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EFFECTS OF 1- AND 2-MeV ELECTRONS ON PHOTOMULTIPLIER TUBES

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16. Abstract

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All the tubes tested showed extremely large increases in dark current. Tube types 541A, 6217, 6199, and 6903 exhibited the largest increases under irradiation, whereas type 1P22 was affected the least. All the damage observed was transient. The luminescence produced in the optical window probably accounts for a large part of the dark-current increases, but there were some effects possibly due to direct irradiation of the photocathode and dynode chain.

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SUMMARY

Various types of photomultiplier tubes useful for space applications were irradiated with 1- and 2-MeV electrons at Van Allen radiation belt fluxes of 10^5 to 10^7 electrons/cm^2-sec. The increase in the dark current due to electron irradiation was observed at various bias voltages under worst-case conditions (no shielding). Results are presented in the form of dark current plotted against electron flux.

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INTRODUCTION

The use of many photomultiplier tubes in satellite navigational systems and scientific research experiments requires that they be able to detect low light levels. When these tubes are subjected to radiation from ionizing particles in the space environment, the generation of background noise (dark current) can seriously affect their proper operation. This can result in errors in experimental data or in malfunction of star tracker systems.

Previously, several experiments have determined that space radiation, especially electrons in the Van Allen belt, severely affects data reception in Earth sensing experiments using photomultiplier tubes (PMT's) as sensors of low light levels. This radiation also affects the pointing accuracy of star tracker guidance systems which use PMT's (refs. 1 to 4). A conclusion from these studies was that the principal part of the dark-current increase is due to radiation-produced luminescence in the glass window of the PMT's. It was found that severe effects on PMT circuit performance occurred with steady-state or slowly changing radiation fields. They found a small (less than 15 percent) increase in dark current due to an increased current leakage through the PMT base and an increased electron density at the first few dynodes. This increased electron density was attributed to direct bombardment of the cathode by the ionizing particles.

The results presented in this paper represent an attempt to obtain experimental data for predicting PMT performance which can be used to measure low light levels in a space radiation environment. However, the experimental conditions described impose certain constraints which must be considered in predicting space response of photomultiplier tubes.

SYMBOLS

I	total photomultiplier current, A
I_d	dark current, A
$I_{d,o}$	initial dark current, A
I_o	signal current, A
S/N	signal-to-noise ratio
Δf	bandwidth
ϕ_R	electron flux, e^-/cm^2-sec

NOTATION

Ag-Bi-O-Cs	silver-bismuth-oxygen-cesium
Ag-Mg	silver-magnesium
Ag-O-Cs	silver-oxygen-cesium
Be-O-Cs	beryllium-oxygen-cesium
Cs-Bi	cesium-bismuth
Cs-K-Sb	cesium-potassium-antimony
Cs-Sb	cesium-antimony

Cu-Be	copper-beryllium
Hg-Mg	mercury-magnesium
K-Na-Cs-Sb	potassium-sodium-cesium-antimony
Mg-O-Cs	magnesium-oxygen-cesium
Ni	nickel
SiO_2	silicon dioxide
A	ampere
Å	angstrom (1 Å = 0.1 nm)
e^-	electron
PMT	photomultiplier tube
UV	ultraviolet

THEORY

The operation of a photomultiplier tube (PMT) is equivalent to the operation of a vacuum photocell and a high-quality amplifier. Photomultiplier tubes can operate up to a frequency of several megahertz. One of the most important characteristics for space applications is their high signal-to-noise ratio S/N, which makes them extremely useful for detecting low light levels. Stray light will decrease S/N even if the light level is constant. The total photocurrent leaving the anode is given by

$$I = I_o + I_d \tag{1}$$

where I_o is the signal current and I_d (dark current) is current due to the internal circuit noise plus background noise (stray light, heat, etc.). This paper discusses background noise resulting from ionizing radiation.

The signal-to-noise ratio S/N, in decibels, is represented by

$$\frac{S}{N} = 10 \log \Delta f - 10 \log\left(\frac{1.59 \times 10^{-8}}{I} + \frac{1.15 \times 10^{-29}}{I^2}\right) \tag{2}$$

where Δf is the bandwidth (ref. 1). Radiation-produced luminescence in glass envelopes can seriously affect S/N, since large increases in the dark current I_d will subsequently increase the total current I and thereby reduce S/N. This will be especially true if the signal current I_o being detected is very low, as it is in many space applications such as star trackers.

There is also the possibility that the electrons will penetrate the glass windows and produce dark current by direct bombardment of photocathodes and dynodes (refs. 5 to 7). For example, in silicon dioxide, the range of 1-MeV electrons is 1.82 mm; of 2-MeV electrons, 4.34 mm (ref. 5). In PMT 6903, the thinnest part of the window is less than 2.0 mm and the thickest part is 4.0 mm. Therefore, it would be possible for some of the electrons to penetrate the SiO_2 window. Similar characteristics can be found for the other types of optical windows.

A summary plot of the space radiation environment is shown in figure 1. For 1- to 2-MeV electrons, the typical flux ranges somewhere between 10^5 and 10^7 e^-/cm^2-sec. These electrons can produce a large amount of luminescence in glass materials. Since the effects of space electrons will possibly affect the performance of optical systems used in space, an investigation was performed to measure radiation-induced luminescence in optical cover materials (ref. 8). The luminescence-producing mechanisms in optical covers include the Čerenkov effect, radiative deexcitation of the excited impurity atoms by charged-particle excitation and ionization effects, radiative decay of excited impurity centers, and radiation-induced color centers. A comprehensive treatment of these various luminescence phenomena is given in appendix A of reference 8.

APPROACH

The experiments were limited to the measurement of dark-current increases in photomultiplier tubes for various fluxes of 2-MeV electrons, with PMT 1P21 and PMT 6903 being tested with 1-MeV electrons in order to determine whether there were any principal differences due to a change in the energy of the electron radiation. The electrons were obtained from an electron accelerator at the Langley Research Center. Extreme care was taken to obtain fluxes typical of those which would exist in a normal space radiation environment.

The test setup is shown in the block diagram of figure 2 and the photograph of figure 3. The target chamber is lighttight and is capable of achieving a vacuum of 10^{-6} torr (1 torr = 133.3 Pa). The electron beam flux is measured by a movable Faraday cup, and when the desired flux is obtained, the current on a beam port is noted and the beam is maintained at that current after the Faraday cup is removed. When the Faraday cup is removed, the electron beam strikes the photomultiplier tube and the radiation-produced dark current is recorded.

The target chamber was carefully checked for lighttightness and other stray sources of noise. The tubes were wrapped in black plastic electrical tape in order to stop luminescence produced in the chamber by the electron beam. It is not known whether the electron beam produces any luminescence in the tape. The diameter of the beam was approximately 5.0 cm. Care was taken to insure that this beam did not strike the readout cables. The initial dark current $I_{d,o}$ of the tubes was measured in a lighttight box before being placed in the test chamber. The tubes were then measured in the vacuum test chamber with the electron beam off, and the level of $I_{d,o}$ was compared with that recorded in the box. No appreciable differences were found.

EXPERIMENTAL RESULTS

The results of the experiments are presented in figures 4 to 18 for the various tubes as they appear in table I. The average of at least three tubes is plotted as a solid line, and the error bars show the maximum and minimum values of I_d recorded for a range of operational voltages plotted as a function of electron flux ϕ_R. Also shown in each figure is the initial dark current before any irradiation $I_{d,o}$. The users will be concerned with a variety of parameters, depending on which tube will be used, the function of the tube, the radiation environment, and so forth. Because of this, it would be very difficult to make specific statements about each individual tube type, and it will be left up to the user to determine specific conclusions that will apply to his applications. This paper will present general conclusions that can be seen in the data.

It was noted that I_d increases were extremely large for all the tubes except PMT 7102, and that the higher the bias, the larger I_d. All the tubes showed step increases in I_d when the electron beam was turned on, and then a linear increase on a log-log scale as the anode voltage increased. Because most PMT's react similarly, one may have confidence in predicting I_d in a single-energy radiation environment over the range of fluxes measured. In order to determine whether any difference existed for a reduction in electron energy by a factor of 2, a test was performed on PMT 1P21 with 1-MeV electrons (fig. 5). A quick comparison of these two energies is given in table II. More damage is produced by 2-MeV electrons than by 1-MeV electrons. For a bias of 500 V as ϕ_R increases, the difference in I_d decreases from a factor of 6 at $\phi_R = 10^5\ e^-/cm^2\text{-sec}$ to a factor of 3 at $\phi_R = 10^7\ e^-/cm^2\text{-sec}$. For a bias of 1000 V, the differences are a factor of 4 and 3, respectively.

The irradiation of PMT 6903 with 1- and 2-MeV electrons is compared in figure 13. In this tube, there is an increase in I_d by approximately a factor of 3 for

2-MeV electrons compared with 1-MeV electrons. This points out that in ascertaining the effects of a space radiation environment on PMT's, the energy of the electrons along with ϕ_R, shielding factors, and so forth should be considered.

The results for PMT 7102, which has a lime glass cover, are presented in figure 14. The tube tested had a Ag-O-Cs photocathode and a Mg-O-Cs secondary emitting surface. As previously mentioned, this tube did not exhibit the large increases in I_d that the other tubes did. PMT 7102 has an S-1 spectral response, which is principally in the infrared region (8000 Å peak response), but also has a response in the UV region. There was no response of this tube to irradiation until $\phi_R \approx 10^8$ e^-/cm^2-sec. This means either that the inherent noise was too large to allow measurement of the luminescence or the luminescence was not in the region of response of the tube. Whatever the case, the tube still did not react as strongly as the other tubes. There is very little effect on the tube until a flux of 10^7 e^-/cm^2-sec is reached, which is a very high rate of irradiation. At the extremely high flux of 10^9 e^-/cm^2-sec, the increase in I_d is still less than an order of magnitude, even at the highest operating voltage tested. The increase in I_d is probably due to penetration of electrons in the optical cover and direct bombardment of the photocathode and dynode chain. This flux is not likely in a normal satellite operation; therefore, no serious effects are expected in measurements using tubes sensitive to the infrared and near-infrared spectral region.

A plot of the average I_d of each tube type tested as a function of ϕ_R is in figure 18. The tubes are compared for an arbitrary operating voltage, which was 1000 V for all tubes except PMT 541A, which was 2200 V. As can be seen, there is a wide variation of response of the tubes to electron irradiation. The spread in radiation-produced I_d is as much as 3 orders of magnitude between PMT 6903 and PMT 1P22 at the same value of ϕ_R. It does not seem that radiation-produced luminescence in the optical window can be the total cause of the increase in I_d. In fact, this plot seems to show that other factors such as direct bombardment of cathodes and dynode chains may have more of a contribution to I_d than previously reported. For example, PMT 6903 shows the largest I_d increase and uses a SiO_2 window; PMT 7200, which is almost $1\frac{1}{2}$ orders of magnitude less sensitive to radiation, also uses a SiO_2 window. Differences in construction of the tubes have an impact on the effect of electron irradiation on photomultiplier tubes. Another example is the large spread between tubes that use lime glass. PMT 1P22 shows I_d almost 3 orders of magnitude less than PMT 6199 at the same value of ϕ_R, but both use lime glass windows. It should be noted that PMT 1P28 is one of the tubes showing the least increase in I_d. This tube can be used to measure the shorter ultraviolet wavelengths.

PMT 541A has been considered by many investigators as a star tracker for satellite guidance systems. The results of this test show this tube to be very sensitive to electron irradiation, with large radiation-produced I_d. Since star tracker systems are required to measure extremely low levels of light, great care must be taken to protect this tube if used in such a system.

PMT 7102 was very noisy and the signal current was difficult to measure at low flux. The increases in I_d are still large, although not as large as for the rest of the tube types.

All the PMT's tested were measured several hours after irradiation. There were no noticeable permanent effects; therefore, the damage can be considered transient.

CONCLUDING REMARKS

Various types of photomultiplier tubes were irradiated with 1- and 2-MeV electrons to determine the effects on dark current. All the tubes tested (except those that are infrared sensitive) exhibited large increases in dark current under irradiation by electrons. As mentioned earlier, many experimenters believe that a major effect of ionizing radiation on photomultiplier tubes is the production of luminescence in the optical windows, which results in a transient increase in dark current. In this paper, however, the wide variation of response to radiation of tubes with the same type of optical windows indicates that there may be a larger increase in dark current due to direct bombardment of certain types of photocathodes and dynodes than previously expected.

All the tubes showed an increase in dark current with increasing radiation flux that resulted in a linear curve on a log-log plot over the range of fluxes tested. This can be helpful in predicting a particular phototube response in a known radiation environment. It was found that 2-MeV electrons produced more dark current than 1-MeV electrons. This would indicate an energy dependence with respect to radiation-produced dark current. The data also show that because of the wide response of tube types, it is necessary to test the individual tube types to be used. The data further indicate that photomultiplier tubes should be shielded for use in a space radiation environment. It was also found that there was no permanent damage to the photomultiplier tubes.

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December 4, 1975

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TABLE I. - IMPORTANT CHARACTERISTICS OF PHOTOMULTIPLIER TUBES TESTED

Tube type (a)	Spectral response	Maximum response, Å	Window type	Photocathode	Dynode	Secondary emitting surface	Structure	Current amplification
1P21/9	S-4	4000	Lime glass (0080)	Cs-Sb	Ni	Cs-Sb	Circular cage	20×10^5
1P22/9	S-8	3650	Lime glass (0080)	Cs-Bi	Ni	Cs-Sb	Circular cage	3.3×10^5
1P28/9	S-5	3400	UV glass (9741)	Cs-Sb	Ni	Cs-Sb	Circular cage	25×10^5
541A/14	Bialkali	3200	Sapphire	Bialkali	Hg-Mg	--------	Venetian blind	10×10^5
931A/9	S-4	4000	Lime glass (0080)	Cs-Sb	Ni	Cs-Sb	Circular cage	8×10^5
6199/10	S-11	4400	Lime glass (0080)	Cs-Sb	Cu-Be	Be-O-Cs	Circular cage	10×10^5
6217/10	S-10	4500	Lime glass (0080)	Ag-Bi-O-Cs	Ni	Cs-Sb	Circular cage	25×10^5
6903/10	S-13	4400	SiO_2	Cs-Sb	Ni	Cs-Sb	Circular cage	15×10^5
7102/10	S-1	8000	Lime glass (0080)	Ag-O-Cs	Ag-Mg	Mg-O-Cs	Circular cage	0.3×10^5
7200/9	S-19	3300	SiO_2	Cs-Sb	Ni	Cs-Sb	Circular cage	10×10^5
8575/12	Bialkali	3850	Pyrex glass (7740)	Cs-K-Sb	Cu-Be	Be-O-Cs	In-line	40×10^5
8644/10	S-20	4200	Borosilicate (7056)	K-Na-Cs-Sb	Cu-Be	Be-O-Cs	In-line	0.8×10^5

[a]The numbers following the slant line denote stages.

TABLE II.- COMPARISON OF 1-MeV AND 2-MeV ELECTRON IRRADIATION OF PMT 1P21

Electron energy, MeV	Dark current, I_d, amperes, at –		
	$\phi_R = 10^5$ e$^-$/cm^2-sec	$\phi_R = 10^6$ e$^-$/cm^2-sec	$\phi_R = 10^7$ e$^-$/cm^2-sec
Bias voltage, 500 V			
1	5×10^{-10}	5×10^{-9}	6×10^{-8}
2	3×10^{-9}	2×10^{-8}	2×10^{-7}
Bias voltage, 1000 V			
1	8×10^{-8}	9×10^{-7}	1×10^{-5}
2	3.5×10^{-7}	3.2×10^{-6}	3.2×10^{-5}

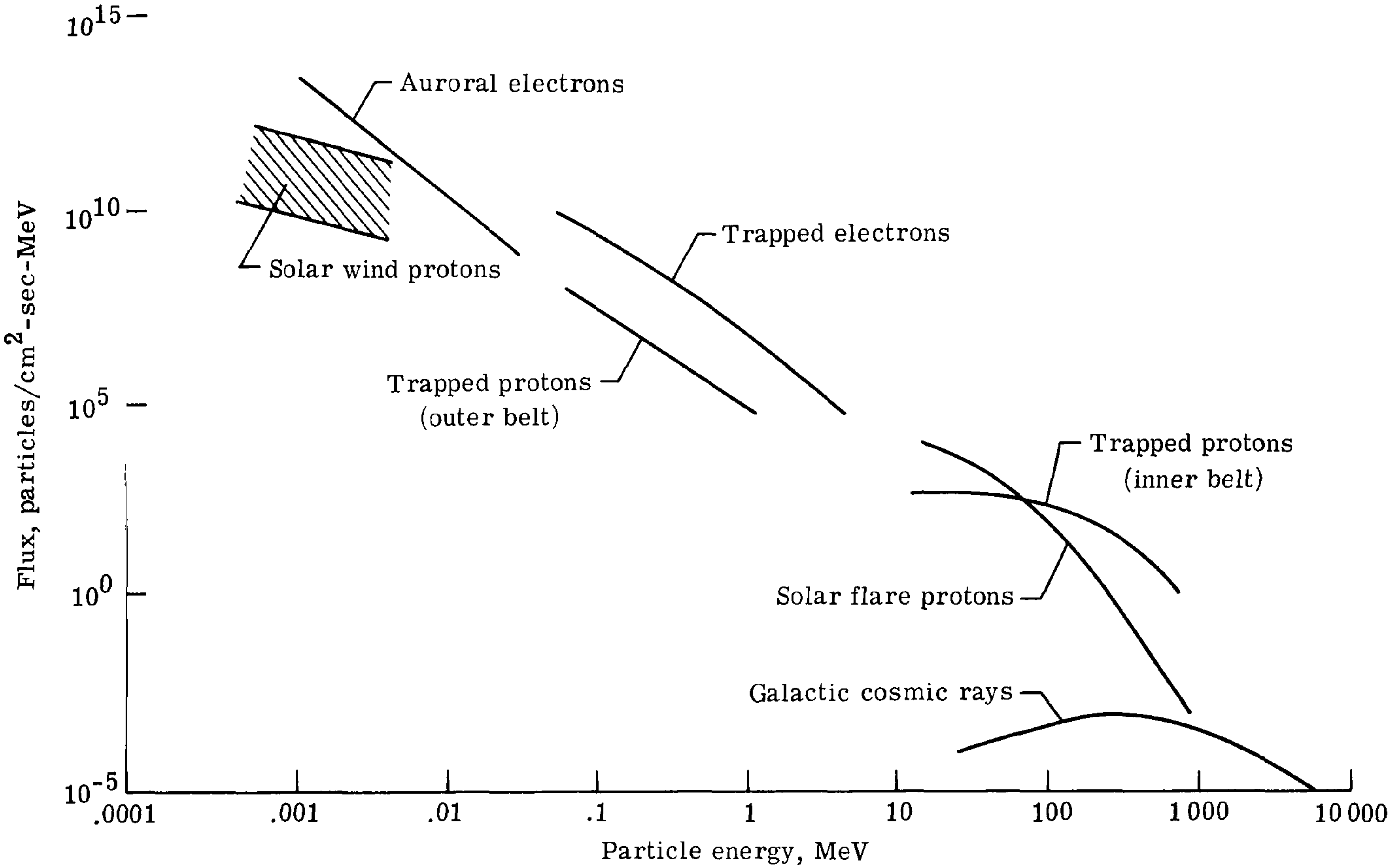

Figure 1.- Typical space radiation environment.

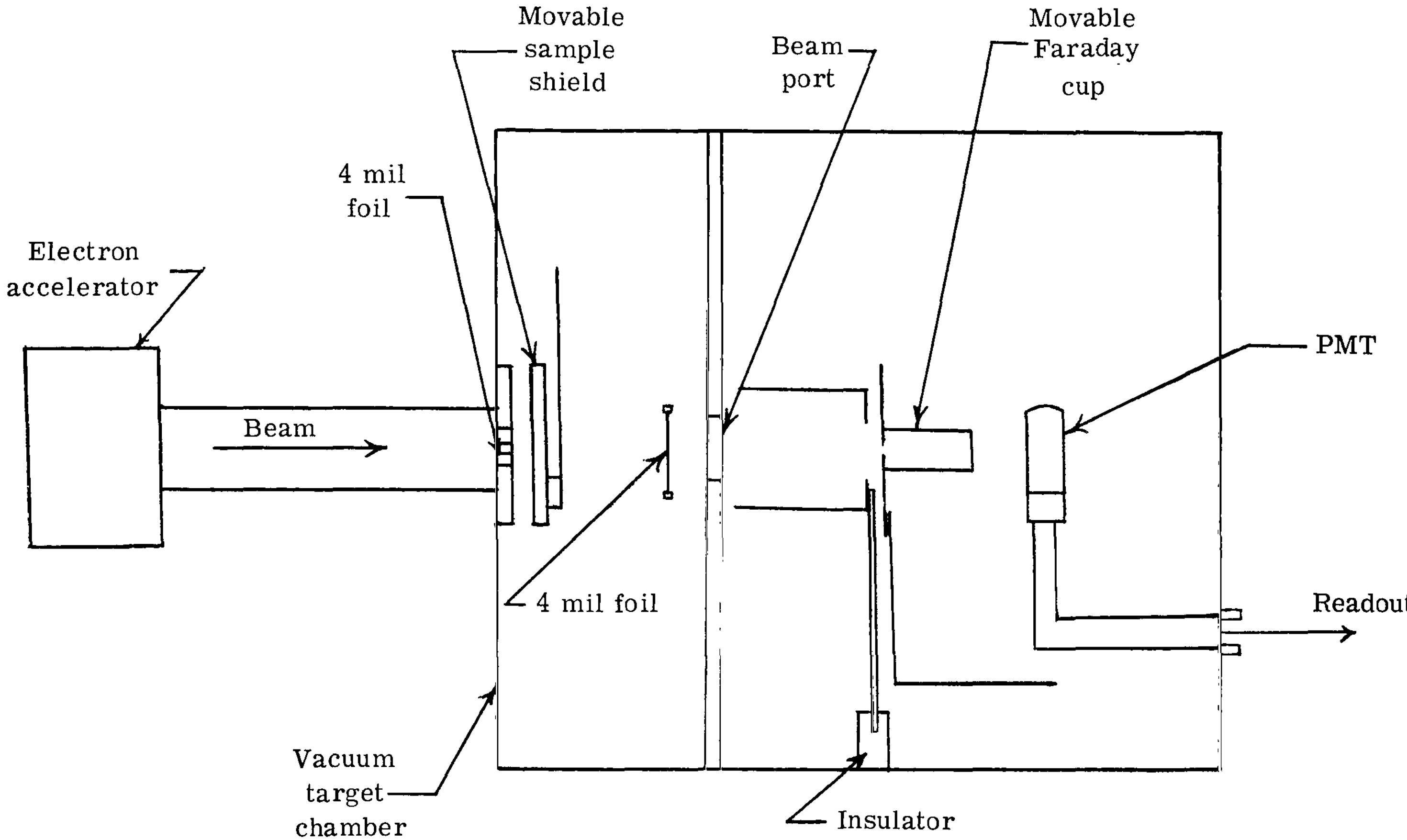

Figure 2.- Block diagram of side view of target chamber.

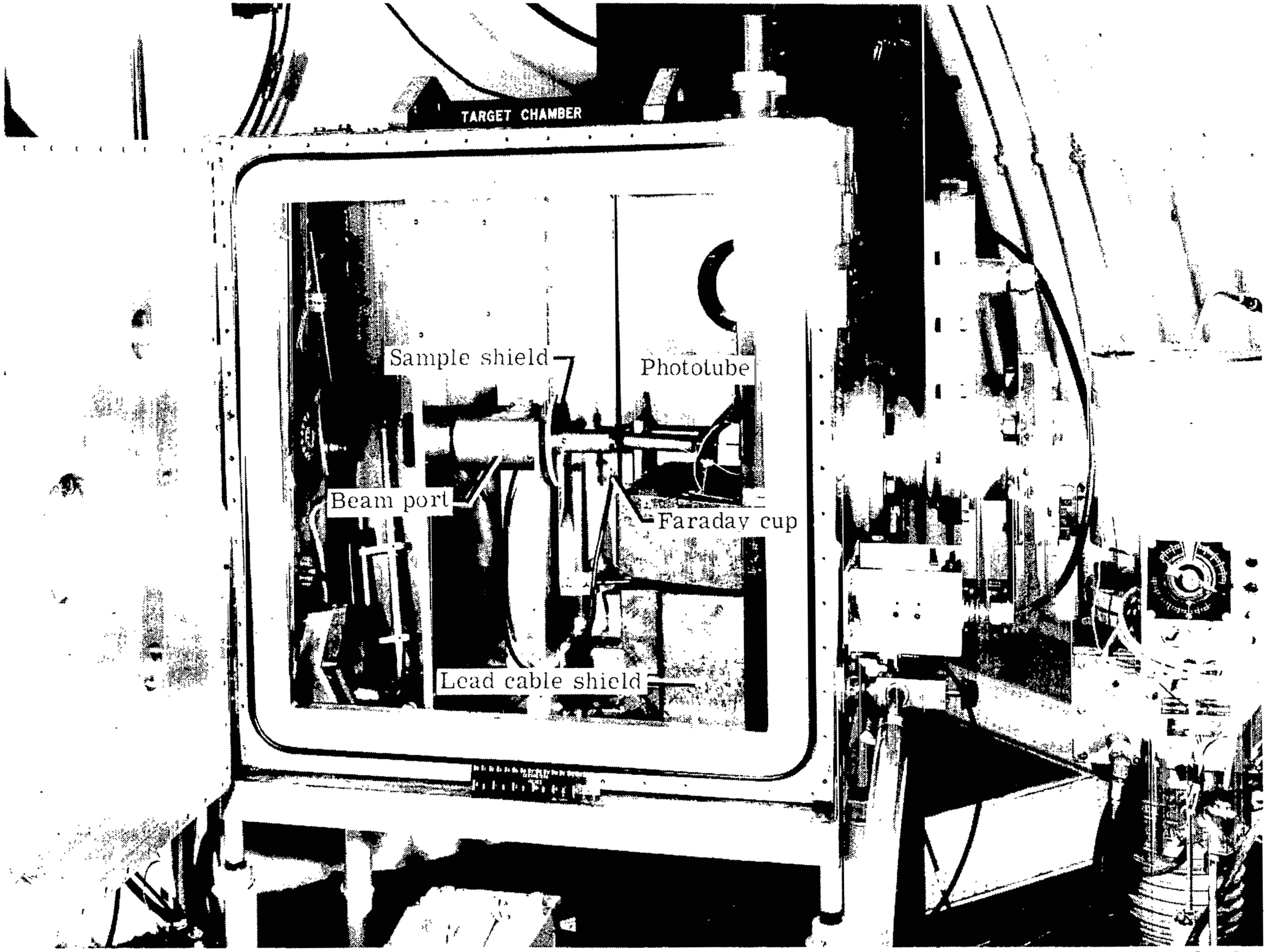

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Figure 3.- Experimental setup.

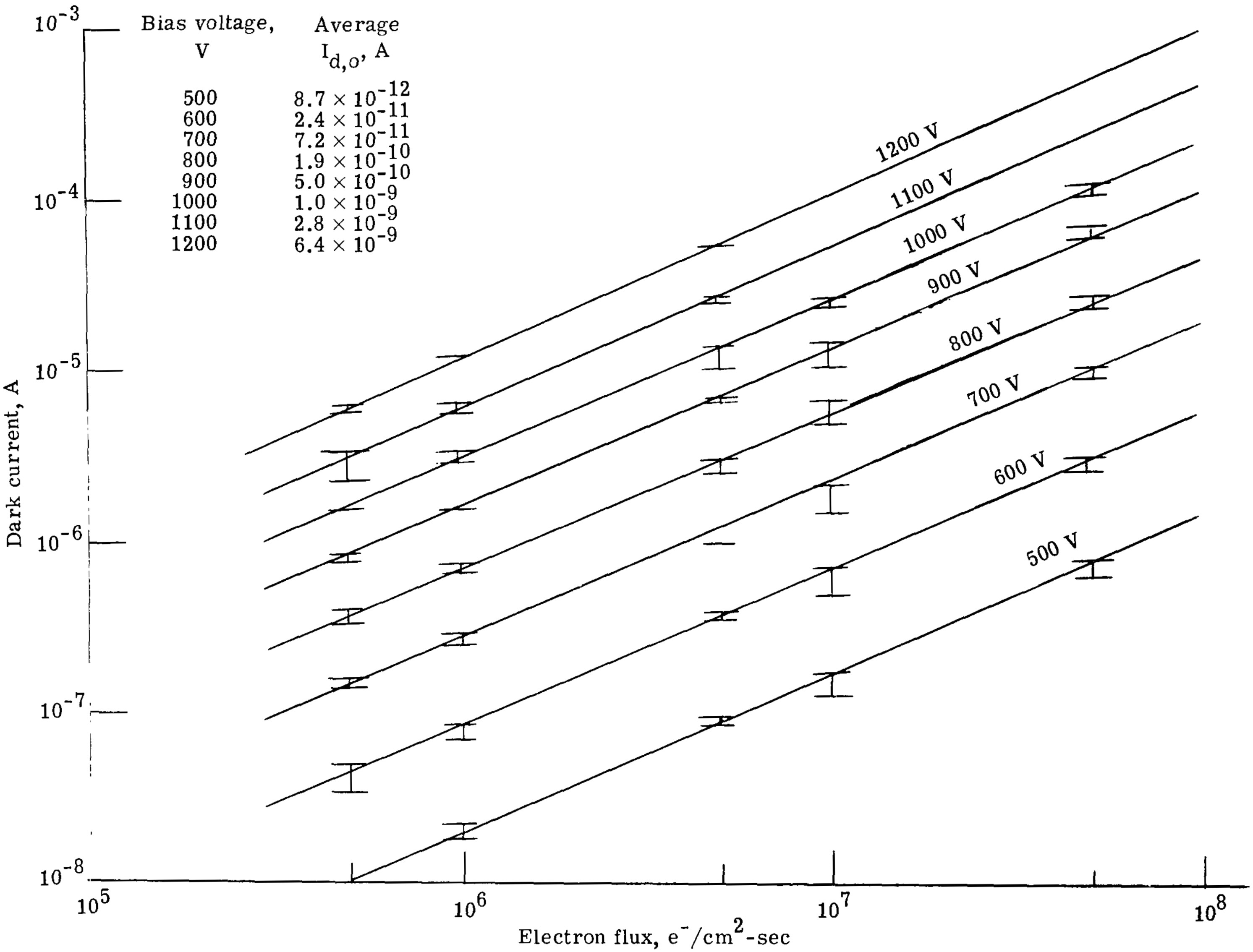

Figure 4.- Results of 2-MeV electrons on PMT 1P21. Lime glass window; Cs-Sb cathode.

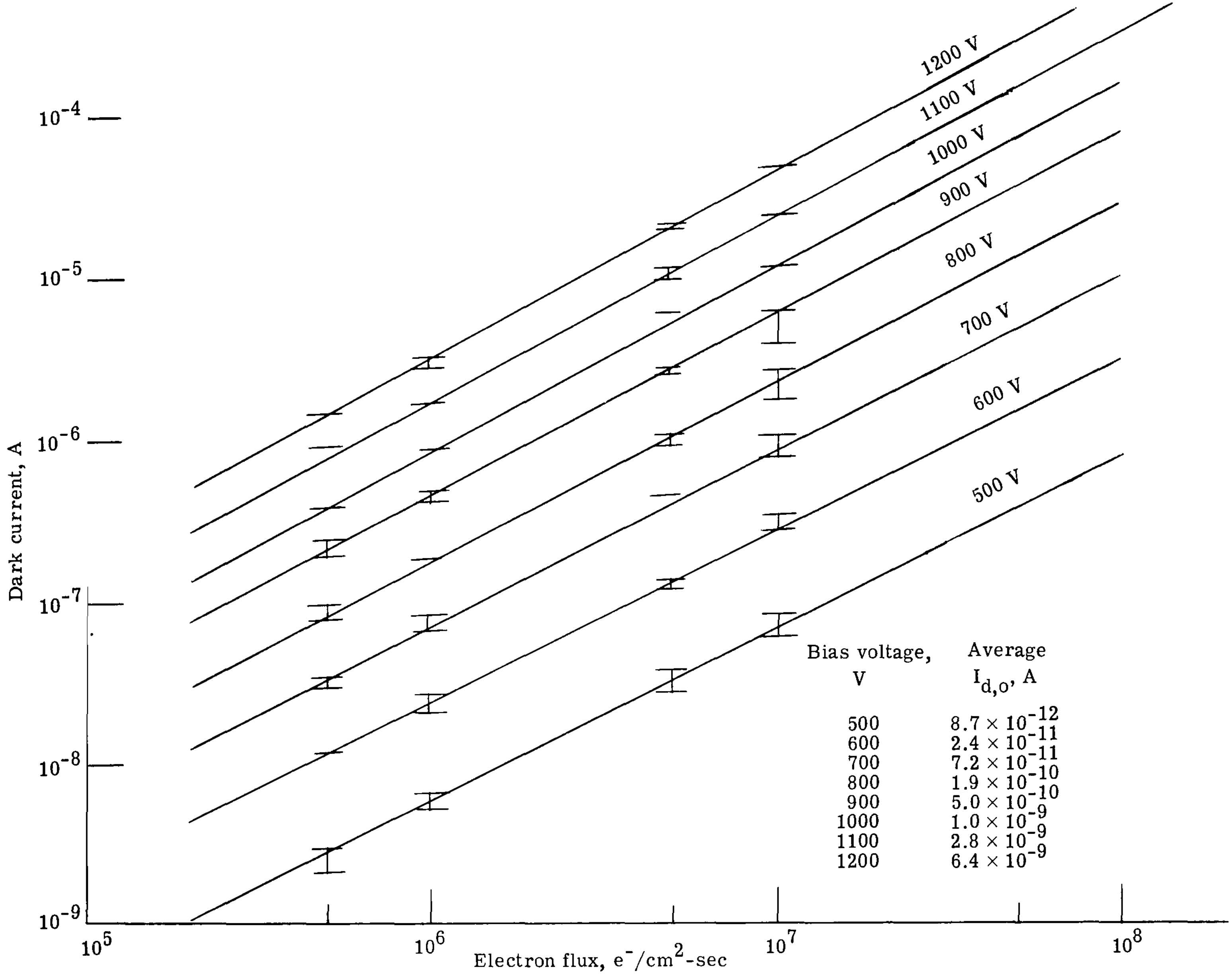

Figure 5.- Results of 1-MeV electrons on PMT 1P21. Lime glass window; Cs-Sb cathode.

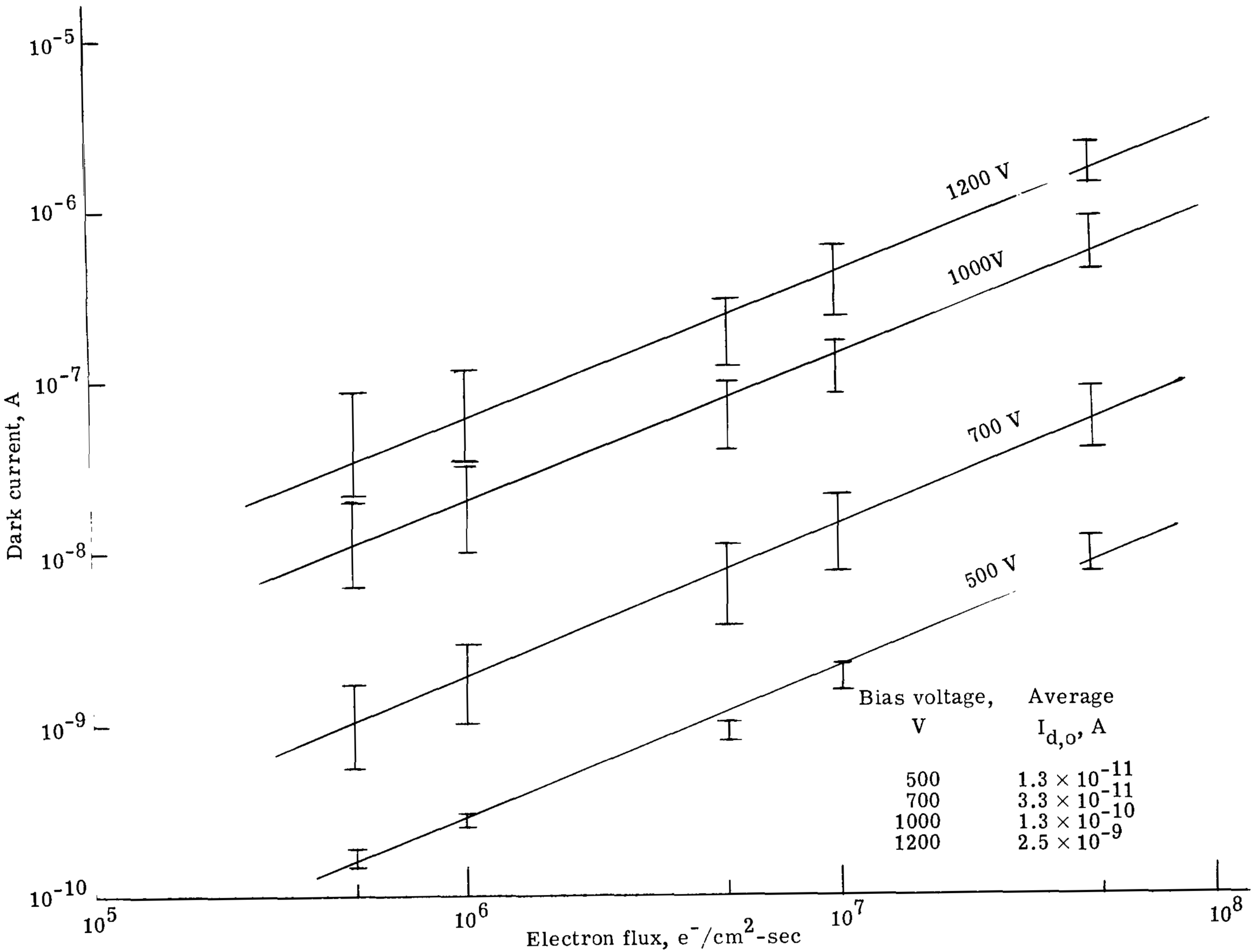

Figure 6.- Results of 2-MeV electrons on PMT 1P22. Lime glass window; Cs-Bi cathode.

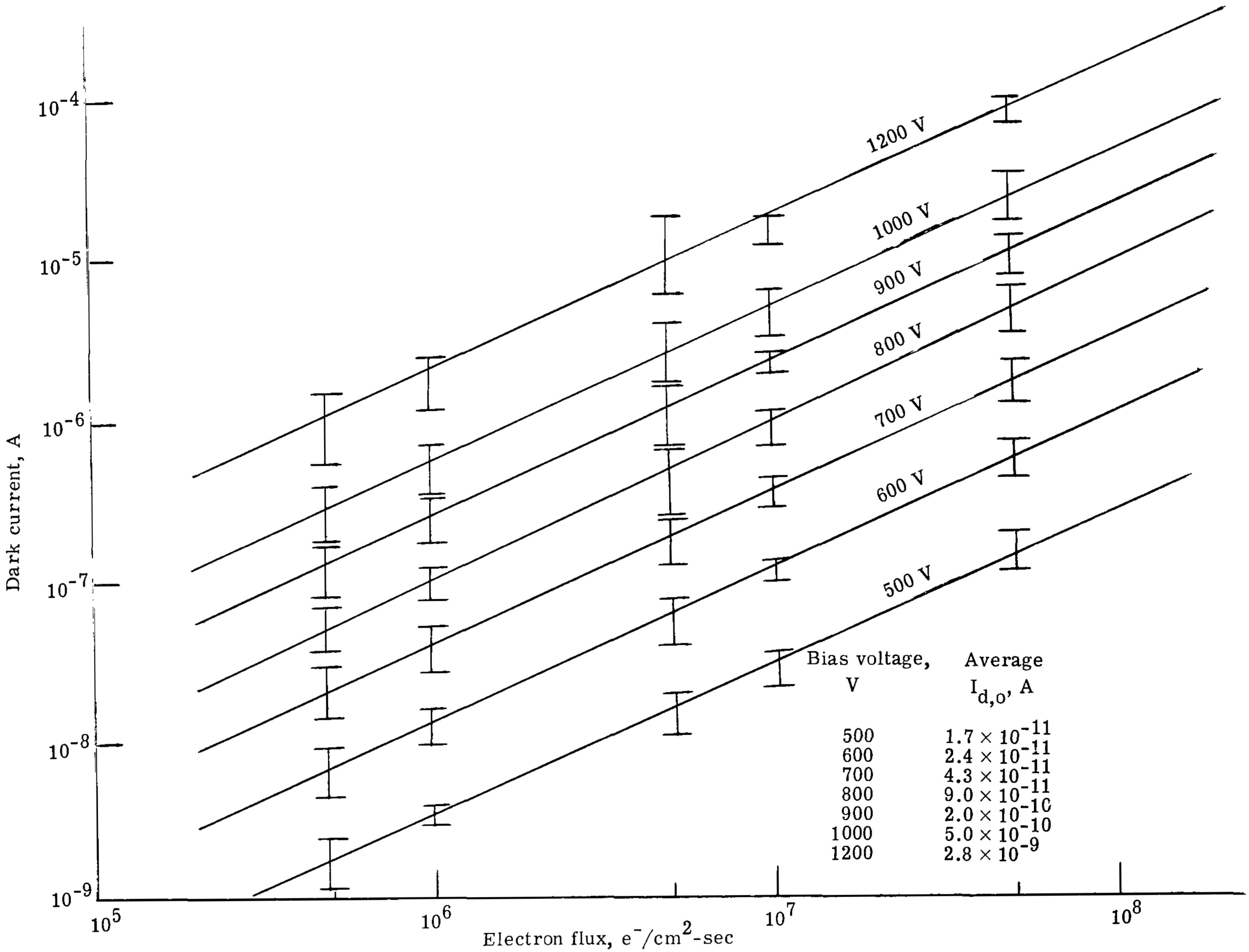

Figure 7.- Results of 2-MeV electrons on PMT 1P28. UV glass window; Cs-Sb cathode.

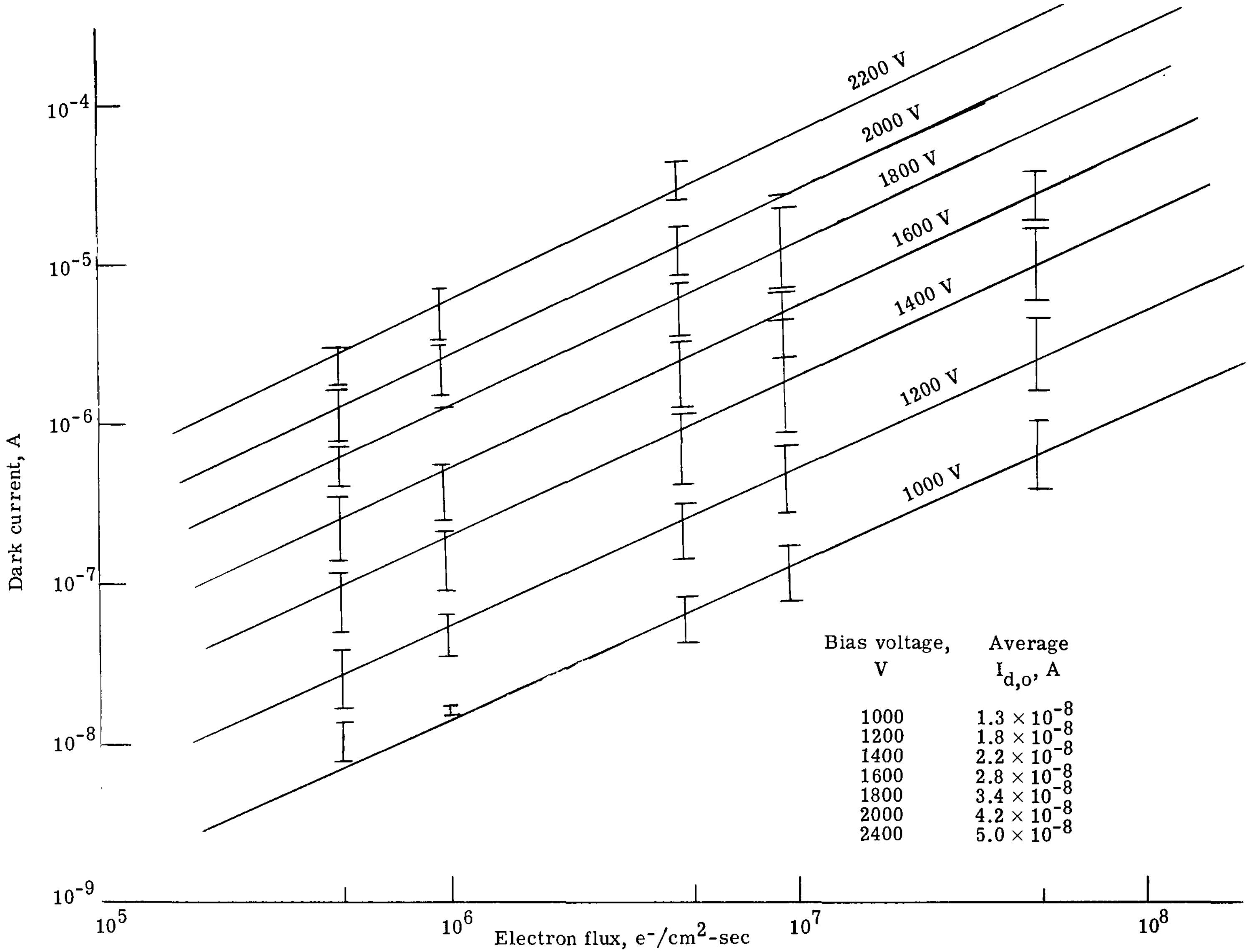

Figure 8.- Results of 2-MeV electrons on PMT 541A. Sapphire window; bialkali cathode.

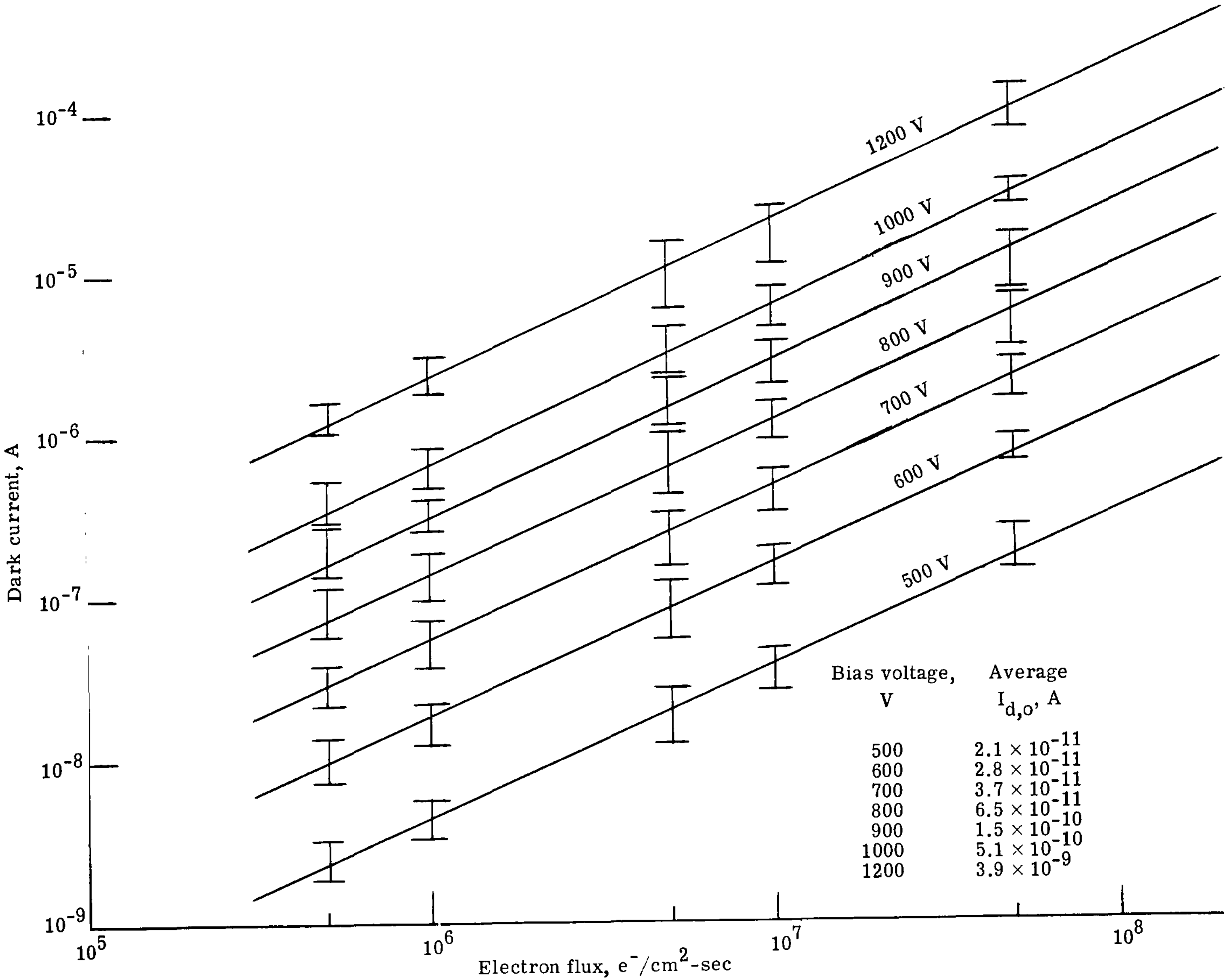

Figure 9.- Results of 2-MeV electrons on PMT 931A. Lime glass window; Cs-Sb cathode.

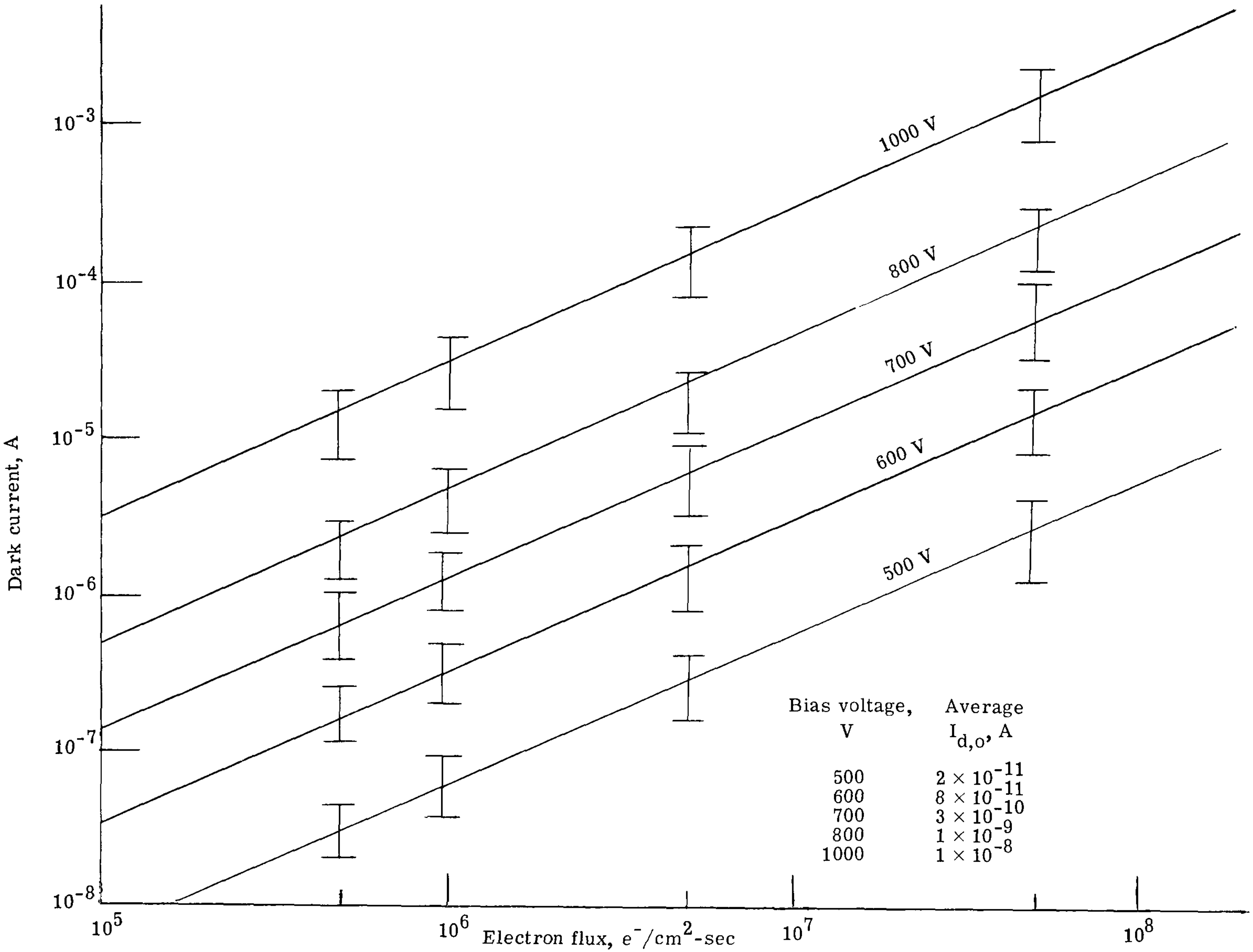

Figure 10.- Results of 2-MeV electrons on PMT 6199. Lime glass window; Cs-Sb cathode.

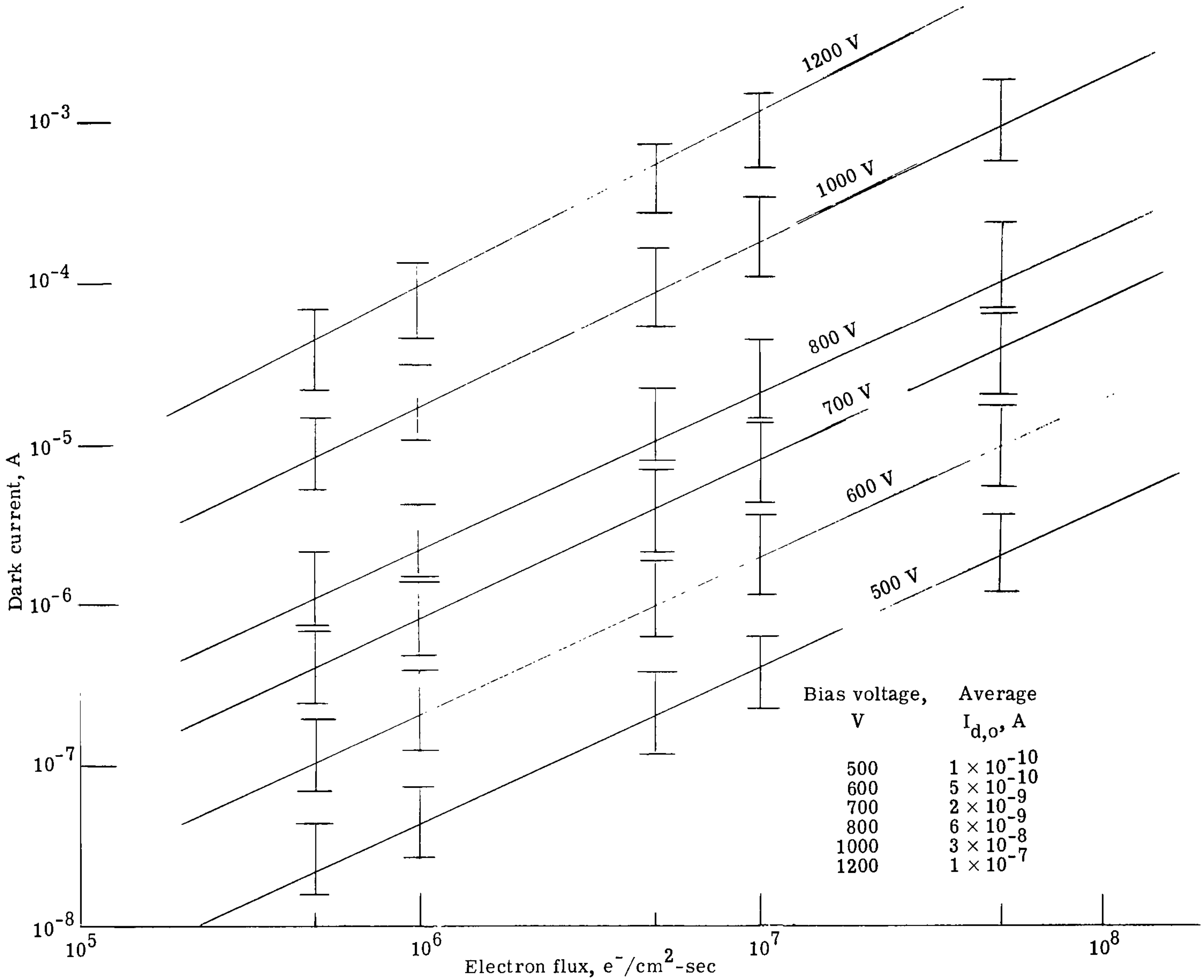

Figure 11.- Results for 2-MeV electrons on PMT 6217. Lime glass window; Ag-Bi-O-Cs cathode.

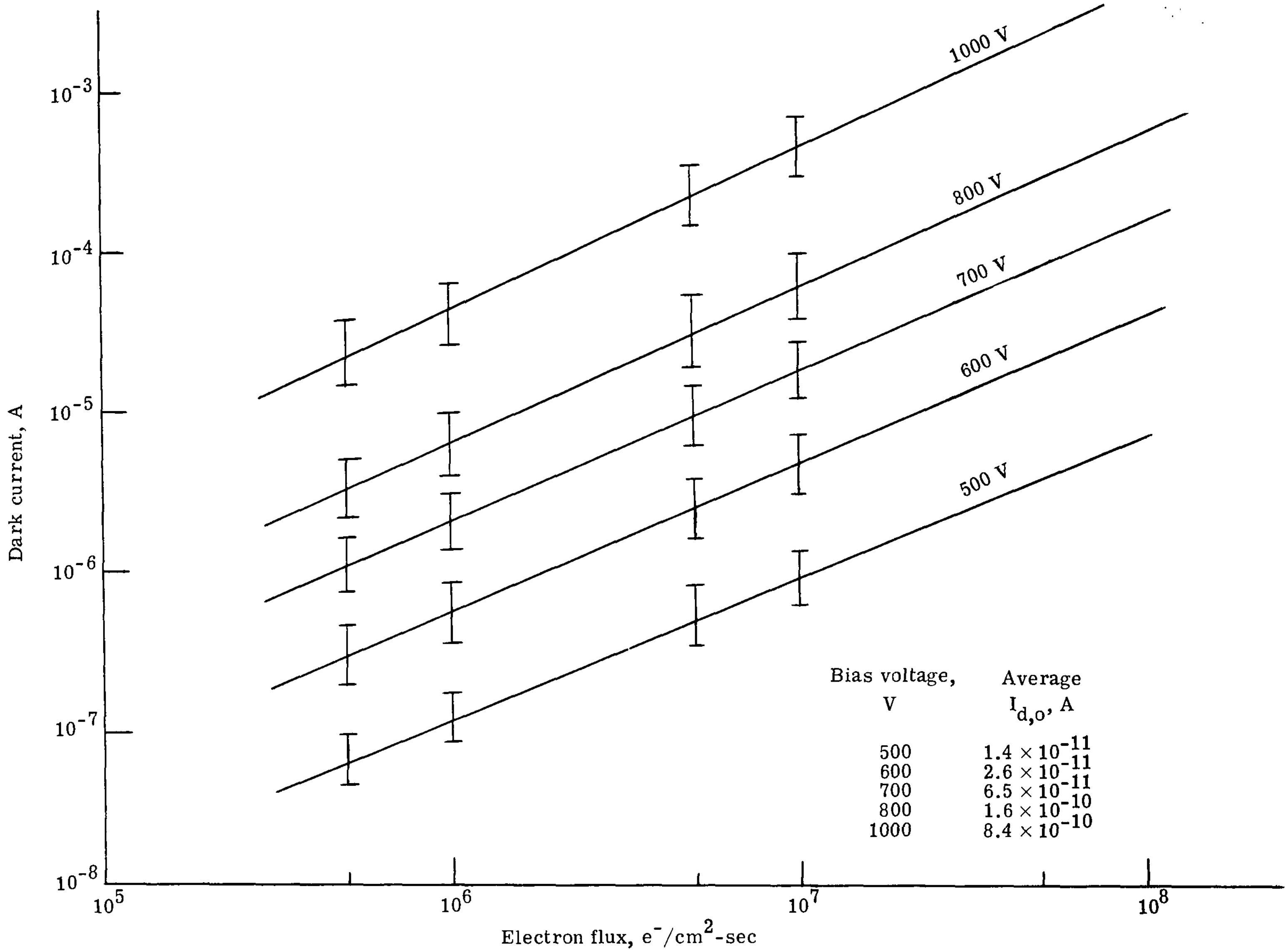

Figure 12.- Results for 2-MeV electrons on PMT 6903. SiO_2 window; Cs-Sb cathode.

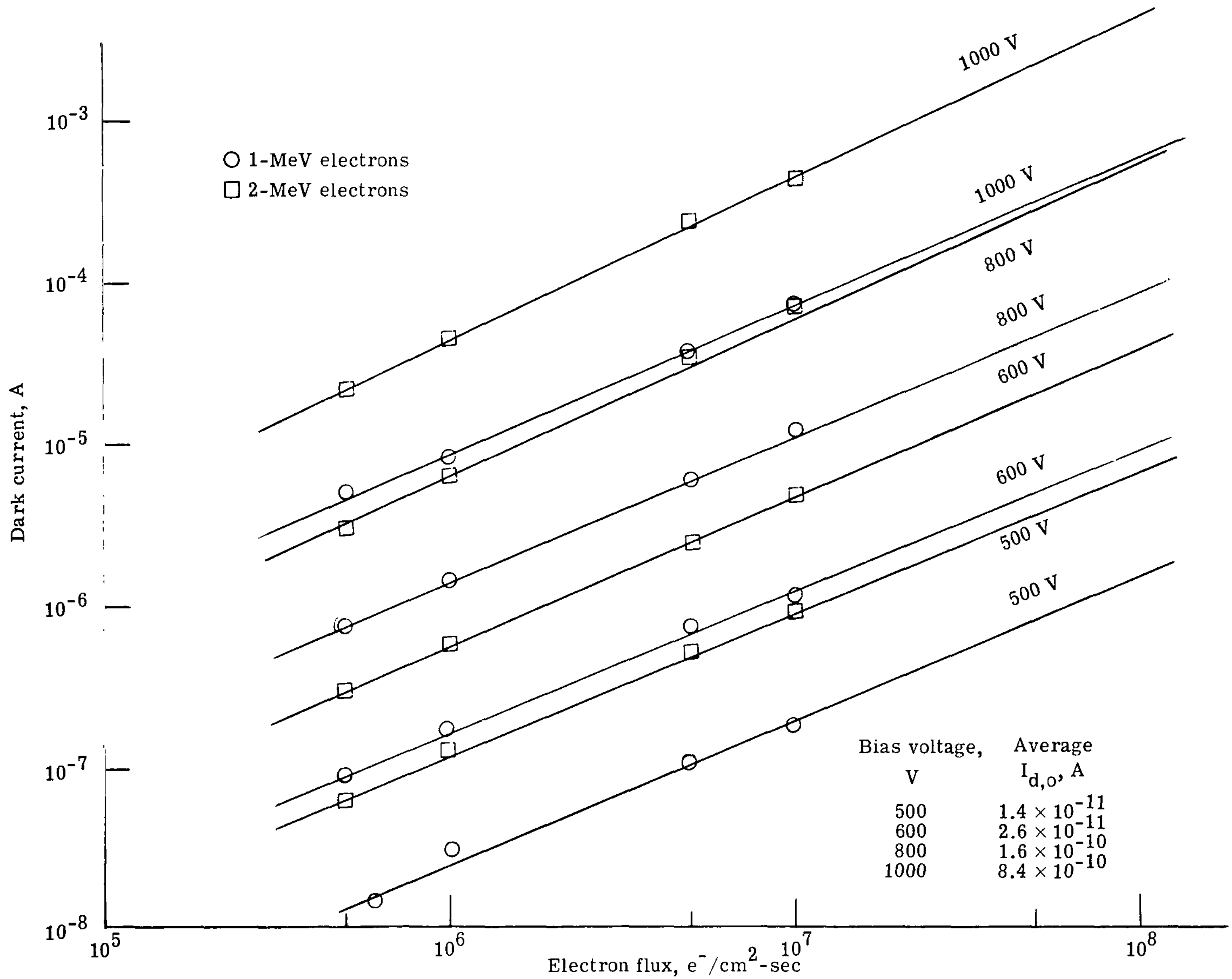

Figure 13.- Effects of 1- and 2-MeV electrons on PMT 6903.

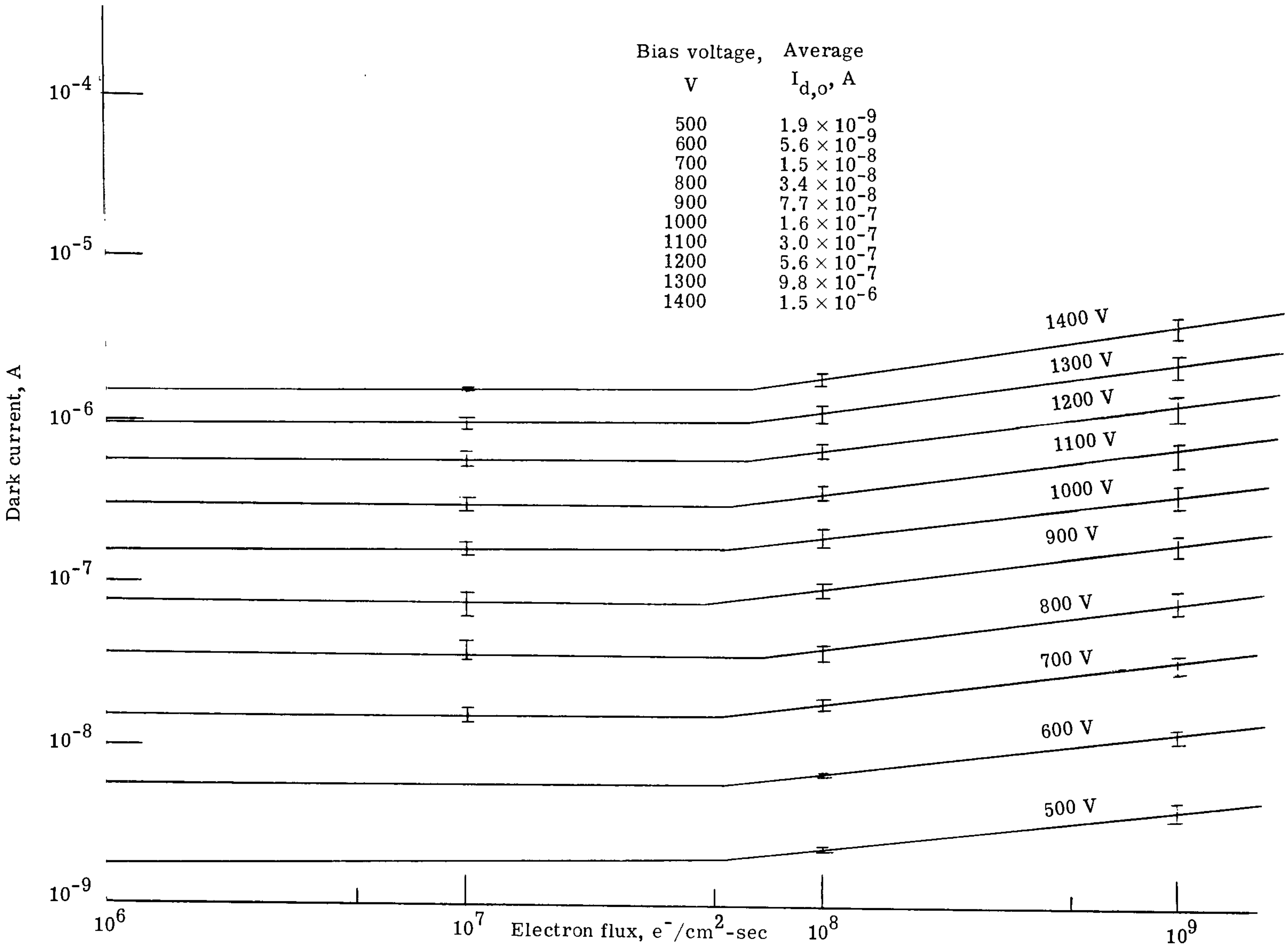

Figure 14.- Results of 2-MeV electrons on PMT 7102. Lime glass (S-1) window; Ag-O-Cs cathode.

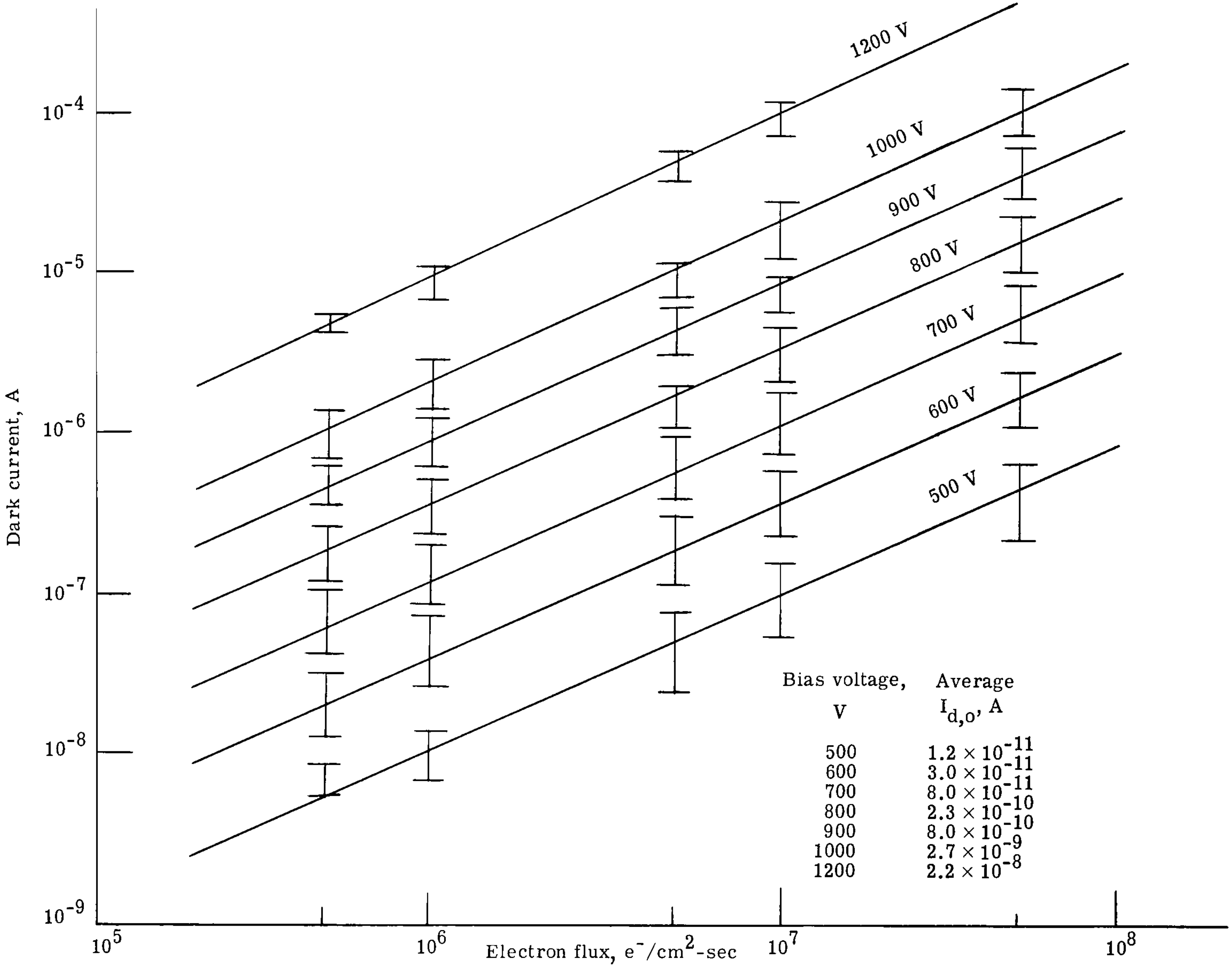

Figure 15.- Results of 2-MeV electrons on PMT 7200. SiO_2 window; Cs-Sb cathode.

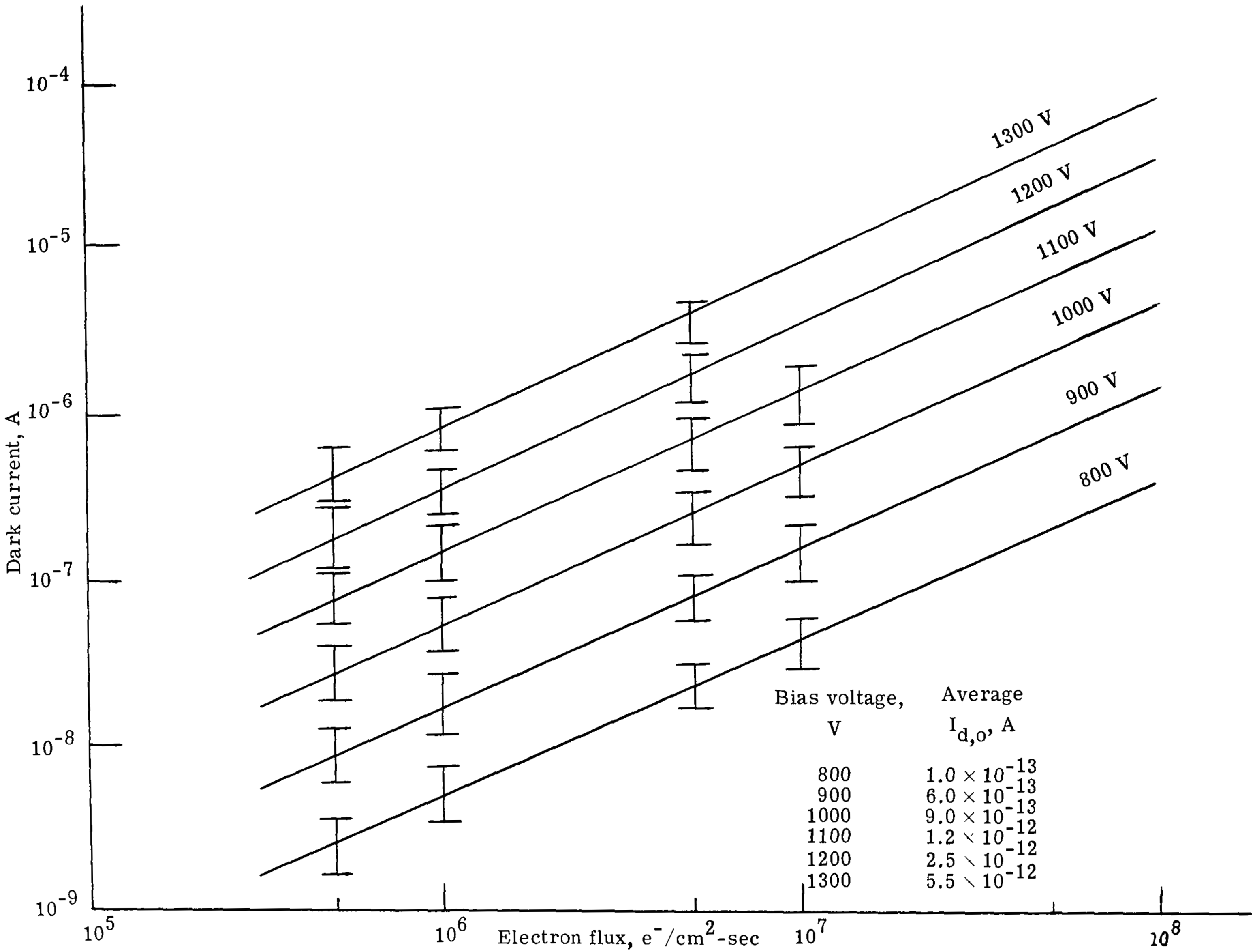

Figure 16.- Results of 2-MeV electrons on PMT 8575. Pyrex glass window; bialkali cathode.

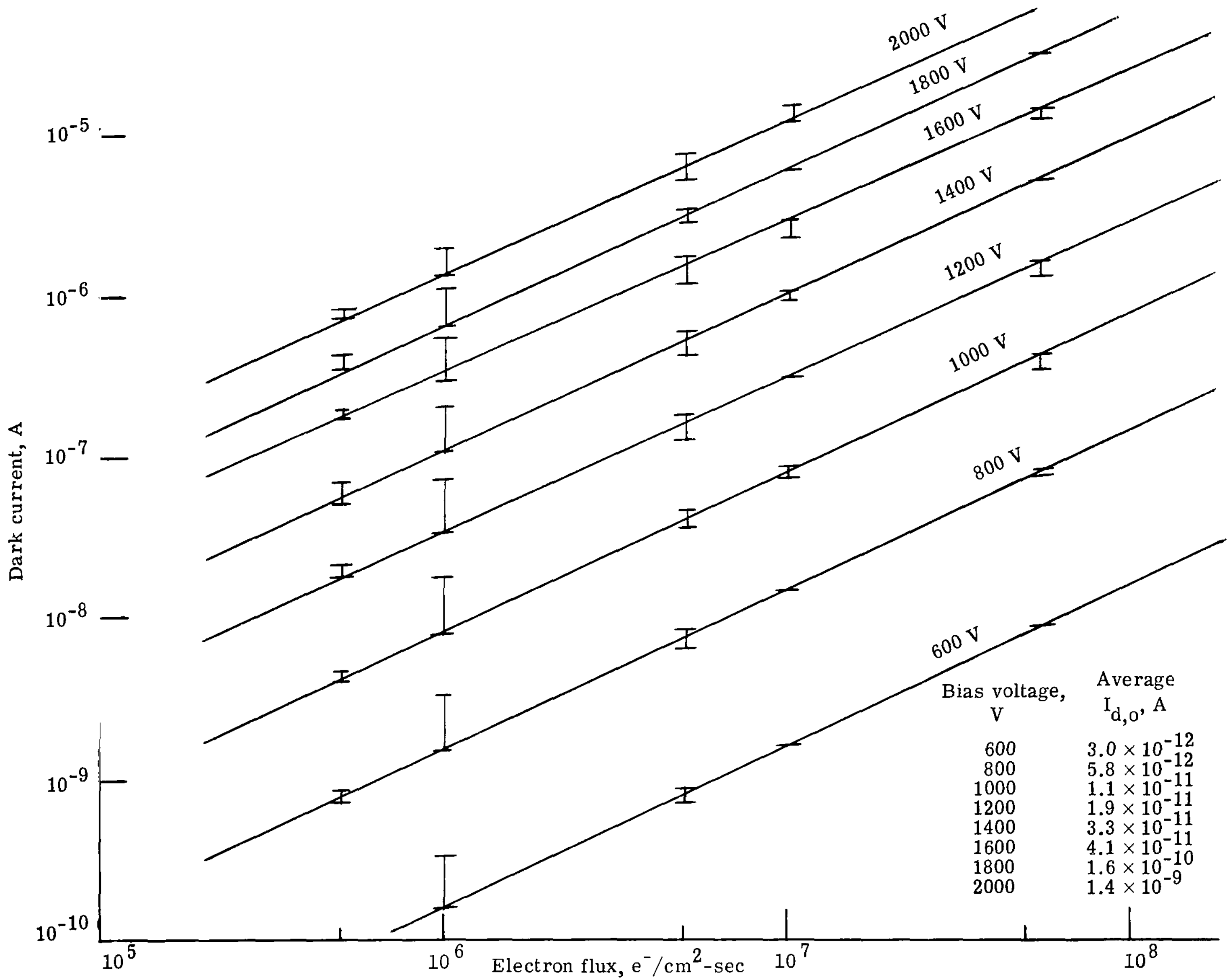

Figure 17.- Results of 2-MeV electrons on PMT 8644. Borosilicate window; K-Na-Cs-Sb cathode.

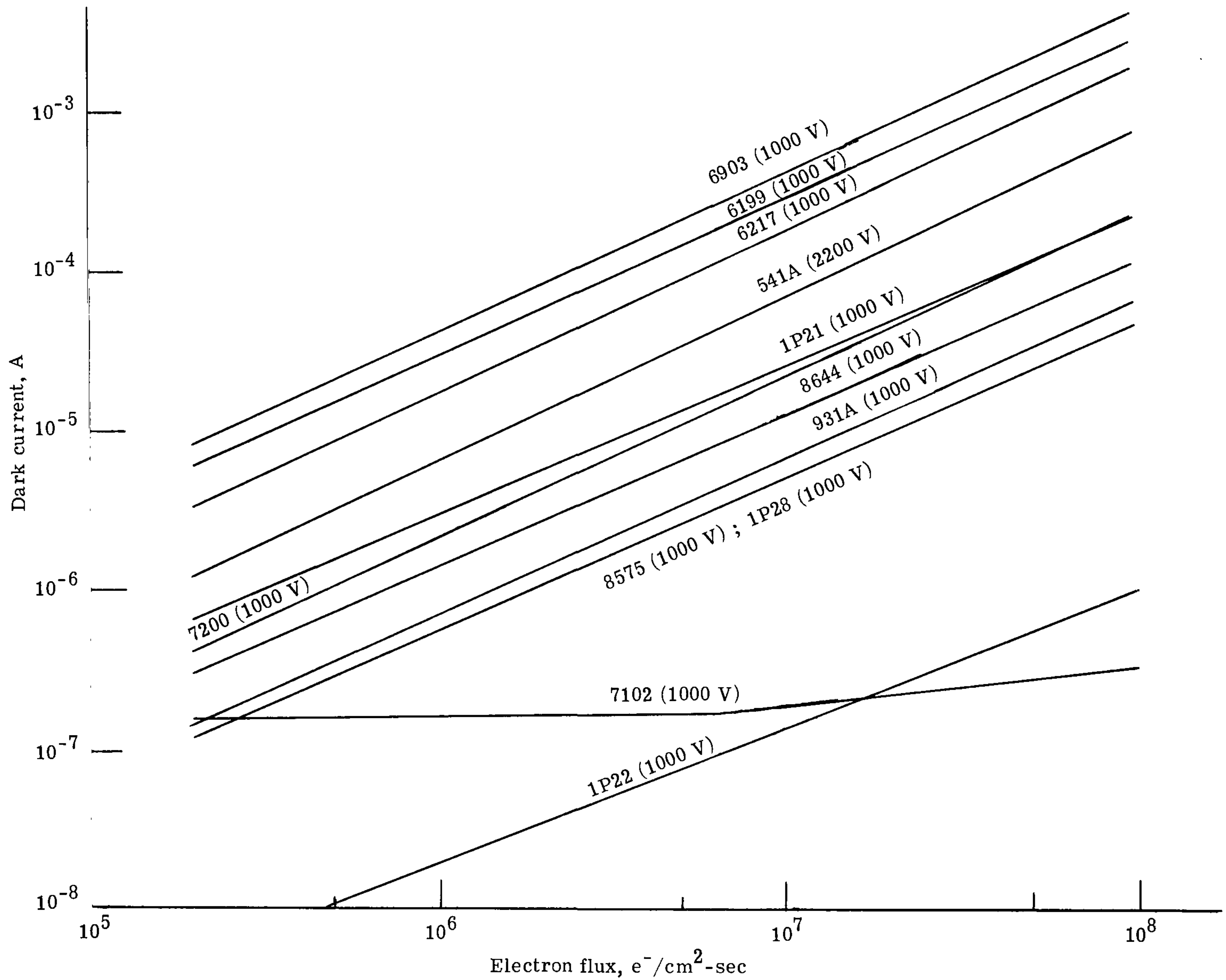

Figure 18.- Comparison of various PMT types at an arbitrary bias voltage for irradiation with 2-MeV electrons.

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