A TRANSMISSION ELECTRON MULTIPLIER; A PRELIMINARY STUDY

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Cone, Donald R.

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A TRANSMISSION ELECTRON MULTIPLIER
A Preliminary Study

Donald R. Cone

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Berkeley, California
ABSTRACT

Preliminary work has been done on the construction of a transmission type electron multiplier tube, wherein the initial electrons are accelerated and focused onto the face of a thin foil with sufficient energy to penetrate the foil and produce secondaries on the far side. These secondaries in turn are accelerated to an adjacent foil where the process is repeated. A cathode ray tube gun was used as the initial source of electrons. For the first test, a beryllium foil about 10 microinches thick was used, with a secondary to primary ratio of 1.7 for 4.6 kv incident electrons. The final experiments were conducted with formvar films about 4 microinches thick, with a thin layer of beryllium evaporated on the emergence side. With these foils, ratios of 2.5 were achieved with 3 to 8 kv incident electrons. In both cases, the secondary to primary ratio was increasing with electron energy, so the figures given do not indicate a limit.

From the results, it seems conclusive that a multi-stage transmission multiplier could be built giving a useful gain with a reasonable overall accelerating voltage.
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INTRODUCTION

1. PURPOSE

The purpose of this experiment was to study the possibility of constructing an electron multiplier of the transmission type, i.e., one in which an accelerated electron, passing through the first of a series of parallel thin foils supporting an emitting surface on their far side, would cause that surface to emit several secondary electrons. These in turn would be accelerated towards the adjacent foil with sufficient energy to penetrate it, knocking out secondary electrons from the far side of it, and so on through successive foils until sufficient electrons are available to supply the necessary signal.

2. HISTORY OF SECONDARY EMISSION

It was about the time of the detection of radioactivity that the phenomenon of secondary emission was discovered. In fact it was in conjunction with experiments on radioactivity that much of the early work on secondary emission was done. It is not clear in the literature just who first discovered the effect. However, prominent among the early experimenters are such well known names as Campbell\(^1\), Rutherford\(^2\), J. J. Thomson\(^3\), and Compton and Langmuir\(^4\).

A fundamental value is the average number of secondary electrons emitted per primary particle incident on a surface. This ratio is variously referred to in the literature as \(\delta\), \(\omega\), \(R\), or \(s_0/p\), and will be designated by \(R\) in this article. The average number of emitted electrons depends on a number of factors:

1. The nature of the surface; heat treated and rough surfaces giving less, contaminated and smooth surfaces more secondaries.
2. The velocity of the primary particles, the number of secondaries increasing with primary velocity up to a few hundred volts, then slowly decreasing as the primary velocity increases still further.

3. The angle of incidence of the primary electrons, the yield increasing with the angle from the normal.

4. In general, pure metals will give a lower yield than their compounds, the compounds of the electronegative metals giving the highest yields. The secondary to primary ratio $R$ ranges from 0.9 to 1.5 for pure metals, 3 to 4 for untreated metals, and may be as high as 8 to 10 for oxidized metals or films of oxidized metals.

5. There is little evidence of any significant change in emission over a several hundred degree change in temperature.

6. The direction of secondary emission appears to be more or less random, although some evidence exists of maxima dependent upon the primary velocity.

The energy of the secondary electrons given off from a bombarded surface ranges from 0 to 10 volts. Normally, there will also be a stream of electrons with about the same velocity as the primary electrons, but this is due merely to primaries reflected with practically no loss of energy.

3. APPLICATIONS OF SECONDARY EMISSION

One of the earliest applications of secondary emission was in the Dynatron vacuum tube designed by Hull in 1910. It achieved a
voltage amplification of 100, but was troubled by voltage fluctuations and emission instability.

Many attempts were made to incorporate secondary stages in otherwise normal thermionic tubes. A typical example is the orbital beam tube developed by Wagner and Ferris. They used small cathode and grid electrodes to give a low input capacity and incorporated a stage of electron multiplication to increase the resulting small current.

Early electron multiplier tubes used crossed magnetic and electric fields to focus electrons from one emitting cathode to the next, but suffered from defocusing. Present commercial types, such as the RCA 931A use electrostatic fields for focusing and accelerating. The initial electrons are emitted from a photo cathode, and progress to the first of nine secondary emitting dynodes. The tubes are normally operated at about 100 volts per dynode, and can achieve gains of $10^6$ or greater.

Other applications of secondary emission are in television pickup tubes, such as the Image Dissector, Image Iconscope, and Image Orthicon.

A recently announced British development is the "venetian blind" multiplier. The dynodes of the tube consist of a "venetian blind" arrangement of nickel slats coated with a secondary emission material. A fine wire screen on the input side of each dynode deflects the secondary electrons through the slats and onto the next dynode. Nine to eleven dynodes are stacked one after the other to form the tube.

Another new development is the RCA 5819, which is essentially a 931A Multiplier tube with a large transparent photo cathode and one
additional stage of multiplication.

An important, and very recent use of electron multiplication is in the field of radiation detectors, enabling one to count individual particles. Allen\textsuperscript{8} describes some tubes built specifically for this purpose, and regular commercial tubes can be adapted to serve. Much of this development is still classified and cannot be reported here.

4. SECONDARY EMISSION FROM THIN TARGETS

Ever since the discovery of the particles given off by radioactive substances, thin metallic foils have been used as a means of attenuating the particles. In fact, as early as 1894, Lenard\textsuperscript{9} used them in his work on cathode rays. Rutherford\textsuperscript{10} used thin aluminum foils in his experiments with the alpha particle around 1905, and Bragg\textsuperscript{11} contributed the knowledge that alpha-particles were not absorbed in the thin foils, but only slowed down.

In 1911, Bumstead\textsuperscript{12} reported that when alpha rays were passed through a thin aluminum foil, approximately eight electrons were emitted from both sides. He also noted that the secondary emission from both gold and aluminum foils transmitting alpha-particles first increased, then rapidly decreased as the alphas approached the end of their range. Hauser\textsuperscript{13} claimed twenty secondary electrons from the emergence side of his aluminum foil for each alpha-particle transmitted.

Terrill\textsuperscript{14}, in 1923, determined the loss in velocity of 25 to 51 KeV electrons in passing through thin foils, and used a magnetic field to return the secondaries emitted.

Schonland\textsuperscript{15} used grids at -100 volts on each side of his foils,
to return the emitted secondaries. He noted that R showed a decrease with increasing primary velocity, and was lower for the lighter elements.

These early experiments were primarily to find the attenuation of particles passing through the thin foils. In 1925, Hartig\textsuperscript{16} made a deliberate study of the secondary emission from the back side of a 3 micron aluminum foil bombarded with electrons. He used a tungsten filament as an electron source, and a nickel plate one millimeter behind the foil to collect the secondaries. The foils were checked for holes over a 100 watt light. The plate was carefully shielded, since he found that electrons were diffused through the vacuum system. His vacuum was $10^{-5}$ cm of Hg. After the foil was bombarded for one-half hour with 2000 volt primaries, reproducible results were obtainable. He noted that all electrons reaching the plate had velocities less than 10 volts with a majority at approximately 2 volts, for primary velocities through 1600 volts. He attributed the plate current both to secondaries and to photoelectrons from the back of the foil due to the X-rays produced by the primaries. Using two foils reduced the current by $10^{-4}$ leaving mostly photoelectrons. A third foil reduced the current by $10^{-1}$. He pointed out also that the mean free path might be greater than thought, and that the secondary current was actually transmitted primary current.

Kurchatov and Sinelnikov\textsuperscript{17} took exception to Hartig's work. They took foils showing no light transmission and showed, by applying air pressure under water, that there were actually small holes present. Using foils with no holes, according to the above test, they
repeated Hartig's experiment and found no current flowing to the plate, even with 15 ma of primary current. Then, they put small holes in a 3.5 micron foil and were able to obtain results similar to those of Hartig.

Schneider experimented with 23 to 53 KeV protons through thin aluminum, copper, and gold films, and found that the secondaries had a continuous energy distribution, with broad peaks at 20 to 40 volts. He found about four electrons per proton, independent of the proton energy, at a 90° angle to the proton beam. The only outgassing of the film was by the proton beam itself.
THEORETICAL DISCUSSION

1. THE TRANSMISSION OF ELECTRONS THROUGH FILMS

When electrons penetrate matter, they are slowed down and finally stopped (assuming there is sufficient material) by collisions with other electrons. Hence, the range in the material depends on the density of electrons in the material. To the first order, the number of electrons per unit mass is constant, so that absorption in milligrams per square centimeter (or other appropriate units) is independent of the material. Actually, of course, the number of electrons per unit mass decreases with increasing atomic number, due to the decreasing ratio of protons to neutrons, so that the stopping power is proportional to \( Z/A \) where \( Z \) is the number of protons in the nucleus and \( A \) is the atomic mass number.

Glendenin\(^{19}\) has compiled a range-energy curve for electrons in aluminum down to 10 Kev, shown in Figure 1. Since the low energy portion of the curve was fairly straight, it was extended to 1 Kev. The extrapolated portion, while not precise, is probably good for order of magnitude approximations.

Nothing was found in the literature concerning the energy distribution or emergence angles of electrons transmitted through thin films. What work has been done was in the preparation of thin windows for beta counters. Backus\(^{20}\) and Ferrance and Stephenson\(^{21}\) give their experimental results, plotting percent electron transmission vs electron energy. Their results are shown in Figures 2 and 3 respectively. They are not in too close agreement. For 4 Kev electrons through a 4 microinch thick film, Backus shows 93 percent transmission and Ferrence and Stephenson 27 percent.
RANGE ENERGY CURVE FOR ELECTRONS IN ALUMINUM (AFTER GLENDENIN)
TRANSMISSION OF 0.1\(\mu\) (4 MICROINCH) COLLODION WINDOW FOR ELECTRONS (AFTER BACKUS\(^{20}\))

**FIG. 2**

PER CENT TRANSMISSION

KILOVOLTS
TRANSMISSION OF ELECTRONS THROUGH FILMS

TRANSMISSION AS A FUNCTION OF VOLTAGE FOR VARIOUS THICKNESSES OF FILM

TRANSMISSION AS A FUNCTION OF THICKNESS FOR VARIOUS VOLTAGES
(AFTER FERRANCE AND STEPHENSON)

FIG. 3
2. ELECTRON TRANSIT TIME

The variation in transit time for electrons in a multiplier tube is of interest since it determines the width and to some extent the height of the output pulse caused by an initiating impulse. The parallel plane geometry of the transmission type multiplier should give very favorable results from this standpoint, since all electrons travel essentially the same path length. The main variations will come from electrons emitted from the foil with a finite component of velocity normal to the foil. True secondary electrons are emitted with nearly zero velocity, usually not exceeding 10 volts, which is small compared with accelerating voltages of several kv. The transit times are calculated for a typical case in Appendix I. With a 4 kv accelerating field and quarter inch spacing between foils, the transit time for an electron with zero emission velocity is $3.38 \times 10^{-10}$ seconds, while one with a normal velocity component of 10 volts would cross the gap in $3.20 \times 10^{-10}$ seconds, or a spread of $1.8 \times 10^{-11}$ seconds.

If a primary electron is transmitted through the foil, and emerges with 500 volts velocity normal to the foil, its transit time is $1.89 \times 10^{-10}$ seconds.

The preceding applies to each stage of a multiplier tube. For n stages, the overall transit time would involve the sum of n independently fluctuating inter-stage transit times. The total spread could be calculated from the statistical theorem which states that "the mean square deviation of the sum of a number of independent fluctuating variables is the sum of the mean square deviations of the independent variables".
3. SECONDARY EMISSION TIME

Since the width of the output pulse from conventional multiplier tubes can be accounted for by the variation in emission velocities and the difference in path lengths, it is reasonable to assume that the time involved in the secondary emission process is short compared to the other variables which are of the order of $10^{-9}$ seconds. Malter\textsuperscript{22} points out that the frequency response of the electron multiplier depends only on the overall transit angle, and not on the scale to which the tube is built. If there were a spread in the time involved in secondary emission comparable to that produced by variations in the initial velocities or path differences, the frequency response curve plotted against the overall transit angle would be different when the scale of the tube was changed. Since there is no change up to 500 megacycles, he concludes that the emission time must be less than $2 \times 10^{-9}$ seconds. An accurate determination of the order of magnitude and variations in secondary emission time must of necessity await the development of electronic circuits and timing equipment much faster than any currently available.

4. SPACE CHARGE EFFECTS

In an electron multiplier tube, space charge effects enter, if at all, only in the final stages, where the current reaches a maximum. The equation for the space charge limited current for parallel plane electrodes is $I = \frac{2.33 \times 10^{-6} V^{3/2}}{d^2}$ amps/cm\textsuperscript{2} \textsuperscript{*} where $V$ is the applied voltage and $d$ the electrode spacing in cm. For an accelerating voltage of 4 kv and a spacing of 0.4 inches, $I = 0.58$ amps/cm\textsuperscript{2} or 1.67 amps for a 3/4 inch diameter foil. Since 1 amp will produce a 50 volt

signal in a 50 ohm cable, it is not expected that space charge will be a limiting factor in a properly designed transmission multiplier tube.

5. EFFECT OF UNIFORM MAGNETIC FIELD

If one assumes that a uniform magnetic field is superimposed axially onto the tube, i.e., parallel to the electric field, then all electrons emitted from the foil surfaces or transmitted through them which do not emerge normal to the surface will be acted upon by the magnetic field, and follow a helical path whose radius

\[ r = \frac{3.37\sqrt{E}}{B} \sin \theta \text{ cm} \]

and whose pitch \( p \), in the absence of the accelerating field \( = \frac{21.2\sqrt{V}}{B} \cos \theta \) cm, where \( V \) is the electron energy in ev, \( \theta \) the angle of incidence with respect to the field, and \( B \) the field strength in gauss.* For a secondary electron with 10 volts energy escaping at right angles to a foil (i.e., grazing the surface) in a magnetic field of 1000 gauss, the radius \( r \) equals 0.004 inches. Since the electron is accelerating due to the electric field, the pitch of the helix will vary as the electron gains energy. One can calculate the instantaneous pitch of the electron at any point along its path. If the accelerating voltage is 4 kv, the pitch for the average velocity \( \left(\frac{4000-0}{2} = 2000 \text{ volts}\right) \) is 0.373 inches, and for the terminal velocity \((4000 \text{ volts})\) is 0.528 inches.

If a primary electron is transmitted from the previous stage again at a grazing angle with a velocity of 500 volts, its radius in a 1000 gauss field would be only 0.030 inches.

6. RELATIVITY EFFECT

In spite of the fact that the total voltage applied to a multi-

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* Terman, Radio Engineer's Handbook, p. 280, equation 21 and 22, respectively.
stage transmission electron multiplier will be of the order of 50 to 100 kv, the maximum velocity the electrons will reach will probably not exceed 5 kv, since they are mostly absorbed in the foils, and the secondaries emerge with velocities of approximately 10 volts or less. For 5 kv electrons $\frac{v}{c} = \frac{\sqrt{5}}{506} = 0.140$. For $\frac{v}{c}$ small, $m \approx m_0(1 + \frac{\frac{v^2}{c^2}}{2})$. Hence, 5 kv electrons experience about 1 percent gain in mass. Since this has a negligible effect in the tests reported, relativity is neglected entirely.
TEST PROCEDURE AND RESULTS

1. FILM PRODUCTION

   A. Film  The critical portion of a transmission electron multiplier is the film through which the electrons are transmitted. They must be thin enough to pass electrons of reasonable velocities, strong enough to withstand the electrical and mechanical forces involved, and give an adequate electron multiplication. In some of the tests described herein, thin beryllium foils were used. These were developed initially by Dr. Hugh Bradner for use as focusing foils for the Berkeley Proton Linear Accelerator, and were made by evaporating beryllium onto stainless steel sheets, and then removing the resulting foils. They were available down to about 5 microinches in thickness and one inch in diameter. However, the very thin foils which were of primary interest in this study were extremely fragile, limited in number and contained small pinholes.

   Development work was undertaken to produce foils specifically for the multiplier. Bradner had demonstrated that beryllium could be evaporated onto thin "formvar" films, and this approach was undertaken as being the most promising. Nylon films were tried first, it having been pointed out by Brown, Felber, Richards, and Saxon that nylon has a higher tensile strength than formvar, zapon, or collodion, the other plastics commonly used for thin film production. Using the techniques of Brown, et al, 2 mil nylon sheet was dissolved in isobutyl alcohol, the alcohol being held at a slow boil for a few minutes to facilitate the dissolving of the nylon. One drop of the concentrated solution dropped on water gives a film of about 2-3 micro-inches thickness. The water should be dust-free neutralized distilled water. The water was neutralized with tri-sodium phosphate, the neutralization.
contributing to the uniformity of the film. A 10 inch diameter glass dish was filled to overflowing with neutralized distilled water. A film holder of 1/64 inch thick stainless steel, 3 1/2 inches on a side, and containing eight 1-inch diameter holes, was placed on the bottom of the dish. The surface was swept off with a glass rod to remove all dust from the surface. As soon as the water quieted down, a drop of the nylon solution was deposited in the center, whereupon it spread out to form a large, fairly uniform thin film. After allowing about 10 minutes for the film to dry, the film holder was raised with one edge at the center of the film. The film was allowed to fold over the top edge and cover both sides of the holder, giving a double thickness film in each of the foil holder holes. Using a double film helps to eliminate small pinholes in the foils. It was found necessary to add a thin bar across the top of the foil holder to prevent the surplus film from drooping over the holder, and to facilitate raising the holder from the water. Figure 4 shows a typical foil holder and film mounted on the lifting mechanism. Films thus produced were quite strong, durable, and elastic. However, it was found that the nylon would not withstand the heat of the evaporation process, all of the foils splitting or cracking before any appreciable layer of beryllium could be deposited. Thus it was necessary to change to formvar film which, while not as durable as nylon at room temperatures, withstood the heat during the evaporation process much better. The formvar was dissolved in ethylene dichloride, and films made using the same process described for the nylon. Aerosol was added to the water to facilitate the operation, as suggested by Fry and Overman. One addition to the technique was to maintain the distilled water at 1 to 2° C by placing the 10 inch diameter dish in a
LIFT MECHANISM WITH FOIL HOLDER AND FILM

FIG. 4

FOIL HOLDER WITH HEAT SHIELD

FIG. 5
larger dish containing water and solid CO₂. This resulted in larger, thinner, and more uniform films.

B. Evaporation Technique In order to deposit a metal surface on the formvar film, the beryllium* evaporation system developed by Bradner was utilized. This consisted of a vacuum chamber 22 inches in diameter and 14 inches deep, mounted on a 14 inch oil diffusion pump, which made it possible to evacuate the chamber to 10⁻⁵ mm of Hg in a few minutes. The beryllium was evaporated from a BeO crucible held in a tantalum ribbon filament 40 mils thick by 200 mils wide which was supported by its two electrodes. The foil holder with its thin film was held about 10 inches above the crucible with an empty foil holder 1/2 inch below it to serve as a heat shield. See figure 5. The setup can be seen in Figures 6 and 7. The evaporation was observed through a glass port. A shutter mounted on the front plate and operated through a wilson seal, could be interposed between the crucible and the foil holder.

In normal operation, the foil holder containing the thin film was placed on a bracket directly above the crucible. With the front port bolted on and the chamber pumped down below 5 x 10⁻⁵ mm of Hg, the shutter was placed between the crucible and foil holder, and the filament heated (85 amps and 6 volts), raising the Be temperature to approximately 1400° C. The shutter was moved aside for 1/2 minute intervals each minute allowing the Be to reach the foil, then interposed again to prevent the foils and holder from becoming too hot. 1 to 3 minutes of exposure served to deposit a dark film on the foils and still leave them somewhat transparent.

* Caution -- Beryllium is toxic, and should be handled with suitable precautions.
EVAPORATION VACUUM CHAMBER

Fig. 6

1. BeO CRUCIBLE
2. TANTALUM FILAMENT
3. FILAMENT HEAT SHIELD - STAINLESS STEEL
4. BERYLLIUM
5. FOIL HOLDER SUPPORT
6. VIEW PORT
VACUUM CHAMBER, SHOWING COVER PLATE AND SHUTTERS

FIG. 7
C. Film Resistance  The resistance of the films thus made was measured by placing a 3/4 inch diameter foil on a glass microscope slide and using Aquadag to make contact to the opposite sides of the disc. One foil, with a medium dark coating measured 50 megohms while one only slightly darker, i.e., with very little more beryllium, measured only 6000 ohms. Apparently, the beryllium deposits initially in semi-isolated islands on the film, and after reaching a certain concentration, with only a slight addition of beryllium, blends together to form a fairly uniform layer. The foils alone, with no beryllium on them, measured greater than 10^10 ohms.

D. Film Thickness  Since the plastic films formed were only a fraction of a light wave length thick, a measure of their thickness and uniformity could be obtained by noting the color and any interference patterns formed. This was also checked by weighing a known area of film on a microbalance, and using the density to determine the thickness.

The results checked rather closely (30-40 micrograms for 3/4 inch diameter foil) with color observations and with results of other experimenters. The average film used was about 4 microinches thick, made up of two layers of plastic.

2. MECHANICAL EQUIPMENT

A. Chamber  The vacuum chamber in which the tests were performed was a 1' x 1' x 2' steel chamber, welded at the edges, and painted with glyptal inside. Suitable ports were available for the insertion of equipment, for carrying electrical connections through the vacuum wall, and for observation. The chamber is shown in
Figure 8. The vacuum system was composed of a 100 liter per second water cooled oil diffusion pump backed up by a Welch Duoseal forevac pump. A liquid air trap was inserted in the vacuum chamber. Pressures of $5 \times 10^{-6}$ mm of Hg were obtainable in about 20 minutes. The vacuum was measured by means of an ionization gauge and associated power supply. Figures 9 and 10 show two views of the equipment. A cylinder containing a cathode ray tube gun was attached to one end of the vacuum system, and a gasket and plate in the vacuum chamber, operated externally through a wilson seal, enabled one to close off the gun cylinder when letting the main chamber down to air, to prevent contamination of the gun cathode.

The foil holders were supported on ceramic standoff insulators mounted on a brass plate which rested on the bottom of the vacuum chamber. Figure 11 shows several foils and holders mounted in place. The disc at lower left is for blocking off the CRT chamber. Leads were brought out through Kovar seals mounted in metal plates or through spark plugs mounted in lucite.

B. Electronic Equipment The electron gun used as a source of electrons in the experiment was a standard Dumont 5LP gun taken from a used cathode ray tube. The tube wall was punctured with a gas flame to remove the danger of implosion, after which the glass was removed to the desired length. An 11 pin CRT socket was mounted on standoffs on the vacuum side of a plate, and the leads brought through on Kovar seals soldered to the plate. A separate chassis was used to control the focus, intensity, and horizontal and vertical beam deflection. Figure 12 shows the chassis with the CRT gun mounted in its socket. Appendix II gives a detail view and circuit diagram of the control
CATHODE GUN
FLUORESCENT SCREEN
COLLECTOR SHIELD
PLATE USED TO ISOLATE CRT GUN WHEN VACUUM CHAMBER LET DOWN TO AIR.

TEST VACUUM CHAMBER
FIG. 8
FIG. 9

FIG. 10

TEST VACUUM SYSTEM WITH CHAMBER, PUMPS, AND VACUUM MEASURING EQUIPMENT.
FOILS AND HOLDERS MOUNTED IN VACUUM CHAMBER. 

FIG. 11

CRT GUN ON VACUUM FLANGE, AND GUN CONTROL CHASSIS.

FIG. 12
chassis. Acceleration was obtained by means of a 0-5 kv d.c. regulated high voltage supply. Currents were measured with a L and N galvanometer and an RCA ultra-sensitive microammeter.

After letting the CRT gun down to air to install it in the system, it was necessary to reactivate it. First it was pumped down to about $5 \times 10^{-6}$ cm of Hg, and hydrogen introduced through a surgical needle valve to raise the pressure to $5 \times 10^{-5}$ mm of Hg. It is not known just what function the hydrogen fulfills. Probably it helps to reduce the outer contaminated oxide layer on the filament, leaving a new emitting surface. Ten volts were applied to the gun filament and maintained for 10 minutes, after which the hydrogen was turned off and the filament voltage reduced to normal. Figure 13 shows the CRT gun chamber and needle valve. This process had to be repeated from time to time, and the guns were replaced periodically. The electron beam was not entirely reliable, and varied with time, but it did serve as an adequate source of primary electrons for the experiment.

3. TEST RESULTS

For the first test, a beryllium foil about 10 microinches thick was cemented with aquadag onto a copper ring plated on a ceramic holder. A copper collector plate, positioned about $1/2$ inch behind the foil, was carefully shielded so that only secondary electrons from the foil or transmitted primary electrons could reach it. The mechanical setup is shown in Figure 14.

A copper tube was used for a collector shield, with a Kovar seal soldered on one end which served both as a mounting for the collector plate and a collector lead feed through. A pumpout hole drilled through the copper tube prevented a pressure differential from breaking
CRT GUN CHAMBER MOUNTED ON VACUUM CHAMBER

FIG. 13
MECHANICAL TEST SETUP  
Fig. 14

ELECTRICAL TEST SETUP  
Fig. 15  
MU 1080
the foil. Metal braid shielded the collector lead to the point where it was brought out of the vacuum chamber. Figure 11 shows this and other foil mounts in position in the vacuum chamber.

A cathode ray tube screen mounted inside the vacuum chamber so that it could be swung down directly in front of the foil, and operated from the outside through a wilson seal, was used for focusing and positioning the electron beam, after which it could be swung up out of the path of the beam, allowing the electrons to strike the foil.

The electrical setup used is diagrammed in Figure 15.

In a typical test, the electron beam energy was varied by varying the hv supply and the currents through A and B recorded. The results were analyzed as follows: Let \( I_p \) be the primary beam current and \( I_s \) the true secondary current. Assume that a fraction \( x \) of the primary electrons are transmitted through the foil and reach the collector. Then the following will apply:

\[
\begin{align*}
A &= I_p(1-x) - I_s \\
B &= I_px + I_s
\end{align*}
\]

From this it follows that \( I_p = A + B \) (3). B is the total collector current, the sum of the transmitted primary electrons plus the true secondary electrons, i.e., the current available for bombarding a
succeeding foil. The ratio \( R \) of \( B \) to \( I_p \) is the measure of the gain in electrons per stage and is of primary interest in this study.

\[ R = \frac{B}{I_p} = \frac{B}{A+B} \]  

A typical graph of the ratio \( R \) plotted against primary electron velocity is given in Figure 17. The primary velocity of the electrons was limited to 4.6 kv by voltage breakdown in the CRT gun. In addition, since the beam impact point moves as the beam energy is varied, different portions of the foil would be bombarded, with corresponding variations in the results due to irregularities in the foil thickness and occasional pin holes.

It is encouraging to note that the curve rises rapidly with increasing voltage indicating that with higher primary velocities, greater ratios may be obtained.

Another obvious alternative is to use thinner foils to achieve higher gains at a given voltage. For example, if one accepts the values of Ference and Stephenson on transmission of electrons through thin films, it can be seen that, taking 10 microinches of beryllium as equivalent to 18 microinches of collodion, one could expect 15 to 20 percent transmission at 4.6 kv. Since the measured secondary emission is attributed to those electrons which penetrate the foil, we can arrive at a new secondary to primary ratio \( R' \) which indicates the increase in electrons due to the primaries actually contributing to the reaction. Thus, from Equation (2) \( I_s = B - I_p x \), and Equation (3) \( I_p = A + B \), it follows that \( I_s = B - x(A + B) \). (5)

For 20 percent transmission, \( x = 0.20 \). From the data for Figure 17, at 4.6 kv \( A = -4.6 \times 10^{-9} \) amps and \( B = 10.4 \times 10^{-9} \) amps. Thus, \( I_s = 0.8B - 0.2A, = 7.40 \times 10^{-9} \) amps, the true secondary current.
VARIATIONS IN SECONDARY EMISSION RATIO WITH PRIMARY VOLTAGE FOR ZAPON AND BERYLLIUM FOILS.

FIG. 17
The transmitted primary beam: \( xI_p = x(A + B) = 1.16 \times 10^{-9} \) amps. Hence \( R' = \frac{I_s}{xI_p} = 6.4 \). This value is probably high, due to assuming too low a percent transmission, but indicates, together with the rapid increase in \( R \) with accelerating voltage, that substantial gains can be achieved by raising the accelerating voltage and/or using thinner foils.

To verify the effect of film thickness, a new foil was tested, using the same techniques previously described, a zapon film about 3 microinches thick. The results are also shown in Figure 17. For the Zapon film, \( R \) started up rapidly at a relatively low voltage, reached a peak between 2 and 3 kv, and dropped off. This curve is somewhat similar to a standard reflection secondary emission curve with the primary voltage axis shifted about 2 kv, this shift being ascribed to the energy lost by the primary electrons in penetrating the zapon. The secondary ratio should reach a maximum when the transmitted primaries have a velocity corresponding to a few hundred volts, and should fall off slowly thereafter, as the curve indicates.

**EFFECT OF COLLECTOR VOLTAGE**

A test was run to determine the effect of collector voltage on the measured current. The setup is diagramed below in Figure 18.

![Collector Voltage Test Setup](image)
The accelerating voltage was set at 4.5 kv and the current through A maintained at $1 \times 10^{-9}$ amps by the CRT intensity control. V was varied from 0 to 60 volts and the corresponding current B read. The curve is shown in Figure 19. This demonstrated that any potential above 20 volts would collect all the secondaries emitted.

**ENERGY OF EMITTED ELECTRONS**

The experimental setup was modified slightly to measure the energy of the emitted electrons. An additional 67.5 volt battery was added in series with the one shown in the previous illustration, and the center point grounded. Thus, the collector voltage could be varied between plus and minus 67.5 volts. The results are shown in Figure 19. This would indicate that essentially none of the primary beam is being transmitted with any appreciable velocity, and that the secondaries are emitted with less than 10 volts energy.

**ATTEMPTS TO RAISE PRIMARY ENERGY**

Two methods were tried to increase the energy of the primary electrons. As mentioned previously, the CRT gun would arc across above 4.5 to 5 kv, so first an attempt was made to float the gun and its hv supply and control chassis so that they could be operated negative with respect to the foil. The 110 V a.c. voltage for the hv and control chassis's was supplied through a 5 kv insulation transformer, and the CRT mounting plate insulated from the vacuum chamber by a 1/2 inch thick rubber gasket, using bakelite bolts to hold it in place. This allowed an additional 5 kv d.c. supply to be placed in series with the first giving the setup pictured in Figure 20.

However, the equipment still arced across inside the CRT cham-
Figure 19

Collector Current - Normalized

\[ V_p = 4.5 \text{ KV} \]

Collector Volts

MU 1082
INSULATED BOLTS (BAKELITE)

O-SKVOC SUPPLY

8 GUN CONTROL CHASSIS

1:1 5 KV INSUL XFMR

110V AC

TEST SETUP

FIG. 20

CRT CATHODE

FOIL COLLECTOR

TEST SETUP

FIG. 21

MU 1083
ber, above 4.5 to 5 kv, and in spite of many efforts to eliminate the trouble, no satisfactory tests were accomplished.

The next method tried was to make the foil positive, and thus increase the primary beam energy. The equipment was set up as indicated in Figure 21.

The leads through the vacuum chamber were guard-ringed to prevent measuring the leakage current across the kovar seals, and the meters insulated from ground. With Vp' at zero, the accelerating supply (Vp) was run up to 4.5 kv; A read $-2.8 \times 10^{-9}$ amps and B read $8.1 \times 10^{-9}$ amps, giving an R of about 1.6. When voltage Vp' was raised to 1 kv, the current through B continued to increase as would be expected but that through A, which had been increasing negatively, started back towards zero. This is attributed to two causes; first, the leakage currents inside the vacuum chamber to the foil and externally to the meter, and second, to low energy electrons picked up by the positive foil and its holder which would be measured but would not have sufficient energy to penetrate the foil and cause secondary emission.

One of the main difficulties encountered so far was that the currents of interest were the same order of magnitude as the leakage currents. A possible solution was to make up several stages of multiplier with the hope that its output current would be well above the leakage currents involved. Consequently, four beryllium foils 9 to 14 micro-inches thick and mounted on brass rings were spaced about one inch apart in a polystyrene tube one inch in diameter. The successive foils were connected with 100 megohm resistors composed of ten 10 megohm 1 watt resistors in series. A brass collector plate at one end was to
collect the output from the final stage. A lucite disc about 3 inches in diameter with a 1/2 inch diameter hole in the center was mounted on the input end of the assembly. A fluorescent powder was applied to the face of the disc so that the electron beam could be focused and directed through the center hole to the first foil. The assembly is shown in Figure 22. The diagram of Figure 23 illustrates the layout.

All leads and resistors were shielded with transflex or metal braid to prevent them from intercepting stray electrons. Pumpout holes were drilled between foils to prevent breaking the foils when the apparatus was pumped down or let down to air. The lead at the input end was brought out through a Kovar seal, while the high voltage and collector leads were brought out through spark plugs mounted in a lucite plate so that the outer portion of the spark plugs could serve as a guard ring if necessary. The apparatus was set up in the vacuum chamber and pumped down for 24 hours. Then a 4.5 kv electron beam was applied to the first foil in the usual manner. Unfortunately, as the positive high voltage was applied to the successive foils, a spark occurred down the axis of the tube, destroying all the foils before any current measurements could be taken. Apparently, the spark was due to outgassing from the polystyrene tube. Following the discharge, with about 25 kv applied, a blue glow was visible near the electrodes, with occasional sparks along the tube.

Since this used up the available supply of very thin beryllium foils, the next step was to develop a technique for making suitable foils. This process is described in a previous section of this report. The resulting foils were formvar, 3 to 4 microinches thick, with a thin layer of beryllium evaporated on them. The first one tested was
FIG. 23

TUBE TEST SETUP

MU 1084
encouraging, the emission becoming appreciable for primary velocities below 1 kv. The secondary ratio $R$ approached 3 at about 3.5 kv. The curve is shown in Figure 24. The reason for the high points near 1 kv is not known, and since the beam burned out the foil it could not be rechecked, but subsequent tests indicate that the high points are in error, and were probably due to a thin spot in the original foil.

For a final test, two new type foils were mounted in series, followed by a collector and preceded by a fluorescent screen with a hole in the center. The foil mounts were made of stainless steel, with pyrex glass insulators. The assembly is shown in Figure 25 and an individual electrode with foil and insulator in Figure 26. The diagram of Figure 27 shows the electrical circuit.

Using the data from Figure 24, $V_p$ was set at 1.1 kv to give $R = 1$, and the emission of foil 2 to the collector measured as the foil 2 accelerating voltage was varied. The results, averaged from 4 runs, are shown in Figure 28. Evidently the second foil was not as thin as the first, since it required a considerably higher voltage to achieve corresponding gains. Apparently better control is necessary to produce uniform foils, but it is believed that the approach used offers good possibilities for success.
FIG. 24

BERYLLIUM ON FORMVAR

R - SECONDARY EMISSION RATIO

PRIMARY VOLTAGE - KV
FIG. 27  
MU 1086
FIG. 28
SUMMARY AND CONCLUSIONS
SUMMARY AND CONCLUSIONS

In the light of the foregoing it is believed that the construction of a transmission electron multiplier tube is quite feasible. Many problems still remain, but the fact that adequate gains were achieved at reasonable voltages indicates that fundamentally the approach is sound.

1. PROBLEMS REMAINING

Following is a summary of some of the problems to be solved in order to build a useful transmission multiplier tube.

A. Foils The formvar foils used in this experiment were superior to the solid beryllium foils in that they were less fragile, and being thinner, gave satisfactory gains with lower accelerating voltages. They do not withstand the heat from the evaporation processes very well, and it is difficult to produce reasonable areas with a uniform thickness. One approach might be in the field of conducting plastics developed recently by Dr. M. A. Coler of New York University in collaboration with the U.S. Naval Ordnance Laboratory.27

B. Emitting Surface No work was done to improve the emitting surface of the foils. Beryllium was used because it has reasonable secondary emission properties, can be exposed to air without deleterious effects, and because the equipment for beryllium evaporation was already available. It should be possible to develop a stable surface which could be applied either directly to the foil or to a metallic surface evaporated onto it, with a greater secondary emission efficiency.

Another point to consider is that both Kollath28 and Schneider29 report that the secondary emission from evaporated beryllium can be increased considerably by heating the evaporated layer to red heat in a
vacuum.

C. Cathode In the experiments carried out, the initial source of electrons was the CRT gun. In practice, these electrons could come from a photosensitive cathode (possibly of the transmission type similar to that used on the RCA 5819 photo multiplier) or from a suitable metal plate in the path of nuclear radiation (alpha, beta, proton, etc.) in either case with the emitted electrons focused and accelerated to the first foil of the tube.

D. Insulation With the high voltages necessary in a tube such as this, it will be imperative to use care in the selection of electrode shape and spacing and the insulators separating them so that the leakage, field emission, and corona currents will be small compared with the signal currents.

2. ADVANTAGES

The transmission multiplier has a number of advantages over the conventional type.

A. Pulse Width Since all electrons travel essentially the same path length, one should achieve a higher frequency response than that obtained from the reflection type where the path lengths for electrons due to one incident particle may vary to a considerable extent.

B. Use in Magnetic Field The multiplier could be used in a uniform magnetic field as long as the plane of the foils was oriented perpendicular to the field (the only effect being that electrons emitted at an angle from the normal to the surface would spiral as they were accelerated to the succeeding stage). This is likely to be the most important advantage in nuclear physics, since so many of the high energy
particle accelerators use strong magnetic fields. In view of this, it would probably be desirable to construct the tube of non-magnetic materials, so that this property could be utilized.

C. Coax Output The geometry of the apparatus lends itself to a coaxial output, which is important if the inherent high frequency possibilities are to be utilized.

D. Non photosensitive For particle detection work, the transmission multiplier could use a metal plate or other suitable target for a cathode, and would not have to be shielded from light to operate, assuming of course, that the secondary emission surfaces were not photosensitive. Reflection type multiplier tubes could be similarly constructed, but are not now commercially available.

3. DISADVANTAGES

A. Thin Foils The thin foils which are the heart of a device such as this are inherently delicate and fragile, making careful handling a necessity. In addition, it would probably be necessary to construct the apparatus so that individual foils could be replaced without too much trouble.

B. High Voltage The experiments indicate that with present foils, 3 to 10 kv per stage are necessary to achieve reasonable gains. Thus, if a multiplication of 4 per stage were realized, the tube would require 30 to 100 kv for $10^6$ overall gain. These voltages, while not difficult to achieve, require a fair amount of equipment, can be lethal, and are in the corona and x-ray region. It is probable that research aimed at developing better foils can substantially reduce this voltage.

Since these disadvantages are inherent in much laboratory equip-
ment, and since the advantages listed could allow one to achieve results not obtainable in other ways, it is believed that the transmission multiplier can and some day will become a useful research tool.
APPENDIX I

THE ELECTRON TRANSIT TIME

The applicable equation for this case is that for the temperature limited parallel plane diode, where the entering current is not a function of the applied voltage and where the effect of the electrons on the potential distribution is negligible. Thus $\frac{1}{2} \frac{e}{m} \frac{V}{d} T^2 + v_0 T - d = 0$ where

$T = \text{transit time in seconds}$
$e/m = \text{electron charge to mass ratio} = 1.77 \times 10^{11} \text{coul./kg}$
$V = \text{applied voltage per stage in volts}$
$d = \text{spacing between stages in meters}$
$v_0 = \text{initial velocity of electrons (component normal to foil)}$
$= 5.97 \times 10^5 \sqrt{V'} \text{meters/sec where } V' \text{is normal component of escape velocity in volts.}$

Case I: $V = 4kv$  $d = 0.25" = 6.35 \times 10^{-3} \text{ meters}$  $v_0 = 0$

$T = d \frac{2}{\sqrt{V e/m}} = 3.36 \times 10^{-6} \frac{d}{\sqrt{V}} = 3.38 \times 10^{-10} \text{ sec.}$

Case II: $V = 4kv$  $d = 6.35 \times 10^{-3} \text{ meters}$

$v_0 = 10 \text{ eV} = 1.9 \times 10^6 \text{ meters/sec}$

From quadratic equation;

$T = \frac{v_0 \pm \sqrt{v_0^2 + 2 \frac{e}{m} V}}{\frac{e}{m} \frac{V}{d}}$

$2 \frac{e}{m} V = 1.4 \times 10^{15} \frac{\text{meters}^2}{\text{sec}^2}$

$T = 3.20 \times 10^{-10} \text{ sec}$

$\frac{e}{m} \frac{V}{d} = 6.98 \times 10^{17} \frac{\text{meters}}{\text{sec}^2}$

Case III:

$V = 4kv$  $d = 6.35 \times 10^{-3} \text{ meters}$

$v_0 = 500 \text{ eV} = 1.33 \times 10^7 \text{ meters/sec}$

$T = \frac{-v_0 \pm \sqrt{v_0^2 + 2 \frac{e}{m} V}}{\frac{e}{m} \frac{V}{d}}$

$= 1.89 \times 10^{-10} \text{ sec.}$
APPENDIX II

CRT Gun Control Unit

Detail Picture and Circuit Diagram
CRT GUN CONTROL CHASSIS

FIG. 29
CATHODE RAY TUBE GUN CONTROL UNIT

GANGED 4M DUAL POTS

CRT CONTROL UNIT CIRCUIT DIAGRAM

FIG. 30

MU 1088
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