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R-F AGING OF SPACE-CHARGE CONTROL TUBES

by

N. T. Lavoo

Report No. 62-RL-(2977 E) March 1962

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ABSTRACT

Space-charge control tubes, particularly those destined for use in microwave applications, are frequently r-f aged at the factory. By this means many marginal tubes may be made to fully pass all specification tests. Although this practice is quite general there is not a common understanding as to why this technique is successful. In this study it is concluded that the major factor is an improvement in activity of the emitter due to electron back bombardment. A discernible effect is noticed as low as 5 volts but is enormously accelerated if the bombarding electrons have an energy of 20 volts.

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R-F AGING OF SPACE-CHARGE CONTROL TUBES

N.T. Lavoo

Transmitting electron tubes have been r-f aged at the factory since the earliest days and it is a common practice in the industry. R-f aging, as used in this report, shall mean the process of attainment of normal performance in a marginal space charge control tube as the result of the application of a sizable microwave voltage super-imposed on the normal operating d-c potentials. This is accomplished in practice by enclosing the tube in a microwave circuit and causing it to oscillate for a time that might vary from a few hours to tens of hours.

There are a number of possible processes that can take place during r-f aging that could contribute to the improved performance. Among these are, degassing of the grids and anode due to electron bombardment and improvement in cathode activity, again as the result of electron bombardment. As we shall discuss in detail later, these effects are uniquely accomplished at microwave frequencies.

This investigation was prompted by the observations made by the Power Tube Department that the degree of improvement in r-f aging was related to the particular microwave frequency used. They reported that certain tubes improved when r-f aged at 500 mc/s, but further improved at 1000 mc/s and even more at 1500 mc/s. At still higher frequencies no appreciable improvement was noted. The upper frequency limit, where no further improvement was noticed, varied among the tube types with the higher frequency correlating with the tube types having the closest grid-to-cathode spacing. Clearly, some sort of transit time phenomena was involved.

In the experiments to be described bearing on these observations,

diodes rather than triodes were used in order to simplify the problem. Thus only two active electrodes need be considered--the anode and the cathode. These elements will now be discussed.

The Anode

One possibility that was considered was the release of an O^+ ion from the surface of the anode as a result of electrons impinging on the anode surface. In the case of a molybdenum anode the O^+ ions are released at 17.7 volts with the yield increasing exponentially up to about 100 volts.(1) At the maximum efficiency point the yield is about 1×10^{-4} ions per electron. Such O^+ ions would have a deleterious effect on the electron emission if allowed to strike the cathode surface. Young has found detectable decay in the oxide cathode thermionic emission for efficiencies as low as 10^{-9}+ ions/electron.(2) These numbers therefore suggest drastic effects on the electron emission in tubes in which the anode has not been thoroughly outgassed. In like manner, it is anticipated that such effects may be largely eliminated by operating at such a frequency that ion-inertia effects prevent the ions liberated at the anode surface, as the result of electron bombardment, from making a complete transit across the space from anode to cathode. It would be expected that such ions would eventually return to the anode surface with a small number missing the anode surface to be captured by the envelope.

Figure 1 shows a photograph of a tube built to investigate the effects of r-f aging on the tube characteristics--and, in particular, the effects of ion-inertia on preventing ions from returning to the cathode. Included in the figure is a standard 2C39B. The test diode consists of the grid-cathode assembly of a 2C39B in which the grid washer has been removed and replaced

with a tantalum disk to form the anode of the diode. A fernico jacket then encloses the anode structure to complete the vacuum envelope. Tantalum was chosen as an anode material since it is a copious source of oxygen ions because of its tenacious oxide film. The tantalum anode was fired at 1000°C for one hour before mounting. The assembly was baked at 450°C for one hour and was pinched off at a pressure of 1.5×10^{-7} mm Hg. The spacing from cathode-to-anode was 0.010".

If the assumption of no space charge is made, the calculation of the ion path leaving the anode surface is*

$$\frac{\omega^2 SX}{V_1 e/m} = \frac{1}{2}\frac{V_o}{V_1}\left(\omega t - \sin^{-1}\frac{V_c - V_o}{V_1}\right)^2 +$$

$$\left(\omega t - \sin^{-1}\frac{V_c - V_o}{V_1}\right)\sqrt{1 - \left(\frac{V_c - V_o}{V_1}\right)^2} - \sin \omega t + \frac{V_c - V_o}{V_1}$$

where

ω = angular frequency

X = distance measured from the anode surface in meters

V_1 = r-f voltage

V_o = d-c voltage

S = spacing of the diode in meters

V_c = threshold voltage at which ions are generated at the anode surface

e/m = charge to mass ratio of the ion; mks units.

The path of an ion that is timed most favorably for traversing the greatest distance from the anode towards the cathode is given by this expression and is shown plotted in Fig. 2. Here the conflicting forces exerted by the applied r-f and d-c voltages are

*See Appendix A.

pretty well in balance enabling the ion to stay within the inter-electrode space for many r-f cycles. For the set of parameters shown (which includes the threshold, V_c, value for the release of O^+ ions from molybdenum) a r-f frequency of 153 mc/s will turn the O^+ ion around halfway across the tube. Figure 3 illustrates the case of a higher d-c bias relative to the r-f and consequently only 60 mc/s is required to turn the O^+ ion around. These theoretical results suggest that ions knocked off an oxidized anode surface are easily prevented from returning to the cathode by employing a high enough frequency voltage during the aging process.

The initial experiments on r-f aging of the tantalum anode diodes were carried out with an applied r.m.s. voltage of 75 and a frequency of 200 mc/s. The high frequency voltage was periodically replaced with 60 cycles/sec to determine the condition of the anode. Figure 4 shows that the emission improves nicely so long as the 200 mc/s voltage is used but that the 60 cycle voltage is very deleterious to the cathode emission. More than just donor depletion is apparently involved since donor depletion is a fairly quick acting phenomenon. Overnight application of the 200 mc/s voltage further improved the emission from 7 to 12 milliamperes as shown in Fig. 5. Again the application of 60 cycles harmed the emission although to a somewhat lesser extent. These experiments were conducted at 0.72 amperes on the heater rather than the normal one ampere so as to minimize heating of the anode by electron bombardment. Figure 6 illustrates the 200 mc/s current-voltage characteristic taken at various intervals in the r-f aging of Tube #2.

Experiments on other tubes in attempts to clean up oxidized anodes were conducted with similar results. This, together with other experiments to be described subsequently, seemed to indicate

that the cathode rather than the anode was the chief beneficiary of the application of the high frequency. Originally it was thought that the O^+ ions could be knocked out of the anode and that a number of these would diffuse to the envelope of the tube where they would be gettered and thus gradually clean up the anode. Apparently this is much too slow of a process to be highly significant in explaining the improved emission generated by r-f operation.

Based on the work of Young one of the other contaminants to be considered is chlorine. Here we might consider that the chlorine is thermally dissociated during cathode activation and subsequently is deposited on the anode. Anode electron bombardment dislodges it to again return to the cathode with a subsequent deleterious effect on the emission. Just as in the case of an O^+ ion released from the anode being prevented from returning to the cathode due to ion-inertia effects, so likewise this would equally be true for Cl^+ with the appropriate potentials and frequency. Moore has found a great deal of similarity between O^+ and Cl^+ released from an electron bombarded surface.[3]

It should be pointed out that in the case of a triode there will be a different balance between the electric forces exerted by the r-f and d-c fields. In the case of the diode a negative bias was applied to the anode with respect to the cathode. This was done purposefully in order to investigate the diodes with oxygen doped anodes. However, in the case of triodes, the anode is normally biased positively with respect to the grid and cathode. Since the r-f plate swing will not exceed the d-c anode voltage, an ion generated at the anode surface experiences a force which varies in magnitude but not in sign until it enters the grid-cathode region. Just as in the case of the diode it was possible to match

a particular ion with a combination of r-f and d-c voltages to cause interesting ion transits, it is also expected that such a combination can also be found for the triode case. However, as in the diode case, such ion transits are completed at relatively low frequencies even for relatively light ions such as oxygen. Since the r-f effects on emission are changing at frequencies far above those required to complete the ion transits, we now turn our attention from the anode to consider the effects at the cathode.

The Cathode

One of the clues that indicated that r-f operation was concerned more with the cathode than the anode was the much greater rate of emission improvement with time that occurred when the frequency of operation was raised from 200 to 500 mc/s. After all, if 200 mc/s is more than sufficient to hold off positive ions from migrating back to the cathode, raising the frequency should have no further effect.* Nevertheless at 216 mc/s, on one tube, whose emission improvement rate was such as to double the emission in an hour, when operated at 500 mc/s the rate stepped up so dramatically that the heater voltage had to be reduced practically immediately to hold the anode dissipation within safe limits. This experiment suggested electron back bombardment of the cathode as being the significant factor taking place.

This was further corroborated by experiments on a number of

*Although our calculations are based on the O^+ ion, our conclusions would also apply to the Cl^+ ion. Since the Cl^+ ion is heavier it would have less excursion at a given frequency. Also, even though its threshold value is different, this is not a significant factor in determining the maximum excursion for the d-c and r-f voltages employed.

heaterless diodes.[4] These tubes are interesting for our purpose since they contain titanium anodes which remain clean because of the special properties of titanium when operated at elevated temperatures and opposite a passive emitter such as oxide coated platinum. Such tubes have very stable emission and can be successfully operated in the temperature limited region. Since the emission in this region is very sensitive to temperature changes one of these type diodes was used in a special circuit to hold the temperature of the diode to be r-f activated to a small fraction of one degree centigrade at 600° C.

Consistent results could not be achieved on these type diodes. Some could not be successfully r-f aged while others improved by a factor of two to three in electronic emission. An r-f power of the order of 1 to 5 watts at 300 to 1000 mc/s was applied for times of a few minutes to an hour in these experiments. Some of the tubes that aged up were found to begin to deteriorate if r-f was applied too long, while others did not. Perhaps one of the most interesting discoveries in experiments with these heaterless diodes was that the highly deleterious effects of operation at too high ambient temperatures (greater than 600° C) could be overcome subsequently by r-f aging. Among those which withstood the r-f without any deterioration were tubes having very smooth, dense, plated oxide coatings. It should be pointed out that the enhanced emission in time would begin to drift back to the initial level of electron emission. The time required to return to near the original level seemed to be proportional to the time that r-f was applied.[5] These results are quite similar to those recorded in experiments on electrolytic aging where quite long periods were required to permanently enhance the emission.[6]

One possibility that has been considered to explain the deleterious effect of the applied r-f is the development of highly localized hot spots on the oxide cathode surface. These hot spots are the result of electron bombardment of the oxide surface where certain areas of the oxide are in less intimate contact with the cathode base metal. The hot spots subsequently release free metal ions that land on the ceramic cathode-grid spacer (which also is at the cathode temperature in these tests). These ions react with the forsterite ceramic with the reduction of one or more of the constituent oxides with an attendant release of a gas detrimental to the electron emitter. For instance, two possible reactions are,

$$Ba + SiO_2 \rightarrow BaO + SiO\uparrow$$

$$Ba + Fe_2O_3 \rightarrow BaO + 2\,Fe + O_2\uparrow$$

The first of these involves silica with the deleterious gas being silicon monoxide. In the latter the reaction involves the impurity iron oxide (in one of a possible number of forms) with oxygen as the deactivating agent.

As in previous experiments with conventional diodes the improvement in electron emission is the result of back bombardment of the oxide coating. The mechanism is believed to be the dissociation of the barium oxide with the attendant rise in free barium which contributes to the donor centers responsible for the thermionic emission. Although there appears to be some divergence of opinion in the literature concerning the degree of thermionic emission and an excess of the alkaline-earth metal, these experiments strongly suggest this mechanism for the enhanced emission.[6] To summarize, although a number

of interesting issues were raised that still need further work for clarification, it seems clear that the r-f enhanced emission is a result of processes taking place at the cathode rather than at the anode.

Equivalent Energy of the Electrons Striking the Cathode During R-F Aging

Since the evidence points so strongly to electron back-bombardment as the process taking place during r-f aging, an effort was made to determine the energy level of these cathode directed electrons.

A number of calculations were made to determine the order of magnitude of the energy of the electrons that left late enough in the accelerating part of the r-f cycle to be turned back towards the cathode. For simplification, no space charge was assumed and a diode geometry was taken operating with a bias of 2 volts and an r-f voltage of 100 volts peak. Electron paths for electrons leaving the cathode at two difference phases are shown in Fig. 7 for 333 mc/s and one phase at 3000 mc/s. The energy with which the electron strikes the cathode is also indicated. The energy of 12 and 35 volts at the two different frequencies are both such as to be able to cause dissociation of the oxide emitter. Also the spacing required of the diode is reasonable.

To obtain more quantitative information as to the energy level of the electrons required for r-f aging, a double cathode tube was fabricated in which the two cathodes were facing each other opposite a titanium grid mesh. An exploded view of this tube is shown in Fig. 8. A schematic of the tube in its circuit is shown in Fig. 9. The experiment was performed in a bell-jar

type vacuum system. It should be noted that the ceramic spacers were isolated from the titanium parts by thin platinum shims. This was to avoid any interaction between the two since the experiment was done with all parts heated to about 700°C during the tests by means of an r-f induced field in a surrounding metal heat shield. The cathode consisted of a thin layer (0.1 mil) of barium-strontium carbonate over a platinum base metal.

In operation the auxiliary cathode is used as a source of electrons to bombard the other. A potential of +7.7 on the grid was sufficient to obtain about 1 milliampere of bombarding current. Figure 9 shows how the initial emission was modified by successively higher bombarding voltages. The results indicate that appreciable enhancement takes place at 10 volts but the process is greatly accelerated at the 20 volt level.

The threshold levels of dissociation of the oxides will be taken as follows:[7]

BaO	9.5 ± 0.5 ev
SrO	14.0 ± 0.5 ev.

The slight emission enhancement at 5 and 8 volts may be the result of the release of adsorbed gases.[6] Presumably the effects at 10 and 15 volts are due to the dissociation of the oxides, although this is by no means certain. The reason for the tremendous effect at 20 volts is not known. The results of Young suggest chlorides as an important factor in oxide coatings although these are also believed to be dissociated at energies below 10 volts.[8] The experiment was terminated when, during the brief interval when the emission level was checked, the mesh grid bowed sufficiently to cause shorting.

RF Aging of Triodes

The general method of aging of triodes has been to insert the triode in a microwave cavity oscillator circuit and let it oscillate for a day or more.

This particular section is included to elaborate on a suggestion that by driving a triode, rather than being self-driven in an oscillator circuit, the aging process can be greatly accelerated. In such an arrangement the r-f energy is applied to the grid-cathode gap of the tube with the anode being operated at a constant negative potential. This negative potential is so chosen as to allow a large fraction of the higher energy electrons to go, say, half-way or more across the interelectrode space between grid and anode before being turned back towards the grid. If the electrons can spend of the order of one-half of an r-f cycle in the decelerating r-f field-free region before re-entering the grid cathode region, then an additional impetus can be given the electrons as they again enter the r-f field that accelerates them towards the cathode.

If we make the simplifying assumption that the transit angle of the electrons in the grid-cathod region near the positive peak of the r-f cycle is small relative to that spent in the grid-plate region we can easily solve for the voltages and the upper limit to the frequency required for r-f aging. Since our earlier experiments have indicated 20 volts as a good energy for r-f aging let us arrange for the electrons to pick up 10 volts on their transit out to the grid, then to be delayed one-half cycle, and then to pick up an additional 10 volts of energy as they return to the cathode. The required expression is*

$$f = \frac{\sqrt{\frac{e}{m}}\,\theta}{4\sqrt{2}\,\pi\,S} \qquad \frac{V_{oa}}{\sqrt{V_{og}}}$$

*See Appendix B.

where

f = frequency in cycles per second that gives a transit angle of θ degrees grid to anode.

e/m = charge to mass ratio of the electron, mks units

S = grid to anode spacing in meters

V_{os} = peak value of r-f voltage applied to grid-cathode

θ = transit angle of electrons in grid anode region entering at a velocity equivalent to V_{og} volts.

Putting this expression into more convenient terms together with our desired value of $\theta = \pi$,

$$f_{mc/s} = \frac{2920}{S_{mils}} \quad \frac{V_{oa}}{\sqrt{V_{og}}}$$

In the grid-anode region the distance, x, the electron travels may be found using the expression

$$\frac{x}{s} = \frac{V_{og}}{V_{oa}}$$

We will arbitrarily take this ratio to be 0.9. Then

$$f_{mc/s} = \frac{3250}{S_{mils}} \sqrt{V_{og}} = \frac{10,030}{S_{mils}} \text{ for } \sqrt{V_{og}} = 10 \text{ volts}$$

Thus for a tube having 20 mils grid to anode spacing the frequency required would be of the order of 500 mc/s. Because of our assumption of low transit angle in the grid-to-cathode region we should apply somewhat more than 10 volts r.f. and at a frequency somewhat lower than 500 mc/s.

Although no experiments have been made as yet to test out this mode of operation, such experiments should prove interesting and rewarding.

ACKNOWLEDGMENTS

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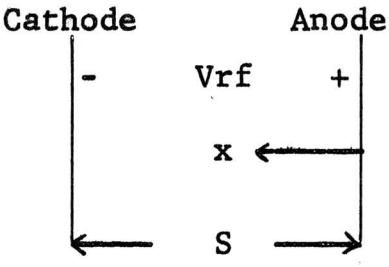
APPENDIX A



Assuming no space charge:

$$F = ma = m\ddot{x}$$

$$\ddot{x} = \frac{e}{m}(E_o + E_1 \sin \omega t)$$

when

$$x = 0 \quad t = t_o \quad \dot{x} = 0 \quad x = 0$$

$$\dot{x} = \frac{e}{m} E_o t \Big]_{t_o}^{t} = \frac{e}{m} E_1 \left[- \frac{\cos \omega t}{\omega} \right]_{t_o}^{t}$$

$$= \frac{e}{m} \frac{E_1}{\omega} \left\{ \frac{E_o}{E_1} \omega(t-t_o) + \cos\omega t_o - \cos\omega t \right\}$$

$$x = \frac{eE_1}{m\omega} \left\{ \frac{E_o\omega}{E_1} \left[\frac{t^2}{2} - t_o t \right]_{t_o}^{t} + t \cos\omega t_o \Big]_{t_o}^{t} - \frac{1}{\omega} \sin\omega t \Big]_{t_o}^{t} \right\}$$

$$= \frac{eE_1}{m\omega} \left\{ \frac{E_o\omega}{E_1} \left[\frac{t^2}{2} - \frac{t_o^2}{2} - t_o t + t_o^2 \right] + t \cos\omega t_o - t_o \cos\omega t_o \right.$$

$$\left. - \frac{1}{\omega} \sin\omega t + \frac{1}{\omega} \sin\omega t_o \right\}$$

$$= \frac{e}{m} \frac{E_1}{\omega^2} \left\{ \frac{E_o}{E_1} \frac{\omega^2}{2} (t-t_o)^2 + \omega(t-t_o)\cos\omega t_o - \sin\omega t_o - \sin\omega t + \sin\omega t_o \right\}$$

since $V_o = S E_o$ and $V_1 = S E_1$

$$\frac{\omega^2 Sx}{V_1 e/m} = \frac{1}{2} \frac{V_o}{V_1} \omega^2 (t-t_o)^2 + \omega(t-t_o)\cos\omega t_o - \sin\omega t + \sin\omega t_o$$

The sum of the r-f and d-c voltages must rise to some threshold value, V_c, before ions are generated at the anode surface. The

positive ions that are generated at this particular phase of the r-f voltage are those that will traverse the greatest distance across the tube towards the cathode.

Since $V = V_o + V_1 \sin\omega t$

at $t = t_o \quad V = V_c$

then

$$V_c = V_o + V_1 \sin\omega t_o$$

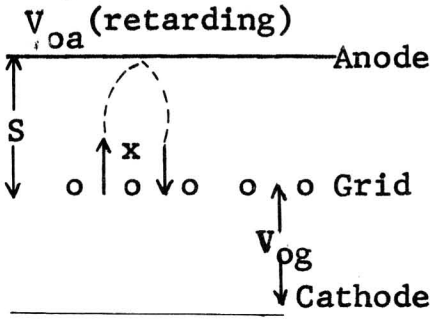
and

$$\omega t_o = \sin^{-1} \frac{V_c - V_o}{V_1}$$

$$\frac{\omega^2 Sx}{V_1 \, e/m} = \frac{1}{2} \frac{V_o}{V_1} \left(\omega t - \sin^{-1} \frac{V_c - V_o}{V_1} \right)^2 + \left(\omega t - \sin^{-1} \frac{V_c - V_o}{V_1} \right) \sqrt{1 - \left(\frac{V_c - V_o}{V_1} \right)^2}$$

$$- \sin\omega t + \frac{V_c - V_o}{V_1}$$

APPENDIX B



We shall assume that grid is extremely fine, that the d-c voltage on the anode, V_{oa}, is retarding and is measured with respect to the grid, and that as the electron passes through the grid plane its velocity is equivalent to the peak r-f voltage, V_{og}, measured with respect to the cathode.

$$\ddot{x} = \frac{e}{m} E_o = - \frac{e}{m} \frac{V_{oa}}{S} \tag{1}$$

$$\dot{x} = - \frac{e}{m} \frac{V_{oa}}{S} t + v_{og} \tag{2}$$

$$x = - \frac{e}{m} \frac{V_{oa}}{S} \frac{t^2}{2} + v_{og} t \tag{3}$$

Since we are adjusting the potentials such that the electron will be turned around in the anode-grid region there will be a point where the velocity goes through zero.

From (2) at the turnaround point

$$t = \frac{v_{og} S}{\frac{e}{m} V_{oa}} \tag{4}$$

The total time spent by the electron in the grid-anode space will be twice this value. Also, multiplying both sides by ω gives,

$$\theta = \frac{2\omega v_{og} S}{\frac{e}{m} V_{oa}} \tag{5}$$

Converting velocity at the grid plane, v_{og}, to voltage,

$$1/2\ mv_{og}^2 = e\ V_{og}$$

$$v_{og} = \sqrt{\frac{2e}{m} V_{og}} \qquad (6)$$

subs (6) into (5)

$$\theta = \frac{2\omega S}{\frac{e}{m} V_{oa}} \sqrt{\frac{2e}{m} V_{og}} = \frac{4\pi\ fS\ \sqrt{2V_{og}}}{\sqrt{\frac{e}{m}}\ V_{oa}} \qquad (7)$$

solving for f,

$$f = \frac{\sqrt{\frac{e}{m}}\ \theta\ V_{oa}}{4\sqrt{2}\ \pi\ S\sqrt{V_{og}}}$$

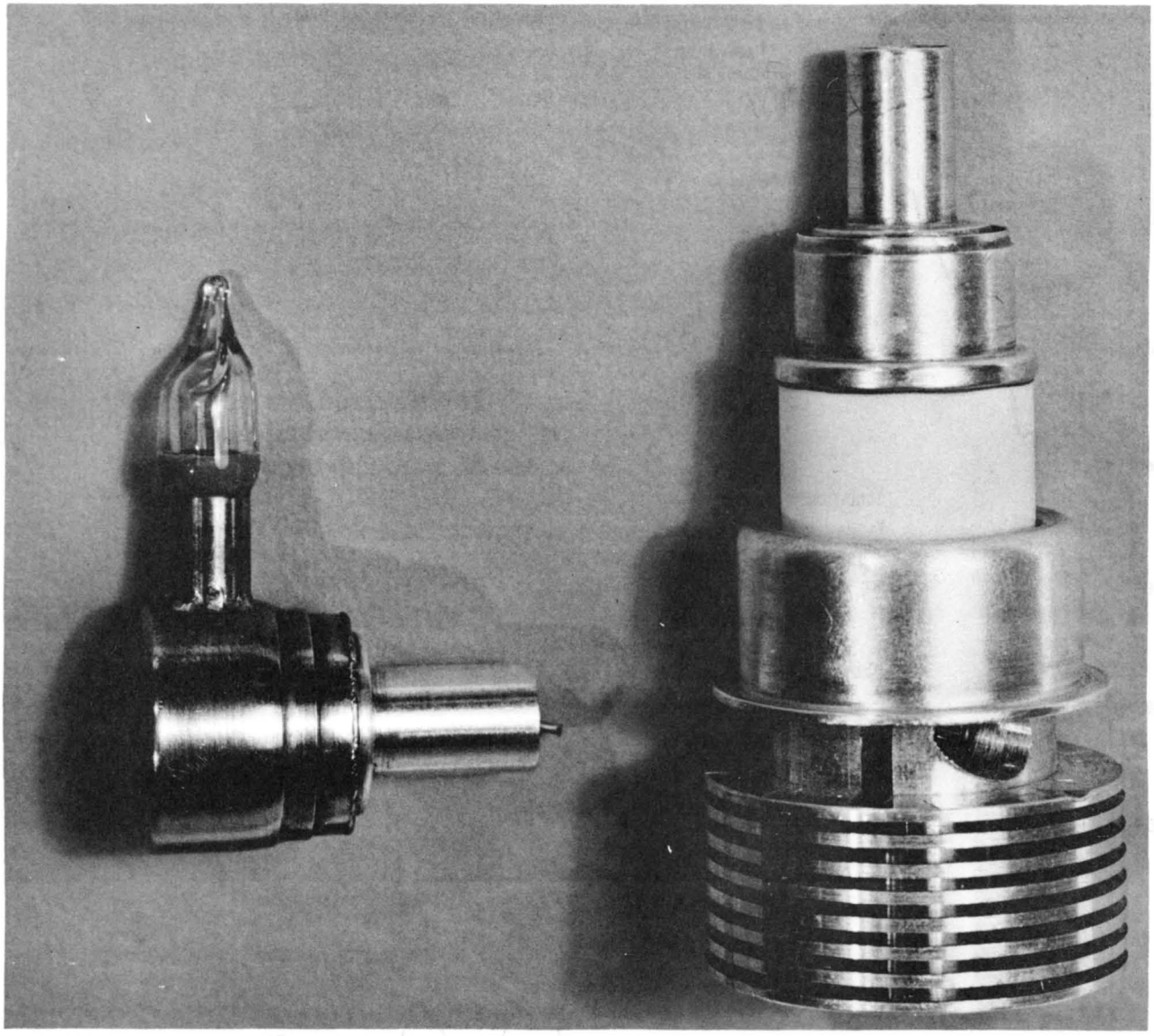


Fig. 1 Experimental diode compared to the 2C39B (right).

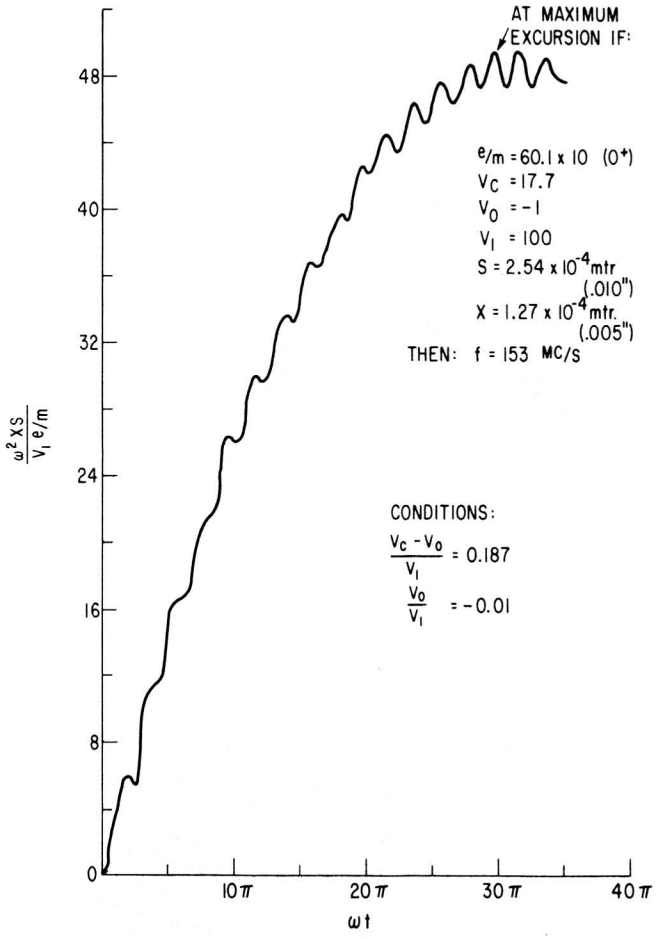


Fig. 2 Normalized trajectory of an ion that is knocked out of the anode of a space-charge free diode. R-f and d-c forces very nearly in balance.

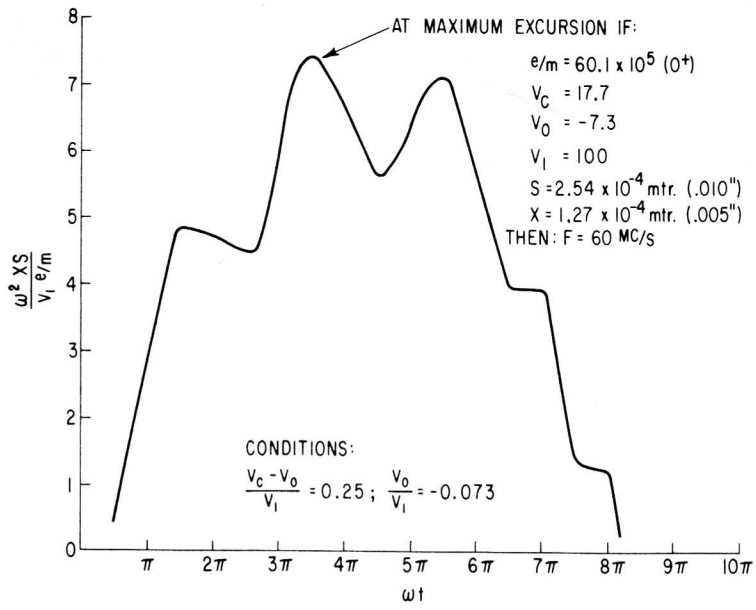


Fig. 3 Normalized trajectory of an ion. D-c force considerably greater than the r-f force.

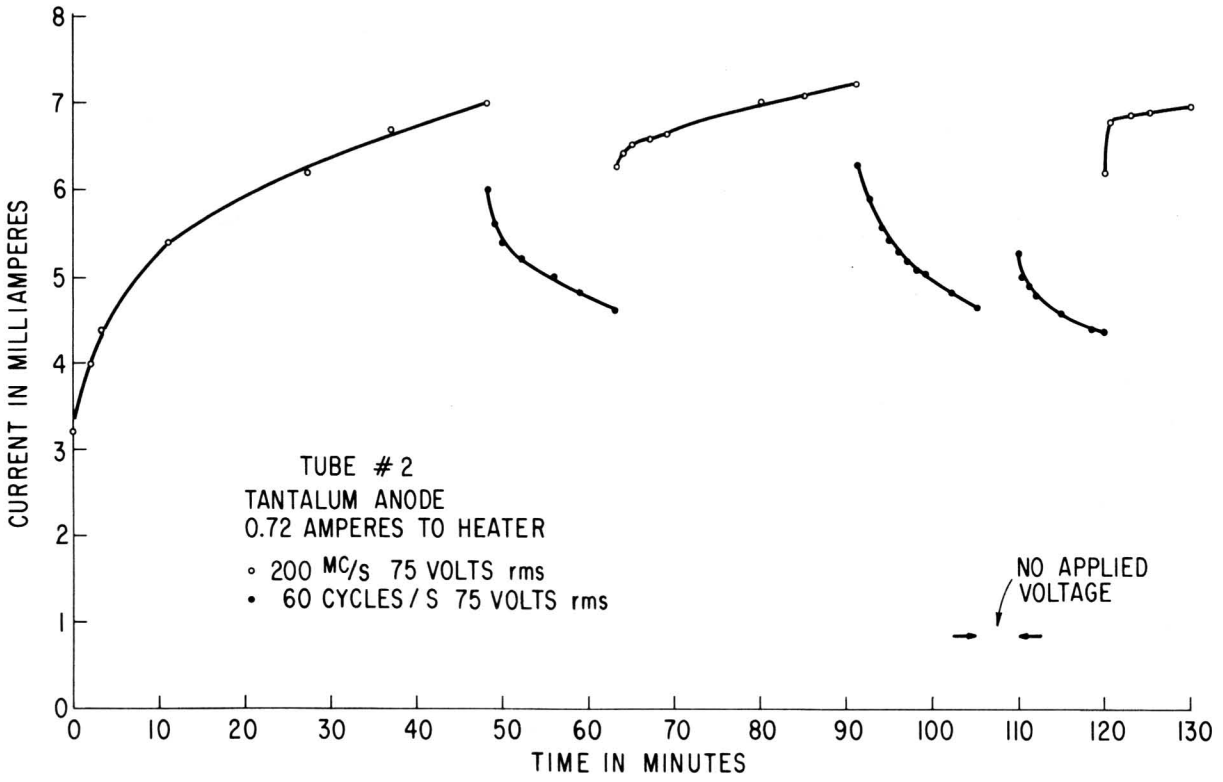


Fig. 4 R-f aging of a diode--early results.

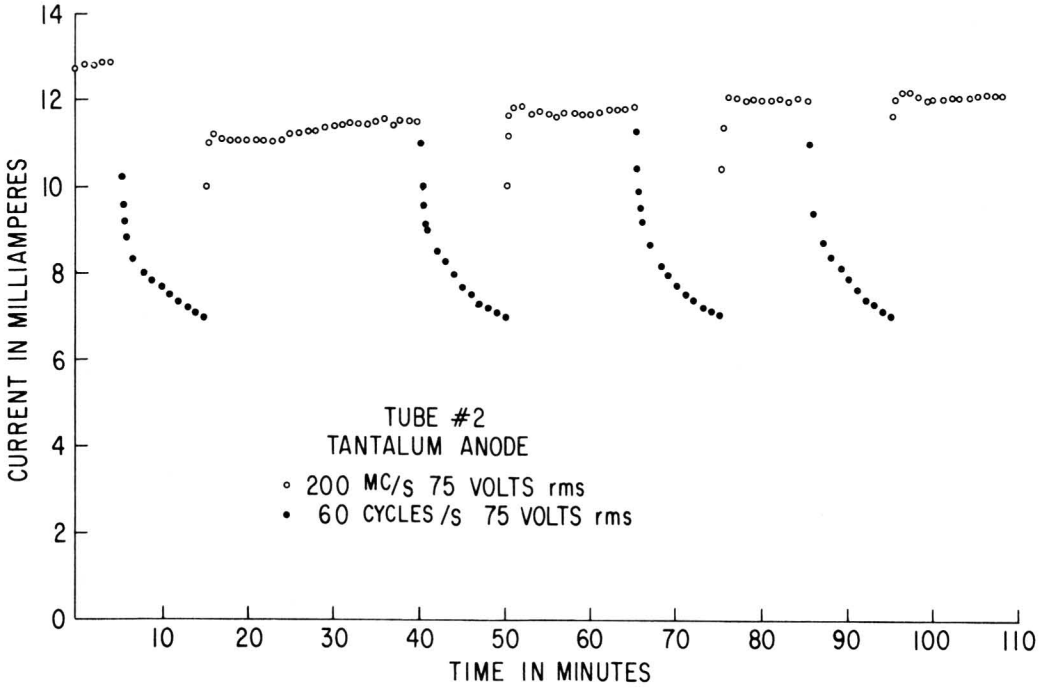


Fig. 5 R-f aging of a diode--later tests.

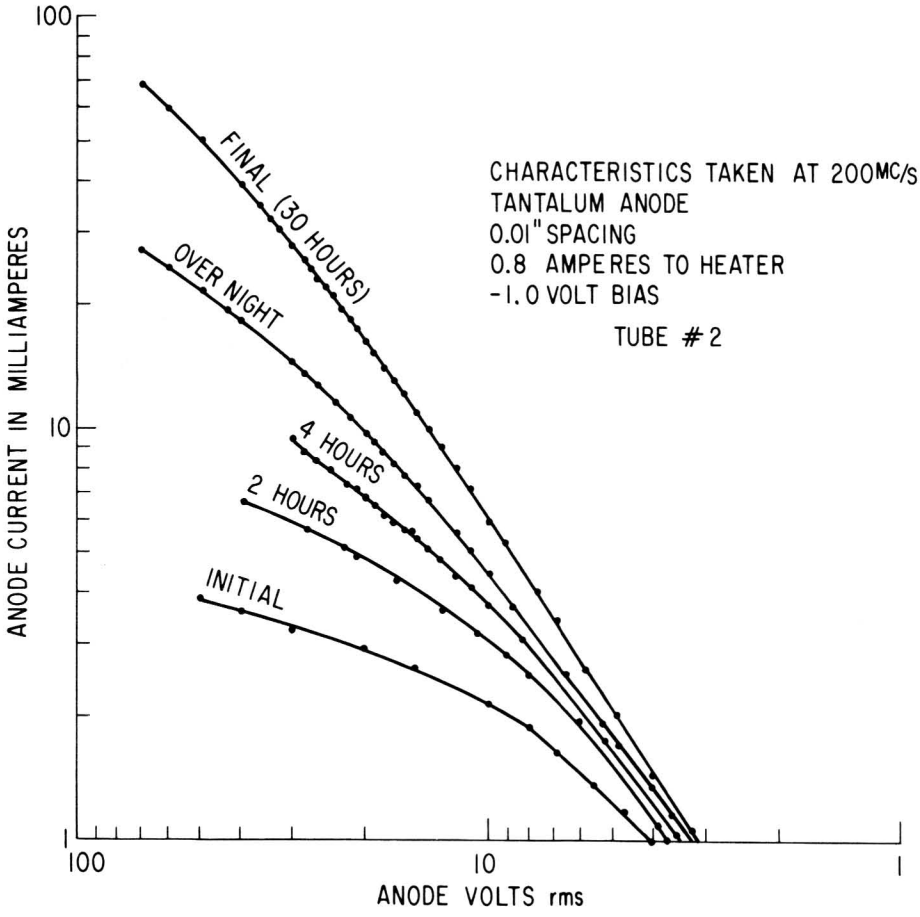


Fig. 6 Characteristics of a diode taken at 200 Mc/s at various intervals during r-f activation

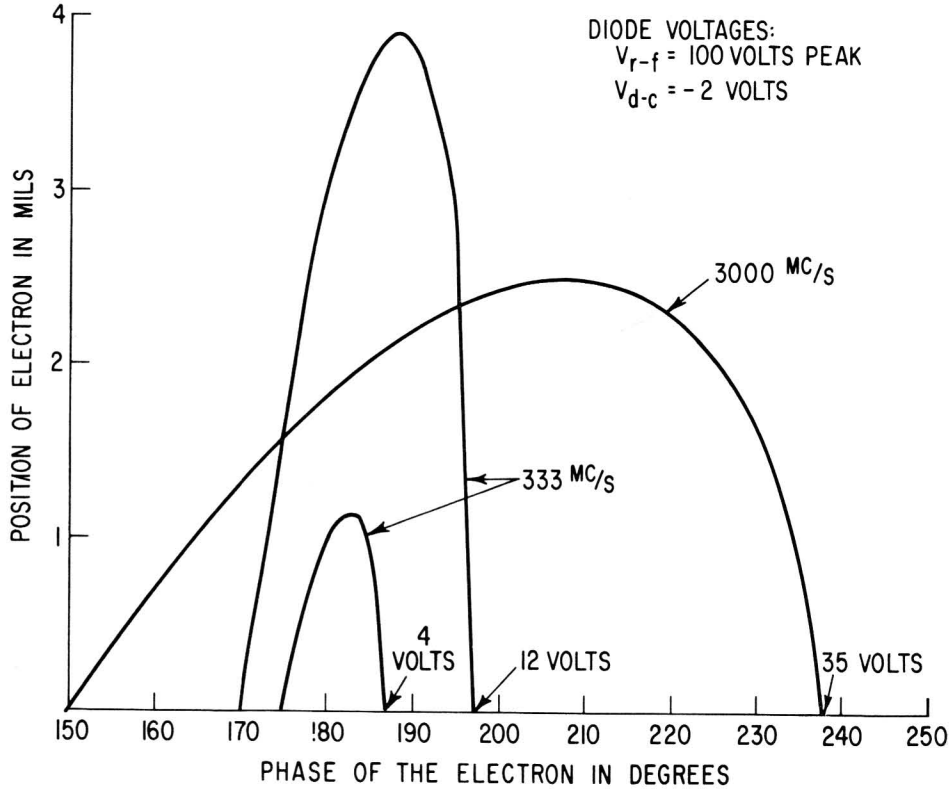


Fig. 7 Theoretical trajectories of electrons that return to the cathode with the indicated energy.

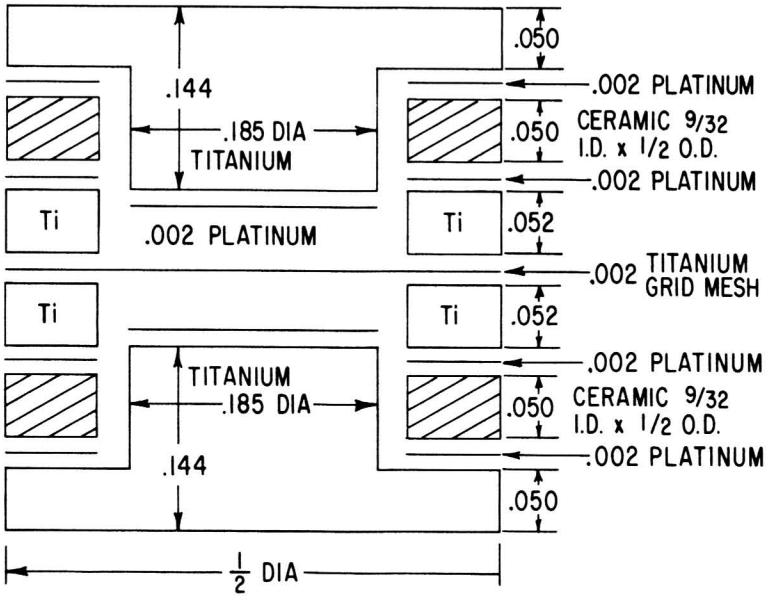


Fig. 8 Exploded view of a diode having an auxiliary cathode to supply a bombarding current.

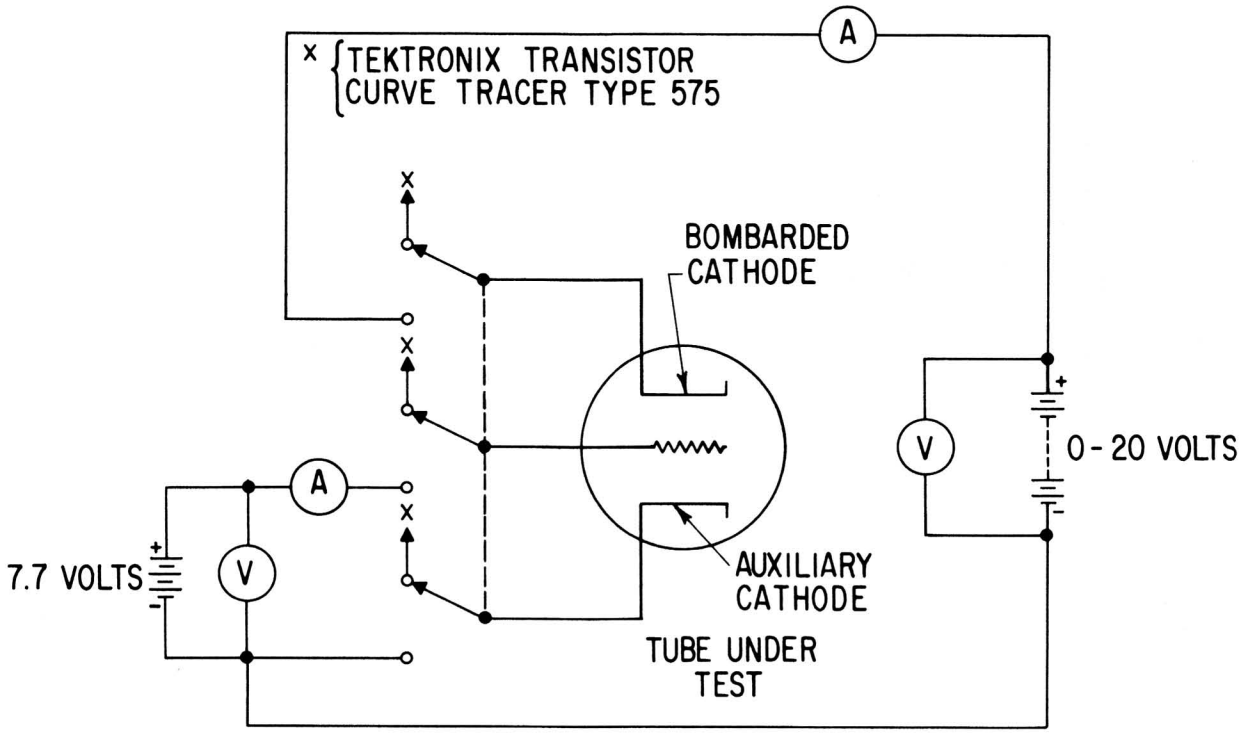


Fig. 9 Schematic of the circuit used in the double cathode tube.

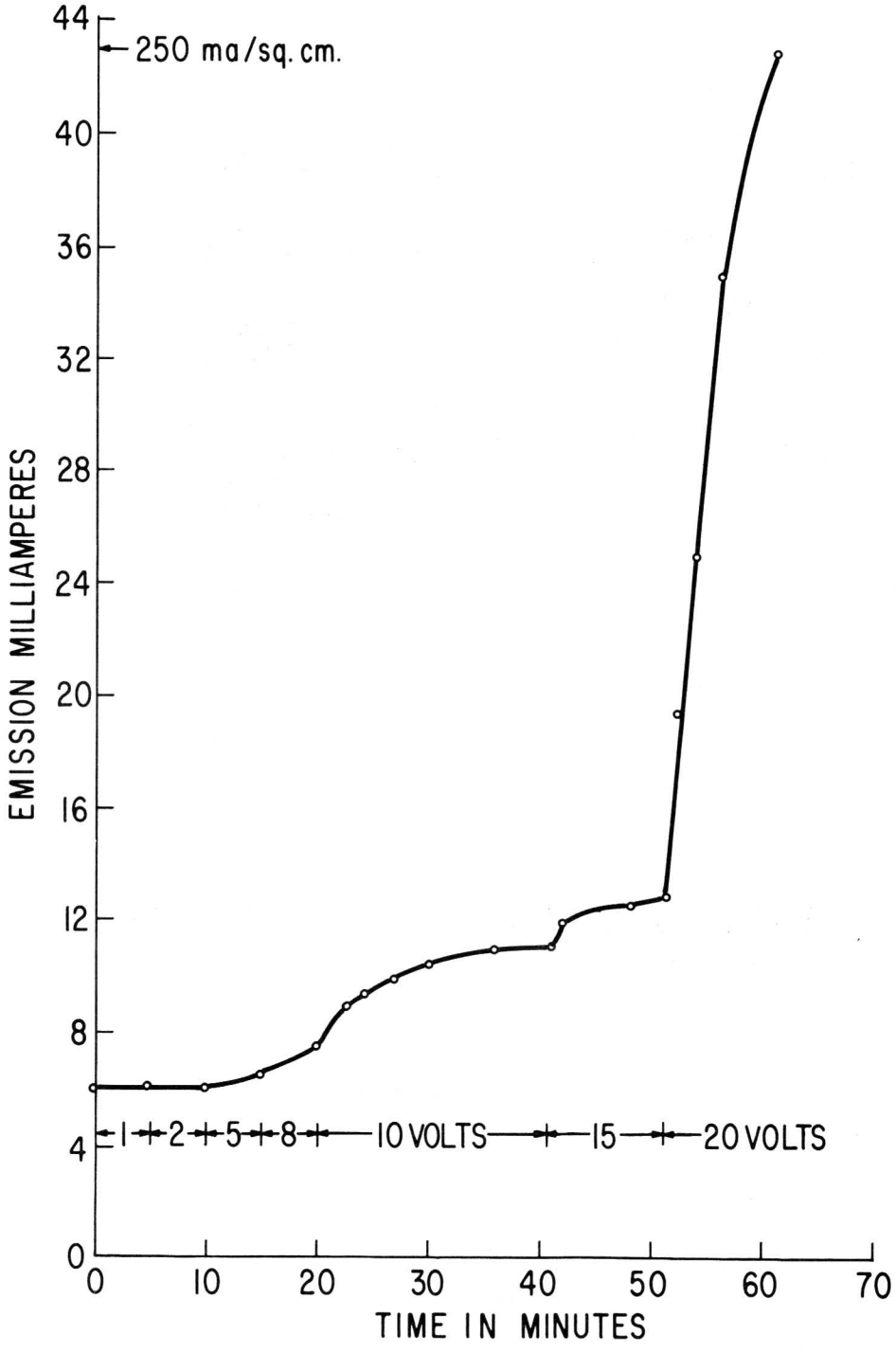


Fig. 10 Emission as a function of the energy of the bombarding current in the experimental double cathode tube.

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TECHNICAL INFORMATION SERIES

Title Page

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Lavoo, N. T.	r-f aging	62-RL-(2977 E)
		DATE: March 1962

TITLE

R-f Aging of Space-Charge Control Tubes

ABSTRACT

Space-charge control tubes, particularly those destined for use in microwave applications, are frequently r-f aged at the factory. By this means many marginal tubes may be made to fully pass all specification tests. Although this practice is quite general there is not a common understanding as to why this technique is successful. In this study it is concluded that the major factor is an improvement in activity of the emitter due to electron back bombardment. A discernible effect is noticed as low as 5 volts but is enormously accelerated if the bombarding electrons have an energy of 20 volts.

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