EXPERIMENTS WITH A CO-AXIAL HALL CURRENT PLASMA ACCELERATOR

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Introduction

Recently, very high values of specific impulse have been obtained with continuous coaxial $\vec{j} \times \vec{B}$ plasma thrusters using self-magnetic fields through $j_r B_\theta$ (ref. 1), Hall currents through $j_\theta B_r$ (ref. 2), and pressure gradients due to electrothermal effects, an effect present in both references 1 and 2. Even though much credit for the final application to propulsion belongs to references 1 and 2, it should be pointed out that the devices essentially in the form used in references 1 and 2 were first proposed and discussed for the specific use of continuous plasma propulsion in reference 3. The important contributions toward understanding of the current distributions for Hall accelerators (ref. 4) is also acknowledged.

In view of the strong interest in reentry simulation at the Langley Research Center of NASA, a coaxial Hall-current device was first studied for high mass flows of from 2 to 5 grams per second with the intent of using the combination of magnetic containment with acceleration to reduce wall losses (ref. 5). Measurements of thrust and specific impulse for the accelerator in reference 5 with increasingly high magnetic fields suggested that very efficient thrust performance could be obtained with low mass-flow rates, high-power inputs, and suitable magnetic-field strength and shape. Thus, because of the success of the study of reference 5 and the high specific impulse of references 1 and 2, an investigation of the low mass-flow rates around 0.01 gram per second was included in our program. It should be mentioned also that in this connection the low mass-flow-rate high-specific-impulse accelerators also offer hopes for solar wind simulators.

The present study differs from that given in reference 2 in that Hall currents and their variation with imposed current and magnetic field have been studied and the product of $I_\theta B_r$ has been related to the variation in thrust. Furthermore, the experiments were performed with argon, nitrogen, and helium, whereas in reference 2, mostly experiments with hydrogen and a few with nitrogen were reported. As will be shown in the paper, anomalously high thrust and specific impulse have been found with argon and nitrogen at comparatively low voltages across the electrodes. The values reported in the present paper are even higher than those mentioned in the abstract for somewhat higher mass flows. The results may have important bearing on the understanding of the accelerating mechanism, or may cause a careful reevaluation of the experimental methods for simulating the space environment. Recent personal communication with G. Cann indicates that he has also measured anomalously high specific impulse in argon and nitrogen.

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Experiments

The original intent of this paper was to present the results of a theoretical and experimental study of a relatively high mass-flow-rate (2 to 5 grams per second) coaxial plasma accelerator, figure 1. This study included measurements of arc characteristics, electron temperatures and densities, Hall-current densities, thrust and specific impulse, electrode and over-all efficiencies versus the important operating parameters, such as arc current, mass-flow rate and magnetic-field strength. A theoretical analysis performed agreed very well with the experimental results. (See refs. 6 and 7.) However, as mentioned in the Introduction, the experimental results indicated that efficient operation could be obtained at low mass-flow rates, for example, 0.01 gram per second. It should be mentioned that the original experiments and the subsequent later low mass-flow-rate experiments were performed mainly with argon as the propellant gas. Also, it should be mentioned that the original experiments were carried out at low power inputs so that clean plasma diagnostic studies could be made of the important plasma properties.

In view of the rather striking results obtained with the low mass-flow-rate experiments and much higher power inputs, this paper is concerned with the coaxial Hall-current plasma accelerator configuration shown schematically in figure 2.

In the figure, the annular ring copper anode is shown attached to the outer copper accelerator body which serves both as a cooling-water jacket and the positive electrical lead. An anode pressure orifice is shown; this orifice is connected to a 0 to 50 millimeters of mercury pressure transducer. A pointed thoriated tungsten cathode is shown attached to the cathode support. This support, as well as being the negative electrical lead, is both the propellant gas inlet duct and cathode water-cooling supply. The insulators shown in the figure are made of boron nitride and teflon. The entire test apparatus was allowed to float electrically in order to eliminate adverse arcing effects.

The external solenoidal magnetic-field coil shown in the figure provides an axial magnetic field in the interior of the electrode region and a combination of soft iron inserts allow adequate field shaping in the vicinity of the anode front surface. The magnetic-field distribution for the accelerator configuration of figure 2 is shown in figure 3 for a coil current of 300 amps.

The argon mass-flow rate was measured with a Fisher-Porter tri-flat flow meter. The two mass-flow rates used during the tests were 0.0237 and 0.0116 gram per second.

Hall-current measurements.- Reference 5 describes in detail the method which was used here to measure the Hall current signal of the plasma. Essentially the method consists of placing a search coil around the outside or boundary of the plasma stream. In the present case the search coil was imbedded in the boron nitride insulator just aft of the anode front surface. The Hall current signal is obtained by crow-barring the plasma arc current into a resister load thereby obtaining a clean arc shutoff. The collapsing Hall magnetic field then induces an e.m.f. in the search coil. The Hall current signal which was obtained in this manner is shown in figure 4 for three values of arc current and a range of magnetic-field strengths corresponding to the current supplied to the field coil. It is seen that the Hall current signal in arbitrary units increases with arc current and decreases only slightly for a given value of arc current with increasing magnetic-field strength. In order to obtain an absolute value for Hall current in amperes, the following calibration was attempted. A small many-turn coil was placed in the approximate position where the Hall current was thought to exist. By passing current through the calibration coil and interrupting the circuit similar to shutting off the arc, a Hall current signal can be induced in the search coil. If it is assumed that the Hall current exists as a single turn in the plasma, then Hall current in amperes can be measured directly. However, it was found that for the same number of ampere turns on the calibration coil and for different coil sizes and placement relative to the search coil, significant differences can be noticed in the signal observed by the search coil. This, of course, is necessary information because the effect of changing arc current and magnetic-field strength may alter both the shape and position besides just the magnitude of the Hall current. Such a method then for measuring Hall current can give, at best, only an indication of the relative magnitude of Hall current for different experimental values of arc current and magnetic-field strength.

Thrust and specific impulse measurements.- The method by which the thrust of the plasma accelerator was measured involves the use of a target upon which the plasma stream impinges and gives up its normal momentum. The target, described in more detail in reference 5, is a 4-inch boron nitride disc which is connected to a pendulum. The pendulum is supported from a strain-gage resistance bridge which is calibrated to measure the moment on the disc and pendulum. The strain-gage components are both shielded from the magnetic field by soft iron enclosures and from thermal effects by water-cooling jackets. Calibration of the target pendulum by applying known forces along the thrust axis allows the direct reading of force from the signal obtained from the system during an experimental run. The diameter of the plasma beam impinging on the target disc was of the order of 1 inch, whereas the disc diameter was 4 inches. The thrust target is insulated from electrostatic effects and also from effects due to bulging currents. As noticed in reference 2, these effects could result in arcing to the thrust target if not properly insulated. Such arcing was not noticed in the present experiments since a major effort was made to insulate the thrust balance.

An experimental check was made in an attempt to investigate the possibility of the existence of underpressures on the rear of the target disc. Such an underpressure could give rise to erroneously increased thrust readings. By installing pressure taps both fore and aft of the thrust disc it was determined that the effect of underpressures was negligible.

Further, it was noticed that a small film of copper from the anode had deposited on the thrust disc; and for this reason the discs were weighed before and after a series of experimental runs. Typically, it was found that the copper deposit on the thrust disc was about 0.039 gram for 700 seconds of running time. In terms of mass-flow rates, this is about 10^3 times lower than the argon mass-flow rates. The boron nitride disc after being examined for copper deposition was investigated for the deposition of cathode material, thoriated tungsten. No appreciable increase in radiation over background could be observed so it was assumed that the cathode deposition was extremely small. Finally, it should be mentioned that the thrust disc underwent negligible spalling as witnessed by the very smooth appearance of the disc after the experiments.

Thrust measurements were made for two different argon mass-flow rates of 0.0237 and 0.0116 gram per second for three different values of arc current, 300, 450, and 600 amperes, and for a fairly wide range of magnetic-field strengths.

Figure 5 presents the thrust data in grams force for the mass-flow rate of 0.023 gram per second. The scale on the left of the figure is thrust in grams and the scale on the far right is specific impulse in seconds calculated by dividing the thrust in grams by the measured mass-flow rate in grams per second times the value of the gravity constant.

Figure 6 shows the same experimental data, however, for the 0.0116-gram-per-second mass-flow rate.

The measured values of the total power supplied to the arc are shown in figures 7 and 8 for the 0.023- and 0.0116-gram-per-second mass-flow rates, respectively. In both the data curves for thrust and power, the best possible fit of a curve was attempted and in both cases the curves appear within limits of experimental error to be linear. With a linear relationship then for these two values, a relation for the ratio of the kinetic energy of the plasma stream to the power supplied to the arc was obtained. This ratio defines the thrust efficiency of the accelerator and is shown in figures 9 and 10 for the mass-flow rates of 0.023 and 0.0116, respectively. The efficiency is shown plotted versus B for three different arc currents. Figures 9 and 10 show that within experimental error for the range of experimental conditions of the present tests, the efficiency increases about linearly with increasing magnetic-field strength.

For reasons discussed later in this paper, the thrust and specific impulse obtained for argon are anomalously high. In an attempt to determine if the experimental results are truly representative of plasma acceleration or are due to other effects, the thrust experiments were repeated using nitrogen and helium. The results of the nitrogen and helium experiments were interesting since the thrusts obtained were approximately the same level as those of the argon tests; however, the voltages measured across the electrodes were noticeably higher. For example, typical voltages for argon were between 25 and 65 volts for nitrogen between 40 and 80 volts and for helium between 60 and 120 volts. The so-called "anomalous" effect discussed below was not noticeable for helium and according to reference 2 neither for hydrogen, another gas of low atomic weight. An effort was made to establish if the high thrust levels could not be due to less glamorous effects, such as, for example, thrust augmentation which occurs when a high-velocity jet exhausts into a still ambient surrounding. This effect is due to the acceleration of the surrounding low-velocity ambient gas and subsequent mixing in the high-velocity stream, with a total pressure gradient across the mixing zone. The most efficient mixing takes place when the ambient gas is at zero velocity, which is the case here. Backstreaming of the exhausted gas from the complete tank and from target to the nozzle exit may also contribute to the jet mixing. In an attempt to determine the effect of backstreaming from the complete tank and ambient mixing the following experiments were performed. The experimental apparatus was modified so that during a test run two halves of a cylindrical shell could be positioned around the exit stream. The enclosing cylinder is positioned just 1/16 inch off the nozzle or anode face and 3/8 inch from the thrust target when enclosing the stream. Also, during these experiments the vacuum chamber back pressure was varied in attempt to determine the effect of varying the ambient pressure. The results of these experiments are shown in table I. In general, the effect of enclosing the stream with the cylinder was negligible except for some runs at high back pressures and power inputs. The effect of possible backstreaming from the thrust target could not be directly determined from this method; however, it is felt that circulation set up due to such backstreaming would have been impeded. The fact that the thrust measurements by G. Cann (personal communication) without a thrust target, but by weighing the reaction on the engine, yields similar results is further indication that backstreaming from the thrust target should not be significant.

Finally, the following electrostatic voltage measurements were made. The floating potential of the vacuum tank was monitored during an identical set of experimental conditions of table I. It was found that the vacuum tank potential was of the order of 10 volts negative to the anode and varied slightly with magnetic-field strength. Also, the test facility was modified in order to measure the potential at any point in the flow stream referenced to the anode; a movable probe was used for that purpose. This probe positioned at any radial position referenced to the accelerator axis of symmetry can be moved in and out of the plasma exhaust during a test and obtain the axial voltage gradients. The probe is shielded both during accelerator startup and shutoff for protection and the average lifetime of the probe tips (0.040-inch tungsten wire) was about 30 seconds. Results of the electrostatic probe measurements have shown that along the center line from the position of the probe at rest (6 in. from the cathode) to the cathode, the voltage fall is only about 5 to 8 volts depending, of course, on the arc current and magnetic-field strength. The arc current and magnetic-field strength govern the magnitude of the total voltage drop across the electrodes and the magnitude of the voltages in the plasma exhaust. In all cases though for high current and high magnetic fields the voltage drop along the axis was very small. However, voltage drops of the order of the drop between the electrodes were shown at small inclinations toward the axis.

Discussion

At first an evaluation is made as to what extent the acceleration could be interpreted in terms of Hall currents interacting with radial magnetic-field components. Other effects are discussed later. It is shown in figure 4 that the Hall current increases with current between the electrodes and decreases of the order of 20 percent with magnetic fields increasing by 500 percent. As indicated, for example, in figures 5 and 6, the thrust varies almost proportionally to the current for the higher magnetic fields, while a somewhat smaller, though still appreciable, linear increase is shown with magnetic field. Thus, the $j_\theta B_r$ force/vol. due to Hall currents thus offers a possible mechanism for plasma acceleration.

The small decrease of Hall current with magnetic field at the small mass flows of the order of 0.01 g/sec in figure 4, as compared to the much more pronounced decrease (after having reached a peak) for the high mass flow of 1.8 gm/sec in figure 49 of reference 5, seems to have its explanation in the fact that the percent ionization is much higher. This is suggested from figure 11 (a reproduction of fig. 49 of ref. 5) for higher mass flows where it is shown that the decrease in Hall current with magnetic field is considerably reduced with increasing current between the electrodes, with resulting increased ionization. The effect of increased ionization on decreasing the rate of decrease of Hall current with magnetic field is consistent with a reduction in ion slip. As shown in reference 5 and in more detail in reference 8, the effect of ion slip can cause a decrease of the Hall current with increasing magnetic field at constant current between the electrodes. Of course, the different configuration used in reference 5 also affects the results. The smaller change in slope of the curve of Hall current versus magnetic field with current at the low mass flows seems related to the fact that a high percent ionization is already obtained at lower currents and thus the change in ionization with increasing current is reduced. The absolute value of the Hall current is, of course, also reduced by the back e.m.f. Since the current paths may change with increasing current and magnetic field this picture is evidently oversimplified and changes in current paths have to be further checked in a manner related to the Hall current measurements, with magnetic probes, or with differential electrostatic probes (ref. 9). Knowledge of the actual current path is, of course, also essential in calibrating the Hall current, when it is measured with a test coil surrounding the plasma beam. Such calibration would yield Hall currents of the proper order of magnitude to account for the $j_\theta B_r$ force/vol. A determination of the ratio of j_θ, the Hall current density, to the density of the driving current which has components in both the axial and radial directions which is related to $\omega\tau$ depends, of course, also on the current distribution.

Evidence of $\vec{j} \times \vec{B}$ plasma acceleration is also given by the distribution of the potential in the accelerator. As noted in the experimental section, the potential along the axis of the accelerator increases only very slightly above the cathode potential along a distance of about 6 inches beyond the accelerator. The potential distribution at various radii suggests that almost the full applied potential drop is being used for plasma acceleration in a direction somewhat inclined toward the axis. The bulging of the currents beyond the electrode region is evident from this picture. The question whether the $j_\theta B_r$ mechanism causes the electrons to pull the ions thus establishing space charge and the voltage drop or if the ions are accelerated in the voltage drop due to formation of a virtual cathode along the axis, with the space charge established due to trapping of electrons, is somewhat premature for this complicated situation.

The self-magnetic $j_r B_\theta$ effects can play a part for the present comparatively low currents only in the neighborhood of the cathode tip where the current densities can be very high. Since the maximum self-magnetic compression should be somewhat behind the cathode tip it could produce a reverse jet bathing the cathode in plasma as well as a slight thrust. The first effect seems to be responsible for the uniformity of the plasma jet and reproducible operation of this device as noted also in reference 1. The self-magnetic $j_r B_\theta$ effects in the region of bulging currents beyond the electrodes should, however, be very small for the present currents.

The effects of pressure gradients due to electrothermal effects would require extremely high enthalpies or temperatures which do not seem to be available for the experiments at comparatively lower power in argon and nitrogen. This seems true even if the higher nonequilibrium electron temperatures are used in the enthalpy evaluation. Since the axial component of the magnetic field reduces the heat transfer to the wall, however, high temperatures especially near the cathode should not be ruled out. Comparative measurements of electromagnetic and electrothermal thrust are required to answer this question in detail. It must be remembered in this connection, however, that even the expansion of plasmas heated by electrothermal means through a magnetic nozzle will also give electromagnetic reactions.

In evaluating the kinetic energy in the plasma streams when operating with argon and nitrogen, results were obtained which suggest that mechanisms for plasma acceleration in addition to those mentioned above may have to be present. The reason is that it was found that for the higher currents, the kinetic energy per particle based on $\bar{v} = \text{Thrust}/\dot{m}$ is larger than the potential energy in the applied voltage available for steady, continuous acceleration of a singly ionized particle, i.e.,

$$\frac{m\bar{v}^2}{2} > ZeV \quad \text{for} \quad Z = 1$$

It must be emphasized that this does not constitute a violation of the first law of thermodynamics for the whole aggregate of particles, since the power due to motion of the plasma stream is smaller than the input power.

$$\text{Thrust} \times \bar{v} < VI$$

A complete power balance including power put into ionization and into heating still has to be made.

On first sight the use of the limit introduced by the energy balance or the first law for a single particle may seem out of place since in the experiments by Carter and Wood discussed in the preceding paper at this conference (ref. 10) it is shown that axial voltages considerably in excess of the applied voltage can be attained in the process of plasma acceleration. It must be realized, however, that the latter experiments apply to the case of partially ionized plasmas and that the kinetic energy per particle in the stream corresponding to $\bar{v} \approx 7000$ meters/sec and higher is still far below the voltage drop across a single pair of electrodes. The many-particle and the single-particle concepts, however, merge for fully ionized plasmas subject to steady or continuous acceleration in the collisionless limit. In this limit the maximum attainable velocity for perpendicular electric and magnetic fields is the drift velocity

$$v_D = Z\left|\frac{E}{B}\right|$$

This velocity is on the average due to a particle dropping through the voltage over the distance of 1 cyclotron radius. The effect of collisions should be generally (with certain exceptions) to reduce, rather than to increase this velocity. The preliminary measurements also indicate that the total voltage drop in the direction of acceleration is not larger than the drop across the electrodes. It should be noted[9] that this limit applies as well to self-magnetic and electrothermal steady acceleration. The maximum ion velocity is approximately determined using stagnation enthalpy and the enhanced sound speed from reference 11, equation 3.2:

$$v = \left(\frac{2}{\gamma - 1}\right)^{1/2} a_{st} \approx \left(\frac{2}{\gamma - 1}\,\frac{Z\gamma kT_e}{m_i}\right)^{1/2}$$

The obtaining of such very desirable results has to be, of course, regarded with suspicion. Thus, before explaining them by some unusual but possible effects, a careful check has been undertaken to check other effects which could give high thrusts as shown in the experimental section. Although the effects of back pressure, backstreaming, and thrust augmentation by ambient jet mixing appear negligible, the need for testing the accelerator in a very low-pressure environment is clearly evident. Plans for doing this are in progress.

Doppler shift measurements are also in progress which could determine the velocities of various atomic states including possible contaminants. One of the unusual plasma mechanisms for kinetic energies in excess of the applied voltage is based on the process of multiple ionization with $Z > 1$. Since the excessively high kinetic energies occur for argon and nitrogen, both of which can form multiple ionization through metastables, this possibility must be further investigated. Preliminary spectroscopic studies show very intense lines of A_{III} or doubly ionized argon and there are indications that A_{IV} states are present in the plasma. More detailed studies will be presented at the meeting if available. It is of interest to note in this connection that comparatively high kinetic energies are attained as the currents are raised at constant magnetic field at approximately constant voltage. Of course some may argue that with this current increase the contamination might also increase. However, the linear increase of thrust with current under such conditions would be accidental.

Another "unusual" mechanism is related to the establishing of nonmaxwellian distributions which could lead to voltages in excess of the applied voltage. These high voltages are caused by trapping of particles (mostly electrons) in stationary potential wells or in waves. The preliminary measurements of the potential distribution do not indicate such distributions; however, the existence of high current densities does not rule out such nonequilibrium effects. Other mechanisms where the charged particles can benefit several times from the accelerating voltage through charge transfer collisions and reionization should also be investigated.

Experiments with a larger vacuum tank and pumping system are in preparation together with measurements using thrust stands weighing the reaction on the engine or the magnet. These studies, together with Doppler shift velocity measurements should fully resolve the preceding problems.

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TABLE I

Arc current, amps	Arc voltage, volts	B, amps*	$\dot{m}$, gm/sec	Thrust without cylinder, grams	Thrust with cylinder, grams	Vacuum chamber back pressure, μHg
300	28	120	0.0239	20.2	20.6	7
450	28	120	0.0239	23.0	23.8	7
600	26	120	0.0239	28.3	28.3	7
300	34	300	0.0239	28.7	32.3	7
450	34	300	0.0239	39.6	42.4	7
600	38	300	0.0239	47.3	46.5	7
300	24	120	0.0239	20.2	20.2	25
450	24	120	0.0239	24.2	24.2	25
600	25	120	0.0239	29.5	29.5	25
300	31	300	0.0239	31.9	33.1	25
450	32	300	0.0239	46.6	42.0	25
600	34	300	0.0239	51.3	50.5	25
300	20	120	0.0239	19.0	21.0	50
450	21	120	0.0239	24.6	25.9	50
600	23	120	0.0239	30.7	32.3	50
300	30	300	0.0239	30.3	39.6	50
450	31	300	0.0239	40.0	48.5	50
600	34	300	0.0239	48.9	51.3	50

*100 amps ≈ 1000 gauss axial field of cathode.

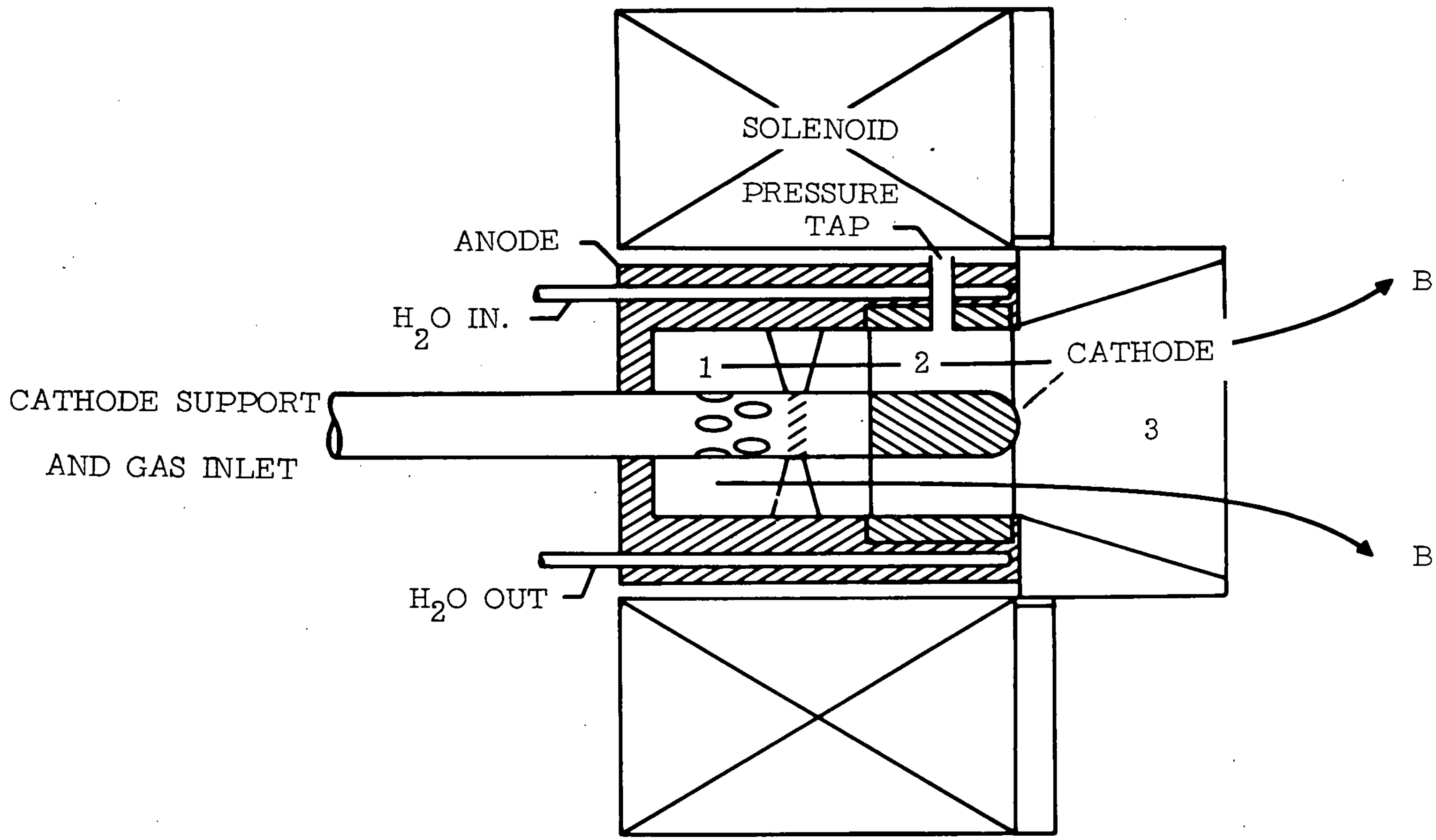

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Figure 1.- Schematic of high mass flow rate plasma accelerator configuration.

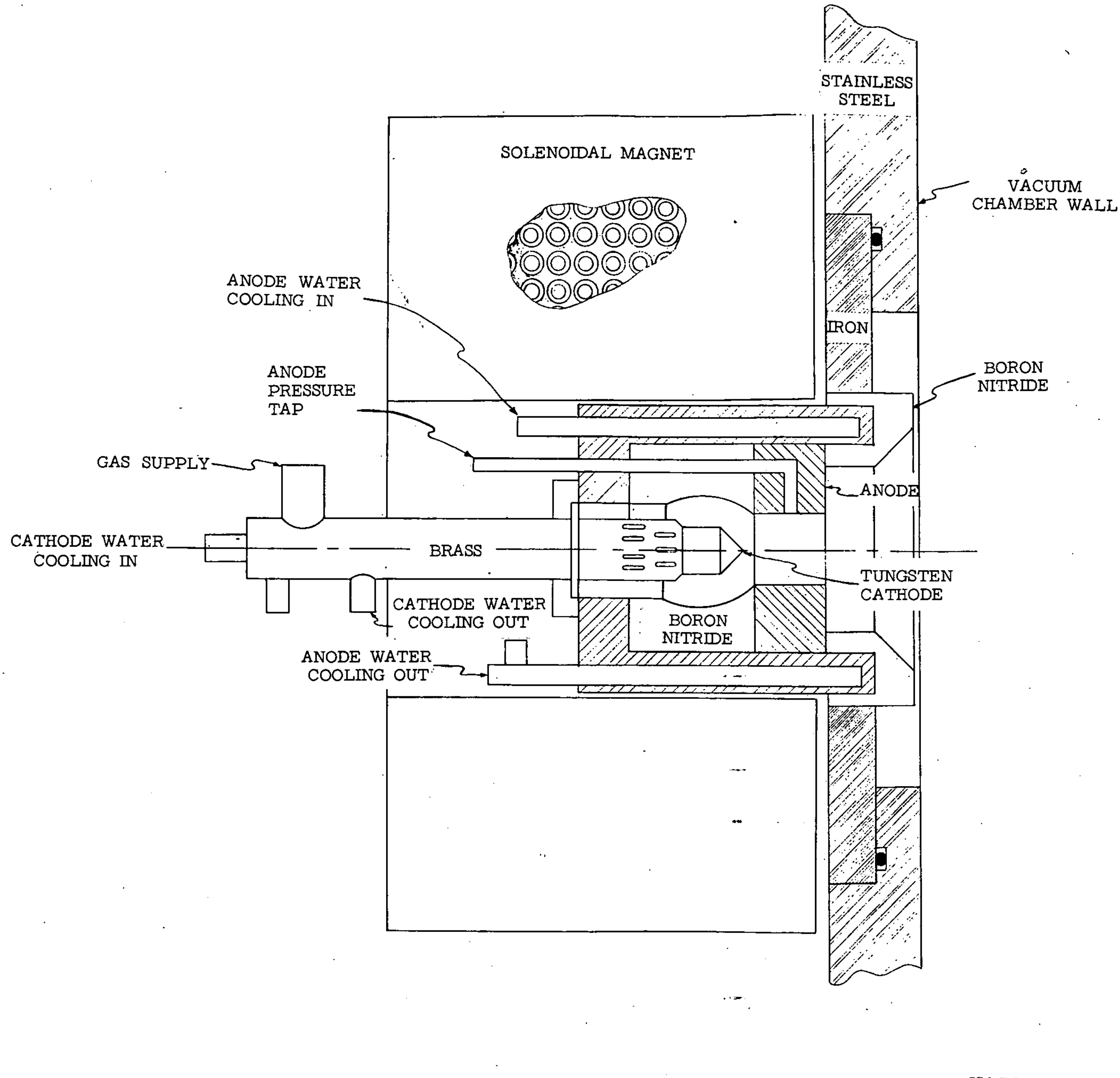

Figure 2.- Schematic of low mass flow rate plasma accelerator configuration.

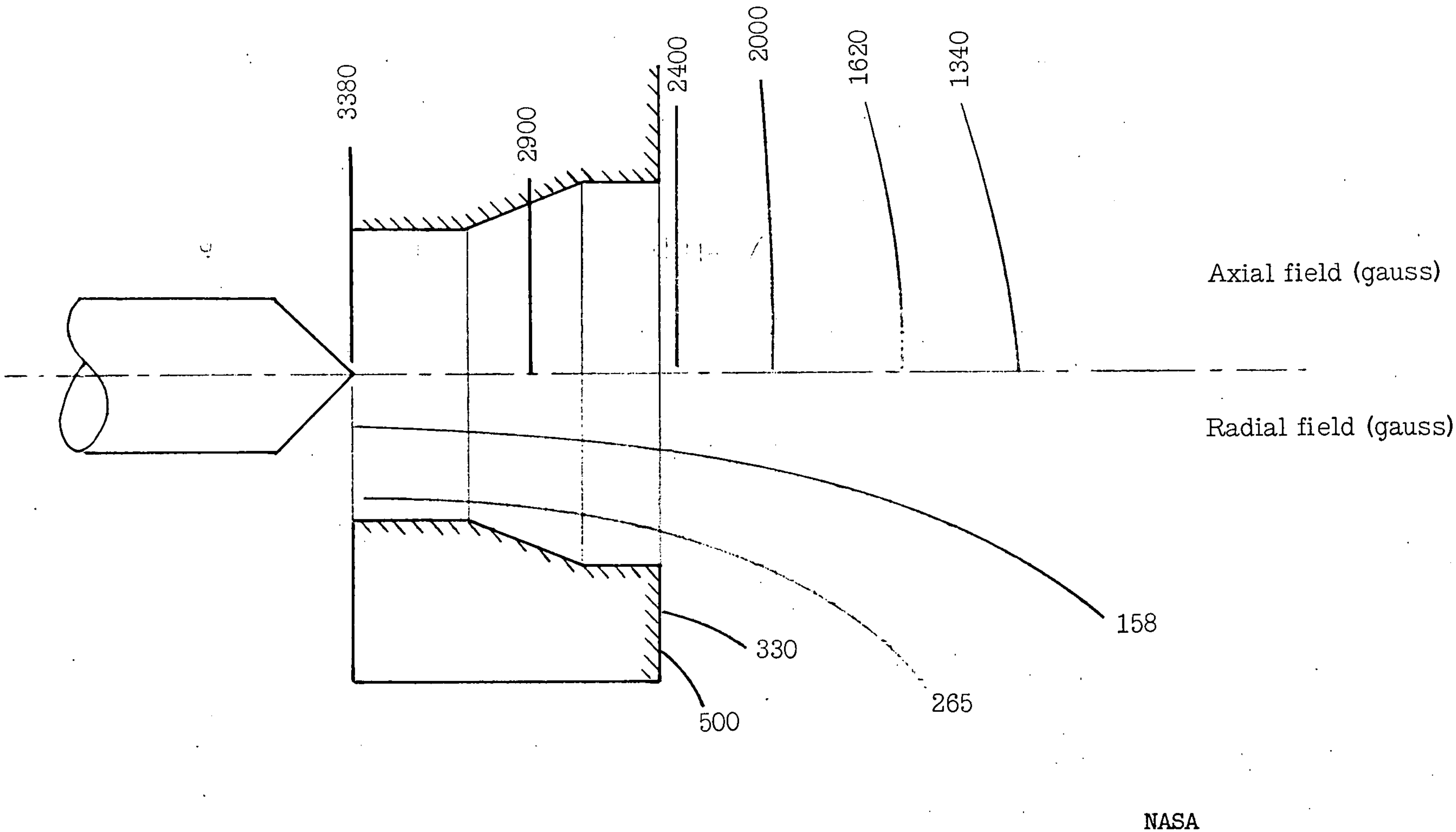

Figure 3.- Magnetic field distribution.

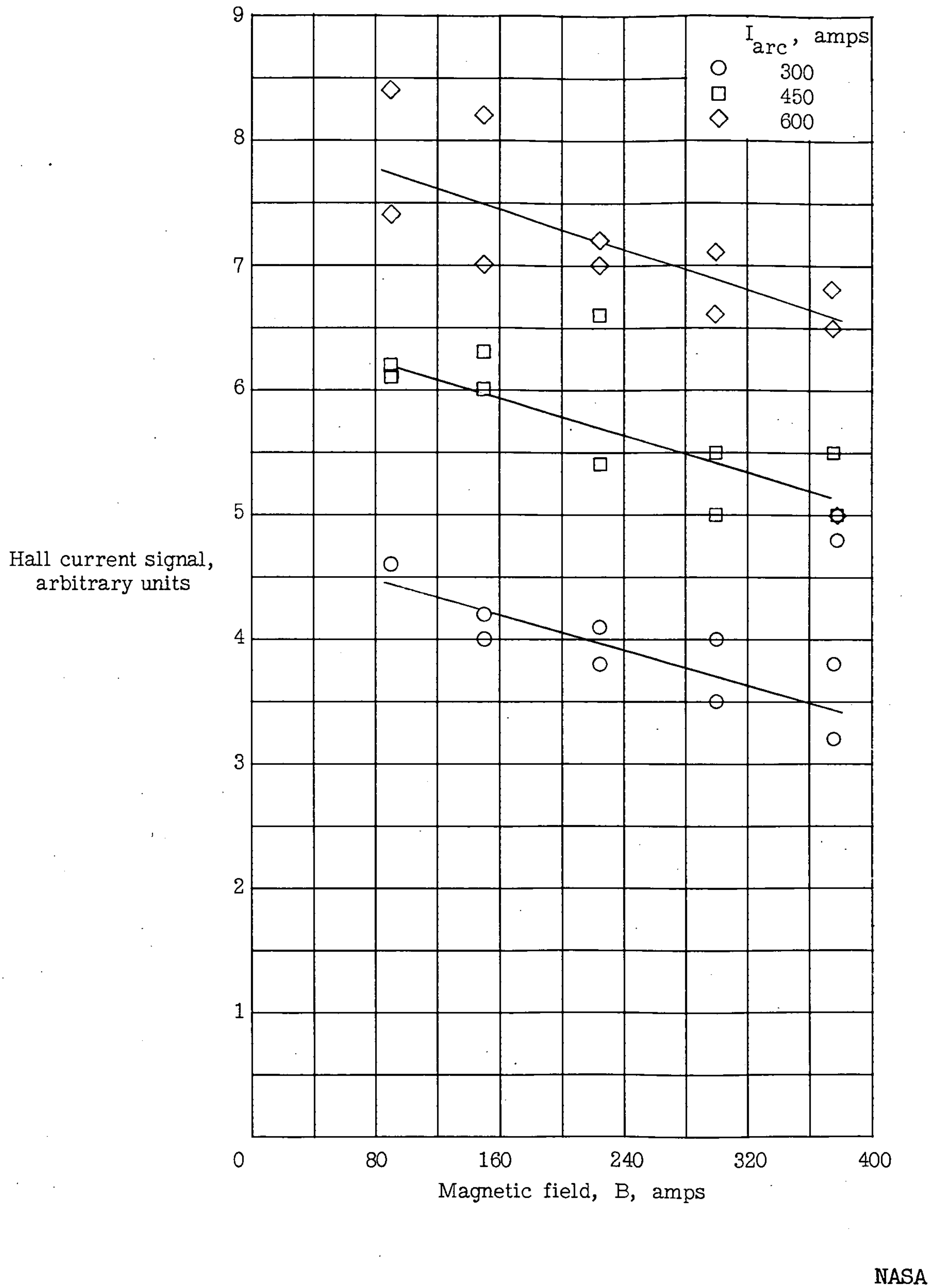

Figure 4.- Experimental Hall current measurements for $\dot{m}$ = 0.0239 g/sec.

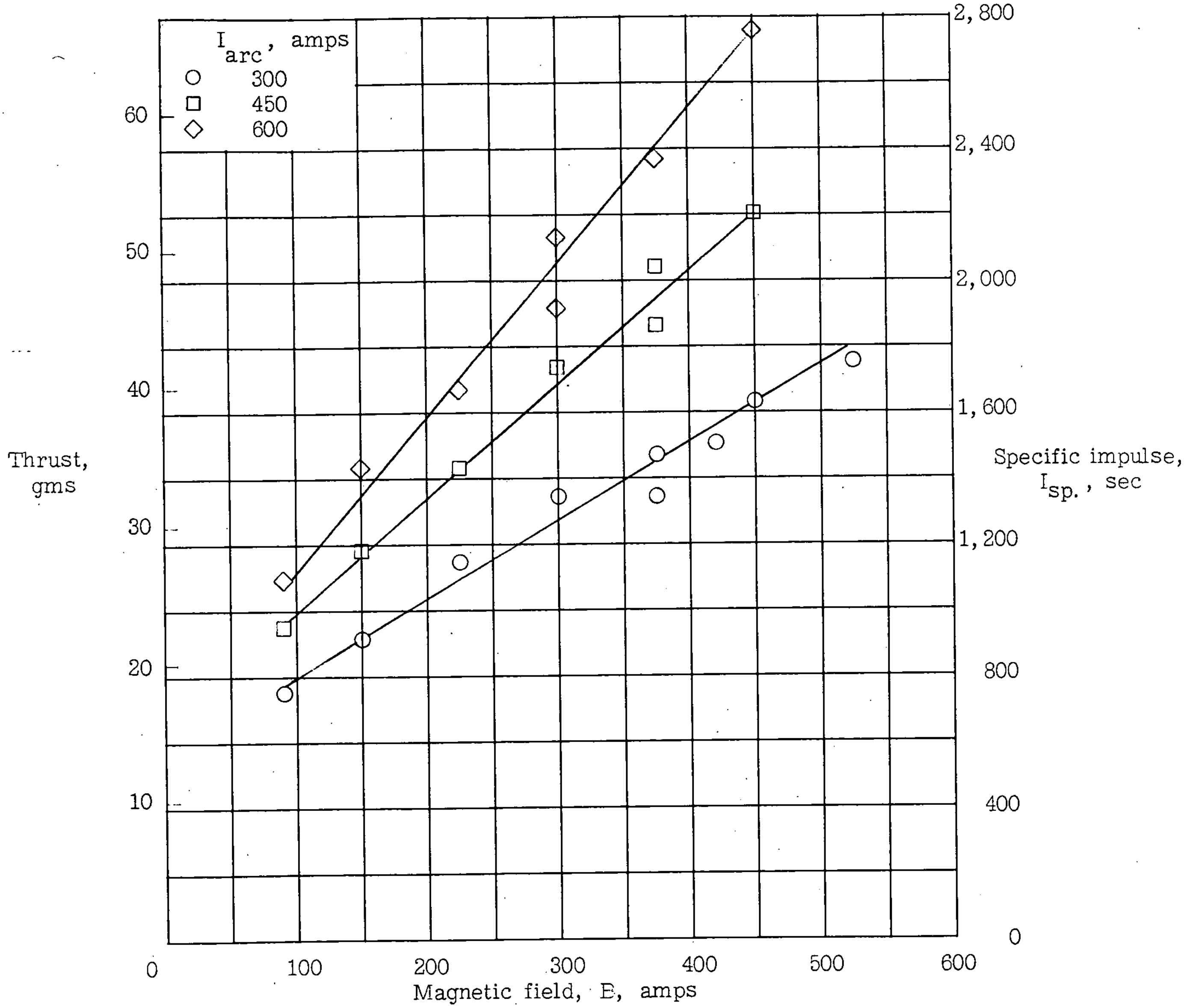

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Figure 5.- Experimental thrust data for argon $\dot{m}$ = 0.0239.

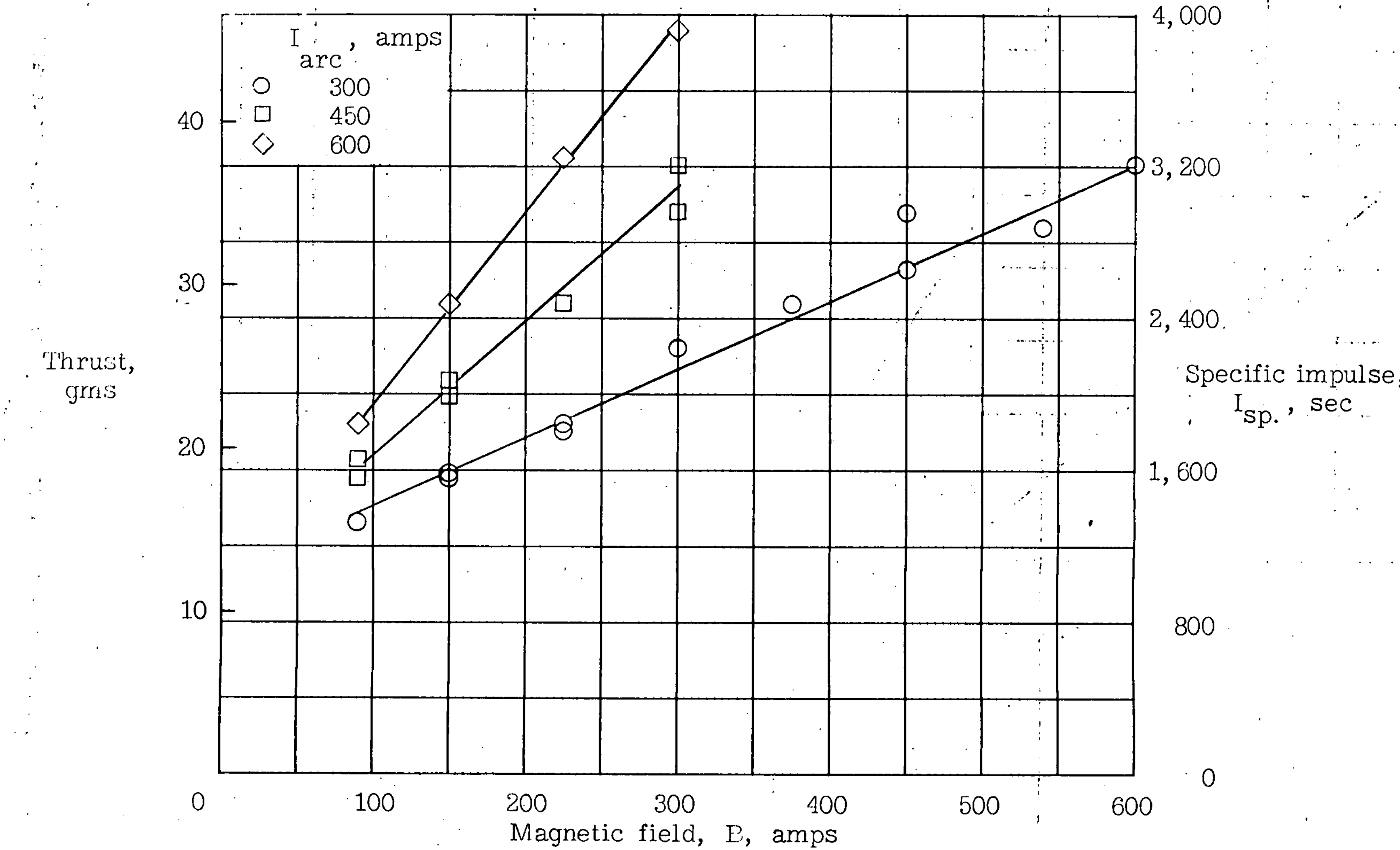

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Figure 6.- Experimental thrust data for argon $\dot{m}$ = 0.0116.

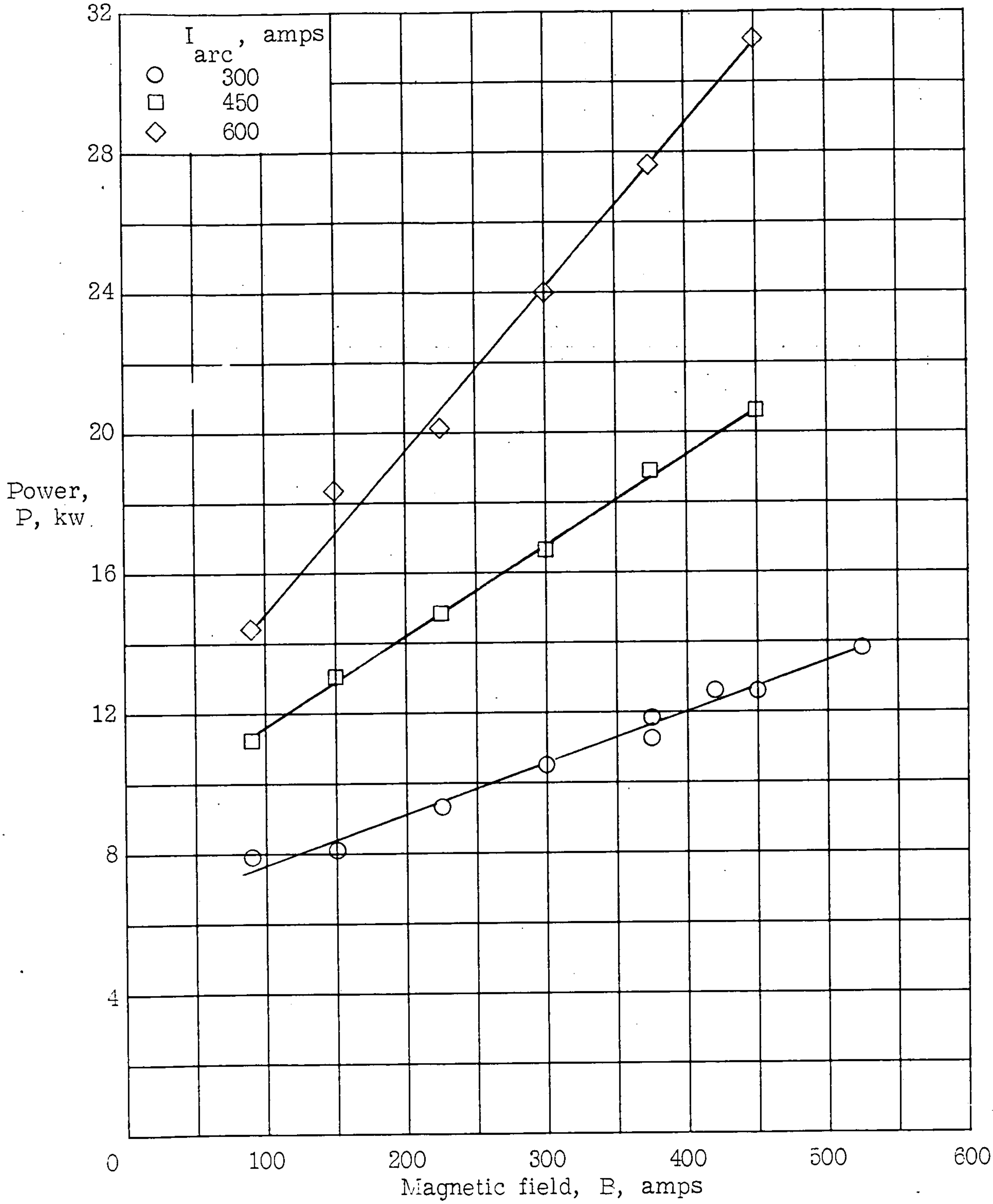

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Figure 7.- Experimentally measured power inputs to accelerator, $\dot{m}$ = 0.0239.

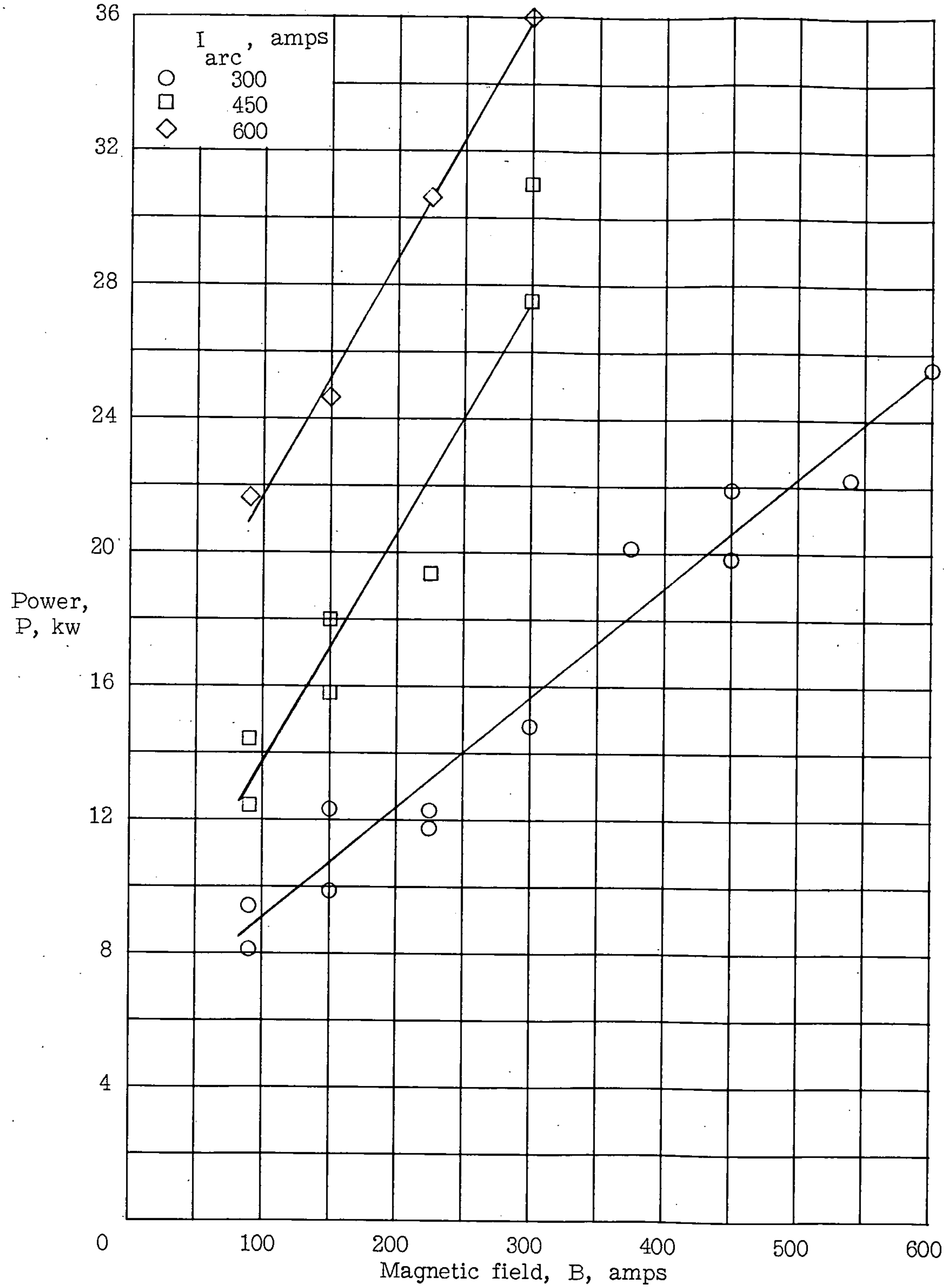

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Figure 8.- Experimentally measured power inputs to accelerator, $\dot{m}$ = 0.0116.

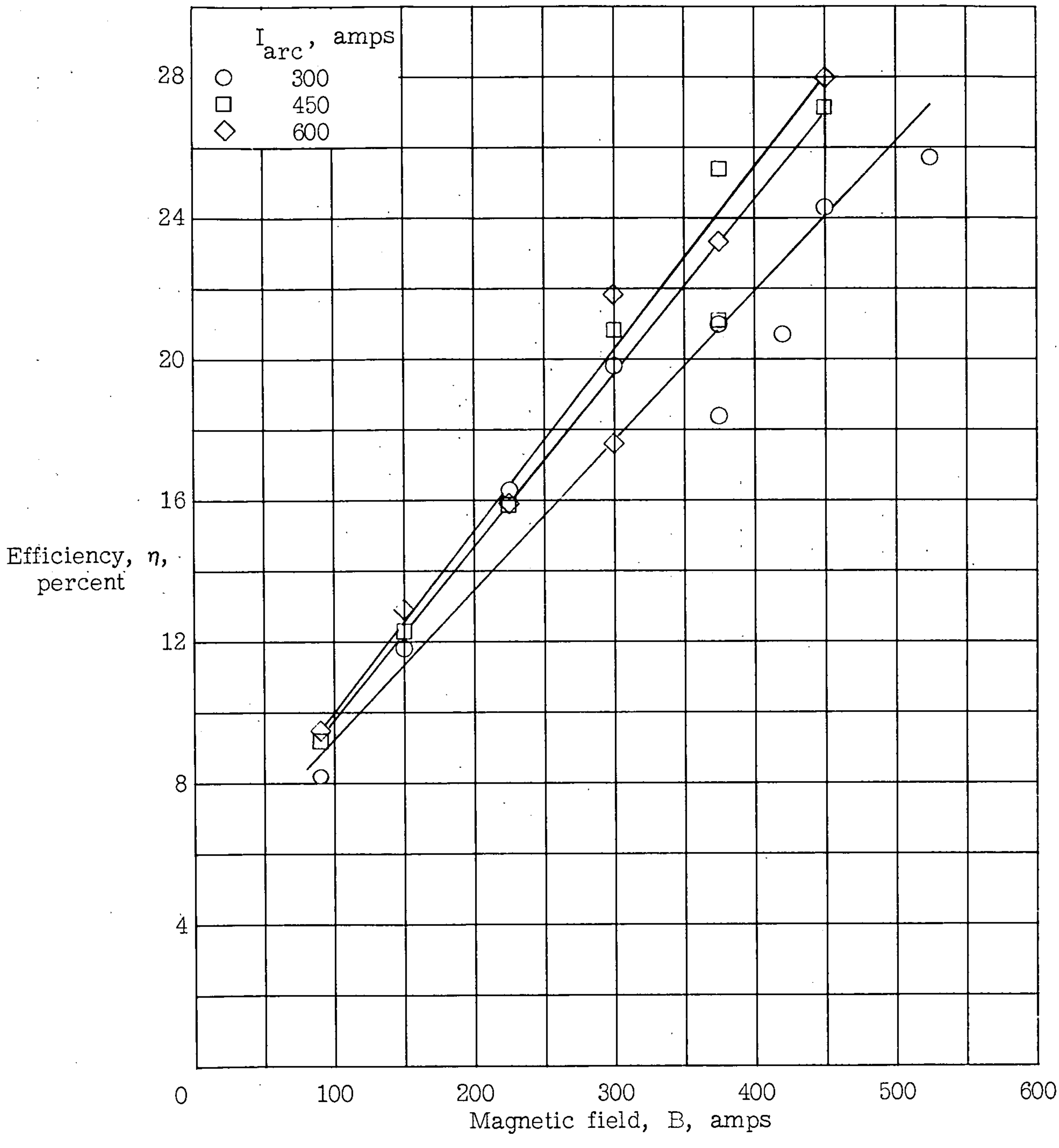

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Figure 9.- Accelerator efficiency, $\dot{m}$ = 0.0239.

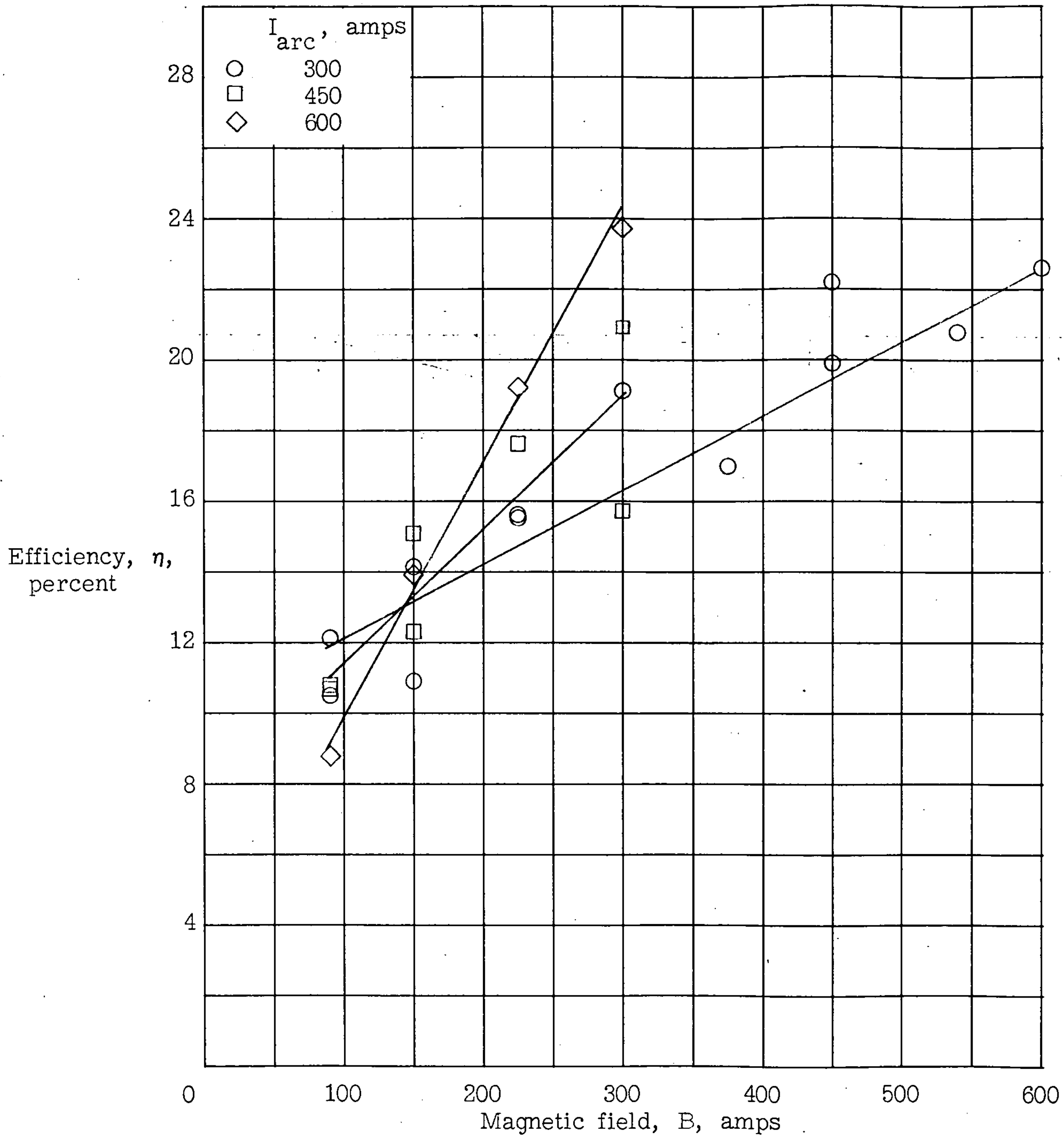

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Figure 10.- Accelerator efficiency, $\dot{m}$ = 0.0116.

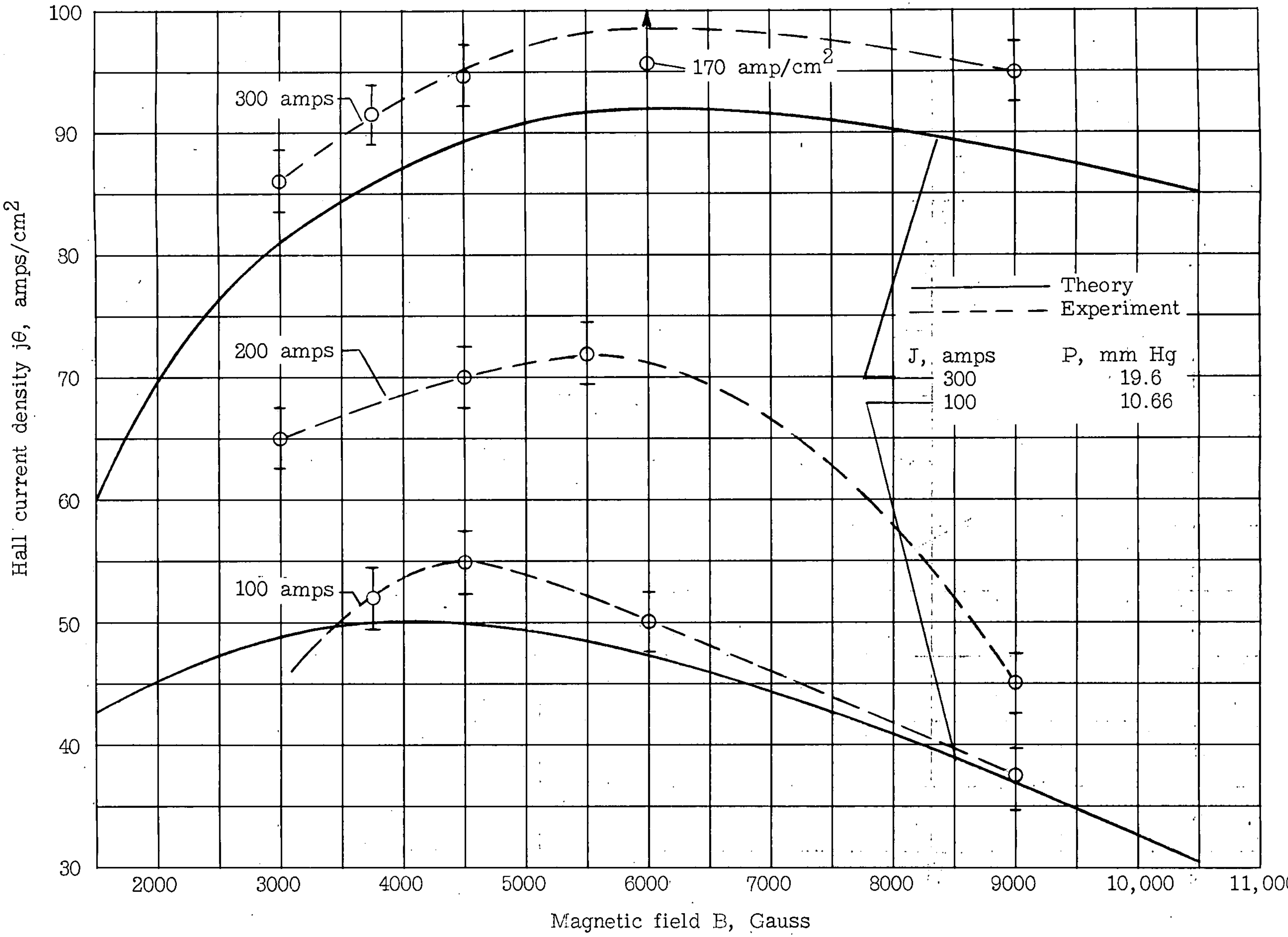

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Figure 11.- Experimental and theoretical variation of Hall current, high mass flow rate configuration, $\dot{m} = 1.8$.

NASA-Langley, 1964