This article first appeared in the Sept. 1944 issue of "Electronics".

Secondary Electron Radiation

By J. H. OWEN HARRIES

A thorough survey of existing American, British, and other information on the subject, arranged for maximum usefulness to electronic engineers engaged in designing electron multipliers, dynatrons, beam tetrodes, pentodes, and other tubes in which secondary electrons resulting from electron bombardment are either utilized or suppressed

When an electron stream strikes an electrode surface, or, indeed, any surface, an emission of secondary electrons is produced. There is no known substance in which this effect does not occur. In fact, there is no substance that is known to act as a perfect absorber of any electrons that may impact onto it.

In electronic tubes, secondary radiation is sometimes useful, and sometimes undesirable. The phenomenon is complex, and information about it is scattered in various treatises many of which are commonly read only by those interested in pure physics. Most of these publications deal with the characteristics of secondary radiation, not from any interest in it for engineering purposes, but as a part of investigations into atomic structure.

This paper includes a survey of the existing information on secondary radiation and is presented from the engineering standpoint. It includes references to the original papers.

Energy Distribution of Secondary Electrons

In most treatises on secondary radiation, the electron energies are expressed in volts. The velocity v in centimeters per second of an electron that has fallen

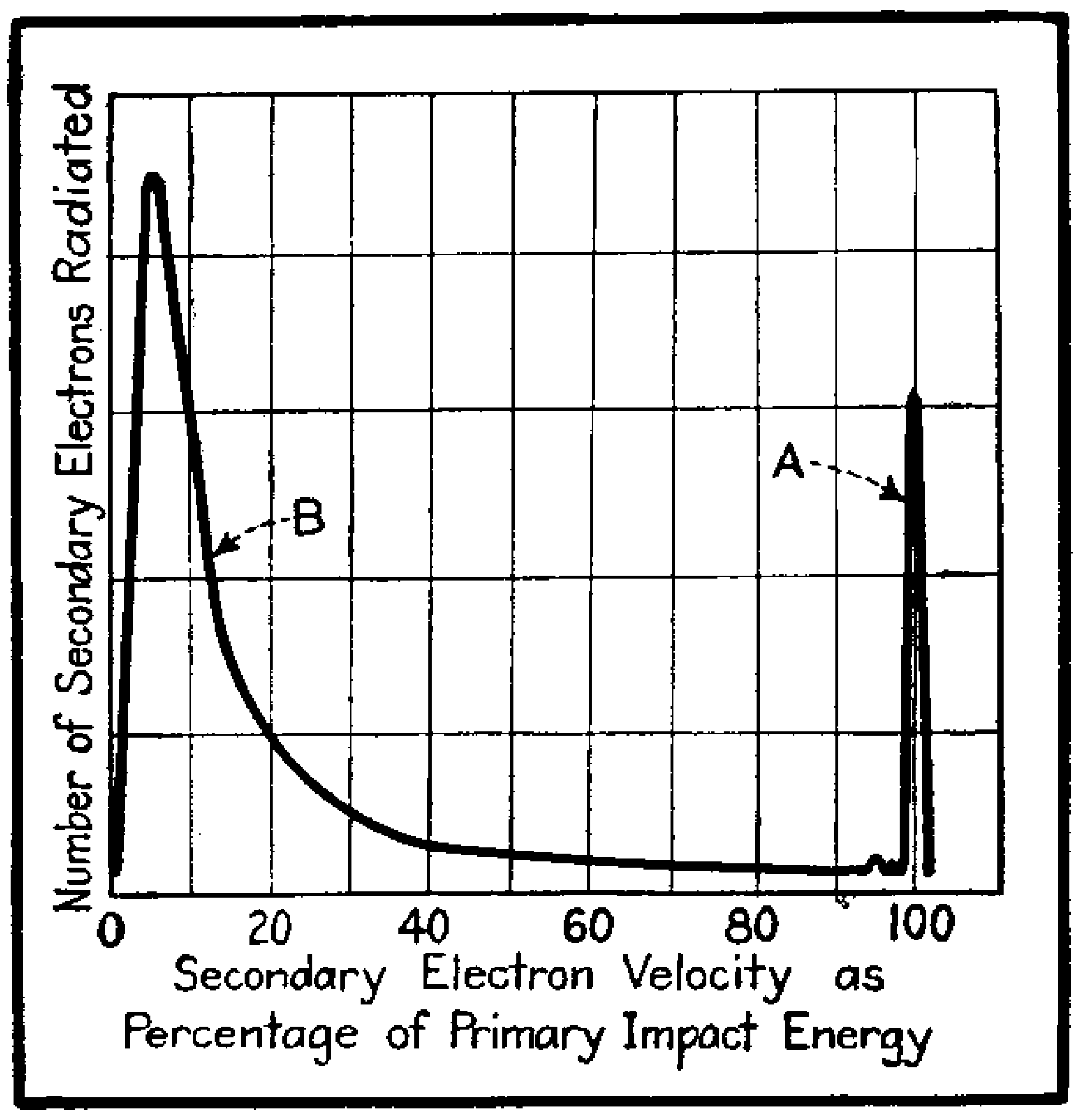

Fig. 1.—Energy distribution of secondary electrons produced by the impact of primary electrons having a kinetic energy of 155 volts. The general shape of this curve holds between 20 to 10,000 volts.

through an electrostatic potential of V volts is $v = 5.95 \times 10^4 \sqrt{V}$. The kinetic energy of the electron is $\frac{1}{2}mv^2$ and is, therefore, proportional to the voltage V.

In many publications on electronic engineering, as distinct from treatises on the physics of secondary electrons, it is sometimes stated that secondary electrons are radiated almost entirely at energies very low compared with the primary impact energy. This is not so.

A typical curve of energy distribution of secondary electrons is shown in Fig. 1. In this graph the number of secondary electrons radiated is plotted against the velocity (energy) with which the secondary electrons are shot out from a radiating surface. These secondary electron energies are plotted as a percentage of the primary impact energy. The primary impact energy is 155 volts. It will be observed that an appreciable number of secondaries are radiated at energies about equal to the primary impact energy, although there are a larger number radiated at very low velocities. Very thorough researches have been made during the last two decades into this question of secondary radiation energy distribution.[1–19]

Methods of Determining Energy-distribution Curve

The general kind of energy distribution of the secondary electrons shown in Fig. 1 appears to hold over quite a wide range of primary impact velocities (20 to 10,000 volts).[2] It has been confirmed very carefully for most of the pure metals, and is known to hold in general for the other materials employed in radio tubes.

This kind of secondary electron energy distribution does not appear to depend on the angle of incidence of the primary beam onto the emitting surface,[13,20] nor does it appear to depend on the angle of emergence of the secondary electrons, though this point does not appear to have been quite so conclusively demonstrated by workers in this field.

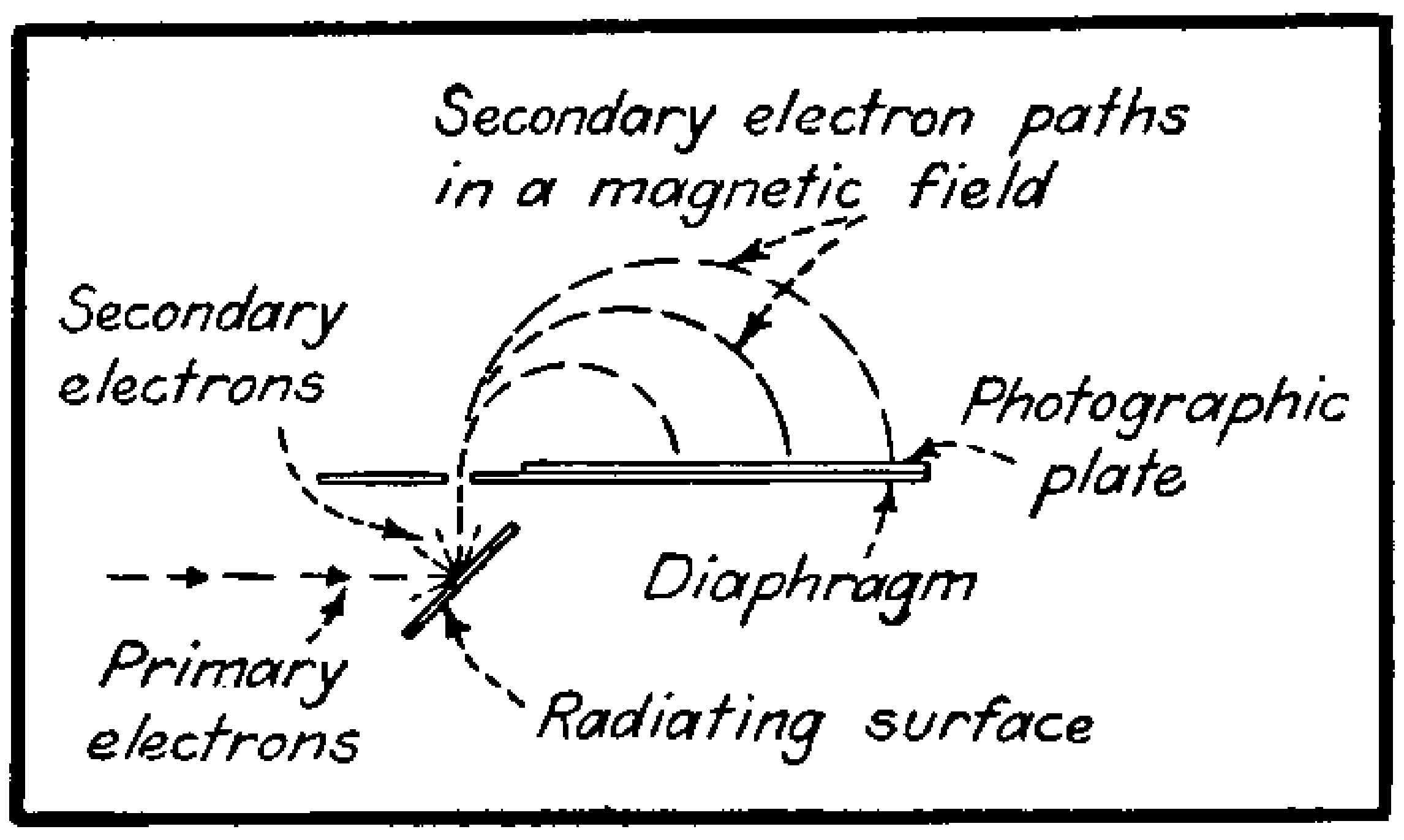

Fig. 2.—Photographic method of determining the velocity distribution of secondary electrons. A magnetic field is assumed to exist in the space above the diaphragm with a direction normal to the plane of the paper.

In Fig. 2 an electron gun is arranged to produce a beam of primary electrons at a known velocity. The primary electrons are arranged to collide with a surface which then radiates secondary electrons. Some of the secondary electrons can pass through an aperture in a diaphragm into a space in which there exists a homogeneous magnetic field in the direction normal to the plane of the paper. It is a well-known property of such a magnetic field that electrons traveling into it as shown will tend to describe circles the radii of which are given by

$$r = 3.37 \sqrt{V_s B} \tag{1}$$

where B is the magnetic flux density, and V_s is the secondary electron energy in volts.

A photographic plate is positioned as shown. The number of electrons of any given velocity reaching the plate will be indicated by blackening at the appropriate place. This method, however, is not very practicable, because the sensitivity of a photographic plate is rather low.

A Faraday cylinder, which has the property of trapping electrons and the secondaries they produce, can be substituted for the photographic plate as in Fig. 3. By varying the magnetic field, the number of secondary electrons of each velocity may be found.

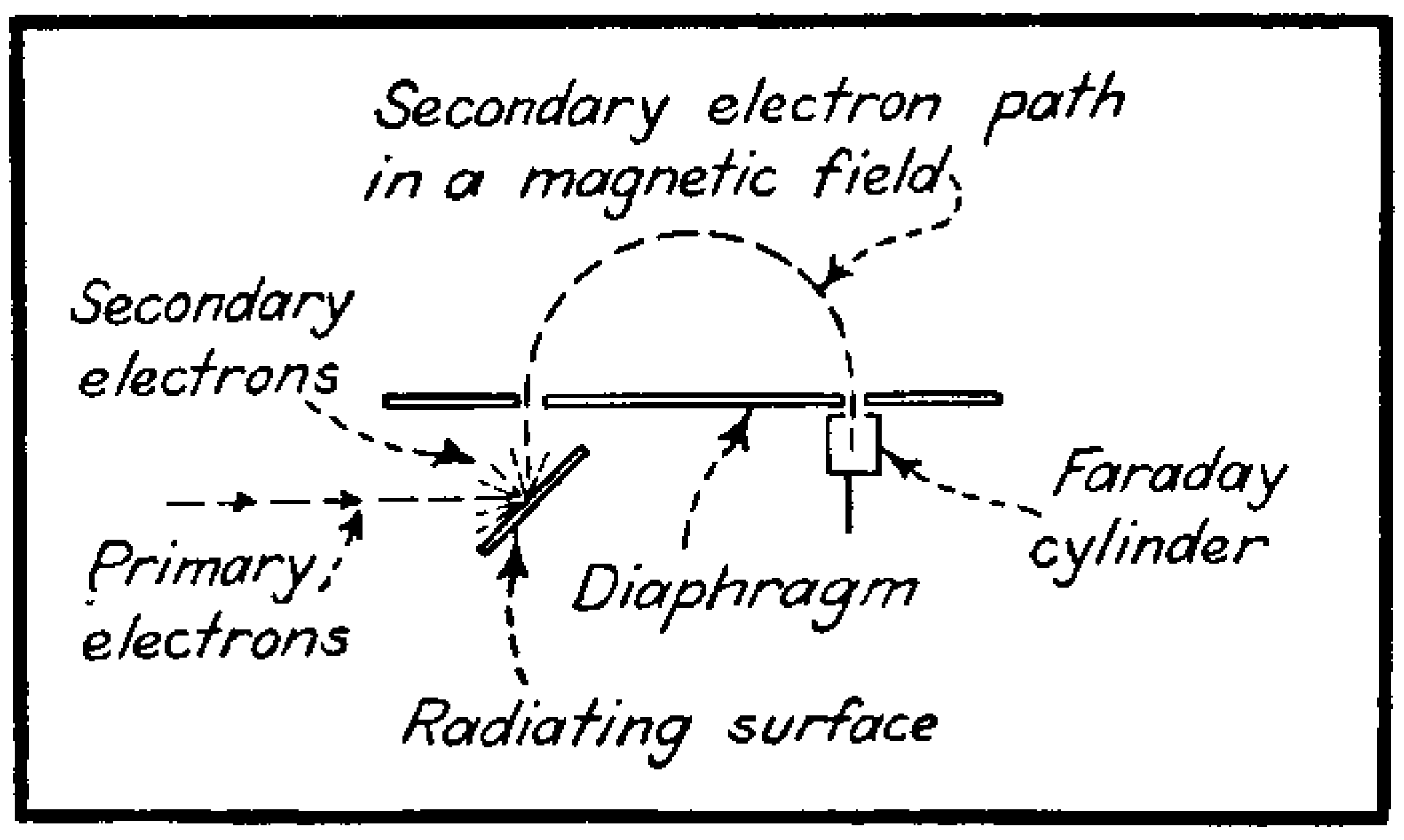

Fig. 3.—Another method of arriving at the velocity distribution of secondary electrons. The magnetic field in this case is variable.

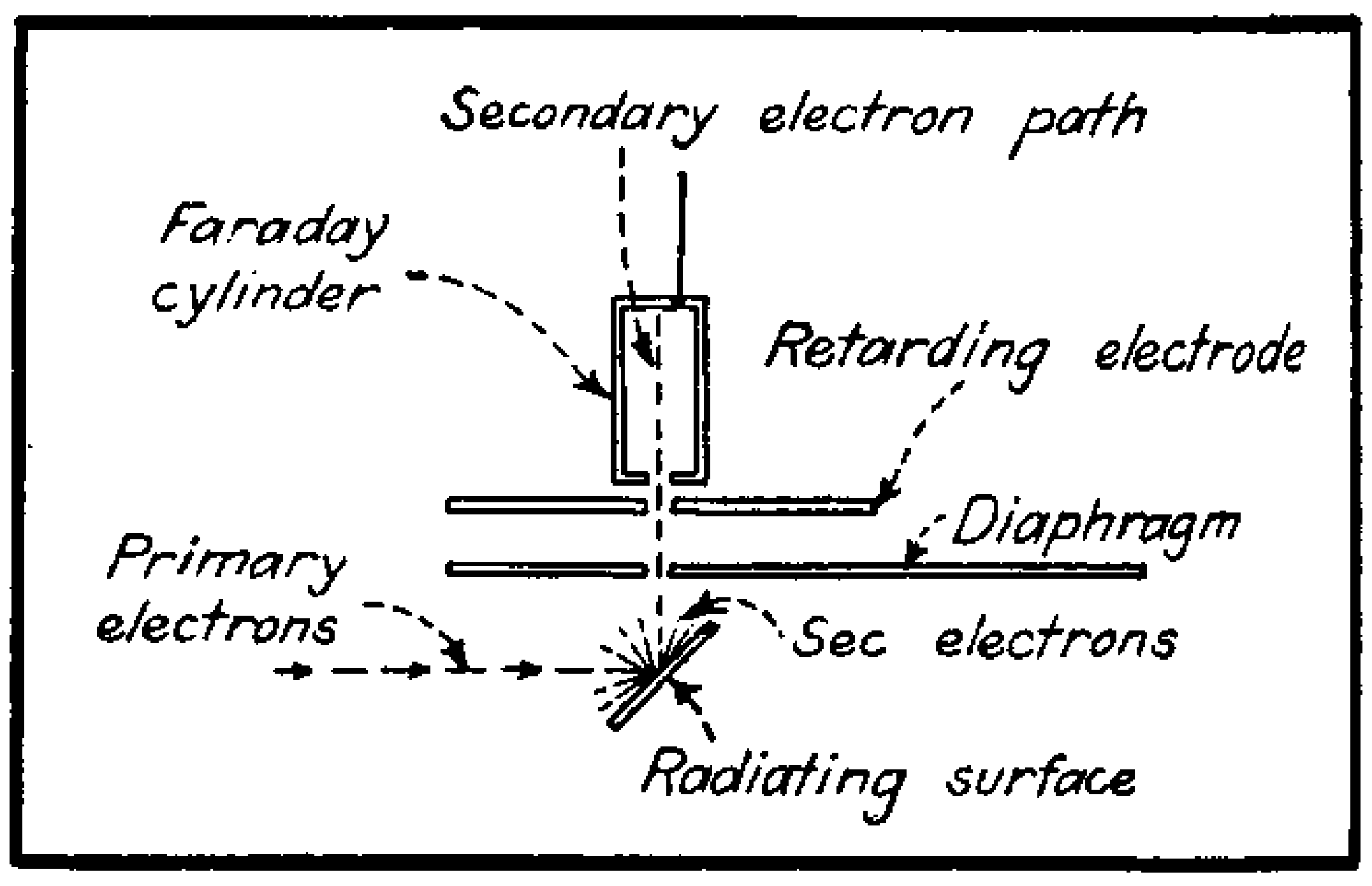

Fig. 4.—The retarding potential method of arriving at the velocity distribution of secondary electrons radiated in a specific direction.

Another method, shown in Fig. 4, does not use a magnetic field but, instead, employs a retarding potential to sort out the secondary electrons in terms of their energies. The primary electrons hit a secondary radiator at a known energy, and secondary electrons pass through a diaphragm into a Faraday cylinder. The amount which are able to enter depends on the potential of a retarding electrode positioned as shown and on the initial energies of the secondaries themselves.

The arrangement of Fig. 5 enables the energies to be obtained for the secondary electrons at all angles. The primary electron beam strikes a radiating surface which is at the center point of a collecting sphere. A retarding potential is applied to this sphere, and the number of electrons reaching it is measured as a function of this potential.

In the arrangements of Figs. 4 and 5, the energy-distribution curve is obtained by differentiation of the curve of current to the Faraday cylinder or collection sphere as a function of the retarding potential.

Interpretation of Curve

The general results of all these methods agree. The particular curve shown in

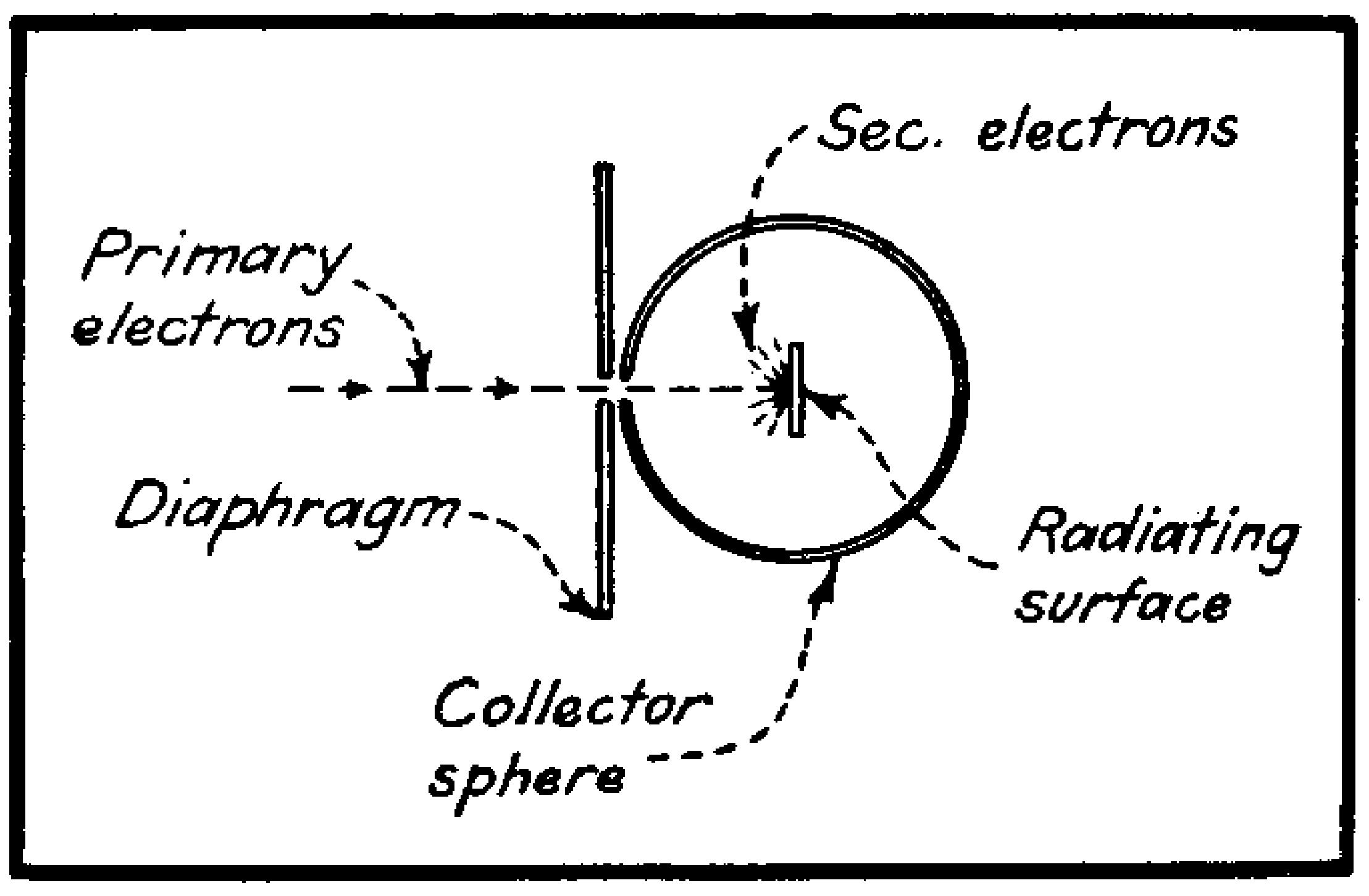

Fig. 5.—The retarding potential method of arriving at the velocity distribution of secondary electrons emitted and reflected from a radiating surface.

Fig. 1 is given by Rudberg and is obtained by the magnetic method.

It is generally agreed that the energy-distribution curve of Fig. 1 may be interpreted as follows: Peak A represents that portion of the emergent electrons which retains the full primary energy. At secondary electron velocities between about 98 and 50 per cent of the primary velocity, the number of secondary electrons radiated does not change much with the secondary electron velocity. Large quantities of secondary electrons are emitted with low velocities, as indicated by peak B, but the number emitted drops rapidly as secondary velocity approaches zero (at secondary energies of the order of tenths of a volt and less).

Peak A of the curve is produced by electrons that emerge after being elastically reflected. They result from diffraction unaccompanied by loss of energy to the atoms that are being bombarded by the primary electrons. All other parts of the curve are produced by secondary electrons that have been deflected by repeated collision accompanied by considerable energy loss.

Those secondaries contributing to parts of the curve other than A are usually referred to as emitted or true secondary electrons. Those contributing to part A of the curve are usually referred to as reflected electrons. For this reason, the phenomenon as a whole is usually referred to as secondary radiation, and the words emitted and reflected are reserved for the special meanings set out.

Action of Low Impact Velocities

With primary impact velocities below about 10 volts, it has been found that the energy distribution of Fig. 1 does not hold. The secondary radiation consists almost entirely of reflected electrons that retain the full primary energy, so that the whole of the radiation is contained in a peak like A on Fig. 1.

The percentage of emitted secondary electrons to reflected secondary electrons increases steadily up to primary velocities of the order of 1,000 volts, after which it falls once again. As previously mentioned, however, the general shape of Fig. 1 holds between about 20 and 10,000 volts.

Space Potential Considerations

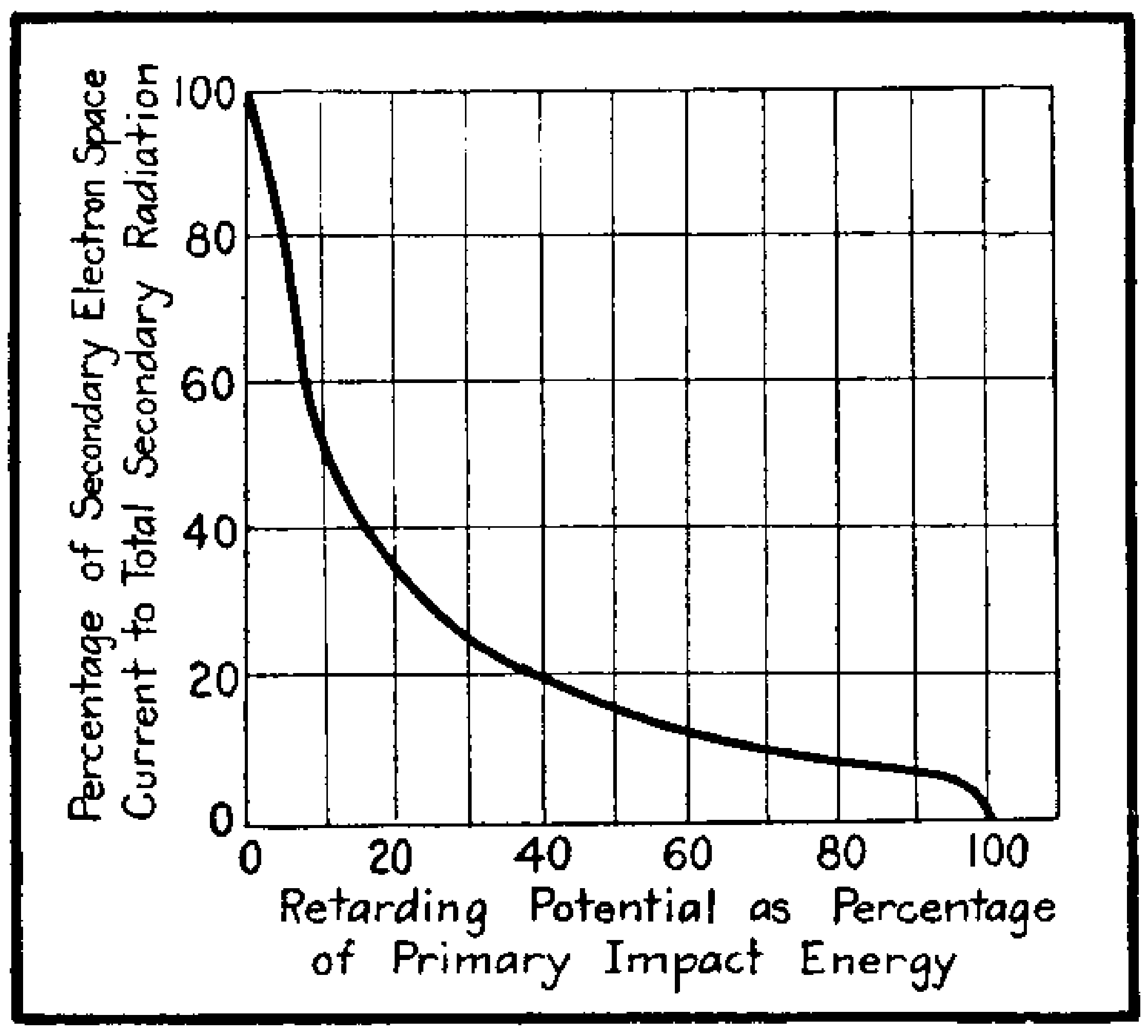

Fig. 6.—Ratio of secondary electron current traveling to a collector and the total secondary radiation, plotted as a function of the retarding potential between the radiator and the collector.

It is important to realize that under electrostatic conditions the velocity of each of the secondary electrons at any point in space will be determined by the space potential V of that point. It follows that an electron emitted at a velocity which corresponds to a voltage V_s will be brought to rest at any point in space where a negative space potential $-V$ numerically equals V_s. This is the principle by which secondary electrons are sorted into their respective velocities (or energies) by means of the retarding electrode or collecting sphere of Figs. 4 and 5, respectively. A potential that is arranged in this way to stop secondary electrons is generally referred to as a retarding potential.

Figure 6, which is obtained by integration of Fig. 1, shows the ratio of secondary electron current to any collector (such as the collector sphere in Fig. 5) to the total secondary radiation current as a function of the retarding potential. This potential is expressed as a percentage of the impact energy in volts.

In pentodes and beam tetrodes, the prevention of the flow of secondary electrons is one of the primary objects of the tube design. With reference to Fig. 5, it will be realized that if the collector sphere is at a potential (with respect to the cathode) which is 90 per cent of the impact potential of the radiator (also measured in volts with respect to the cathode), then a retarding potential of 10 per cent will exist between the collector sphere and the radiator. Figure 6 shows that under this condition the secondary radiation current flowing to the collector electrode will be 54 per cent of the total secondary radiation from the radiator.

All this, of course, assumes quasi-steady-state conditions as regards voltage (*i.e.*, that the voltage does not vary rapidly with time) and that no appreciable space charge due to the primary or secondary electrons exists in the space between the emitter and the collector sphere. The physics measurements quoted in this paper are all made under static conditions, and care has been taken to avoid space-charge effects, but these effects must not be forgotten when applying the information to practical radio tubes.

Table 1.—Maximum Total Secondary Radiation Coefficients

Secondary emitter	Max. value of sec. radiation coeff.	Primary impact velocity (volts) at which max. of sec. radiation coeff. occurs
Cesium (compound layer)	8.5	400–600
Rubidium (compound layer)	5.75	700
Beryllium	5.4	600
Calcium	4.95	520
Barium	2.72	530
Potassium (compound layer)	2.5	600
Aluminum	2.4	400
Silicon	1.63	380
Platinum	1.52	1,000
Silver	1.47	800
Gold	1.45	780
Tungsten	1.33	625
Nickel	1.3	500
Tantalum	1.3	625
Copper	1.27	600
Iron	1.27	400
Molybdenum	1.27	375
Niobium	1.17	400
Carbon (lampblack)	0.6–1	

Such tubes when in operation are seldom free from space-charge effects.

Some relationship exists between the secondary energy distribution curve and the material of the emitter. This has been found by Sharman[15] to be in agreement with the atomic properties of the material. At voltages of the order of 8,000 volts, however, Stehberger[21] failed to find any such connection. The answer to this question is rather vague at present.

Angular Distribution of Secondary Radiation

The relative amount of secondary radiation at various angles from a surface may be determined by apparatus such as that illustrated in Fig. 7. The Faraday collector is rotatable with respect to the radiating surface. The angle of incidence of the primary electrons to the normal of this surface is indicated by α and the angle of secondary radiation by β. The number of secondary electrons per unit angle may thus be determined.

Measurements of angular distribution have been carried out by a number of workers.[21-25] While there is some experi-

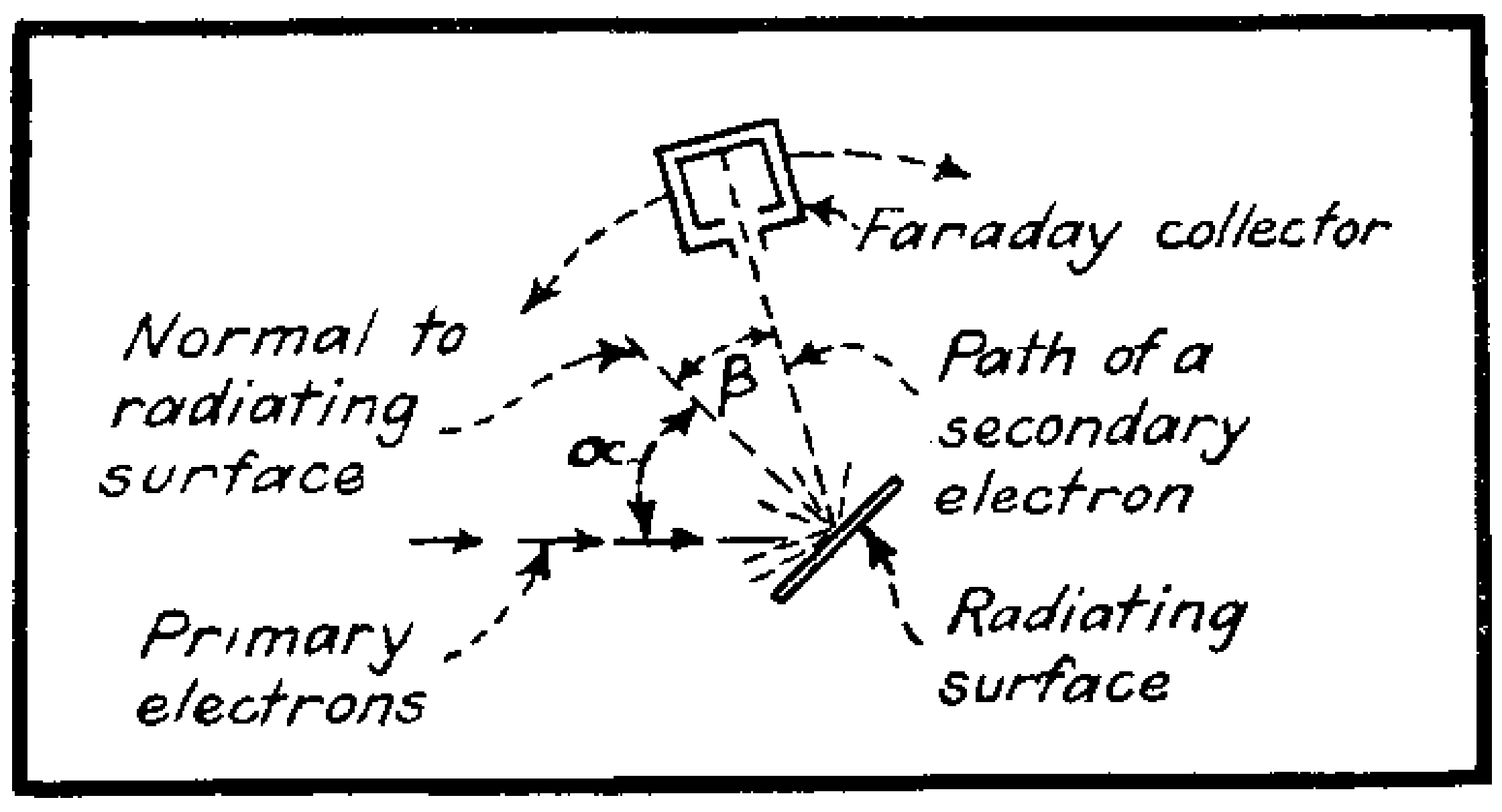

Fig. 7.—Use of an angularly adjustable collector to measure the secondary radiation coefficient of both reflected and emitted electrons as a function of the angle of emission to the normal.

mental evidence[23] of optical reflection of the primary electrons (*i.e.*, $\alpha = \beta$), the evidence of this effect is by no means generally accepted. At present it seems reasonable to assume a cosine distribution of secondary radiation, as shown in Fig. 8; *i.e.*, the intensity of the secondary radiation varies as $\cos \beta$, and this distribution is virtually independent of α. The maximum value of the secondary radiation varies, however, with α. This effect is discussed in greater detail later.

Total Secondary Radiation Coefficient

The arrangement of Fig. 5 may clearly be used for measuring the total radiation of secondary electrons if the collector sphere is at a slightly higher potential than the radiating surface. This measurement is in fact a summation of the curve of Fig. 1, and gives the ratio between the total number of secondary electrons and the total number of primary electrons striking the emitter. This ratio is generally referred to as the total secondary radiation coefficient. It must always be remembered, when interpreting values of this ratio, that in all cases a velocity distribution must be assumed. In the case of impact energies between about 10 volts up to the order of 10,000 volts, this distribution would be that of Fig. 1.

In practical electronic devices, the actual ratio of secondary electron current to a given electrode near the emitter to the primary electron current will depend (among other things) on this velocity distribution. Not all the secondary electrons necessarily contribute to the secondary electron current.

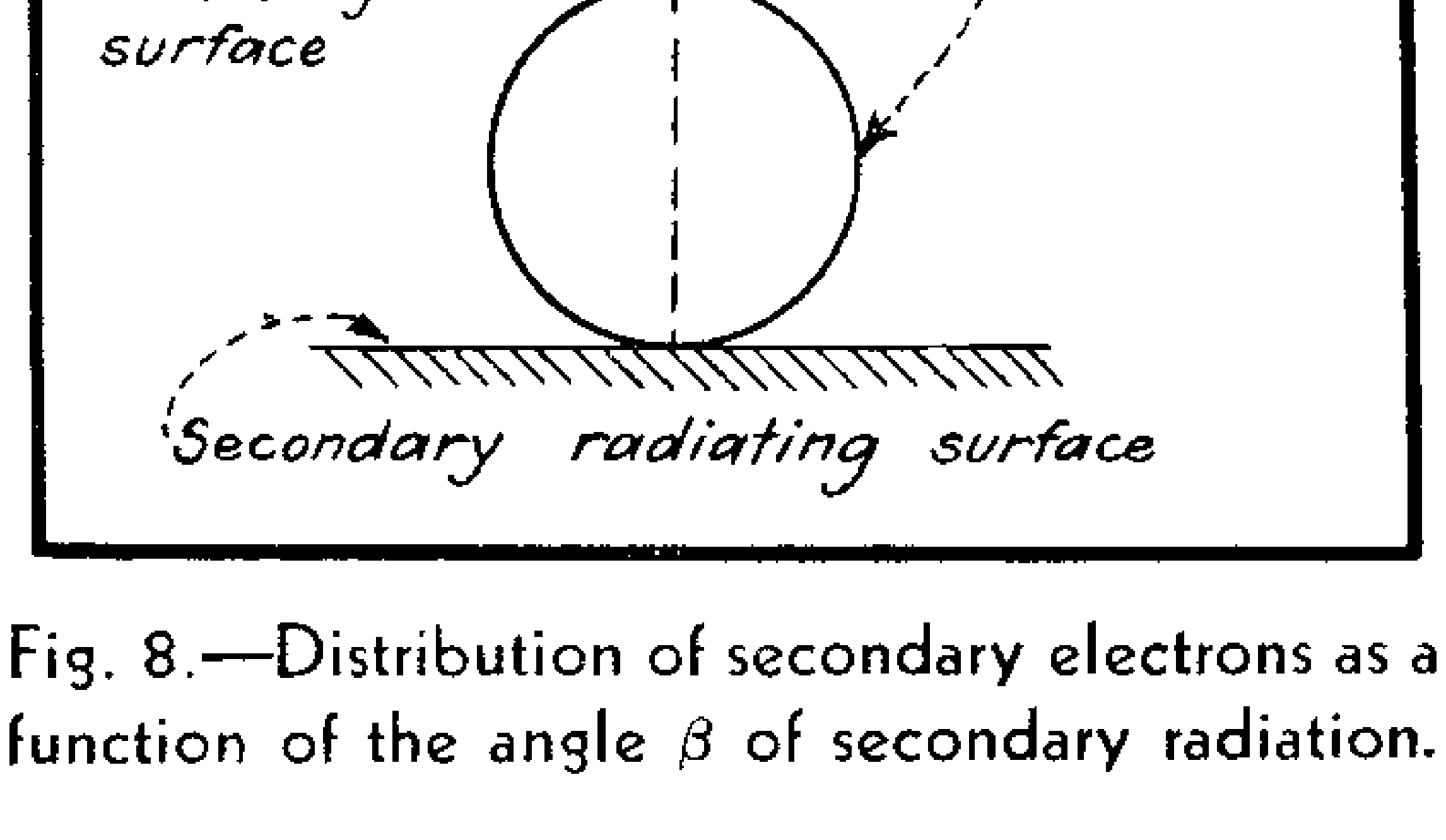

Fig. 8.—Distribution of secondary electrons as a function of the angle β of secondary radiation.

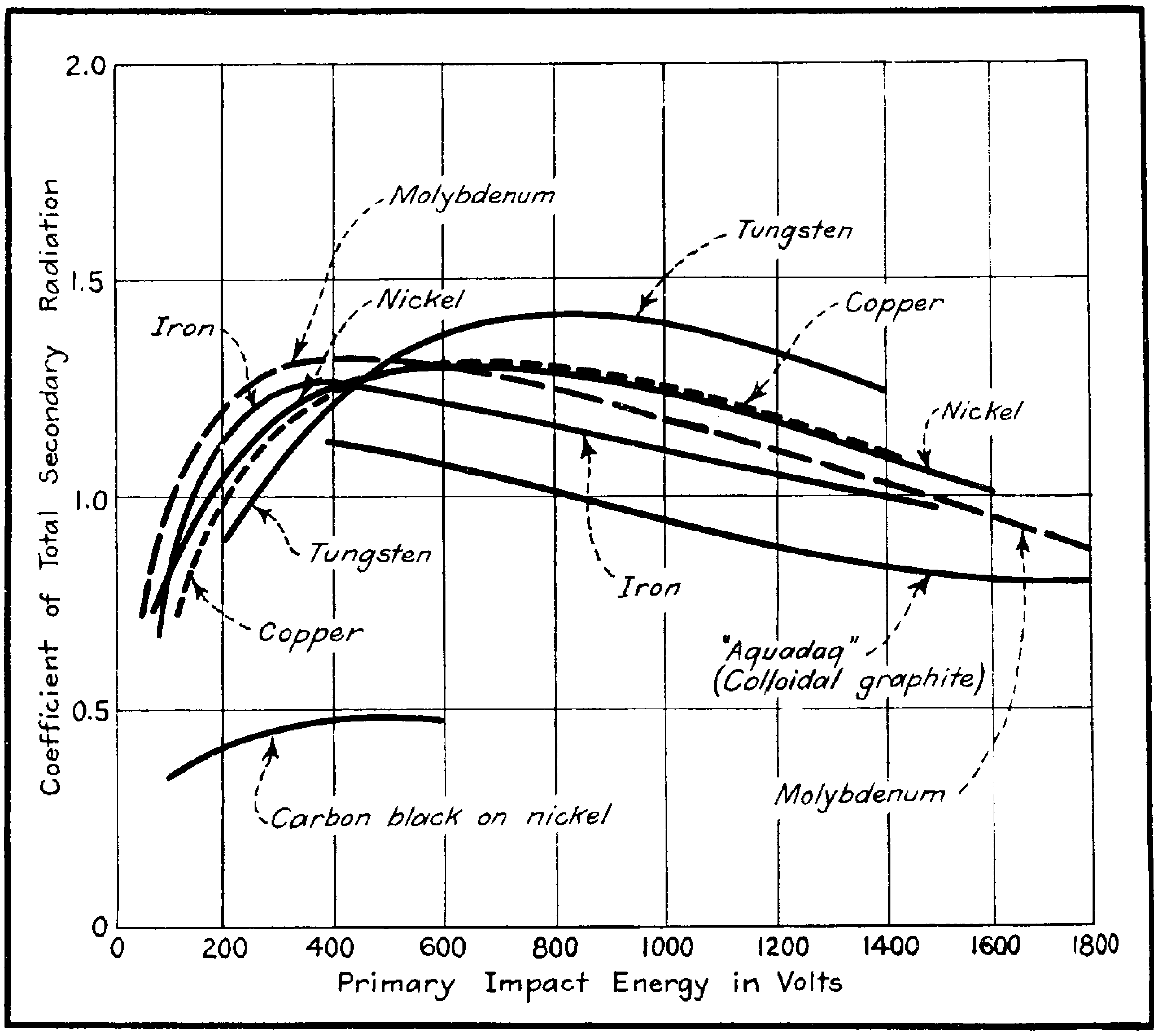

Fig. 9A.—Coefficient of total secondary radiation as a function of primary impact energy in volts for the materials commonly used in vacuum tubes.

The total secondary radiation coefficient plotted against the primary electron impact energy was one of the characteristics to be investigated by the earliest workers.[26-30]

Secondary Radiation Coefficient of Pure Metals and Carbon

Typical measurements of the total secondary radiation coefficient are shown in Figs. 9*A* and *B*. These curves have been confirmed by many investigators. The curves rise to a maximum and then fall as the primary impact velocity increases still further. The maximum value of coefficient obtained lies between about 1.2 and 5.5 in the case of pure metals. Its highest value is of the order of 8 to 11 for compound surfaces of caesium of the kinds used in secondary electron multipliers and the like. Not many substances have coefficients of less than unity. That for carbon varies between 0.6 and 1.0.

Provided that the metal surfaces are clean and are completely degassed, the secondary radiation coefficient is found to be about the same by many different investigators.[31-39]

Table I (from Kollath[40]) shows typical values of the maximum secondary radiation coefficient, and the values of primary impact energy at which it occurs, for a number of substances.

Secondary Radiation Coefficient of Evaporated Layers

Copeland[32,35,41] has obtained interesting results by evaporating various substances

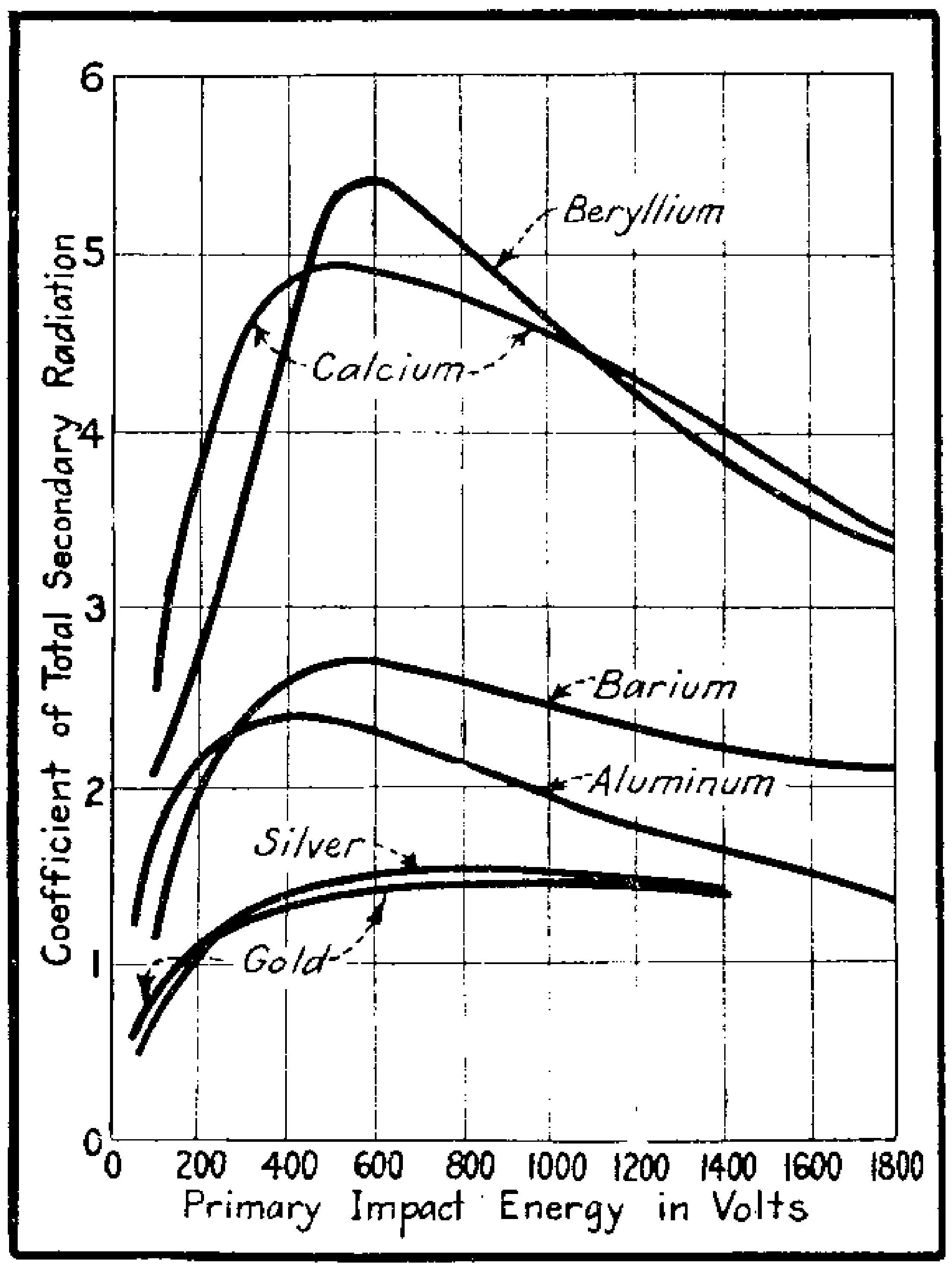

Fig. 9B.—Coefficient of total secondary radiation as a function of primary impact energy for various substances.

onto a metal foundation. Evaporating caesium onto gold increased the secondary radiation coefficient of the combination several times over that of gold alone. He also investigated other combinations of layers and foundations. The results appear to be explainable in terms of the degree of penetration of the primary electrons through the surface layer, and the varying absorption of the secondary electrons by the different substances used.

Secondary Electron Coefficient of Composite Surfaces

It was found[35] that composite materials have a high secondary radiation coefficient. For instance, evaporated deposits of calcium onto gold, and lithium onto tantalum, produce coefficients of the order of 4 to 5. It was observed that calcium and lithium belong to the alkaline-earth group of metals. They have low work functions and a high thermionic and photoelectric emission. An investigation of caesium–caesium-oxide–silver was a natural step, and high secondary electron coefficients resulted. It was discovered, however, that neither a low work function nor a high photoelectric sensitivity is the only factor concerned in producing a high secondary electron coefficient. Typical results for composite surfaces on silver are shown in Fig. 10.

Table II is given by Weiss[42] for various values of the maximum secondary radiation coefficient for caesium-caesium oxide deposits on various metal foundations.

The processing of the layer produced is of great importance. The deposit used as the composite surface is probably of the order of monoatomic thickness.

In detail, the production of secondary electron emissive surfaces is, like the production of coated thermionic cathodes, largely an empirical process.

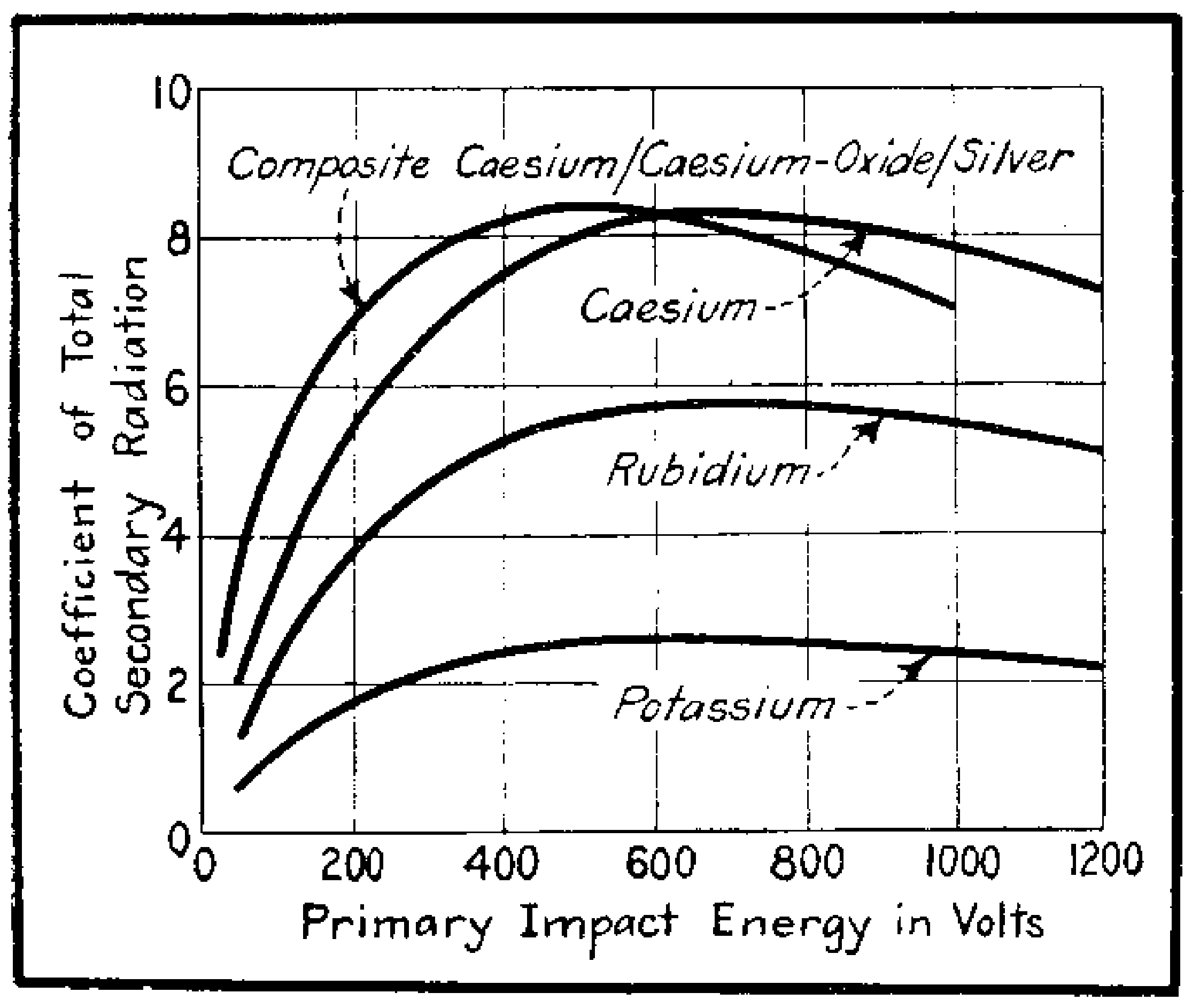

Fig. 10.—Coefficient of total secondary radiation as a function of primary energy in volts for pure metals and a composite oxidized layer on silver.

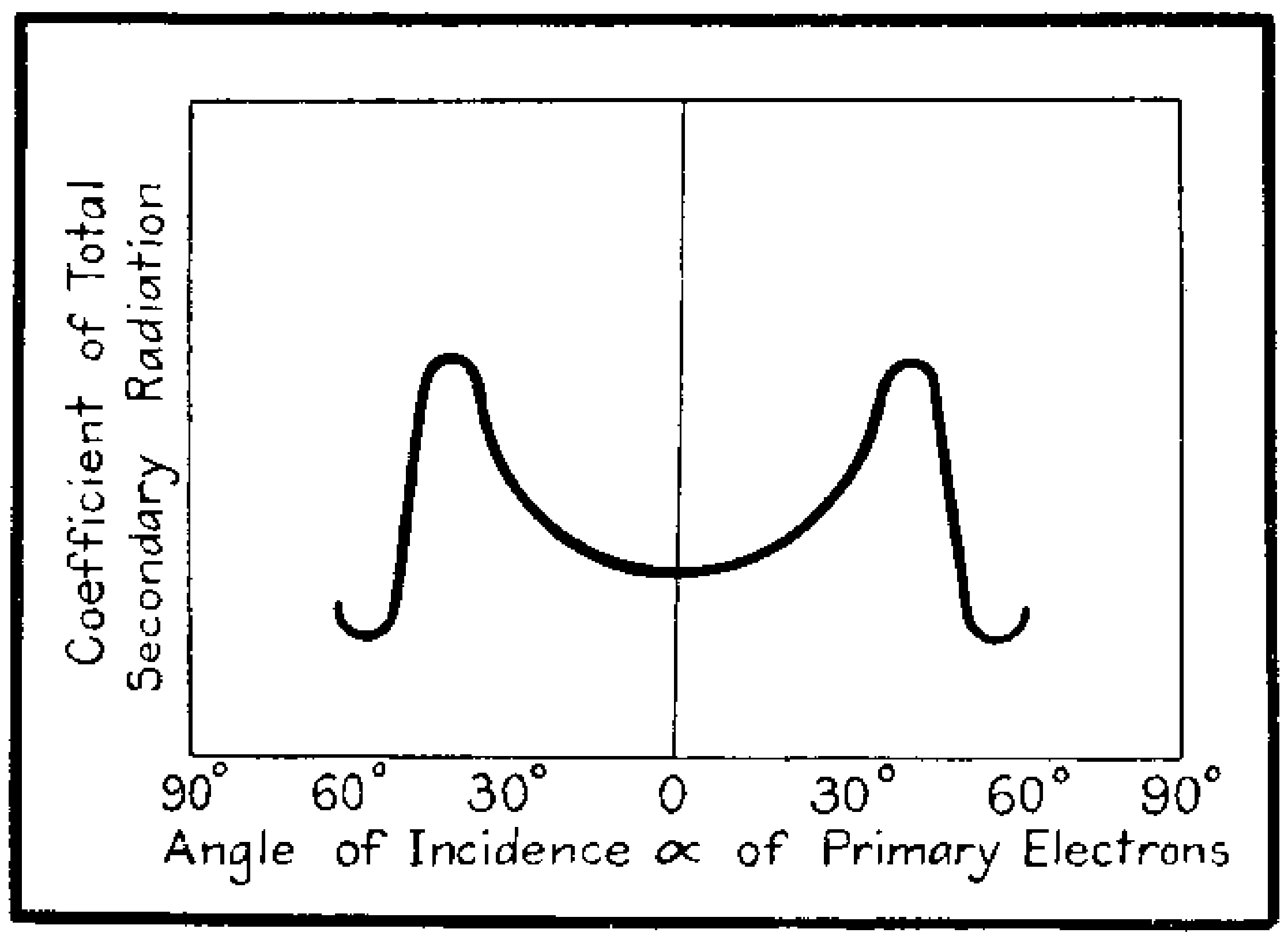

Fig. 11.—Coefficient of total secondary radiation from an insulator as a function of the angle of incidence of the primary electrons. A critical angle of incidence will be observed.

Table II.—Maximum Secondary Radiation Coefficient for Caesium Layers on Various Metal Foundations

Metal	Max. value of sec. radiation coeff.	Primary impact energy (volts) at which max. of sec. radiation coeff. occurs
Silver	8–11	600
Magnesium	6.8–7.5	700
Tantalum	4.1–5.5	600
Zinc	4.5–5.4	600
Nickel	4.6–5.2	550
Aluminum	4.4–4.7	600
Copper	3.5–4.0	600
Tungsten	3.8–3.9	600
Lead	2.3–3.3	650
Molybdenum	2.5–3.1	500
Iron	1.9–2.7	500
Gold	2.3	600

Secondary Radiation Coefficient of Insulators

There is comparatively little information in this matter, but it seems[24,25] that secondary emission from insulators consists largely of electrons that have a low velocity compared with the primary electron velocity. The cosine law of distribution appears to hold, and the coefficient can exceed unity. There is, however, a difference with regard to the angle of incidence of the primary electrons impacting the radiator. In the case of conductors, the secondary radiation coefficient increases continuously with the angle of incidence, but in insulators this is not so. The coefficient increases up to a critical angle of incidence in either direction from 0 deg, beyond which the coefficient drops sharply and then again increases, as shown in Fig. 11.

This critical angle has been found to be evident only at certain levels of primary impact velocity in the range from 1,300 to 3,000 volts. The critical angle increases with increasing voltage, and eventually vanishes. It is also affected by temperature. For example, a critical angle that is 35°C at room temperature falls to 15°C at the temperature of liquid air. It vanishes at 150°C. At this and higher temperatures, the phenomenon is the same for insulators as for conductors.[24,42,44-50]

Explanations[21,51,52] assume that a surface layer of negative space charge is produced on the insulator and affects the emission of secondary electrons. An insulating surface does not necessarily have a negative charge, however. The charge will depend on the conditions of the experiment and on the secondary radiation coefficient of the material.

Variation of Secondary Radiation Coefficient with Primary Angle of Incidence

In general, at low primary impact energies (up to about 100 volts or so), the secondary radiation coefficient is the same for all angles of incidence.

At higher voltages this is not so. A typical result due to Müller[55] is for a primary impact energy of 2,500 volts, and is shown in Fig. 12. It is interesting to note (Kollath[40]) that if the coefficients for various metals are plotted in order of increase of coefficient with incidence they will then be arranged more or less in descending order of their specific gravities. The secondary radiation coefficient, as a function of the angle of primary incidence to the normal, rises with decreasing specific gravity.[53-56] The results previously described apply to angles of incidence in the neighborhood of the normal unless otherwise specified.

Secondary Emission at High Primary-impact Velocities

Primary impact energies have been investigated which are very much greater than the few thousand volts to which the previous remarks have been confined, but

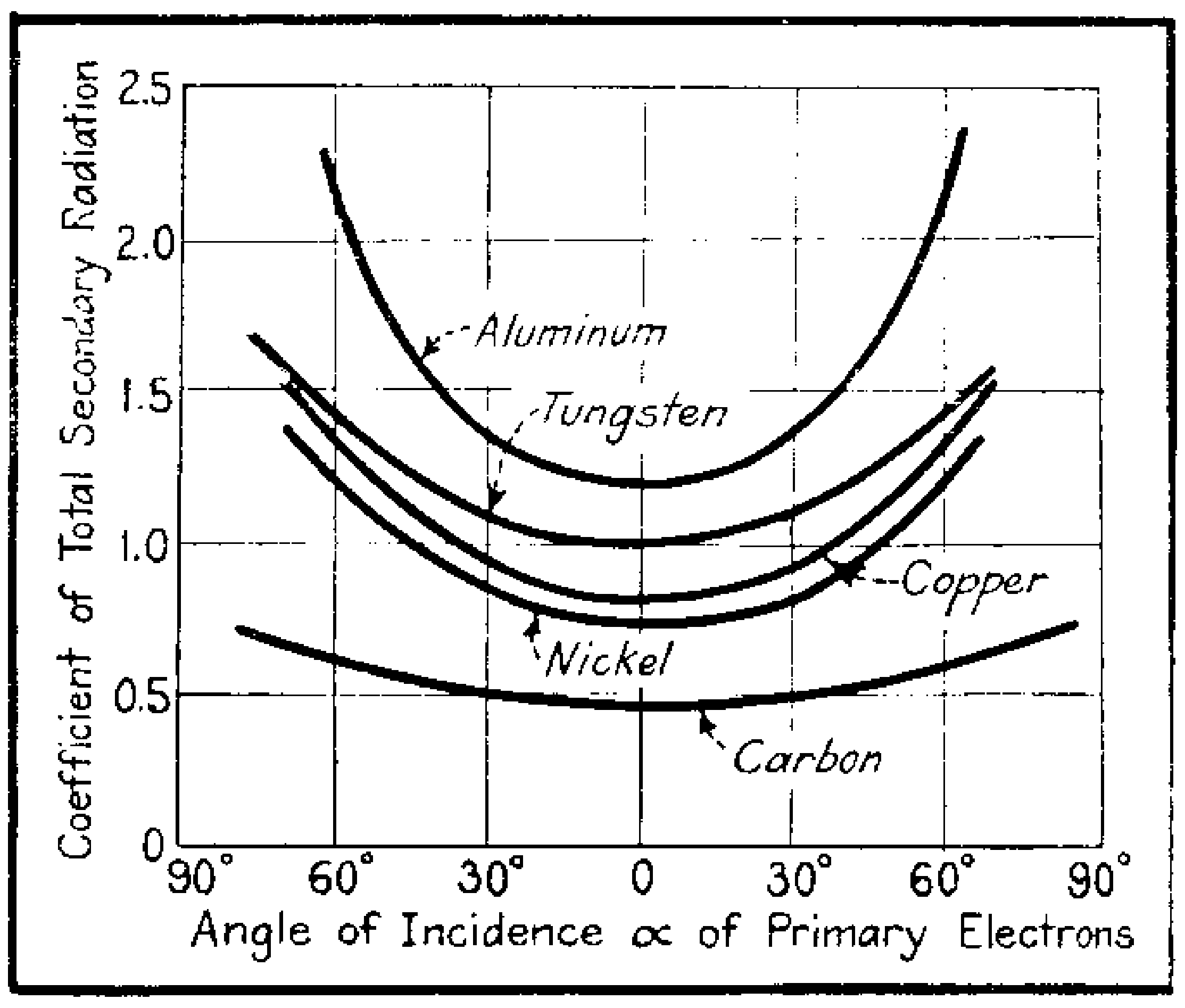

Fig. 12.—Coefficient of total secondary radiation from various conductors as a function of the angle of incidence α of the primary electrons. The primary impact energy is 2,500 volts.

high-voltage results differ little. The velocity distribution curve of Fig. 1 is affected only insofar as peak A increases in relative area (*i.e.*, the reflected electrons increase in number).[20,21,23,57,58]

The secondary radiation coefficient as a whole falls with increasing primary impact energies. The increased penetration of the primary electrons of high velocity into the metal results in the secondary electrons being reabsorbed in the surface layers of the material. This fall in secondary radiation coefficient is to some extent counteracted by primary electrons which emerge in a direction different from the normal to the surface, and cause secondary electrons to be emitted from the surface layer of the material. In fact, this latter effect predominates in producing secondary radiation at very high values of primary impact velocity.[21] The angular distribution of the radiation follows the cosine law.

Consideration of the depth at which emission is produced is of considerable importance where radiation is obtained from both sides of a thin foil through which primary electrons are arranged to pass.[3]

Many investigators[7,16,59-63] have shown that the structure of the radiating surface has considerable effect on the coefficient. No effect on it is noted by Hayakawa[61] at the magnetic transformation points of ferromagnetic materials, but sudden changes have been shown to occur at the points of allotropic modification of the surface structure. An abrupt variation in the secondary radiation coefficient of iron at the Curie point has, on the other hand, been recorded by another worker.[62]

Further Investigation Needed

According to Rao,[63] a nickel monocrystal gives a lower secondary radiation coefficient than an ordinary polycrystalline nickel surface. An opposite result is obtained by H. E. Farnsworth[7] with respect to copper. His result appears to agree with the experimental fact that the secondary radiation coefficient of finely precipitated carbon or platinum black has a particularly low coefficient of secondary radiation.

Further investigation seems to be needed. In the meantime it seems that either monocrystal surfaces of different materials have different effects on the coefficient, or that there is perhaps some optimum size of crystal which gives a maximum coefficient.

Effect of Temperature on Secondary Electron Coefficient

As far as can be ascertained, there is no temperature effect. According to Kollath[40] this point might, however, be worth further investigation, particularly with regard to the complex surface coatings now commonly used in commercial practice.

Effect of Gas on Secondary Radiation Coefficient

All materials contain a certain amount of gas before they have been heat-treated by the usual valve (tube) manufacturing processes which are necessary to produce a high vacuum. Occluded gas has a considerable effect on the secondary radiation coefficient, and, until the radiator is completely degassed, repeatable results are not obtained. Measurements on the effect of gas have been made by Farnsworth,[7] Warnecke,[36] -and Ahearn.[64] In general, the presence of gas increases the secondary radiation coefficient, often several times.

Mechanism of Secondary Electron Radiation

The quantitative analysis of the atomic mechanism of the phenomenon is in a very rudimentary state. In fact, a survey of the subject reduces itself largely to an unsatisfactory recital of disjointed experimental facts rather than to a coherent statement of theory. Kollath's paper[40] gives an excellent outline of the situation up to 1937. The relationship between secondary radiation phenomenon and the atomic structures of various metals gives no very conclusive result, nor has the work function any very useful relationship, though there has been shown to be some proportionality between the secondary radiation coefficient and this quantity. The depth of penetration of the primary electrons has been estimated, and Becker[14] arrives at a calculated depth of penetration of about 30 A (about 15 to 20 atomic layers) at primary impact velocities of the order of 500 volts.

Emission Time of Secondary Electrons

As far as the author is aware, no measurements or computations of this quantity have yet been made. It may prove, however, to be very important in view of the increasing use of extremely high frequencies in electronics. So far, the only conclusion appears to be—and this is a unanimous one[65-72]—that the time of emission is less than 10^{-9} sec. This is as much as several times the periodic time at the highest radio frequencies now being brought into use. Modern u-h-f technique might enable the time to be measured. A suggestion due to Kollath[40] involves comparing the times of arrival of electrically reflected primary electrons with those of secondary electrons. Experimental difficulties appear, however, to be considerable.

Secondary Emission Transit Times

In view of the initial velocity spectrum (Fig. 1) common to all secondary radiation (the fact that secondary electrons are not all emitted at the same velocity), secondary electrons traveling from the emitter to another electrode do so with differing transit times. This effect is of substantial importance to the operation of vacuum tubes at very high frequencies, and is dealt with later.

Secondary Radiation in Electronic Engineering

In electronic engineering, secondary radiation is sometimes found to interfere with the desired operation of the radio tube in which it occurs. Sometimes, on the other hand, it is utilized as an essential part of the mechanism of operation.

The Dynatron

In a tetrode, when the screen grid is at a higher potential than the anode, secondary radiation from the anode may travel to the screen grid and produce a negative resistance characteristic in the anode circuit over a range of anode voltages. Hence the valve can be made to generate oscillations. This effect was first described by Hull.[72] In considering these results with respect to modern radio techniques, due regard must be paid to secondary radiation transit angle effects.

Secondary Electron Multipliers

Secondary electron multipliers[74] of both the magnetic and electrostatic types are so well known that it is unnecessary to describe them in detail. In multipliers, the primary electrons strike an emissive surface which is of such a kind as to produce a high ratio (usually between 8 and 11) of total secondary radiation coefficient. Secondary electrons thus radiated are caught by another plate from which further secondaries are again radiated. This process is repeated several times in order to produce a very high total magnification of the original primary-electron-beam current.

The primary electron beam can be controlled either by photoelectric effects[75] or by voltage control. Greater importance appears to attach to the amplifica-

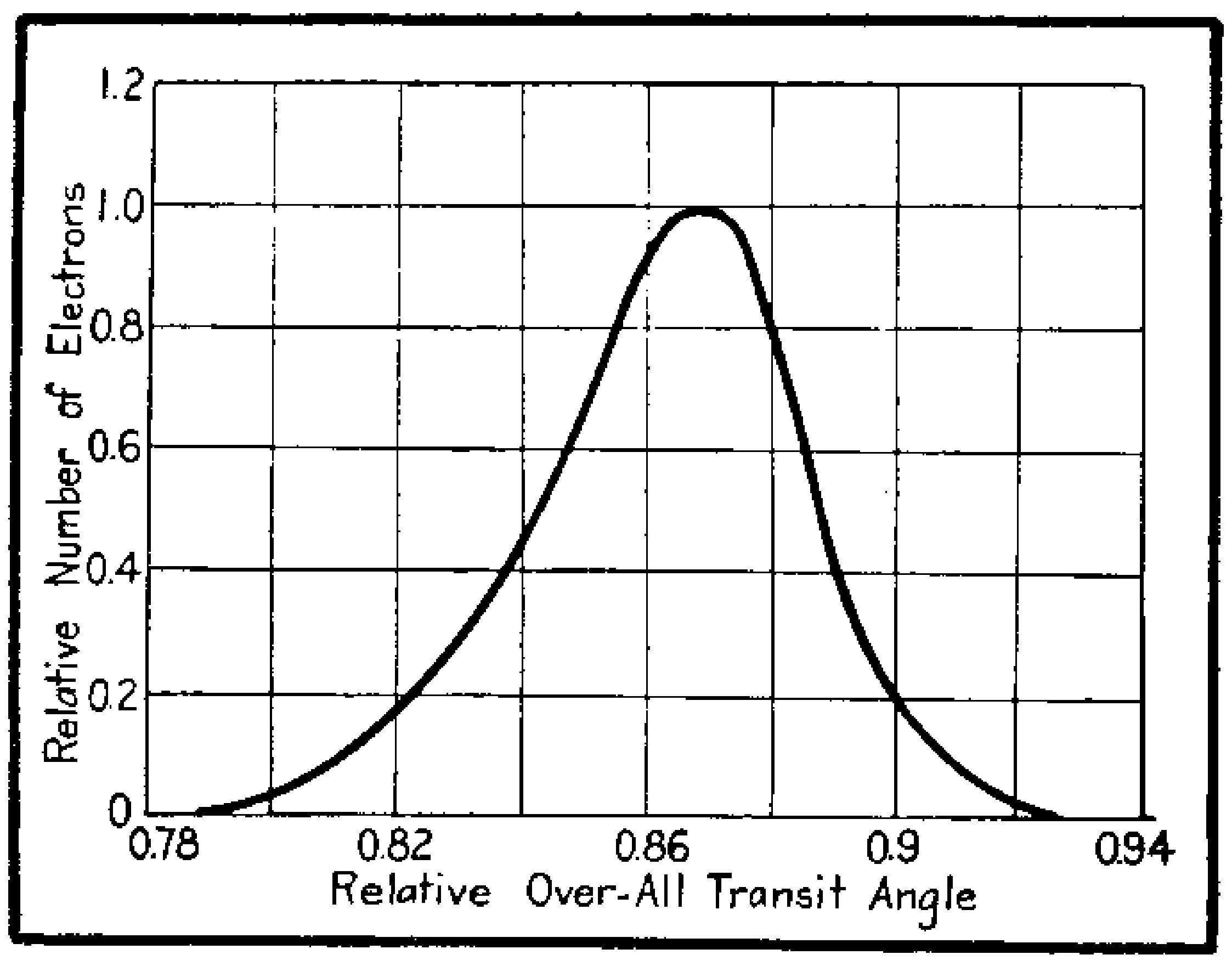

Fig. 13.—Variation of transit angle of secondary electrons in a secondary electron multiplier. This variation is due to the distribution of secondary electron energies illustrated in Fig. 1. Note that this graph ignores peak A of Fig. 1.

tion of photoelectric currents than to voltage control, as the limitations of the latter type cause it to be rather specialized in application.[76] An interesting and comparatively recent example of voltage control has been described by Wagner and Ferris.[77] Control of the primary electrons in secondary multipliers by deflecting them instead of using a control grid appears to have been first described by Hopkins.[78] The composite cesium–cesium-oxide–silver curve in Fig. 10 shows the ratio of secondary emission current to primary current obtained from one of the radiating surfaces in a multiplier.

Since secondary electrons are not emitted with a single velocity, but with a spectrum of velocities, the transit angle between the radiators in the multiplier also has no single value.

In Fig. 13, the ordinates represent the relative number of secondary electrons emitted at each of various relative over-all transit angles of the secondary electrons in a three-stage electron multiplier. The relative over-all transit angle is expressed as a fraction of the transit angle that would exist if the secondary electrons were emitted with zero velocity. It will be observed that the transit angles of the individual secondary electrons vary over a wide range. Furthermore, secondary electrons are radiated from different parts of the radiator, and have to travel along paths of different lengths to reach the next electrode.

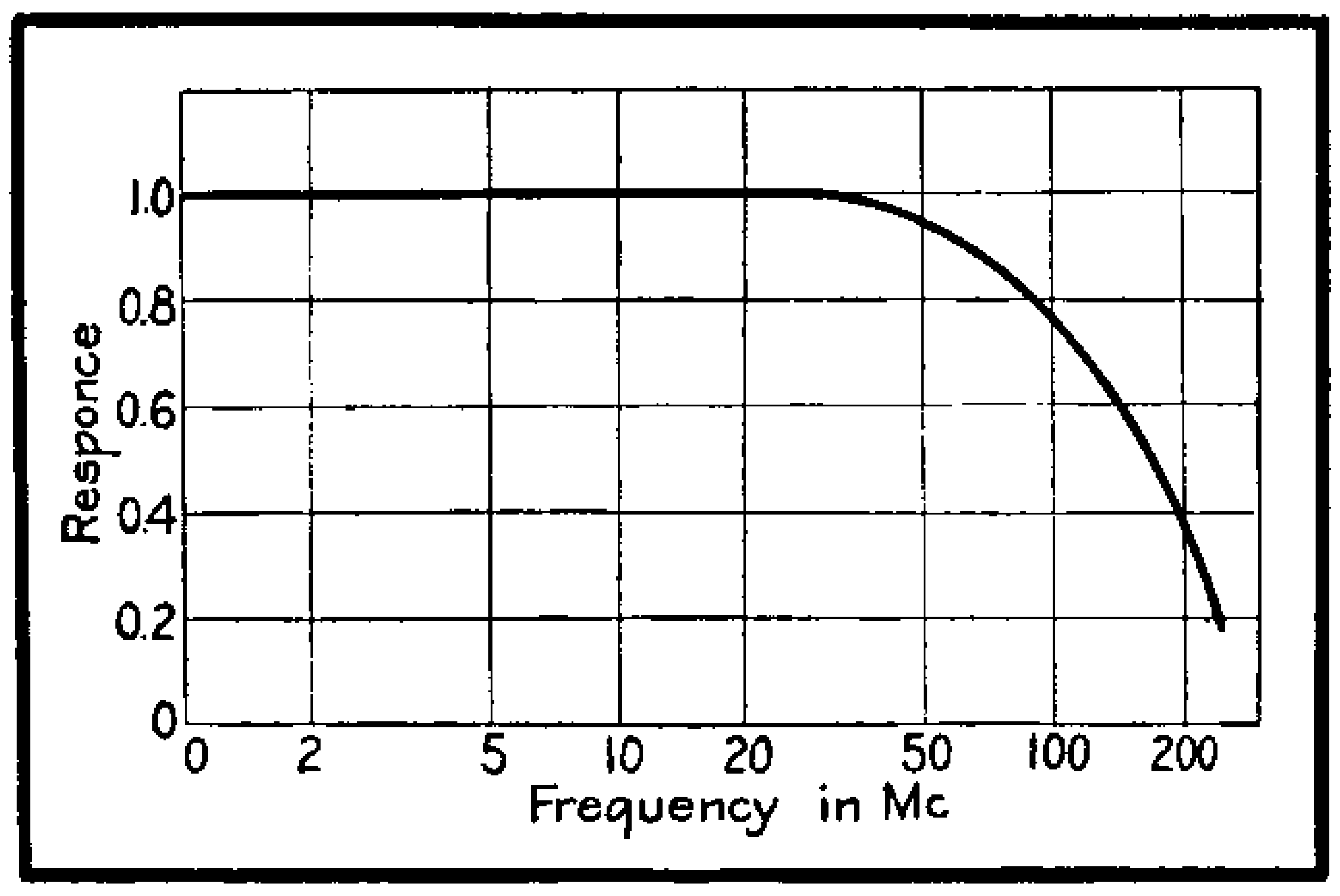

Fig. 14.—Frequency response of an electron multiplier, showing fall off at very high frequencies due to the transit angle effect illustrated in Fig. 13.

The result of these combined effects has been shown by Malter[87] to produce an h-f cutoff in the response of the multiplier as a whole. The resulting frequency cutoff of a typical multiplier is shown in Fig. 14.

Farnsworth Multipactor

Another application of secondary electron multiplication involves the utilization of transit time to produce h-f oscillations. This idea was first put forward by Philo T. Farnsworth.[78]

Reduction of Screen Grid Current

In many screen-grid radio tubes, the anode is maintained during operation at a potential higher than that of the screen grid. Secondary radiation of quite a considerable amount is produced at the points of impact on the screen grid of the primary electrons that constitute the space current. The secondary electrons travel from the screen grid to the anode and so decrease the screen grid current and increase the anode current, very considerably. This results in an increase in the static transconductance of the tube. It must not be forgotten that, owing to the varying transit angles of the secondary electrons, this increase will not hold at very high frequencies. The phenomena produced will be somewhat similar to that exemplified above with respect to secondary electron multipliers. There seems to be no published information in this matter.

Secondary Radiation from Cathodes

In certain tubes—notably the magnetron—the cathode may be bombarded by primary electrons which return to it at considerable velocities. By adding to the emission, the resulting secondary radiation may have an appreciable effect on the operating characteristics of the valve.

The Pentode

In the great majority of electronic tubes, secondary radiation is a nuisance and elaborate steps have to be taken to prevent it from interfering with the operation of the tubes. It will be clear from Fig. 5 and the associated text, however, that attempts to prevent the radiation of secondary electrons from the electrodes of radio tubes are foredoomed to failure. In fact, quite early engineering experiments confirmed this.[89]

Since secondary radiation itself cannot be prevented, the only remaining thing to do is to prevent the secondary electrons traveling from one electrode to another. This is the idea behind the pentode.

It is almost unnecessary to describe this well-known tube in detail.[81] The traverse of secondary electrons from the anode to the screen grid when the anode is at a lower potential than the screen grid during operation is prevented partly by the use of a retarding potential. A grid (called the suppressor grid) is interposed between the screen grid and the anode and is maintained at a low potential.

Primary electrons pass through the spaces between the suppressor grid wires. A retarding potential exists between these spaces and tends to reduce the secondary radiation current from the anode to the screen grid to a fraction of the primary electron current (see Figs. 4 and 6). At the same time, owing to the cosine law of distribution (Fig. 8), only a small number of the secondary electrons are directed toward the gaps in the suppressor grid. This results in a still further reduction of the total secondary electron current.

A further effect that tends to reduce the adverse flow of secondary electrons is the addition to the retarding potential caused by space charge effects. Both primary and secondary electrons contribute to the space charge potential. The combination of all these effects (and possibly others) operates in a very complex manner, and the author is not aware of a satisfactory quantitative theory, but pentode valves may readily be designed by empirical means.

Remembering that the potential of the spaces between the wires of the suppressor grid cannot be zero (or the primary electrons themselves would be prevented from arriving at the anode), it is untrue to say that the operation of a pentode is explained merely by the interposition of a retarding potential between the anode and screen grid. A retarding potential that did not reduce the potential between the wires of the suppressor grid to zero would still leave a considerable amount of secondaries flowing. This is clear from Fig. 6. Curves *A* in Fig. 15 shows the familiar dynatron characteristic which is produced in the absence of a suppressor grid. Curve *B* shows the characteristic found in a pentode, and curve *C* shows the type of characteristic that might perhaps be expected if the suppressor

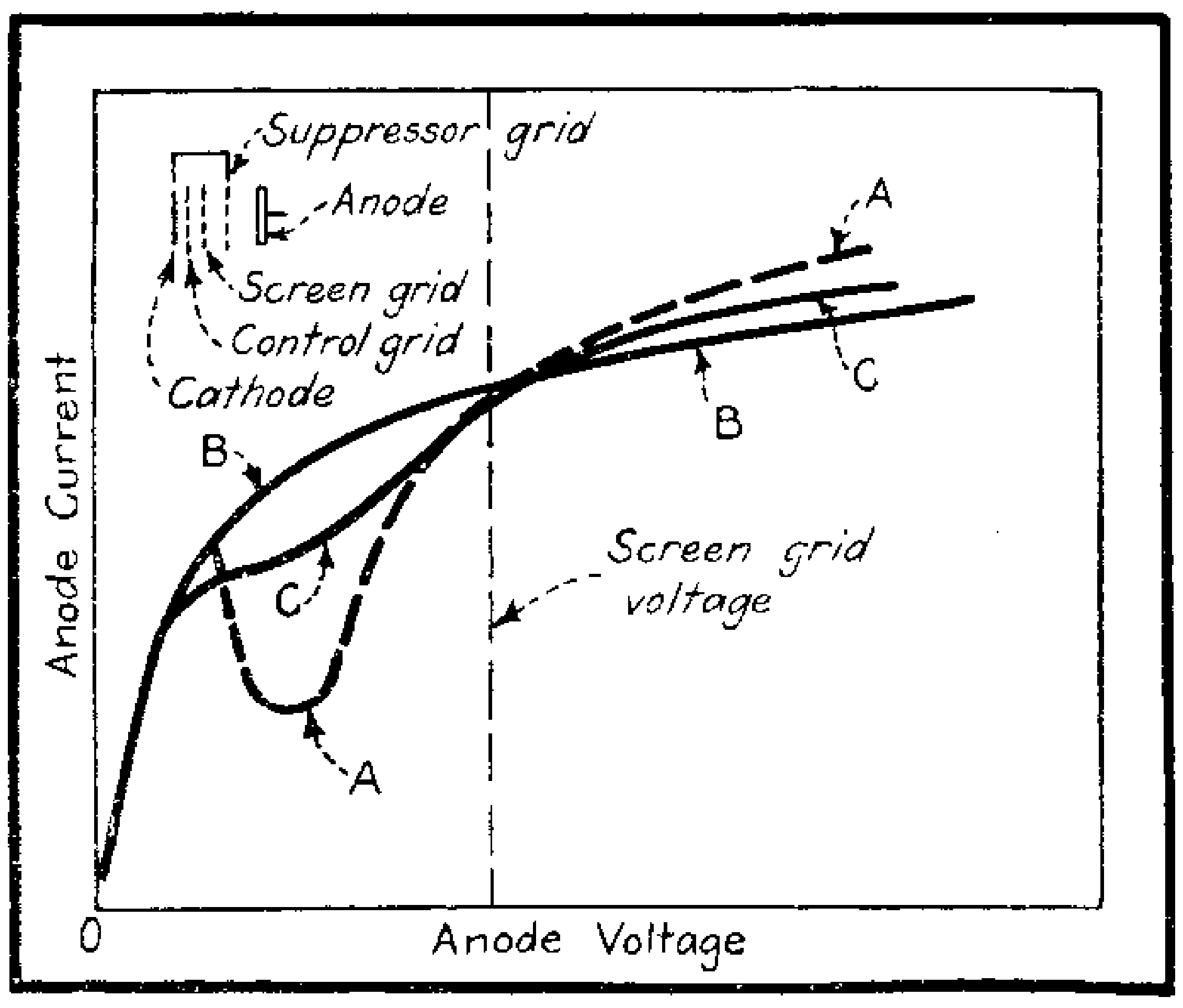

Fig. 15.—Curve A is the anode characteristic of a dynatron valve. Curve B is that of a pentode. Curve C is the approximation to the kind of curve that might be expected if a suppressor grid is assumed to operate solely by producing a retarding potential.

grid retarding potential alone were the only operative factor in preventing the flow of secondary electrons.

Secondary Electron Traps

Owing to the cosine distribution of secondary radiation (Fig. 8), if a beam of primary electrons enters an enclosed metal cavity (at a positive potential) through a small aperture as in Fig. 16, only a very small part of the resulting secondary radiation will succeed in leaving the cavity. This is the principle of the Faraday cylinder previously referred to (Figs. 3, 4, and 7). Attempts have been made and suggested[80] to utilize such cylinders as the anodes or collector electrodes of practical radio tubes. Since in such radio tubes the effective anode area for the collection of primary electrons must usually be considerably greater than the small aperture illustrated in Fig. 16, these attempts have not been very successful as far as the author is aware.

Critical-distance Beam Tetrodes

In 1931 the author, working on the production of the then novel idea of producing beams of electrons of appreciable fractions of an ampere at a few hundred volts, found that if the space current in a dynatron type of tetrode is confined into a beam, an optimum value exists for the distance of the anode from the screen grid (accelerating grid; he named this distance the critical distance) at which the passage of secondary electrons from the anode to the accelerating grid is prevented. The anode characteristic then obtained is of the kind illustrated in Fig. 17.[82-86] The sharp knee at the left-hand side of the curve is characteristic of this type of tube and results in a considerably lower distortion level[82,86] than the more rounded knee of the pentode (Fig. 15).

Tubes of this kind were made in 1931 and were put on the market in England by a commercial firm in 1935. They came into wide use, under the name of beam tetrode when this tube was first marketed (in America) in 1936; yet, like the pentode (the invention of which dates from 1926), there is again no satisfactory published theory. The straight part of the anode characteristic of this valve (Fig. 17) can be accounted for only by the reduction of the traverse of secondary radiation to a very small fraction indeed of the total radiation. By reference to Fig. 6, it will be seen that this appears to infer a retarding potential virtually equal to the primary impact velocity itself.

Attempts have been made to explain this critical-distance characteristic in terms of the potential minimum produced by space charge,[88,89] but the author has shown[86] that the magnitude of the retarding potentials predicted by this theory is not sufficient (by a factor of several times) to prevent the occurrence of the dynatron kink in the anode characteristics. Moreover, the problem is not merely one of preventing the passage of secondary radiation at one set of values of anode current, anode voltage, and screen voltage. It is, on the contrary, that of maintaining a flat working surface of the characteristic over a wide variation area (Fig. 17). A purely space-charge retarding potential theory leads to no such range of working currents and voltages.

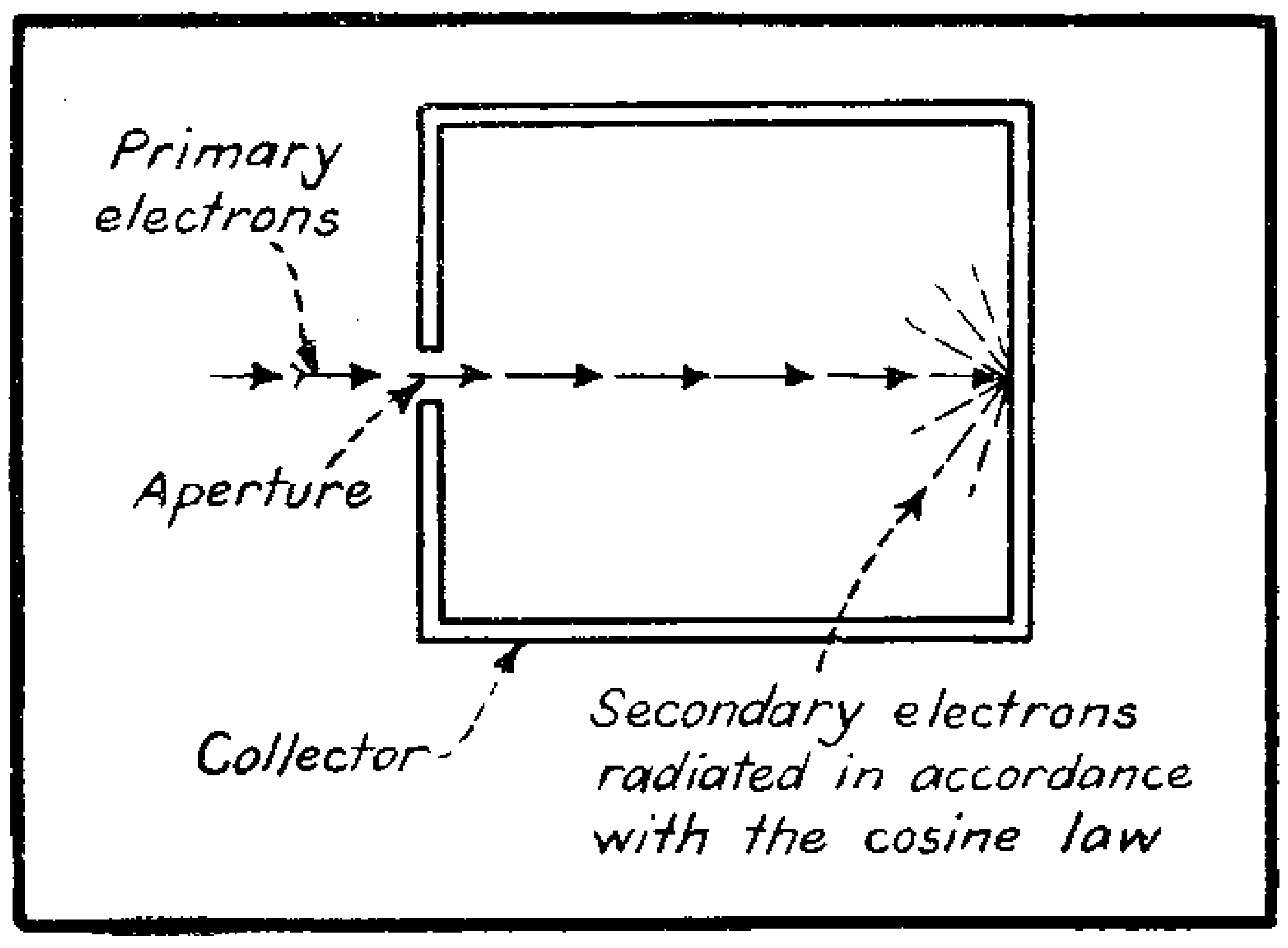

Fig. 16.—A Faraday cylinder or electron trap.

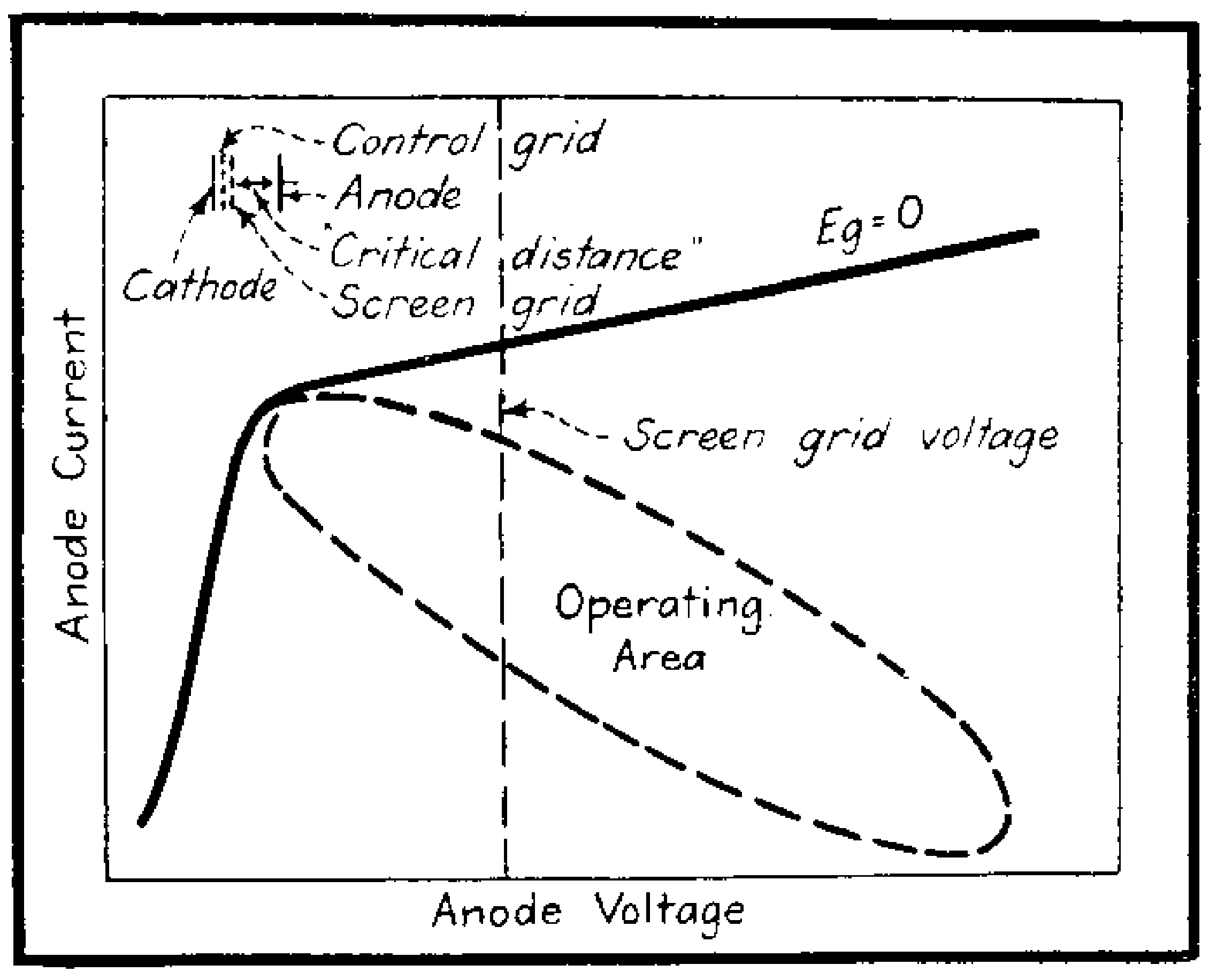

Fig. 17.—A critical-distance beam-tetrode characteristic.

A complete formulation of the problem must include the effects of the formation of the primary electrons into a beam (without which the effect seems not to take place in practice), the variation of the density of this beam with control grid voltage, the energies of the secondary electrons, the angular distribution of the secondary radiation, the end effects, and the depression of space potential due to the presence of low-potential conductors near the screen grid-anode space.

It has been pointed out by the author some time ago[83] that if the accelerating voltage is higher than a few hundred volts, the critical-distance effect is not produced satisfactorily. This appears to have a relationship to the increase in the area of peak *A* in the secondary radiation energy distribution curve (Fig. 1) at the higher primary impact velocities.

Secondary Emission from Grids

Grids and other electrodes in electronic tubes that are struck by electrons will emit secondaries which, particularly in tubes where optical images are to be formed, may be very undesirable. Such effects may be minimized, though not eliminated, by treating the surfaces involved. Coating with carbon black or like methods are used (Fig. 9*A*).

Secondary Radiation from Insulated Electrodes and Insulators in Vacuum Tubes

If an insulated conductor is positioned in the path of a beam of primary electrons, its potential will depend on the impact energy of the primary electrons and on the secondary electron coefficient of the conductor.

For instance, referring (Fig. 9*A*) to the curve for nickel, it will be seen that it becomes unity at a primary impact velocity of approximately 1,750 volts. The initial potential of a clean insulated electrode made of nickel will, in the absence of a flow of primary electrons, be that of the space in which it is situated. If this potential and the impact energy of the primary electrons on the nickel electrode are both above 1,750 volts, then, from Fig. 9*A*, the total secondary radiation coefficient will be less than unity. The insulated nickel electrode will therefore charge negatively until its potential reaches 1,750 volts, when the secondary radiation coefficient is unity, and the number of electrons leaving the electrode will be equal to those reaching it. This, of course, assumes space-charge-free conditions, and assumes further that all the secondary electrons emitted by the nickel are collected by other electrodes in the tube.

If, again, the space potential of the insulated nickel electrode and the initial energy are between about 160 and 1,750 volts, then, from Fig. 9*A*, the secondary radiation coefficient will be greater than unity, and the electrode will tend to charge positively until an equilibrium potential of about 1,750 volts is again reached.

If, however, the space potential and the primary impact energy are below 160 volts, then, from Fig. 9*A*, the total secondary radiation coefficient is less than zero. The insulated electrode will charge up negatively until it reaches zero potential, at which no primary electrons strike it. Therefore, in general, an insulated conductor upon which electrons impinge tends to take up either a potential tending to zero, or a high positive potential. It has been suggested to employ this effect to maintain a suppressor grid in a pentode at the order of zero potential. Clearly, if the electrode is contaminated, or otherwise has a greater secondary radiation coefficient than the pure material (and this may very easily occur in a practical radio tube), the impact potential at which the total secondary radiation coefficient is unity may well become very high.

The equilibrium potentials of insulators (such as the glass walls of a vacuum tube) due to secondary radiation may vary discontinuously and profoundly affect the space potential in the tube as a whole, and therefore in many instances upset the operation of the device. In the absence of more information on the secondary radiation coefficients of insulators, and because of the complicated nature of their behavior, it is not possible to state any useful theory. In radio tubes, care is taken to minimize the results of bulb charging. This is done by causing the electrode assembly to be self-shielding (*i.e.*, semi-enclosed as far as the operative part of the electron beam is concerned) or by putting a conductive film (such as collodial graphite) on the walls of the glass envelope and connecting it to a suitable part of the electrode system. This is found to be necessary in cathode-ray oscilloscope tubes where the beam is not enclosed by the metal electrodes.

References

(1) Rudberg, E., *Phys. Rev.*, **50,** 138, 1936.

(2) Becker, A., *Ann. Physik*, **78,** 228, and 253, 1925.

(3) Becker, A., *Ann. Physik*, **84,** 779, 1927.

(4) Brinsmade, J. B., *Phys. Rev.*, **30,** 494, 1927.

(5) Campbell, N. R., *Phil. Mag.*, **24,** 783, 1912.

(6) Dadourian, H. M., *Phys. Rev.*, **14,** 434, 1919.

(7) Farnsworth, H. E., *Phys. Rev.*, **25,** 41, 1925.

(8) Farnsworth, H. E., *Phys. Rev.*, **31,** 405–413, March, 1928.

(9) Haworth, L. J., *Phys. Rev.*, **37,** 93, 1931.

(10) Haworth, L. J., *Phys. Rev.*, **42,** 906, 1932.

(11) Haworth, L. J., *Phys. Rev.*, **48,** 88, 1935.

(12) Haworth, L. J., *Phys. Rev.*, **50,** 216, 1936.

(13) Langenwalter, H. W., *Ann. Physik*, **24,** 273, 1935.

(14) Rudberg, E., *Proc. Roy. Soc. (London)*, **127,** 111, 1930.

(15) Sharman, C. F., *Proc. Cam. Phil. Soc.*, **23,** Part 5, 523 to 530, January, 1927.

(16) Soller, T., *Phys. Rev.*, **36,** 1212, 1930.

(17) Wells, D. A., *Phil. Mag.*, **5,** 367, 1928.

(18) Davisson and Kunsman, *Phys. Rev.*, **22,** 242 and 256, September, 1923.

(19) Davisson and Kunsman, *Science*, **54,** 404, 522 to 524, Nov. 25, 1921.

(20) Fuchtbauer, C., *Physik. Z.*, **7,** 748, 1906.

(21) Stehberger, K. H., *Ann. Physik*, **86,** 825, 1928.

(22) Seitz, W., *Ann. Physik*, **6,** I, 1901.

(23) Tate, J. T., *Phys. Rev.*, **17,** 394, 1921.

(24) Daene, H., and Schmerwitz, G., *Z. Physik*, **53,** 404, 1929.

(25) Farnsworth, H. E., *Phys. Rev.*, **31,** 414, 1928.

(26) Baeyer, O. v., *Physik. Z.*, **10,** 168, 1909.

(27) Baeyer, O. v., *Verh. deut. physik. Ges.*, **10,** 96 and 935, 1908.

(28) Baeyer, O. v., *Physik. Z.*, **10,** 176, 1909.

(29) Campbell, N. R., *Phil. Mag.*, **25,** 803, 1913.

(30) Gehrts, A., *Ann. Physik*, **36,** 995, 1911.

(31) Copeland, P. L., Thesis in the Department of Physics, State University of Iowa, July, 1931.

(32) Copeland, P. L., *Jour. Franklin Inst.*, **215,** 435, 1933.

(33) Copeland, P. L., *Jour. Franklin Inst.*, **215,** 593, 1933.

(34) Copeland, P. L., *Phys. Rev.*, **46,** 167, 1934.

(35) Copeland, P. L., *Phys. Rev.*, **48,** 96, 1935.

(36) Warnecke, R., *Jour. phys. radium*, **5,** 267, 1934.

(37) Warnecke, R., *Jour. phys. radium*, **7,** 270, 1936.

(38) Farnsworth, H. E., *Phys. Rev.*, **20,** 358, 1922.

(39) Farnsworth, H. E., *Phys. Rev.*, **27,** 413, 1926.

(40) Kollath, R., *Physik. Z.*, **38,** 202–224. 1st Apl., 1937.

(41) Copeland, P. L., *Phys. Rev.*, **35,** 293. 1930.

(42) Weiss, G., *Fernsehen und Tonfilm*, **41,** 1936.

(43) Kalckhoff, G., *Z. Physik*, **80,** 305. 1933.

(44) Wehnelt, A., *Ergeb. exakt. Naturw.* **4,** 417, 1928.

(45) Schmidt, W., Diss. Berlin, 1923.

(46) Nickel, G., Diss. Berlin, 1922.

(47) Beyschlag, B., Diss. Berlin, 1926.

(48) Uredat, E., Diss. Berlin, 1930.

(49) Wehnelt, A., *Z. Physik*, **48,** 165. 1928.

(50) Knoll, M., *Z. tech. Physik*, **16,** 467. 1935.

(51) Joffé, A., *Z. Physik*, **48,** 737. 1928.

(52) Klemperer, O., *Z. Physik*, **47,** 417. 1928.

(53) Strübig, H. *Physik. Z.*, **37,** 402. 1936.

(54) Bruining, H., *Physica*, **3**, 1046. 1936.

(55) Müller, H., *Z. Physik*, im Druck.

(56) Baltruschat, M., and Starke, H., *Physik. Z.*, **23,** 403, 1922.

(57) Chylinski, S., *Phys. Rev.*, **28,** 429. 1926.

(58) Chylinski, S., *Phys. Rev.*, **42,** 393, 1932.

(59) Farnsworth, H. E., *Phys. Rev.*, **31,** 419, 1928.

(60) Farnsworth, H. E., *Phys. Rev.*. **34,** 679, 1929.

(61) Hayakawa, K., *Soc. Rep. Tobohu Imp. Univ.*, (I), **22,** 934, 1933.

(62) Tartakowsky, P., and Kudrjawzewa, W., *Z. Physik*, **75,** 137, 1932.

(63) Rao, S. R., *Proc. Roy. Soc. (London)*, **128,** 57, 1930.

(64) Ahearn, A. J., *Phys. Rev.*, **38,** 1858, 1931.

(65) Aldous, W. A., and Campbell, N. R., *Proc. Roy. Soc.*, **151,** 694, 1935.

(66) Hayner, L. J., *Physics*, **6,** 323, 1935.

(67) Hayner, L. J., and Hull, A. W., *Phys. Rev.*, **33,** 281, 1929.

(68) Moullin, E. B., *Proc. Roy. Soc. (London)*, **147,** 100, 1934.

(69) Penning, F. M., and Kruithof, A. A.,*Physica*, p. 793, 1935.

(70) Ziegler, M., *Physica*, **2,** 415, 1935.

(70*a*) Ziegler, M., *Physica*; **3,** I, 1936.

(71) Ziegler, M., *Physica*, **3,** 307, 1936.

(72) Hull, British patent 1555, 1915.

(73) Zworykin and Rejchman, *Proc. IRE*; **27,** 558 and 566, September, 1939.

(74) Iams and Salzberg, *Proc. IRE*, **23,** 55–64, January, 1935.

(75) Thompson, *Proc. IRE*, **29,** 583–587. November, 1941.

(76) Wagner and Ferris, *Proc. IRE*, **29,** 598–602, November, 1941.

(77) Hopkins, U. S. patent 1,920,863 (1932).

(78) Farnsworth, P. T., U. S. patent 2,071,515, U. S. patent 2,174,488.

(79) Hull and Williams, *Phys. Rev.*, **27,** 423, 1926.

(80) Telleghen, British patent 287,958.

(81) Harries, *Wireless World*, Aug. 2d, 1935.

(82) Harris, British patents 380, 429, and 385, 968, 1931; and *Wireless Eng.*, **13,** 190–199, April 1936.

(83) Harries, *Wireless Eng.*, **15,** 212, April 1938.

(84) Harries, *Electronics*, May, 1936, p. 33–35.

(85) Harries, *Wireless Eng.*, **14,** 63, February, 1937.

(86) Harries, *Electronic Eng.*, January. 1942, 586–587.

(87) Malter, *Proc. IRE*, **29,** 587–598, November, 1941.

(88) Salzberg, and Haeff, *RCA Rev.*. **2,** 336–374, January, 1938.

(89) Dow, "Fundamentals of Engineering Electronics," Chapman & Hall, Ltd., London.