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LANGMUIR PROBE MEASUREMENTS IN A SERT II THRUSTER DISCHARGE CHAMBER

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SUMMARY

A hollow cathode Kaufman thruster of the type used in the SERT II mission was operated in a vacuum bell jar without application of high voltage to extract a beam. Electron density, electron temperature, and plasma potential values were deduced from Langmuir probe measurements at various points in the ion chamber and in the cathode pole piece region. The purpose of the tests was to find out what changes occur in the plasma parameters as ion chamber geometry and operating conditions were varied from the SERT II values. Changes were made with respect to baffle position, flow conditions, and magnetic field, and the resulting plasma parameter profiles were compared. Only slight changes in the electron density, electron temperature, and plasma potential levels were found for considerable variation of conditions. However, the shape of the profiles of these parameters changed noticeably. The gradients in these parameters may play a significant role in thruster performance.

INTRODUCTION

Component research and development has substantially increased the efficiency of Kaufman-type ion thrusters in recent years, as evidenced by the performance attained in the development of the SERT II (Space Electric Rocket Test II) thrusters (ref. 1). The belief has been expressed (ref. 2) that a more detailed understanding of the plasma processes in a thruster may lead to further improvements in thruster design and performance.

A knowledge of plasma characteristics at operating conditions that are now believed to give optimum performance is desirable. The way in which these characteristics change as operating conditions or geometry are varied may give further information about the desirable features of the plasma configuration in the ion chamber. Once it is known what characteristics of the discharge plasma lead to improved performance, it may be possible to aim toward these in future thruster designs.

Langmuir probe measurements are simpler to carry out when no ion beam is extracted and the thruster is not at a high potential. It is known that beam extraction affects the plasma conditions (ref. 3), but this effect does not preclude the possibility of identifying the trends that lead to a better or worse performance. Therefore, the present studies were done with an ion thruster operated in a bell jar, with the cathode at ground potential and no beam extracted.

APPARATUS AND PROCEDURE

Experimental Setup

A 15-centimeter-diameter Kaufman thruster with its accelerator grid removed was placed in a vacuum bell jar. The bell jar was 45 centimeters in diameter and was evacuated by an oil diffusion pump. With a liquid-nitrogen cold trap, the bell-jar pressure was approximately 5×10^{-7} torr. As mercury flow was added, the pressure increased to between 10^{-6} and 10^{-5} torr.

Nine Langmuir probes were affixed to the screen grid, so that they protruded into the ion chamber, and an additional axially movable Langmuir probe protruded into the cathode pole piece interior from the rear. Figure 1 shows a cross-sectional sketch of the thruster with the positions of the probe measurement points indicated. The probes at any one radius were placed with 120° azimuthal separation to avoid clustering of the supporting ceramic stems. In the interpretation of the data, cylindrical symmetry in the discharge was always assumed.

Ion Thruster and Components

The thruster used had the same basic geometry as that employed in the SERT II mission (ref. 1). The hollow cathode tip was a 0.1-centimeter-thick, 2-percent-thoriated tungsten-alloy disk with a diverging orifice of 0.015 centimeter diameter upstream and 0.025 centimeter diameter downstream. The discharge baffle was supported somewhat differently than in the SERT II thruster. It was mounted by a 0.16-centimeter-thick, straight tantalum wire attached to the rim of the baffle disk, and extending through the boron-nitride rear plate. This method of support was used to provide for ease in changing baffle position.

Eight bar magnets were used to provide the thruster magnetic field in all runs, except when the effect of the absence of a magnetic field was tested. With the magnets present, the axial component of the magnetic field was measured at several locations in the chamber and was found to be between 20 and 40 gauss, as expected for the SERT II-type thruster. Figure 2 shows the general shape of magnetic field lines in a plane containing the axis of the ion chamber. The field shape was obtained by the technique of dispersing iron filings on a cardboard.

Mercury was fed to the cathode and to the thruster distributor manifold by two independent temperature-controlled porous-tungsten vaporizers. The vaporizer for the cathode was 0.32 centimeter diameter, and the one for the main flow was 0.64 centimeter diameter. The mercury was supplied to each vaporizer from an external precision-bore calibrated glass tube. The average flow rates were determined from periodic readings of the mercury levels.

An electrical circuit schematic of the thruster and the probes is shown in figure 3. A variable resistance in series with the ion chamber discharge helped to stabilize operation under varied conditions. With the cathode grounded as shown in figure 3, the discharge chamber voltage was equal to the anode potential, that is, to the potential difference between the anode and ground.

The Langmuir probe outputs could be alternately fed into the external probe circuit by means of a multiterminal switch. The probe circuit, also shown in the figure, consisted of a 90-volt battery across a variable resistor, which was used to bias the probe. The probe current and voltage outputs were monitored by an X-Y recorder. Potentials were referred to the cathode, which was grounded to the bell-jar support structure.

Langmuir Probes

The probes were made of pure tungsten wire 0.0076 centimeter in diameter. The exposed length of each probe was 0.3 centimeter.

The probe construction is shown in figure 4. The probe wire extended from the interior of a quartz tube with a thin gap between the wire and the quartz. The axes of the probes were parallel to the ion chamber symmetry axis.

Procedure

Once the thruster was lit and a stable discharge established, the keeper current was set at 0.2 ampere, and the main discharge current at 2 amperes by means of the current limiting power supplies. The keeper voltage for these conditions was always about 10±2 volts. A probe trace was obtained for each of the nine probes in the chamber, and four additional traces for four positions of the probe in the pole piece region. The traces were obtained by varying the bias voltage on the probes from about -40 to +40 volts with respect to the cathode and recording a current against voltage curve with the use of the X-Y recorder.

The parameters that were varied to obtain the various sets of probe traces were as follows: main flow, cathode flow, ratio of flows, baffle position, presence and absence of baffle, and presence and absence of magnetic field. Table I lists the operating conditions for each run. Table II summarizes the runs which are compared for each of the effects investigated.

RESULTS AND DISCUSSION

General

The plasma characteristics, namely, electron density, electron temperature, and plasma potential obtained from an analysis of the probe traces, are shown as a function of position in figures 5 to 10. The plots are grouped to facilitate qualitative comparisons with respect to the effects of varied conditions.

While detailed examination of the results shows certain interesting changes in plasma characteristics with the variation of a given condition, some remarks can also be made regarding the general shape and appearance of the plasma parameter profiles obtained.

In general, the electron density was high inside the cathode pole piece ($\sim 10^{17}$ electrons/m^3) and along the thruster axis, and showed a substantial decrease with distance toward the anode. Usually there was little drop in density from the axis to the intermediate radial positions, with a more substantial drop occurring near the anode.

The electron temperature was generally low in the cathode pole piece region (about 1 to 2 V) and higher in the main discharge chamber region (2 to 5 V). This apparent shift in electron temperature level in going from one region to the other may be the result of a shift in population of primary electrons and Maxwellian electrons. As pointed out in reference 2, some investigators are of the opinion that the electron population in the ion thruster is composed of two groups. One type are the so-called monoenergetic primary electrons that are emitted from the cathode sheath into the discharge. The other group has a Maxwellian energy distribution that results from electron-atom interactions in the discharge. The population of this latter group increases with distance from the cathode, and its energy content is raised as the velocities of primary electrons are randomized in collisions.

The plasma potential was between 10 and 15 volts inside the pole piece. This is typical for a mercury plasma in front of a hollow cathode of the type used in this work (ref. 4).

The general level of plasma potential in the main part of the chamber varied with conditions of baffle position and flow. There was usually a considerable difference in potential across the gap between the baffle and the pole piece, with a rise from the cathode region toward the main discharge region. This potential rise, however, was less than that found in operating hollow cathode thrusters by other investigators (ref. 5). A further rise in potential occurred toward the anode, resulting in a potential trough in the main discharge along the axis of the thruster. The plasma potential slope in the axial direction in the main chamber was very slight.

In the present work the plasma potential at all points measured was found to be below anode potential. Previous investigators of this type of discharge have generally found plasma potentials somewhat above anode potential at most points in the chamber. However, in those tests thermionic cathodes were used (refs. 3 and 6), except in one instance (ref. 5) where no data were taken in the absence of beam extraction. It is not known at present whether, in hollow cathode thrusters, beam extraction alone may be responsible for raising the plasma potential to above anode potential, as a comparison of the two results appears to indicate.

The present result suggests that a higher-than-anode plasma potential is not a universal characteristic of the type of discharge investigated. Perhaps a better understanding of these plasmas could lead to methods of lowering the plasma potential with respect to anode potential. Such a reduction could restrict ion impingement on the anode surface and result in improved performance.

Variation of Neutral Flow Rates

Figure 5 gives a comparison of plasma parameter profiles for three significantly different main flow rates, namely, 0, 350, and 600 equivalent milliamperes, respectively. The cathode flow was constant (50 equivalent mA) for each case.

In general, the differences in the plasma parameters are more appreciable from 0 to 350 milliamperes than from 350 to 600 milliamperes. For example, the electron density is about an order of magnitude higher for 350 milliamperes than for 0-milliampere flow, and about the same for 350- and 600-milliampere flow. There is a corresponding, but not so pronounced, drop in the electron temperature level as the flow increases.

With no main flow, there is a nearly flat potential region in almost the entire ion chamber, with an approximate 30 volts rise within 0.5 centimeter of the anode. In such a configuration, much energy is spent in the acceleration of electrons that bombard the anode and cannot produce ionization. At increasingly higher flows, the plasma potential profile acquires a gradual slope from the axis toward the anode. At the same time, a lower anode potential is obtained for a 2-ampere discharge. Hence, the sharp rise in potential at the anode is eliminated.

Figure 6 gives a comparison of plasma parameters for three different cathode flows. There was no main flow in each case and again the anode voltage was adjusted to give a constant 2-ampere discharge. Variation of the cathode flow has an effect somewhat similar to that observed for the main flow. The anode potential is reduced with more flow, and the plasma potential tends to increase radially. But there is still appreciable potential rise at the anode even at 300 milliamperes cathode flow. Also the electron density remains quite low at positions near the anode.

Figure 7 shows a comparison of two cases of equal total flow (300 mA): In the first case (fig. 7(a)), all flow is supplied to the cathode. In the second case (fig. 7(b)), only 50 milliamperes goes through the cathode, and 250 milliamperes through the main distributor manifold. The region mainly affected appears to be the upstream region near the anode, where the electron density is considerably larger with main flow introduced. (Compare points marked by triangles at 5-cm axial distance.) The steep radial potential rise at the central portion of the anode is seen to be somewhat more pronounced in the case with cathode flow only, which is known to be the worse thruster performance condition. This again indicates that a flat potential plateau in the chamber with a large rise very near the anode is undesirable.

Baffle Position

Figure 8 gives a comparison of three baffle positions: the baffle flush with the pole piece end (referred to as the standard position, fig. 8(b)), 0.5 centimeter upstream from this (fig. 8(a)), and 0.5 centimeter downstream from this (fig. 8(c)), respectively.

With the baffle in the upstream position, the general electron density level was distinctly lower as compared with the standard case. For the downstream baffle position, a reduction in the electron density was found only along the axis. This caused the spatial maximum (or ridge) to lie at an intermediate radial position, rather than along the axis.

The position of the baffle appears to have a strong influence on the plasma parameters at the downstream end of the chamber near the anode. (See the position marked with triangles at 12-cm. axial distance in fig. 8.) At this location, both the electron temperature and the plasma potential were strongly reduced with the baffle upstream, while the same parameters were increased with the baffle downstream. Except for this location, the plasma potential profiles retained a gradual increase from the axis toward the anode for either upstream or downstream baffle position, with about an additional 10 volts rise within 0.5 centimeter of the anode. For both displaced baffle positions, the anode potential necessary to maintain 2 amperes of discharge current was slightly lower than when the baffle was in the standard position.

In figure 9 the plasma parameters for the case of the baffle completely removed are compared with those for the case of the standard baffle position. With the baffle removed (fig. 9(b)), the electron temperature was considerably higher (3 to 6 V) in the region near the anode.

While the removal of the baffle had the effect of lowering the anode potential considerably, the measured plasma potentials at radial positions near the anode were increased. Thus the potential at these points was close to anode potential. A nearly flat potential plateau remained in the central region, similar to that observed in other cases typical of low performance configurations. However, in this case the plateau did not extend radially to the immediate vicinity (to within less than 0.5 cm) of the anode.

From these findings it appears that at least one function of the baffle in the discharge chamber of an ion thruster is to maintain the electron temperature more or less uniform in the entire chamber and also to keep it at a moderate level. Its effect on the plasma potential seems to be to make it rise gradually from the axis to the region near the anode.

Magnetic Field

Removing the magnetic field (fig. 10), as expected, caused a general drop of the electron density in the chamber. However, the electron density in the pole piece region remained unchanged.

The electron temperature was noticeably lowered with the magnetic field removed, both inside the pole piece and in the main chamber. Plasma potential in the pole piece region remained the same with the magnetic field removed, but the level in the main part of the chamber was reduced to an almost uniformly flat plateau close to the pole piece value of the plasma potential (~ 13 V). This gives rise to a large potential drop at the anode which may be a location of large discharge power losses observed in thrusters with weak or no magnetic field (ref. 7).

CONCLUDING REMARKS

The present investigation of Langmuir probe measurements in the discharge chamber of an ion thruster operating without high-voltage beam extraction indicates that the general level electron density, electron temperature, and plasma potential are altered only moderately with wide variations in operating conditions. However, changes in the spatial variation of these parameters are usually noted when conditions of flow, baffle position, or magnetic field are altered.

It is apparent from the present work that externally controllable parameters have an influence in shaping the plasma parameter profiles in the ion chamber, which, in turn, affect thruster performance. It is hoped that, with more insight as to how to control the plasma parameters by means of shaping the hardware geometry and magnetic field of a thruster, these findings will be useful in future design considerations.

In this experiment, conditions that are known to yield good performance in an operating thruster appear to be associated with a plasma potential profile that forms a trough and slopes gradually upward toward the anode. A rather flat potential in the bulk of the chamber with a steep rise at the anode tends to be associated with cases of generally poor thruster performance. Good thruster performance also appears to be associated with a fairly uniform electron temperature at a level between 1 and 3 volts, and with an electron density that drops nearly two orders of magnitude from the center of the chamber to positions near the anode. It must be kept in mind, however, that ion beam extraction, in general, will have an effect on the parameters.

In this investigation, the determined values of the plasma potential in the ion chamber were always found to be below anode potential. Various other experiments with beam extraction or with thermionic cathodes have shown plasma potentials in the discharge chamber somewhat higher than anode potential. If the discharge chamber plasma could somehow be held a few volts below anode potential in an operating thruster, this should result in reduced ion impingement on the anode surface and improved efficiency. However, no method of achieving this is known at present.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 16, 1970,
120-26.

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TABLE I. - SUMMARY OF OPERATING CONDITIONS

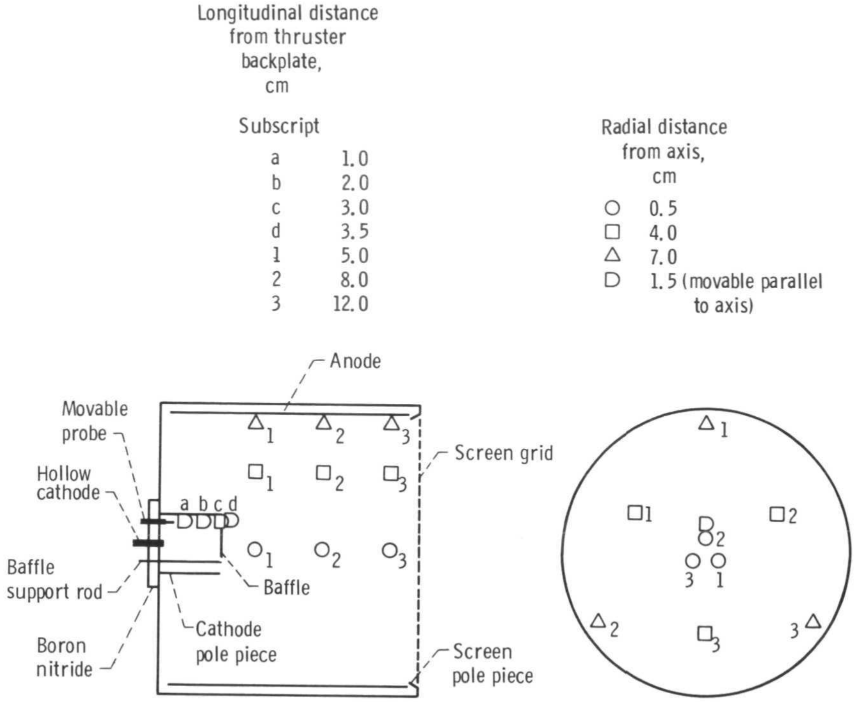
[Discharge current constant, 2 A; keeper current constant, 0.2 A.]

Run	Main flow, equivalent mA	Cathode flow, equivalent mA	Discharge voltage, V	Baffle position	Magnetic field
1	0	50	50	Standard	Yes
[a]2	350	50	37		
3	600	50	35		
4	0	200	41		
5	0	300	39		
[a]6	250	50	40	Standard	Yes
7	250		36	0.5 cm upstream	
8	250		39	0.5 cm downstream	
9	350		33	No baffle	
10	350		31	Standard	No

[a]Approximates SERT II thruster operating conditions.

TABLE II. - SUMMARY OF CONDITIONS SHOWN ON FIGURES 5 TO 10

Type of change	Condition	Run	Figure
Main flow variation (with 50-equiv.-mA cathode flow), equiv. mA	0	1	5(a)
	350	2	5(b)
	600	3	5(c)
Cathode flow variation (with no main flow), equiv. mA	50	1	6(a)
	200	4	6(b)
	300	5	6(c)
Division of flow (300-equiv. mA total flow), main flow/cathode flow	0/300	5	7(a)
	250/50	6	7(b)
Baffle position variation	0.5 cm upstream	7	8(a)
	Standard	6	8(b)
	0.5 cm downstream	8	8(c)
Absence of baffle	Baffle present	2	9(a)
	Baffle absent	9	9(b)
Absence of magnetic field	Field present	2	10(a)
	Field absent	10	10(b)



(a) Representative probe measurement points in thruster cross section.

(b) Actual azimuthal positioning of probes, viewed from downstream end.

Figure 1. - Probe positions in ion thruster.

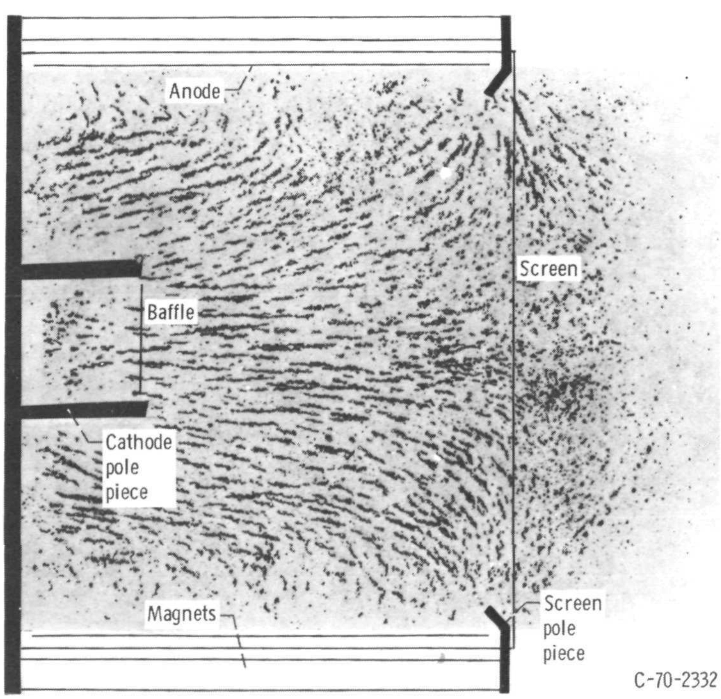


Figure 2. - Shape of magnetic field lines in thruster. (Iron filings method.)

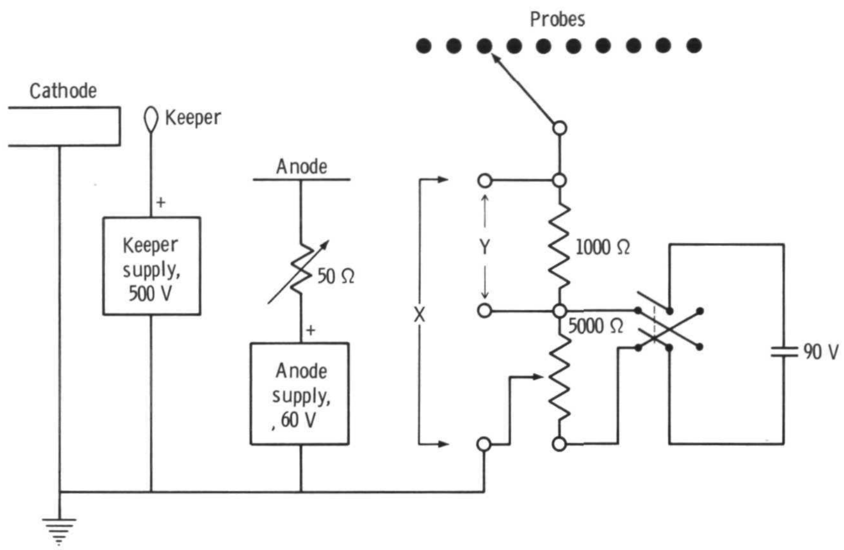


Figure 3. - Electrical circuit schematic of thruster and probes.

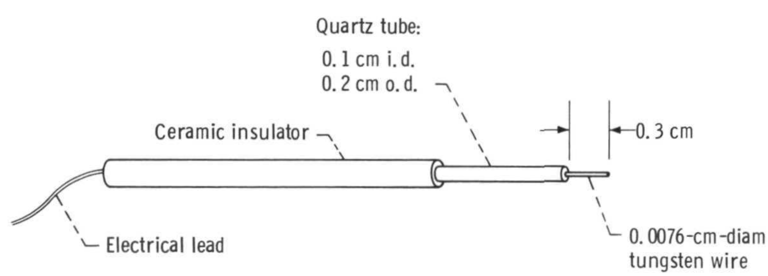
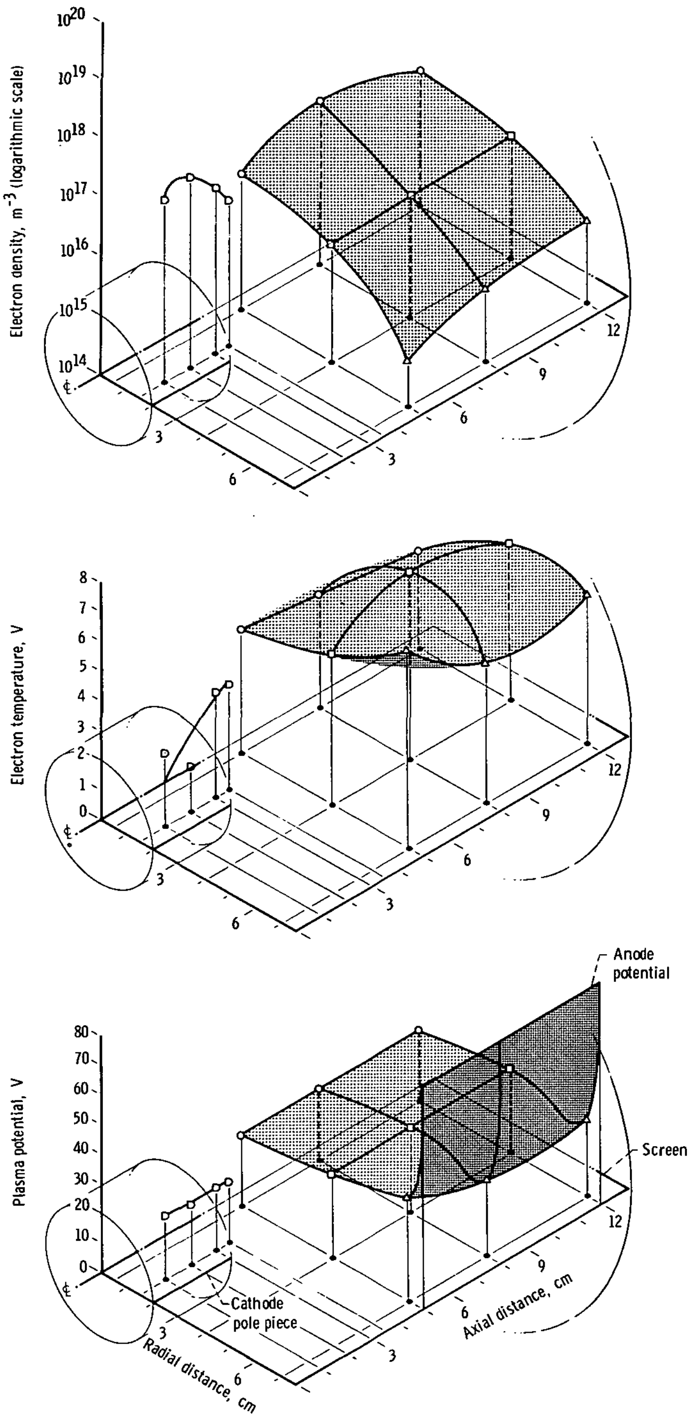


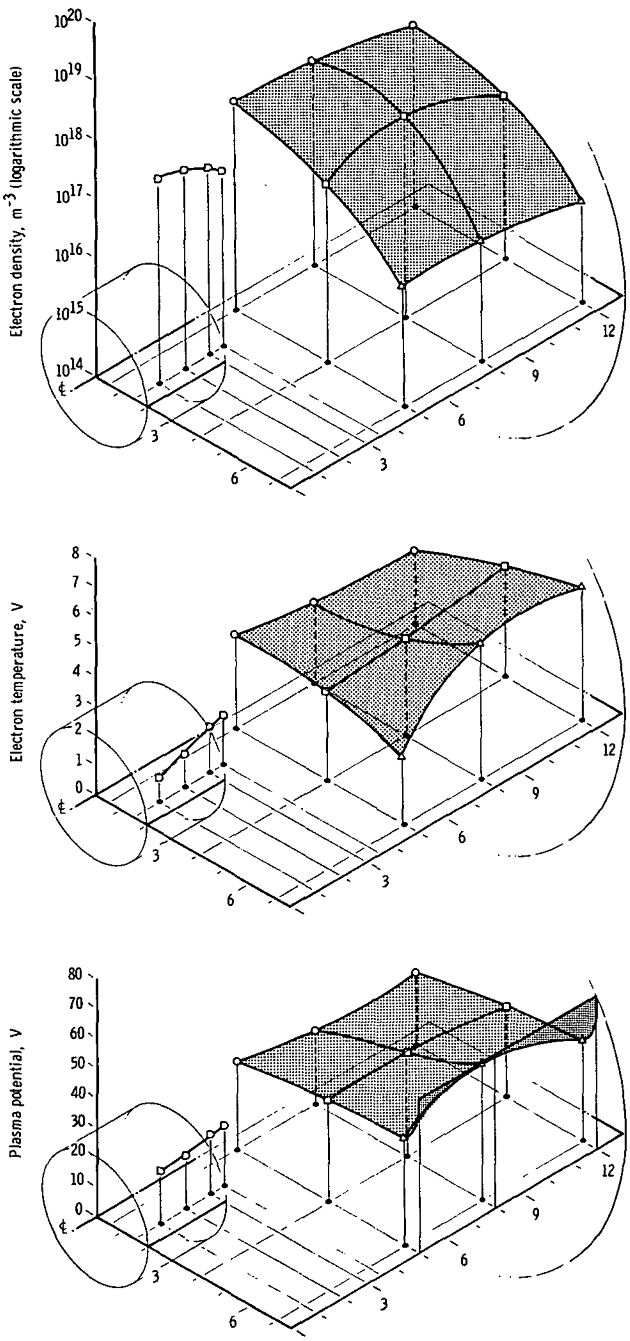
Figure 4. - Langmuir probe construction.



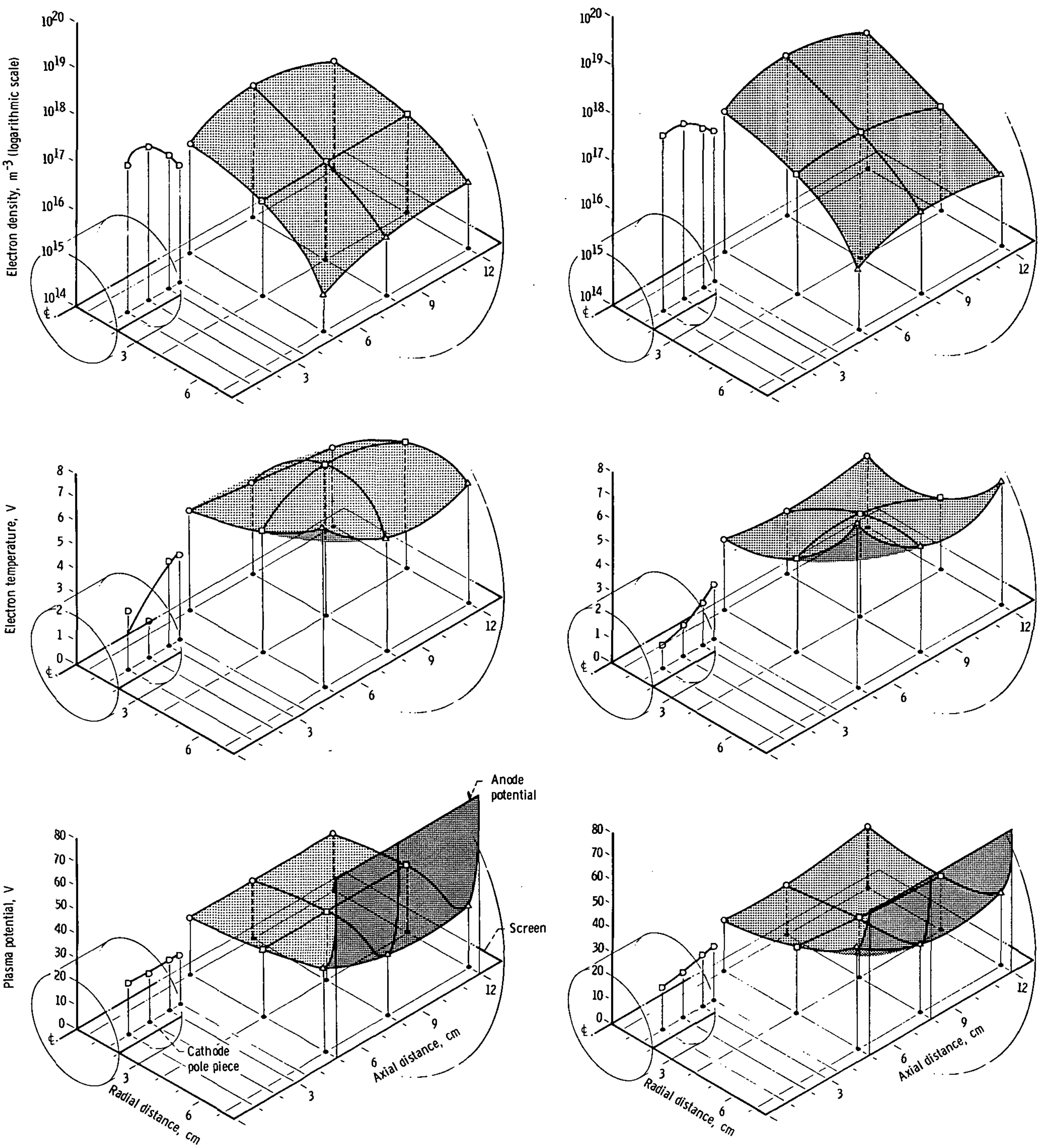
(a) Main flow, 0 equivalent milliampere. Run 1.

(b) Main flow, 350 equivalent milliamperes. Run 2.

Figure 5. - Effect of main flow. Discharge current, 2 amperes; cathode flow, 50 equivalent milliamperes. (See fig. 1 for symbol identification.)



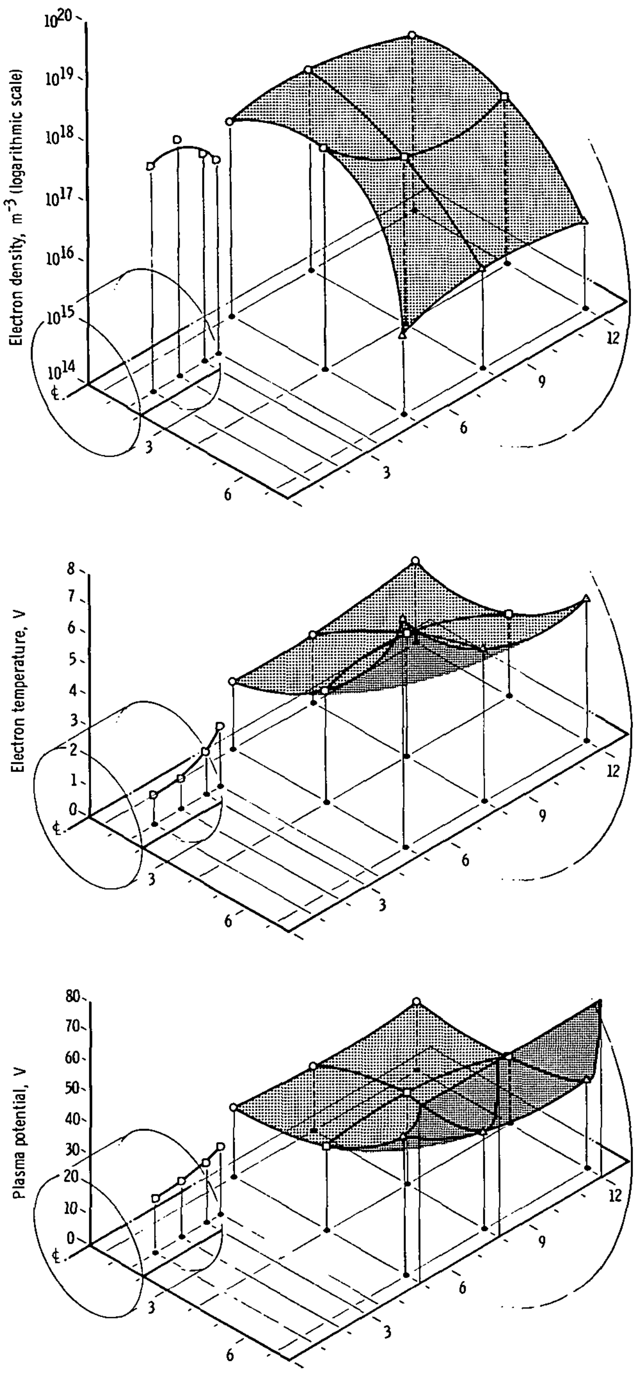
(c) Main flow, 600 equivalent milliamperes. Run 3.



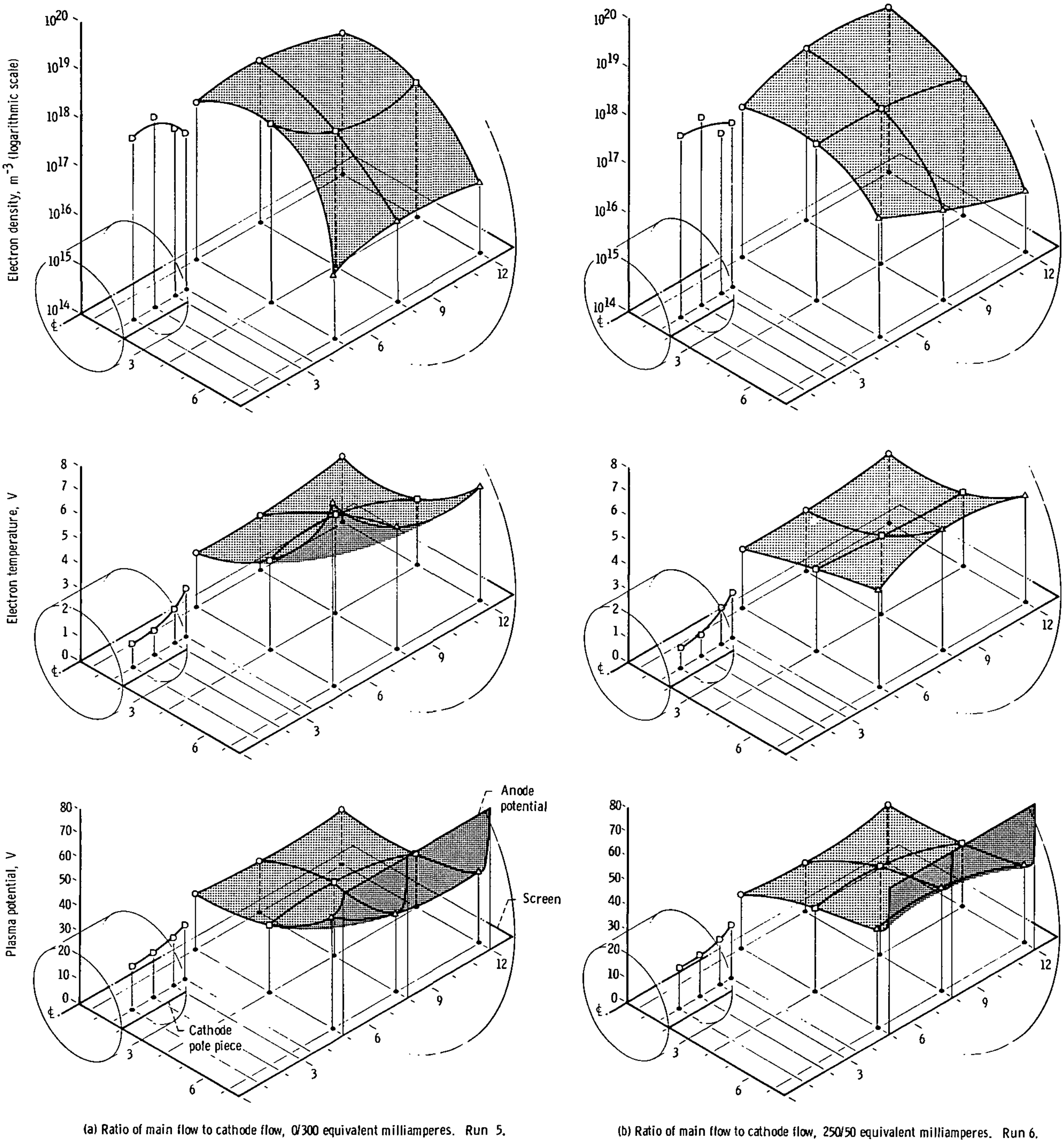
(a) Cathode flow, 50 equivalent milliampere. Run 1.

(b) Cathode flow, 200 equivalent milliamperes. Run 4.

Figure 6. - Effect of cathode flow. Discharge current, 2 amperes; no main flow. (See fig. 1 for symbol identification.)



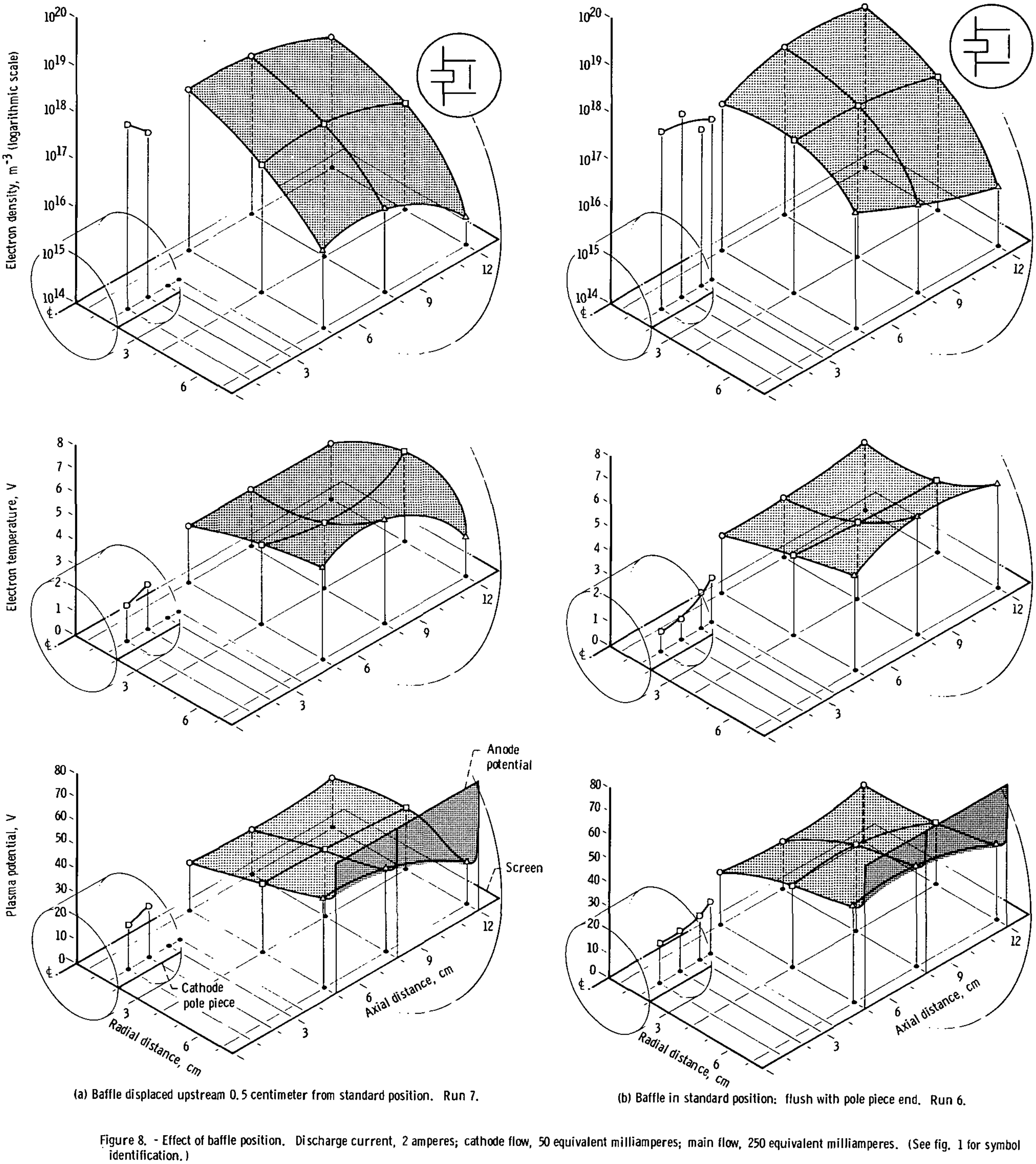
(c) Cathode flow, 300 equivalent milliamperes. Run 5.



(a) Ratio of main flow to cathode flow, 0/300 equivalent milliamperes. Run 5.

(b) Ratio of main flow to cathode flow, 250/50 equivalent milliamperes. Run 6.

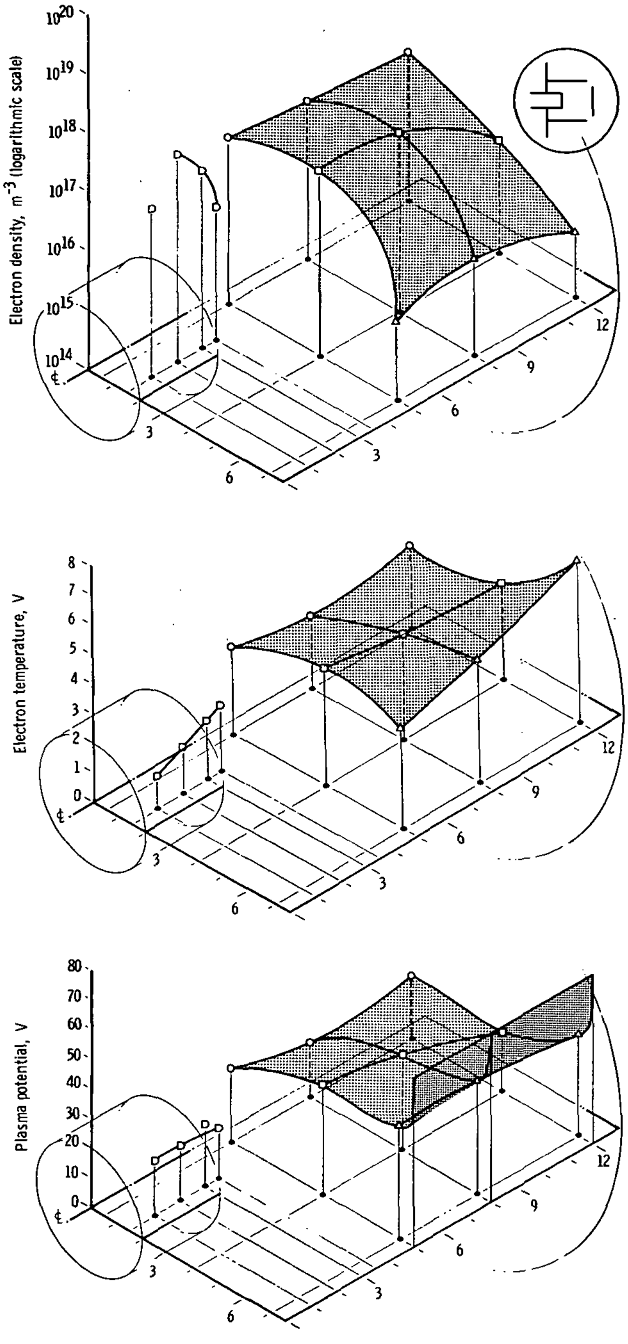
Figure 7. - Effect of division of flow. Discharge current, 2 amperes; total flow, 300 equivalent milliamperes. (See fig. 1 for symbol identification.)



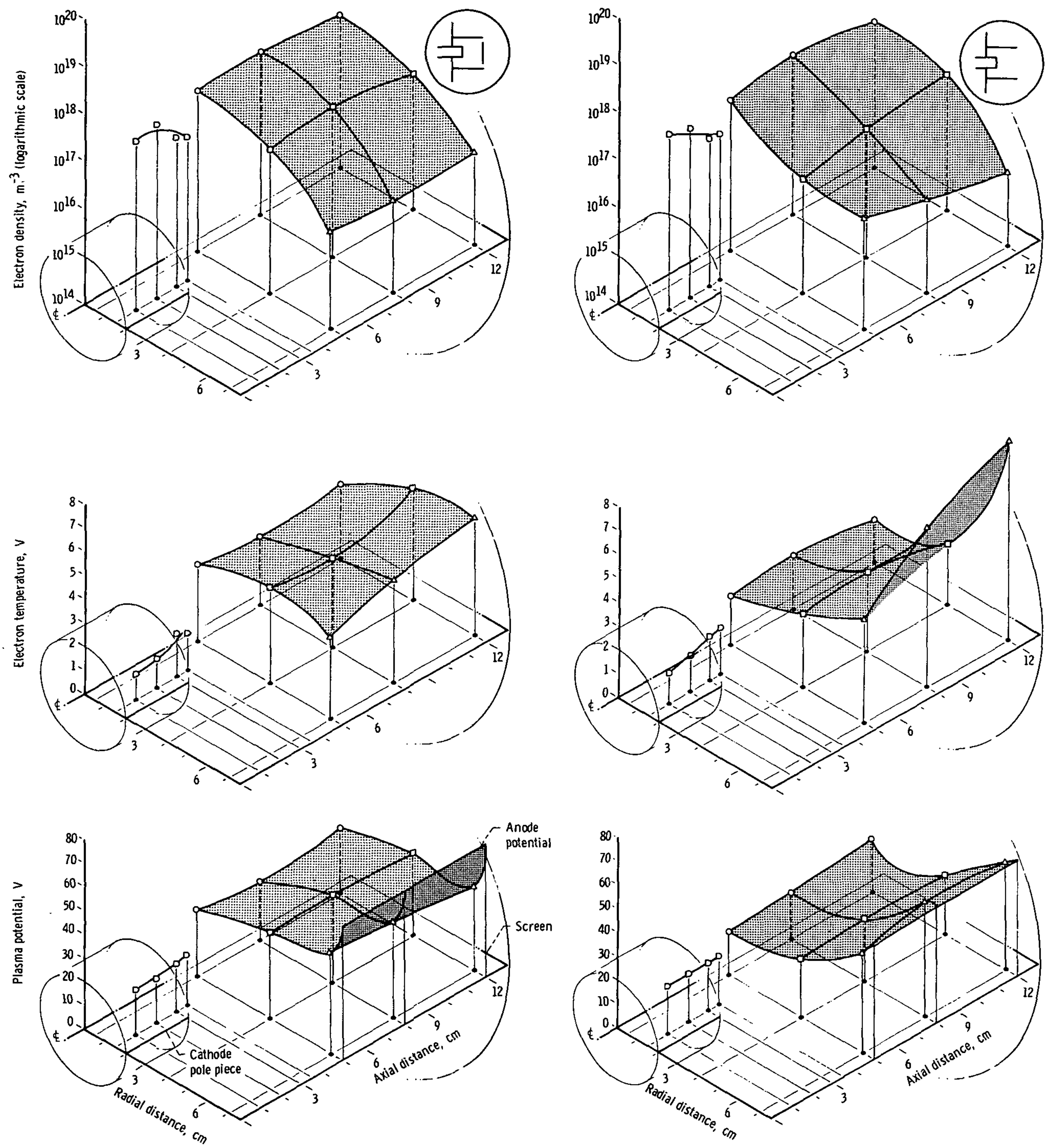
(a) Baffle displaced upstream 0.5 centimeter from standard position. Run 7.

(b) Baffle in standard position: flush with pole piece end. Run 6.

Figure 8. - Effect of baffle position. Discharge current, 2 amperes; cathode flow, 50 equivalent milliamperes; main flow, 250 equivalent milliamperes. (See fig. 1 for symbol identification.)



(c) Baffle displaced downstream 0.5 centimeter from standard position. Run 8.



(a) Baffle in standard position: flush with pole piece end. Run 2.

(b) Baffle absent. Run 9.

Figure 9. - Effect of absence of baffle. Discharge current, 2 amperes; cathode flow, 50 equivalent milliamperes; main flow, 350 equivalent milliamperes. (See fig. 1 for symbol identifications.

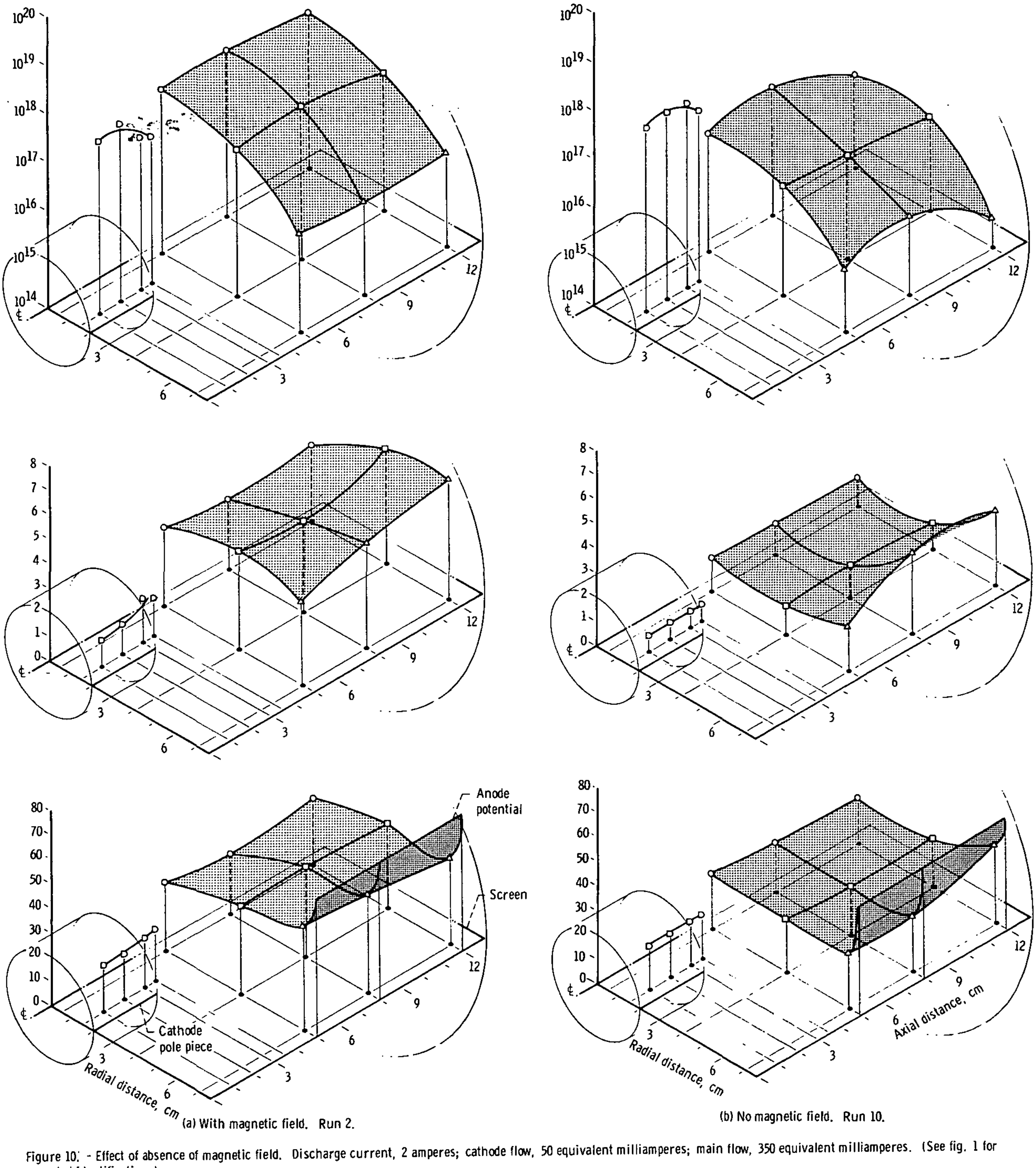


Figure 10. - Effect of absence of magnetic field. Discharge current, 2 amperes; cathode flow, 50 equivalent milliamperes; main flow, 350 equivalent milliamperes. (See fig. 1 for symbol identification.)

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