space.

PIX II was launched on January 25, 1983, into a nearly circular polar orbit and attained an altitude of approximately 900 km. It was launched as a piggyback experiment on the IRAS spacecraft launch. It remained with the Delta rocket second stage and used the Delta's telemetry system. Approximately 18 hr of data were received: this was the life of the Delta's telemetry battery.

In addition to the solar array segments, PIX II had a hot-wire-filament electron emitter and a spherical Langmuir probe. The emitter was operated when the array segments were biased positively above 125 V. Thermal electrons from the emitter aided in balancing the electron currents collected by the array.

This paper presents laboratory and flight results of PIX II. At high positive voltages on the solar array segments, the flight currents were approximately an order of magnitude larger than the ground test currents. This is attributed to the tank walls in the laboratory interfering with the electron currents to the array segments. From previous tests it is known that the tank walls limit the electron currents at high voltages. This was the first verification of the extent of the laboratory "tank effect" on the plasma coupling current.

## INTRODUCTION

The Plasma Interaction Experiments (PIX I and II) are part of a broad investigation by the Lewis Research Center to develop design guidelines, materials, devices, and test methods for controlling detrimental interactions between high-voltage systems and the space environment. Systems of interest include solar arrays, power systems, conductors and insulators, and other exposed components. Surface-plasma interactions include current drains, charge buildup on insulators, and discharges to or through the space plasma.

Future satellites, including space stations, will require operating power from tens of kilowatts to megawatts. In the near future most, if not all, of this power will be generated by arrays of solar cells. To keep the weight of the power distribution and conditioning components to a minimum, the arrays will have to operate at much higher voltages than the 100 V or less of present arrays. Previous investigations (refs. 1 to 7) have shown that solar arrays biased at voltages greater than approximately 150 V positive and operating in a plasma like that of the lower ionosphere attract large currents of electrons from the plasma environment. That is, the electron currents are enhanced at these voltages. These electron currents are balanced by ion currents attracted to other portions of the spacecraft that are negative with respect to space potential. Thus circuits are created through the plasma for parasitic currents. Because these parasitic currents are in parallel with the load current, they represent power losses.

On a spacecraft operating with a negative-grounded, high-voltage solar array, large portions of the spacecraft surface will be negative with respect to space plasma potential. This is caused by the difference in the electron and ion mobilities and the requirement that electron currents to the spacecraft be balanced with ion currents (i.e., the net current to the spacecraft must be zero). Even though there will be surfaces at relatively high negative voltages, the ion current to these surfaces will be low and therefore will not be a problem. However, there are other adverse effects. On laboratory test arrays biased negatively more than approximately -250 V, blowoff arcing discharges have been observed. PIX I (ref. 1), which was launched in March 1978, verified that both the current enhancement for positive bias and the arcing for negative bias occur in flight. The present paper presents results from the second plasma interaction experiment (PIX II).

The objective of the PIX II flight experiment was to obtain flight data on plasma - solar array interaction phenomena by using a much larger solar array (2000 $cm^2$) than the one flown on PIX I (100 $cm^2$). These interactions include plasma coupling currents and negative bias arcing. The data obtained can also be used to calibrate ground test facilities. The experiment consisted of four identical array segments of about 500 $cm^2$ each. Various combinations of these segments were biased over a range of voltages from -1 to 1 kV. A spherical Langmuir probe was used to measure local plasma densities. As expected, a range of densities was encountered during each orbit. An emitter was activated at high positive voltages to prevent the whole spacecraft from being driven greatly negative by the large electron currents collected at such voltages. The solar arrays were voltage biased in a preprogrammed step sequence.

The PIX II flight package consisted of the 2000-$cm^2$ solar array panel mounted on a 91.4-cm-diameter plate that was truncated to 81.3 cm on one side, an electronics enclosure box housing all of the electronics hardware, the emitter, and the spherical Langmuir probe. On the Delta, the electronics enclosure box was mounted 180° around the perimeter from the solar array panel.

## EXPERIMENT AND PROCEDURE

The experimental setup is shown in figure 1. For positive bias each electrometer could measure currents from $10^{-7}$ to $10^{-2}$ A; for negative bias the range was $10^{-8}$ to $10^{-3}$ A. The power supply was capable of an output of 80 mA at 1000 V and was programmed for output voltages of 0, ±30, ±60, ±95, ±125, ±190, ±250, ±350, ±500, ±700, and ±1000 V. Even though the solar array segments were operated individually and in combinations, the current to each segment was always measured individually.

The PIX II telemetry systems operated in real time. However, full real-time telemetry ground coverage was not possible with the limited number of ground receiving stations available. So PIX II was given the capability of storing data for 68 min. After 68 min from PIX II turnon, the old data were overwritten continuously at a rate of 64 bits/sec. The stored data were also read continuously at a rate of 512 bits/sec. Both the stored and the real-time data were transmitted continuously. With this system, almost full orbit coverage of PIX II data was possible. As a precaution against a failure of the data storage unit, the sequence was preprogrammed to sweep each of the solar array segments at least once positive and once negative in view of a ground telemetry-receiving station.

The emitter was a loop of 0.025-cm-diameter tungsten wire connected at one end to spacecraft ground. It was activated for positively biased solar array voltages greater than 125 V. To see the effect of the emitter on the results, some voltage cycles were operated with the emitter off. The emitter was mounted such that, when deployed, it extended 71 cm on a boom fastened along an edge and perpendicular to the face of the electronics enclosure box (fig. 2). The emitter operated with no accelerating grid as a passive thermonic emitter of electrons. The positive potential of the plasma relative to the spacecraft served to draw the electrons from the spacecraft.

The Langmuir probe was used to determine ambient plasma densities. The probe, a 1.9-cm-diameter aluminum sphere, was deployed on a 71-cm boom. It was mounted on an edge of the enclosure box such that when deployed it was tangent to the Delta (fig. 2). (The emitter extended radially outward from the Delta from an edge of the enclosure box far from the Langmuir probe.) During a Langmuir scan the probe's voltage was stepped from -20 to 110 V. The voltage was stepped in 5-V increments from -20 to 20 V and in 10-V increments from 20 to 110 V. When not being scanned, the Langmuir probe was held at 50 V and its collection current monitored.

## GROUND TESTS

The complete flight package was ground tested in a plasma environment before the flight (fig. 3). The tests were performed in a 9-m-long by 4-m-diameter vacuum chamber. The solar panel and the electronics enclosure box were mounted back to back in the center of the chamber perpendicular to its centerline. The solar panel faced opposite to the deployed emitter probe. The plasma was generated by four plasma sources: two mounted at least 2.5 m from the solar array and two mounted at least 2.3 m from the electronics enclosure box.

## RESULTS AND DISCUSSION

All activities on PIX II were preprogrammed to occur at particular program counts in a sequence. Each program count was held for 16 sec. The program count timer was activated at PIX II turnon. After program count 2047 (9 hr, 5 min, 52 sec) the sequence returned or "rolled over" to program count 0 and the sequence was repeated. Data were obtained on PIX II until program count 248 after the second rollover. There were some gaps in the data after the first rollover because of less ground coverage than earlier orbit passes.

## Langmuir Probe

Typical Langmuir probe current-voltage curves are shown in figure 4. The program counts shown on the figure are for the beginning of each sweep. Each voltage step between -20 and 50 V was held for 4 sec, the 60-V level was held for 1 sec, and all others were held for 2 sec each. The maximum current the Langmuir electrometer could measure was $1 \times 10^{-4}$ A. This limit caused the leveling off of the current shown for program count 1343 in figure 4.

The electron plasma densities were determined from the electron saturation region of the curve (fig. 5). As expected, the current varied quite linearly with voltage above 30 V. This behavior was typical of all of the Langmuir sweeps.

In the saturation region of the spherical Langmuir probe characteristic, the equation for the current (ref. 8) is

$$I = neA \left(\frac{kT}{2\pi m}\right)^{1/2} \left(1 + \frac{eV}{kT}\right) \tag{1}$$

where $V$ is the voltage measured with respect to the plasma potential, $e$ the electronic charge, $k$ Boltzmanns's constant, $m$ the mass of the electron, $T$ the temperature, and $A$ the area of the probe. Taking the derivative with respect to voltage allows the density to be written in terms of the slope as

$$n = \frac{(2\pi mkT)^{1/2}}{Ae^2} \frac{dI}{dV} \tag{2}$$

where $dI/dV$ is the slope. The electron saturation region data for each scan of the PIX II probe were plotted as in figure 5 and the slopes determined graphically. Twenty-three Langmuir scans were made during the life of PIX II.

To find the density at times when the Langmuir probe was not being scanned, the Langmuir probe current at a voltage of 50 V and the density at program count 878 were used as references. It was assumed that the Langmuir probe current at 50 V varied in proportion to the density. The density at any program count was found from

$$n = I \, (n/I)_{PC878;50V}$$

where $n$ and $I$ are the density and Langmuir probe current at 50 V, respectively. In using this equation, care was exercised that the spacecraft ground voltage remained constant. This was achieved by limiting the use of this equation to program counts where the applied voltage to the solar array was less than 60 V. It was felt that voltages in this range were low enough that the currents collected by all of the exposed grounded metallic surfaces on the Delta would be enough to balance the currents collected by the solar array without driving the Delta's ground potential negative. This method was used to estimate the ambient plasma densities for the flight results presented herein.

Plasma density varied as much as two orders of magnitude during an orbit (fig. 6). Revolution 8 (fig. 6(b)) had the most uniform density. Even here the variation was more than an order of magnitude. Although large variations over the poles were expected, the density elsewhere was expected to be more uniform. Some of the nonuniformity was caused by the Langmuir probe being in the ram or wake of the Delta, as shown in reference 9.

## Emitter Operation

The emitter was operated for positive biases of 125 V and higher on the solar array segments. Since there were no accelerating grids on the emitter, it emitted electrons only when the spacecraft ground potential became negative with respect to plasma potential.

The emitter operation was first tested in the laboratory. The PIX II flight package was mounted so as to float electrically in the vacuum chamber. As in flight the PIX II was operated in a plasma environment. The emitter-on currents (fig. 7(a)) were approximately an order of magnitude larger than those for emitter-off operation. The results shown for the emitter-on operations compare very closely to those obtained when the PIX II structure was grounded to the tank walls. From this it was concluded that the emitter kept the PIX II flight package near tank ground potential.

In flight (fig. 7(b)) the emitter-on current was approximately five to six times larger than the emitter-off current. This difference is smaller than that observed in laboratory tests. In flight the solar array segments were operated at different times in different locations. Thus the smaller effect observed in flight as compared with ground tests may have been caused by the difference in the densities during operation of the segments.

The Langmuir probe current was very sensitive to emitter operation both in the laboratory and in flight (fig. 8). The voltage on the Langmuir probe was 50 V. With the emitter off, the Langmuir probe collected ions with a bias of 200 V or greater on the solar array in the laboratory tests and 350 V or greater in flight. This implies that the spacecraft floated at least 50 V negative in this voltage range. Even with the emitter on, the Langmuir probe dropped about an order of magnitude when the voltage on the array was increased to 1000 V.

For the emitter to operate properly, the spacecraft must float negatively with respect to plasma ground. The floating potential (fig. 9) was found from the following procedure:

(1) The Langmuir probe current-voltage characteristic curve was determined with the solar array segments at zero voltage.

(2) The corresponding voltage was found by using the Langmuir probe current reading when the solar array segments were at the applied voltage and the Langmuir probe current-voltage characteristic curve from step 1.

(3) This voltage minus 50 V was assumed to be the floating potential.

The floating potential is a function of the ambient density and the applied voltage to the solar array segments. Since each set of segments was operated in different parts of the flight, each had a different density environment. The sets of segments therefore could not be compared directly. However, the trend is obvious from figure 9, namely, higher positive solar array voltages produce higher negative floating potentials on the spacecraft. In general, the floating potential increased almost linearly with applied solar array voltage after snapover.

## Solar Array Positively Biased

Since the laboratory and flight plasmas for solar array segments positively biased to 1000 V had different densities and temperatures, corrections were made to the flight results for direct comparison with the laboratory results (fig. 10). If we assume that the currents to the solar array segments vary linearly with $V$, $eV/kT >> 1$, and if $I_0$, $T_0$, and $n_0$ are known current, electron temperature, and density, respectively, at one plasma condition, the current $I$ at any other temperature $T$ and density $n$ can be found by using the spherical probe equation (1).

$$I = I_0 \frac{n}{n_0}\sqrt{\frac{T_0}{T}} \tag{4}$$

Equation (4) was used to compute the flight values in figure 10 by using the laboratory values of $kT = 1.8$ eV, $n = 3.4\times10^3$ cm$^{-3}$, and flight values of $n_0 = 3.0\times10^3 \sqrt{kT}$ for solar array segments 2 and 3 and $n_0 = 5.5\times10^3 \sqrt{kT_0}$ for solar array segments 1 to 4. The $n_0$ is the flight result determined from the Langmuir probe readings. So the two flight curves in figure 10 are the values the flight data would have had if the flight ratio $n/\sqrt{kT}$ had had its laboratory value.

In figure 10 it appears that the laboratory currents are truncated above 200 V. This is caused by the tank wall interfering with the current collection. The calculated sheath at a voltage of 200 V at these plasma conditions extends approximately 1.6 m from the solar array. This is beyond the tank wall. Thus this verifies the hypothesis that sheath-wall interactions occur during laboratory tests at high voltages and limit the current collection.

The flight data for solar array segments 2 and 3 (fig. 10) show that current increased slightly less than linearly with voltage for voltages greater than approximately 350 V. This was as expected since for an infinite flat plate the current would be a constant and for a plane small compared with the Debye length it would vary linearly. This array was between these sizes. The current for all four segments varied even more slowly. This is also in agreement with rough expectations.

Another set of curves for the total current collected by one, two, and four array segments (fig. 11) also shows that the current increased almost linearly with voltage above about 350 V. It is tempting to compute an area effect from this figure. However, it is not known whether the array was in the ram, the wake, or neither when each of these sets of array segments was activated. Also it is not known whether the ambient densities were the same during these times. The density can vary by over two orders of magnitude over an orbit (fig. 6). These facts prevent a definite determination of the area effect.

## Solar Array Negatively Biased

The maximum total steady current measured for negative biases on any of the sets of array segments was approximately 5 μA. This level of current does not pose a problem for operation of high-voltage solar arrays in space. The problem associated with negative bias is the probability of arcing. During arcing, there are high surges of current through the array. These surges reach levels of milliamperes and higher. In both ground and flight tests, once arcing begins, it continues through the higher (more negative) voltage levels. In fact, the arcing becomes more frequent and intense at the higher voltage levels.

Most of the arcs were initiated between -500 and -1000 V (table I). There was one initiation at -255 V. On closely examining the data, it was noticed that the arcing inception voltage tended to increase with time. That is, fewer arcs occurred at -350 and -500 V near the end of PIX II life. Out of the 106 times the segments were activated negatively, the solar array segments reached -1000 V, without arcing, 12 times.

## SUMMARY

PIX II consisted of four 500-cm$^2$ solar array segments, a spherical Langmuir probe, an emitter, and associated electronics. The Langmuir probe data indicated densities that varied over two orders of magnitude over an orbit and large differences from orbit to orbit. Some of these density variations are thought to be attributable to the Langmuir probe being in the ram or wake of the spacecraft. Since the attitude of the spacecraft was not known, separation of the ram/wake effect from the ambient density variation is very complex and has not been attempted in this work.

Spherical probe theory fitted the Langmuir probe data very well. This suggests that the densities determined from the Langmuir probe were the actual densities surrounding the probe. However, the solar array segments were mounted on the opposite side of the Delta from the Langmuir probe. So the densities surrounding the solar array were not necessarily those of the probe.

Different combinations of the solar array segments were activated by using a preprogrammed sequence throughout the life of PIX II. The sequence was chosen to maximize the information received by the limited real-time ground coverage in case the data storage/playback unit failed to operate. As it turned out, all units on PIX II operated as designed and data were obtained through program count 247 after two rollovers of the sequencer (two full and one partial sequence, approximately 19 hr).

For positive bias on the solar array segments, the data showed current enhancement for voltages greater than approximately 200 V. This current enhancement was larger than that predicted by ground tests. The difference is attributed to suppression in the ground test currents by the interaction of the sheath with the walls of the vacuum chamber. Suppression in the ground test currents was observed for all of the solar array segments whether run singly or in combinations. This implies that only relatively small solar arrays can be completely plasma tested in present ground facilities.

For negative bias on the solar array segments, arcing occurred. In both ground and flight tests the current sometimes increased from microamperes to milliamperes and higher during arcing. In flight, arcing was observed for voltages as low as -255 V. The arcing inception voltages tended to increase negatively with time. There were fewer arcs observed at -500 V and lower near the end of PIX II life than in the beginning. This suggests that preconditioning high-voltage solar arrays by operating them at high negative voltages in a plasma environment on the ground may help to drive the arc inception voltage in flight more negative.

The emitter was a passive hot-wire filament and was activated for positive biases on the solar arrays of 125 V or greater during part of the experiment sequence. This was necessary since the second stage of the Delta had very little exposed bare metal surface to collect ions for balancing the electrons collected by the array. The largest negative potential observed on PIX II with the emitter operating was approximately -50 V, as compared with voltages greater than -200 V without the emitter. Thus the emitter was able to keep the spacecraft within reasonable proximity of the space plasma ground.

## CONCLUSIONS

Four 500-cm$^2$ solar array panel segments were biased positively and negatively in steps to ±1000 V on a spacecraft in a polar orbit at an altitude of approximately 900 km. Various combinations of the four array segments were activated during the flight. At each voltage level the current collected by each solar array segment was measured. When the array was biased positively to 125 V or higher, an electron emitter was activated to aid in keeping the spacecraft near plasma potential. A spherical Langmuir probe was used to determine the plasma density throughout the flight.

The following conclusions were drawn from the data for positive bias on the array segments:

1. Even the large laboratory plasma simulation facilities at Lewis are too small to correctly estimate the plasma coupling current at high positive voltages to solar arrays that are 2000 cm$^2$ or larger in area.

2. If the negative terminal of a spacecraft array is connected to spacecraft ground, the spacecraft will float far negatively with respect to space plasma potential if large bare metallic areas are not provided for ion current collection, which is necessary to balance the electron current collected by the solar array.

3. The plasma coupling current may vary over an order of magnitude between ram and wake conditions.

The following conclusions were drawn for negative bias on the array segments:

1. Arcing is the most serious detrimental effect.

2. The arcing inception voltage may be as low as -255 V on conventionally constructed solar arrays.

3. Arcing may occur at densities as low as $10^3$ electrons/cm$^3$.

TABLE I. - PIX II ARCING INCIDENCE RESULTS FOR NEGATIVE BIAS

[Arcing occurred at -350 V with densities of $10^3$/cm$^3$. Arcing inception voltage tended to increase with time.]

| Array segments active | Applied voltage for arc initiation, V | | | | | Number of arcs[a] | Total |
|---|---|---|---|---|---|---|---|
| | -255 | -350 | -500 | -700 | -1000 | | |
| 1 | ---- | 2 | 2 | 5 | 6 | 1 | 16 |
| 2 | ---- | 1 | 3 | 5 | 5 | 5 | 19 |
| 2,3 | ---- | 1 | 3 | 3 | 5 | 3 | 15 |
| 1,4 | ---- | ---- | 9 | 5 | 4 | ---- | 18 |
| 1,2,3 | ---- | 1 | 4 | 6 | 3 | 1 | 15 |
| 1,2,3,4 | 1 | 1 | 6 | 6 | 7 | 2 | 23 |
| Total observations | 1 | 6 | 27 | 30 | 30 | 12 | 106 |
| Incidence, percent of total | 0.9 | 5.7 | 25.5 | 28.3 | 28.3 | 11.3 | --- |
| Cumulative incidence, percent | 0.9 | 6.6 | 32.1 | 60.4 | 88.7 | 100 | --- |

[a] Combined total of arcs initiated after being at voltage level a few seconds plus arcs that occurred on first reaching this level from the previous nonarcing one.

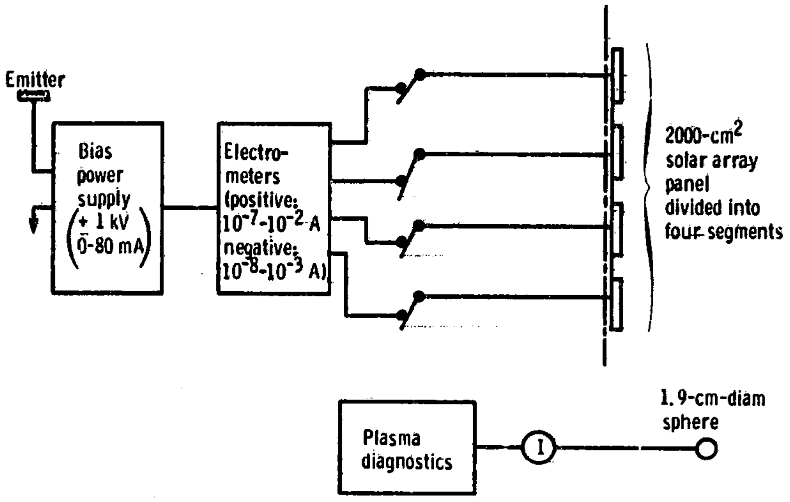


Figure 1. - PIX II electrical arrangement.

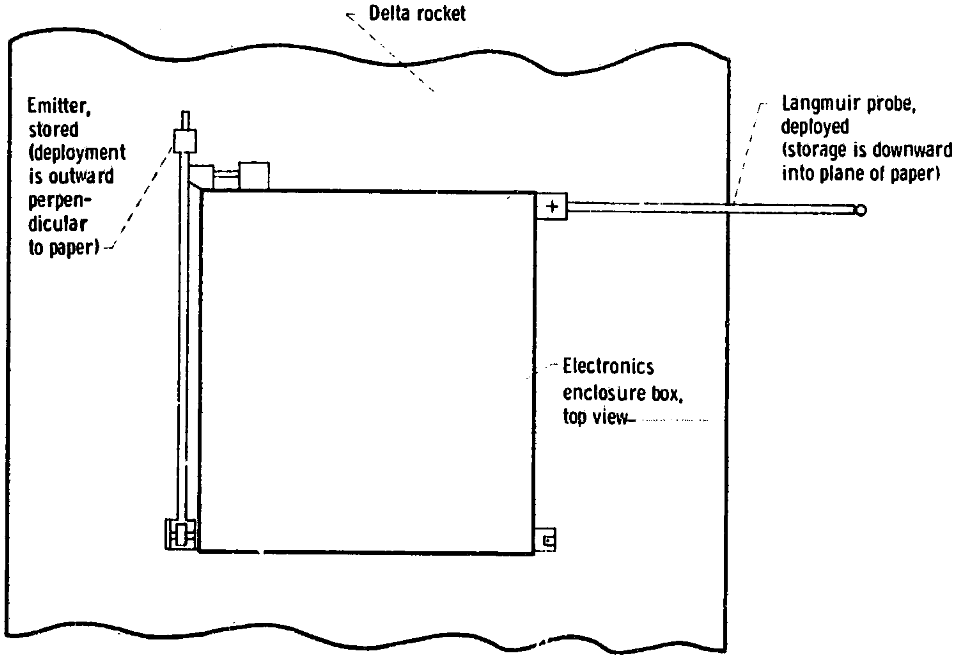


Figure 2. - Electronics enclosure box showing emitter and Langmuir probe positions.

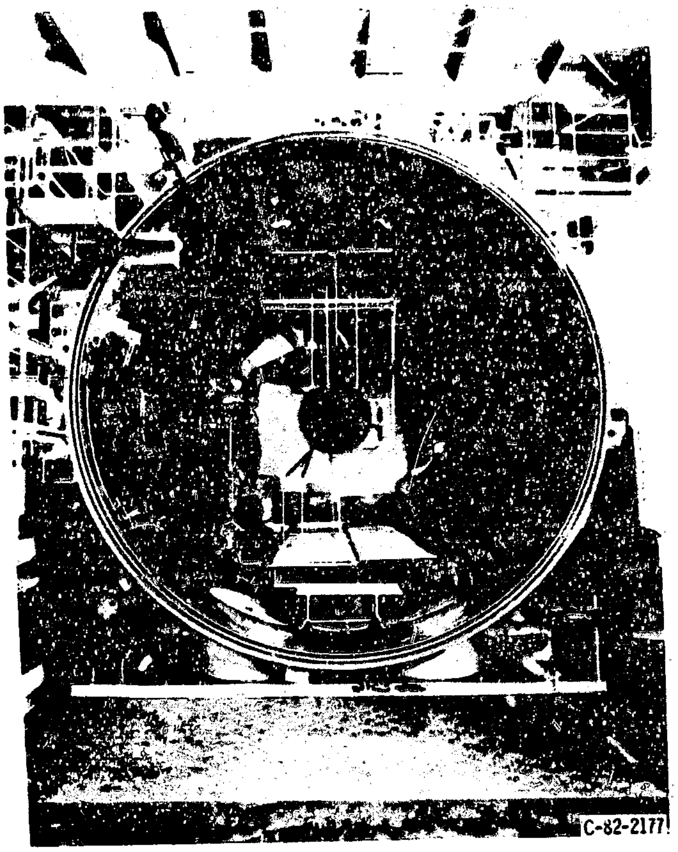


Figure 3. - PIX II setup in large vacuum facility for ground testing.

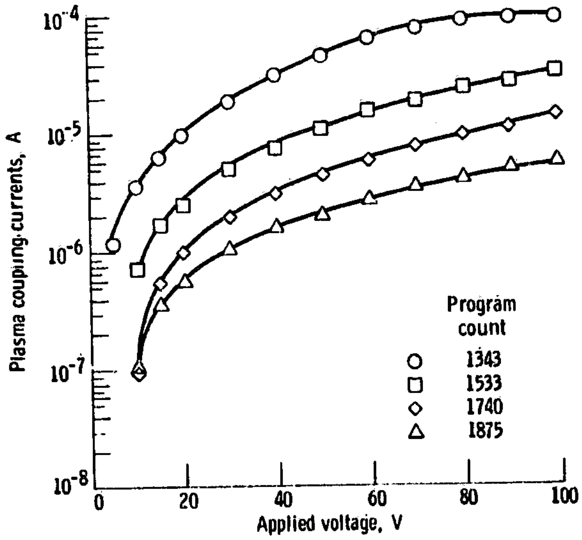


Figure 4. - Typical sweeps of Langmuir probe during flight.

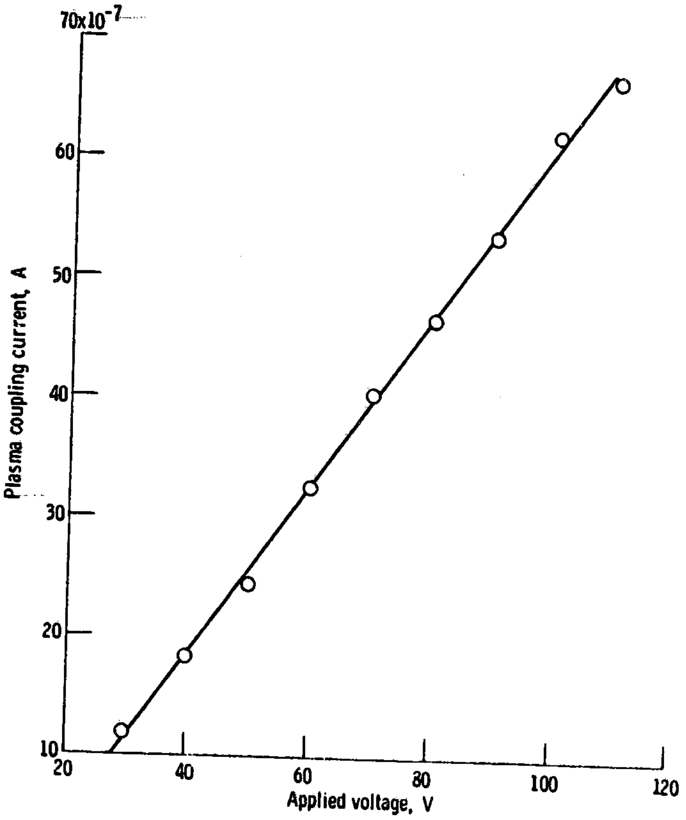
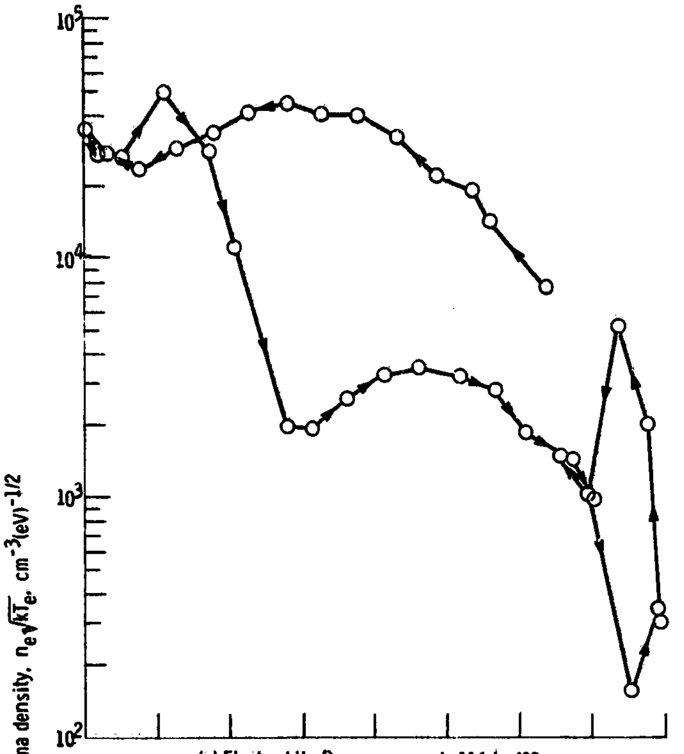
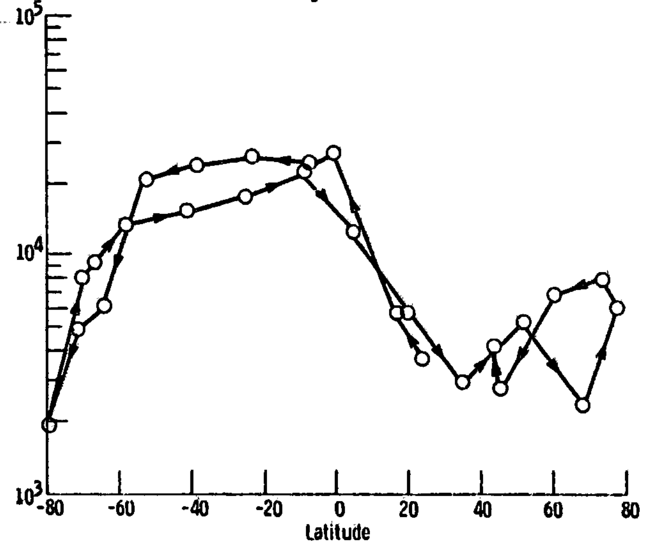


Figure 5. - Typical sweep of Langmuir probe in electron saturation region, showing linear behavior. Program count, 878.

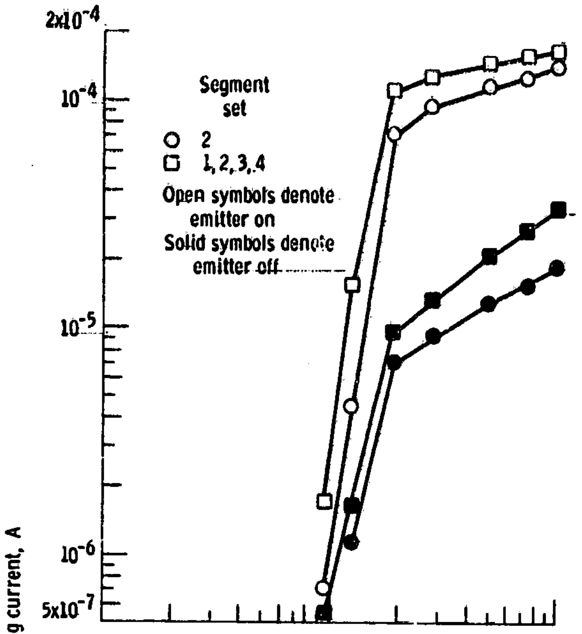


(a) First orbit. Program counts 116 to 499.

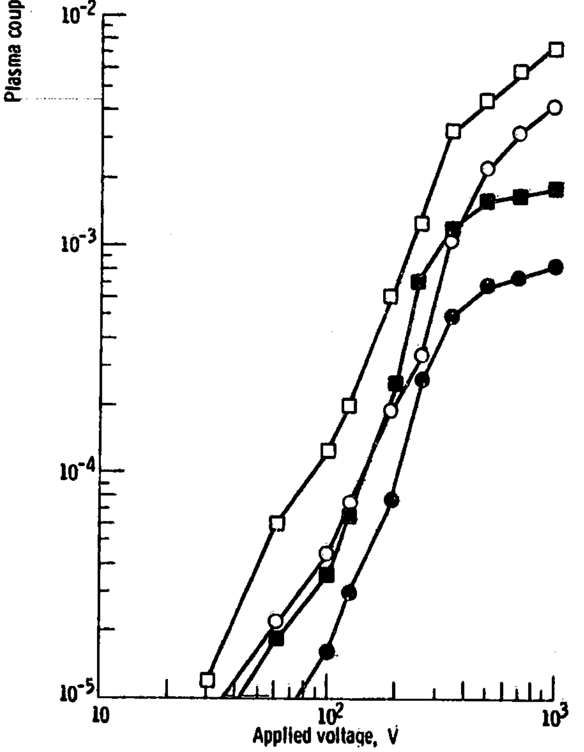


(b) Program counts, 751 (RO) to 1133 (RO).

Figure 6. - Electron plasma density divided by square root of electron temperature as function of latitude. (Arrows denote direction of spacecraft travel.)



(a) Ground tests.



(b) In flight.

Figure 7. - Emitter on/off operation on total plasma coupling current for solar array segment 2 and combination (1, 2, 3, 4) as function of applied voltage.

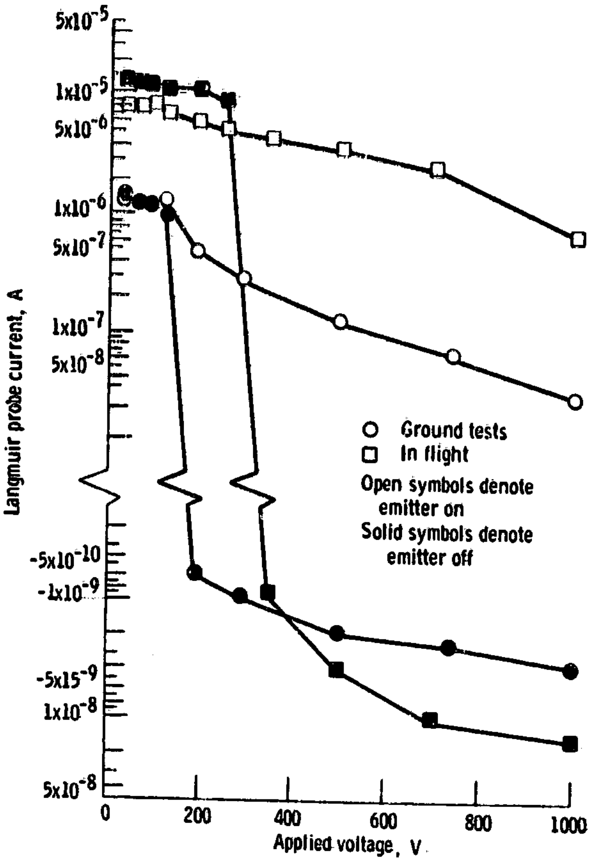


Figure 8. - Emitter on/off operation on Langmuir probe current as function of applied voltage to solar array segments for ground and flight operations.

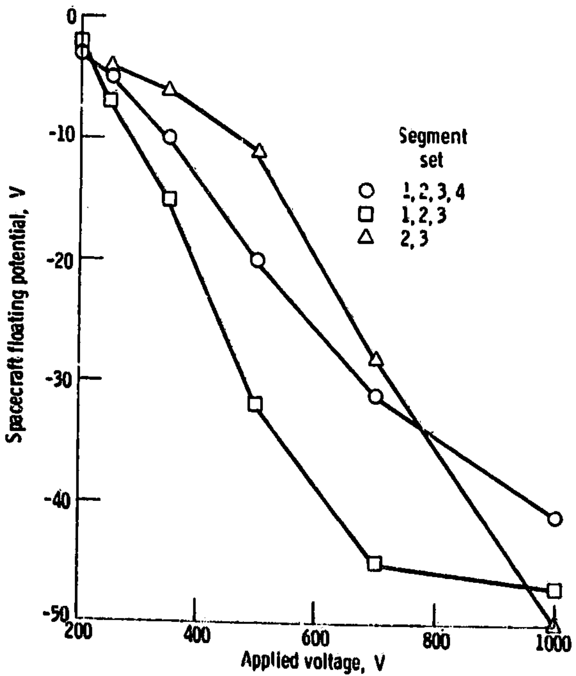


Figure 9. - Spacecraft floating potential as function of applied voltage to solar array segment sets (2, 3), (1, 2, 3), and (1, 2, 3, 4). Emitter on.

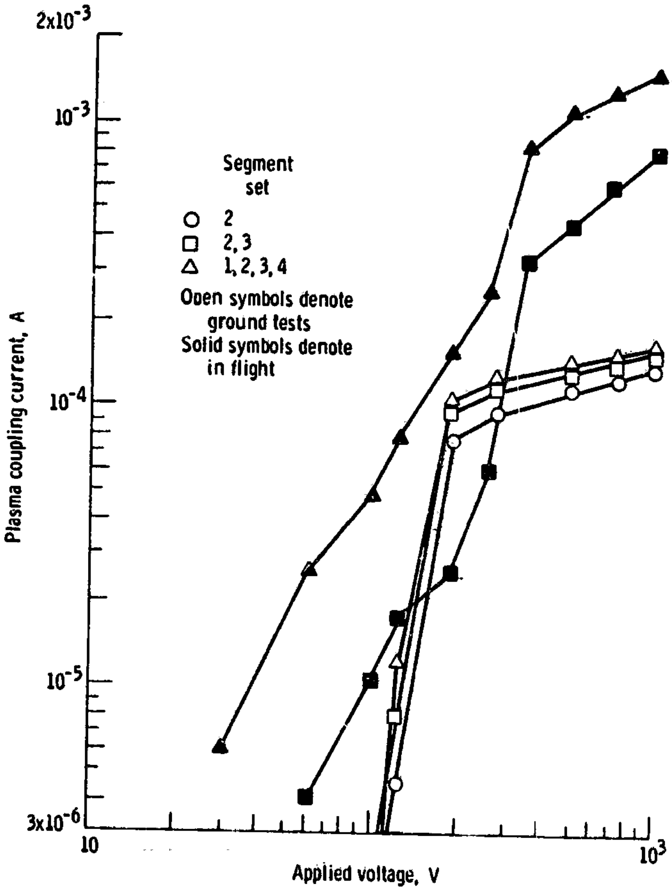


Figure 10. - Total currents to different combinations of solar array segments for flight and ground testing. Emitter on.

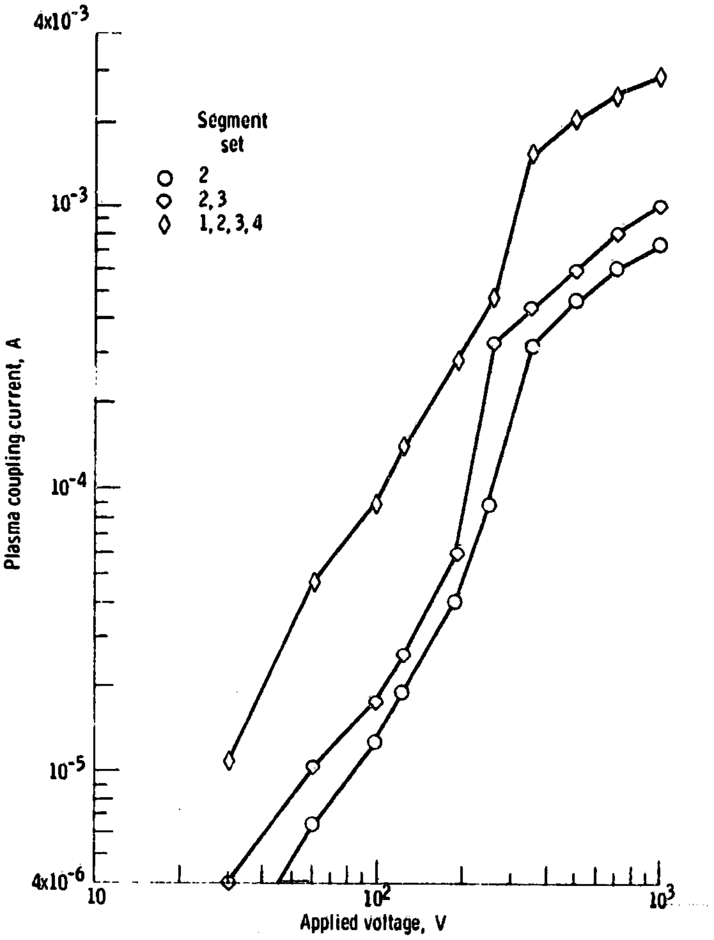


Figure 11. - Typical flight total current to combination of solar array segments as function of applied voltage. Emitter on.