ANALYSIS OF TYPICAL VOLTAGE-CURRENT CURVES
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Abstract

A detailed analysis of voltage-current curves taken in thermionic diodes can yield information concerning the mechanisms of operation. These include: (1) evaluation of the emitter work-function; (2) evaluation of the collector work-function; and (3) the identification and description of the conduction mechanism by which electrons flow from the emitter to the collector. It is important to understand ion production processes.

Based on the studies of Taylor and Langmuir supplemented by the researches of Houston, the average properties of tungsten in the presence of cesium can be displayed on a readily-usable chart. This chart is made by plotting the emitter temperature as the abscissa, and the cesium condensation temperature as the ordinate, with lines on the chart that correspond to constant effective work-function values and the corresponding emission current capability. Based solely on the data of Houston, similar charts have been prepared for the properties of tantalum and molybdenum. On these charts, it is possible to draw a line of demarcation, to the left of which an insufficient number of ions are produced thermally to neutralize the space charge; to the right, adequate ionization can be expected.

Houston has observed voltage-current characteristics of a diode having a tantalum emitter. He maintained the cesium temperature constant at 573°K and varied the emitter temperature from 1415 to 2270°K. Data are available from the Thermo Electron Engineering Corporation for which the emitter temperature was maintained constant at 1843°K and the cesium temperature varied from 573 to 698°K. These two sets of data are analyzed in detail and it becomes evident that as the experimental conditions are changed from the "ion-rich" area toward the "electron-rich" region, the need to generate the plasma situation prior to the delivery of high current to the circuit is clearly a common feature of both sets of data.

Motive diagrams are presented which show on a quantitative basis the probable sheath structure at each electrode. An analysis based on these diagrams indicates that the arrival of electrons at the cesium-coated collector with an energy of 1 to 2 volts results in an increased ion concentration. The mechanism by which such ions are generated with such low energy electrons is being investigated. As the emitter injection sheath develops to 1 ev or more, additional ions are produced in space. These ions flow back to the emitter and steady-state conditions are associated with an appreciably lower emitter work-function than would otherwise have been available.

This report is designed to give a few examples of the extent to which detailed mechanisms can be understood by the analysis of voltage-current curves subject to the availability of basic data that are now being accumulated.

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Introduction

A detailed analysis of current-voltage curves taken in the operation of thermionic diodes can yield significant information related to the mechanisms involved. Two sets of data are presented, both of which were observed in diodes with a plane parallel configuration having a tantalum emitters, Cesium was present to coat both the emitter and the collector surfaces and modify the space-charge distribution in the inter-electrode space. The first study to be discussed depends on Houston's[1] data in which he held the cesium condensation temperature constant and varied the emitter temperature over the range from 1415°K to 2270°K. The cesium condensation temperature was 573°K. The second set of data depended on studies made at the Thermo Electron Engineering Corporation and was supplied for analysis by Dr. Hatsopoulos. For the study to be reported, the emitter temperature was held constant at 1843°K and the cesium condensation temperature was varied from 573°K to 698°K.

The first step in the analysis depends on the availability of information by which the work-function of the emitter, under all of the specified conditions of operation, can be estimated with reasonable accuracy. A new method of analysis of work-function data as it applied to tungsten surfaces was presented at the Round Table Discussion on Thermionic Processes and Materials held in Philadelphia in January 1961 and was included in the Proceedings[2]. Since that time, more detailed information has become available mainly through the researches of Dr. John Houston and reported in the Proceedings of the Round Table Discussion sponsored by the Power Information Center and held in June 1961[1]. These new data not only permitted a revision of the original display of tungsten data but supplied information by which the properties of cesium-coated tantalum and cesium-coated molybdenum can be estimated. Although this report will make use only of the tantalum data, those for tungsten and molybdenum are also presented here in order to make them available to others who may want to use them in lieu of still more accurate results which it is hoped will be forthcoming in the future. These three sets of data are shown in the charts of Figs. 1, 2 and 3.

Linear Plots of Work-Function Data

The research results of Taylor and Langmuir[3] were analyzed to establish, for a given cesium concentration or condensation temperature, the effective work-function of tungsten as a function of the tungsten temperature and supplementing these data are those of Houston. When this information is plotted as shown in Fig. 1, lines of constant work-function are nearly straight lines and an analysis of the general problem indicates that such a result is not unreasonable.

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[*] This work was supported in part by the U.S. Army Signal Corps, the Air Force Office of Scientific Research, and the Office of Naval Research.

The work-function values used to establish the location of these lines depended not only on electron emission but also to some extent on atom evaporation data as explained by Taylor and Langmuir[3].

It is to be anticipated that in the entire area to the left of the "dash-plus" line, the work-function will be equal to or less than that indicated by these lines. It can be lower especially whenever there is a positive ion sheath formed over the surface to inhibit positive ion evaporation from the surface. This can bring about an increased coverage over that associated with the "zero-field" condition. In the higher temperature area to the right of the "dash-plus" line, the work-function is likely to jump discontinuously to that of pure tungsten if the surface field is strong enough to accelerate ions away as fast as they are produced. This situation is seldom realized in thermionic diodes and therefore in the presence of ion space charge, work-functions in this area are realizable. Again the true values may actually be slightly lower than those shown because most of the ions produced at the surface will be returned to it and a steady state is achieved only when the atom evaporation rate is equal to the atom arrival rate.

Reliable data on the properties of tantalum and molybdenum in the presence of cesium are still very scarce and therefore this principle of linear extrapolation has been applied to the data published by Houston[1] specifically applicable to the two cesium temperatures of 423 and 473°K. As additional data are obtained, it may be necessary to relocate these lines although it is anticipated that no major shift will be demanded. It is on this basis that the voltage current curves analyzed in this report will use the data of Fig. 2 for tantalum.

Space-Charge Neutralization

Both the production rate of ions and the electron emission rate from a heated surface in the presence of cesium depend on the temperature of the cesium T_{Cs}, the temperature of the emitter T_1 and the associated effective work-function ϕ_1. It is therefore possible to establish a line across any one of the Figs. 1, 2, and 3 which divides the whole region into two areas. To the left of the line the electron emission is too great to be neutralized by the cesium ion generation that occurs at the same surface. To the right of this demarcation line, an excess of cesium ions forms a positive ion space-charge sheath and so permits the full current density of electron emission to become available either as a current injected into the plasma space or as a current to be conducted across this space and observed at the collector. This line of demarcation is shown on each of the figures by a dot-dash line.

Graphical Display of Experimental Conditions

Figure 4 is a reproduction of that part of Fig. 2 needed to indicate by the set of cross marks and circles all of the test conditions included in the studies of Houston and TEE which are displayed in Figs. 5 and 7 and discussed in this report. It is of particular interest to note that most of the experimental conditions explored lie to the right of the dot-dash line whereas some lie very close to it or slightly to the left. It is associated with these conditions that one finds it necessary to initiate the plasma form of diode operation by carrying the collector surface potential to a sufficiently high positive potential to generate a good positive ion emitter sheath which otherwise would not be present. Before this sheath is developed, electron emission is limited by electron space charge as will be indicated in the next section.

Analysis of Houston's Diode Characteristics

The diode characteristics published by Houston will be used for the first example. The data are presented in graphic form in Fig. 5. These experiments covered a range in emitter temperature from 1415°K to 2270°K, while the cesium bath temperature was maintained constant at 573°K. The voltage current curves shown were obtained automatically by means of a "X-Y" recorder. The nine emitter temperatures, indicated in Fig. 5, are displayed by "X" marks in Fig. 4.

For the four highest temperatures, neutralization takes place without additional stimulation being needed to set up a plasma condition. The three temperatures of 1530°K, 1595°K and 1655°K are definitely borderline in this respect, since they lie so close to the demarcation line. A plasma condition can be generated and maintained by first driving the surface potential of the collector in the positive direction enough to set up space ionization at the collector surface to supplement the surface ionization at the emitter. The details of this generation of the plasma can be worked out in a plausible manner and will be presented as they apply to the emitter temperature of 1530°K. The analyses applicable to the next two higher temperatures follow the same pattern and will not be given.

Over considerable range of applied voltage near zero, the current conducted across the diode is practically constant and is therefore limited by some barrier presumably located 2.98 ev negative with respect to the emitter Fermi level. Figure 4 shows that the anticipated work-function was 2.4 ev and therefore the indication is that in the immediate neighborhood of the emitter there is a 0.58 volt retarding potential for electrons and the same value of accelerating potential for those ions that are produced and injected into the interelectrode space. Over the range of applied voltage of -0.7 to +0.7 practically none of these ions can escape to become neutralized on the surface of the collector because of the ion retarding potential there. A region of high conductivity and practically zero space charge will exist across the space. This motive diagram is shown by lines A and B in Fig. 6.

As the collector surface potential is made more and more positive in passing from -2.4 ev (shown at s_2) to -1.0 ev, the collector sheath expands somewhat toward the emitter as shown by the dotted line B of Fig. 6. and the drop in potential over this sheath increases. There is no appreciable increase in the current conducted because it is still limited by the motive barrier shown to be close to -2.98 ev. Under the conditions shown no appreciable electron emission will leave the collector and no ion current can arrive there. At an applied voltage of +0.75 volt, the electrons that cross the collector sheath bombard the surface with an energy of approximately 2 electron volts. Electrons having this energy can produce cesium ions by a two-stage process of first exciting the atoms and then ionizing them. It seems improbable that there will be a sufficient ion production by this process to neutralize the space charge of the electrons that are arriving at the collector surface. It is therefore assumed that some other mechanism for ion production must exist. The hypothesis is made that two-volt electrons can bombard cesium atoms which are in the process of evaporation from the collector and create ions which in the presence of an ion accelerating field can be injected into the interelectrode space. An experiment is now in progress designed to test the validity of this hypothesis.

Ion production by two-volt electrons becomes copious enough to create a zero field condition at the surface of the collector. Injection of additional ions modifies the limiting barrier of -2.98 ev and permits more electrons to flow which in turn produce more ions and a "runaway" condition develops. The space-charge limitation of current flow from the emitter into the space is removed and an entirely different form of the motive diagram is created. This is illustrated by the dashed line C of Fig. 6. The current density can then rise to at least 4 a/cm^2 or a total diode current of 20 amperes or more. Electrons injected into the space and others that bombard the collector surface can generate enough ions to maintain the situation illustrated by the motive diagram of line C of Fig. 6.

Houston in his curves shows no detail concerning the variation of diode current between an applied voltage of +0.75 and the critical voltage of -0.2 volt. Presumably the total current remains fairly constant, although it is anticipated that more and more ions will be accelerated out of the plasma space to be neutralized at the collector as the surface potential is made more negative. Again, a critical situation can develop, at which the combined ionization rate of all of the possible ionization processes is insufficient to maintain the ion density required to continue the operation of the diode with a strong ion space-charge sheath at the emitter. When this sheath is lost, limitation of the diode current by an electron sheath redevelops and the motive diagram reverts back to line A of Fig. 6. A return to the emission-limited plasma form of line C can be accomplished by repeating the cycle described above.

A similar analysis may be applied to the three higher temperatures of 1595°K, 1655°K, and 1725°K. In all cases the shift to the fully developed plasma form of diode operation occurs when the electron bombardment energy at the surface of the collector exceeds one volt. With the higher emitter temperature, fewer additional ions will be needed to change the operation from one limited by electron space charge. The fully saturated current density can be at least 2 amperes per cm^2 at 1725°K.

At the highest temperature included in these data of 2270°K, the zero field emitter work function could be expected to be 4 ev or slightly less. Thermal ionization takes place and a strong injection sheath of probably more than 2 volts may be expected.[4] Over the range of applied collector voltage more negative than 2 volts, the rise in current is dominated by the arrival of electrons from the plasma space and the logarithmic plot of the data suggests an electron temperature of approximately 7,000°K. As the surface potential becomes more positive, there is a slight tendency towards "saturation," but the upward trend that begins at approximately -1 volt applied suggests again the development of additional ionization and the suppression of ion emission from the emitter. These two effects lower the work-function of the emitter and provide a greater current than would be expected otherwise.

To summarize this section, the following statements are made:

1. The estimation of the effective work-function of a tantalum emitter surface at 1530°K in the presence of cesium condensed at 573°K seems to be consistent with that indicated by Fig. 2 and be close to 2.4 ev.

2. Ions seem to be trapped in the interelectrode space and thus reduce the electron space-charge limitation of current flow but do not eliminate it. The spacing is approximately 30 times the mean free path.
3. A limited displacement of the collector surface potential in a positive direction expands the collector sheath but does not result in an increase in diode current. The motive diagrams by which this fact is illustrated are shown by curves A and B of Fig. 6.
4. When electrons are accelerated across the collector sheath with an energy of approximately 2 volts, runaway ionization takes place, implying the development of a new means of ionization either as a two-step process in cesium or the direct ionization of atoms in the process of evaporation from the collector.
5. After a complete plasma is set up an ion space-charge sheath develops both at the emitter and at the collector as illustrated by curve C of Fig. 6.

TEE Current Voltage Curves at 1843°K

The data as illustrated in Fig. 7 were furnished by Dr. Hatsopoulos of the Thermo Electron Engineering Corporation and apply to a plane parallel diode having an area of 4.25 cm^2 and a spacing of 3.2 x 10^{-3} cm. The emitter temperature was maintained at 1843°K and the cesium temperature was varied from 573°K to 698°K.

Some of the pertinent facts with regard to these data are best presented by means of Table 1. The various curves are identified by the letters A through I in the order of increasing cesium condensation temperature. These

Table 1

Operating Condition for TEE Tube 222

T_1 = 1843°K Emitter temperature
ϕ_2 = 1.63 ev Collector work-function
w = 3.2 x 10^{-3} cm Spacing
a = 4.25 x cm^2 Area

	°K		ev	a/cm^2	a/cm^2	ev	v.
Run	T_{Cs}	w/λ	ϕ_1	$_oI_1$	$-1.58\,I_c$	ϕ_b	V_p
A	573	2	3.21	0.7	0.5	3.25	1.2
B	588	3	3.12	1.2	0.5	3.25	1.07
C	605	4	2.98	2.8	0.4	3.30	0.91
D	617	5	290	4.9	0.3	3.34	0.70
E	638	8	2.76	12.0	0.2	3.40	0.43
F	652	11	2.69	29.0	0.1	3.52	0.20
G	673	16	2.56	44.0	0.1	3.52	0.11
H	687	19	2.48	66.0	.05	3.62	
I	698	23	2.40	110.0	.03	3.70	

temperatures are listed in the second column. As the cesium density is increased, the mean-free path decreases and the third column of Table 1 indicates the approximate number of mean-free paths between the two electrodes of the diode. The data of Fig. 2 are used to estimate an upper limit to the emitter work-function as mentioned previously. Under operating conditions for which there is a positive ion space-charge sheath at the emitter, the surface coverage by cesium atoms is likely to be increased somewhat with a corresponding lowering of the emitter work-function. The values of ϕ_1 can be combined with the temperature T_1 of 1843°K to compute the estimated available electron emission capability of the emitter even though these current densities generally are not realized because of space-charge effects. The next column expresses the observed current density at an applied potential of - 1.58 volts. Note that as the cesium pressure is increased, the current delivered to the collector decreases as would be expected in the presence of a limiting barrier created by the excess electron emission. The electron volt equivalent of the barrier which corresponds to the emission indicated is recorded in column 7.

Inspection of Fig. 4 shows that at a cesium temperature of 573°K the location in the diagram is sufficiently far to the right of the dot-dash line to indicate an anticipated excess of ions so that the electron emission into the plasma space should not be limited by electron space charge. The computed[4] potential difference over this sheath, based on the available information, is listed in the last column of Table 1. Direct observations of saturated ion current densities would serve as a better means of determining the injection sheath potential but those data are not available.

The first curve to be analyzed in detail is that identified by "A" which corresponds to the cesium temperature of 573°K. At an applied potential of - 1.58 volts the surface potential of the collector at s_2 should have been practically equal to the surface potential of the emitter at s_1. The observed current density at this applied potential was only slightly less than that expected from an emitter of this work-function and operating temperature. The calculated space-charge sheath potential difference is shown in Table 1 to be 1.2 volts. Since ions cannot leave the surface because of the ion space charge, the effective work-function is probably less than that predicted by the data in Fig. 2. This increase in coverage could lower the work-function from 3.21 ev to 3.0 ev. The corresponding available current density would then be 2.5 a/cm^2. This density is achieved at an applied potential of -0.1 volt which in turn corresponds to a collector surface potential close to 1.37 ev negative with respect to the Fermi level of the emitter. Under this condition electrons arrive at the collector after having been accelerated across the collector space-charge sheath with an energy of 1.3 ev or more. The continued rise in the curve which is shown in Fig. 7 at an applied potential up to +1.4 volts brings the current to 22.4 a/cm^2. For this current to be realized, the emitter work-function must not exceed approximately 2.65 ev. The increased arrival rate of cesium ions at the emitter surface continues to build up the surface layer and thus can account for the continued reduction in surface work-function as higher and higher accelerating potentials are applied.

Curve B of Fig. 7 shows much the same characteristics as curve A and its progress to 27.2 a/cm^2 is explained in the same way. A new feature is exhibited in curve C in that at -0.85 a very noticeable enhancement in the emission takes place following the alteration of the surface potential of the collector by only 0.2 volt. The calculated ion sheath at the surface of the emitter for this cesium temperature was 0.91. There are approximately 4 mean-free paths in the spacing and therefore if the motive diagram is similar to that shown in Fig. 8, some electrons will arrive near the collector to produce additional ions by some electron impact process. These ions would then sweep across to the emitter, lower its work-function and build a still higher injection sheath. A new motive diagram expected with an applied voltage of -0.2 is shown in this figure as line 2. As the applied voltage is made positive, the efficiency of ionization increases and the I-V curve shows the characteristic rise already discussed in connection with curves A and B.

Curve D exhibits many of the same characteristics as curve C. A more positive surface potential of 0.1 volt is needed and is equal to the anticipated decrease in emitter work-function. Electrons of the same energy as for C start the generation of the new supply of ions which return to the emitter and lower its work-function. At zero applied volts, the work-function must have dropped close to 2.7 ev compared with the anticipated value of 2.9. As positive potentials are applied, ionization efficiency due to impact phenomena in the neighborhood of the collector rises rapidly to produce still more ion bombardment of the emitter which adds to the surface coverage and lowers the work-function.

Curve E starts its trend upward as the collector surface potential reaches about -2.2 volts and the mechanisms previously discussed seem to apply. At the next higher cesium temperature shown of 673°K for curve G, the ion production capability at the emitter surface is much too small to neutralize the available electron emission. The electron space-charge barrier is therefore maintained at approximately 3 volts until an applied potential of -0.35 is placed on the collector. Through this augmented ionization the motive diagram of Fig. 9 suddenly shifts from that shown by the solid line 1 to that shown by the dotted line 2. The development of the positive ion sheath in the immediate neighborhood of the emitter wipes out the electron space-charge limitation and permits an injection sheath to form as illustrated by line 2. This situation is stable for applied voltages positive relative to -0.45 volt and under this mechanism of operation at this rather high cesium concentration an emission of 40 a/cm^2 is observed at an applied voltage of +0.1 (line 3 of Fig. 9). As the applied voltage is made more negative than - 0.45 volt, the plasma is unable to maintain itself and the electron space-charge limitation takes over to convert the motive diagram back to the original form shown by the solid line 1 of Fig. 9. This transfer from the electron space-charge-limited condition to the plasma operation is similar in many respects to that discussed previously in connection with the work of Houston.

At the very high cesium concentration associated with a condensation temperature of 698°K, the results are displayed by curve I of Fig. 7. Here again space-charge limitation inhibits electron flow unless the applied potential is made positive with respect to 0.1 volt. The motive diagram just before the plasma is formed is similar to that of the solid line 1 of Fig. 9 and after the formation the plasma, it should shift to the configuration shown by the dotted line 2. This is stable for applied voltages positive compared to -0.3, but at more negative applied voltages, the plasma form of discharge cannot be maintained, and a reversion to electron space-charge limitation occurs.

Although a very high electron current might have been expected from an emitter with such a low work-function as 2.4, a very large fraction of the electrons that enter this space are presumably returned to the emitter even though the actual electron emission is not limited by space charge. In order to traverse the interelectrode space with practically no accelerating field, many elastic as well as inelastic collisions will take place so that the net drift current in the immediate neighborhood of the emitter can very well be as low as 2 to 5 per cent of the random current. It is the random current that can equal or exceed the emission current. As more and more positive potential is applied after the plasma has been generated, the drift current becomes larger in comparison with the random current and at an applied potential of 0.3 volt becomes approximately 50 per cent of it.

Comparison of Two Sets of Data

A direct comparison between Figs. 5 and 7 shows that one of the important features that groups the various curves together relates closely to the demarcation line of Fig. 4. Thus the Houston curves taken with a low emitter temperature and a constant cesium temperature are very similar to those of the TEE curves identified by the letters G and I. These curves correspond to a high cesium concentration and a fixed emitter temperature. The fact that in both cases the demarcation line for space-charge neutralization classifies the curves as well as it does is an indirect indication that the lines of Fig. 2 can be taken as the best available information concerning the thermionic emission properties of tantalum in the presence of cesium.

The more detailed analysis of these curves (Figs. 5 and 7) repeatedly suggests that increased ionization is associated with the arrival of electrons at the surface of the collector with an electron energy considerably less than the ionization potential and in fact it seems as though electrons with energies only slightly in excess of 1.3 electron volts can produce an increased supply of ions. Associated with this increased ionization is either a reduction in the space-charge limitation or even a conversion from an electron space-charge-limited operation to the plasma operation. Generally, plasma operation results in a positive ion sheath at the emitter surface capable of electron injection into the plasma space.

Conclusions

It would be desirable to have much more reliable and well-established data for the determination of the emission properties of refractory materials operated at high temperature in the presence of cesium. Inadequate though the present data are, they seem to be capable of giving at least a semi-quantitative interpretation of the very complex voltage current curves found by most observers.

Still more confidence could be placed in the analyses if voltage-current data were taken over a wider range of applied voltage. Specifically, it is desirable to obtain data with applied voltages even more negative than the open-circuit voltage. These data should be taken with the collector at various temperatures, first to establish the ion arrival rate under specific emitter conditions, that is, emitter temperature and cesium temperature.

The collector temperature should be low enough so as to reduce its thermionic emission to a negligible quantity. After that, and with other conditions maintained constant, the collector should be set at various temperatures in the range for which the thermionic emission current is equal to or even greater by as much as a factor of 100 than the ion arrival current. From these data, a good evaluation of the collector work-function should be possible. This work-function combined with knowledge of the ion arrival rate serves as a direct measure of the drop in potential over the collector sheath. With the emitter work-function known, a direct determination of the emitter sheath potential is then possible. Data of this type, well organized so that spurious factors including leakage currents and the like are eliminated, can go far to improve the understanding of detailed mechanisms involved in plasma diode operation. Significant improvements in performance will follow.

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Figure Captions

Fig. 1 Emission properties of tungsten in the presence of cesium based on Taylor-Langmuir data supplemented by experiments of Houston.

Double dot-dash line for exact equalization of space charge according to Langmuir-Saha equation.

Single dot-dash line for exact equalization of space charge according to modified Langmuir-Saha equation.

Plus-dash line: critical line for complete ionization of cesium atoms when ions are carried away by a strong ion accelerating field. Work-functions to the right of this line realized only in the presence of ion space charge.

Fig. 2 Emission properties of tantalum in the presence of cesium based on experiments of Houston.

Double dot-dash line for exact equilization of space charge according to Langmuir-Saha equation.

Single dot-dash line for exact equilization of space charge according to modified Langmuir-Saha equation.

Plus-dash line: critical line for complete ionization of cesium atoms when ions are carried away by a strong ion accelerating field. Work-functions to the right of this line realized only in the presence of ion space charge.

Fig. 3 Emission properties of molybdenum in the presence of cesium based on experiments of Houston.

Double dot-dash line for exact equilization of space charge according to Langmuir-Saha equation.

Single dot-dash line for exact equilization of space charge according to modified Langmuir-Saha equation.

Plus-dash line: critical line for complete ionization of cesium atoms when ions are carried away by a strong ion accelerating field. Work-functions to the right of this line realized only in the presence of ion space charge.

Figure Captions, cont.

Fig. 4 Display of experimental parameters used by Houston and TEE for voltage-current curves of Figs. 5 and 7 applicable to a tantalum emitter.
Houston's selected emitter temperatures represented by x
TEE cesium temperatures at constant emitter temperature shown by circles.

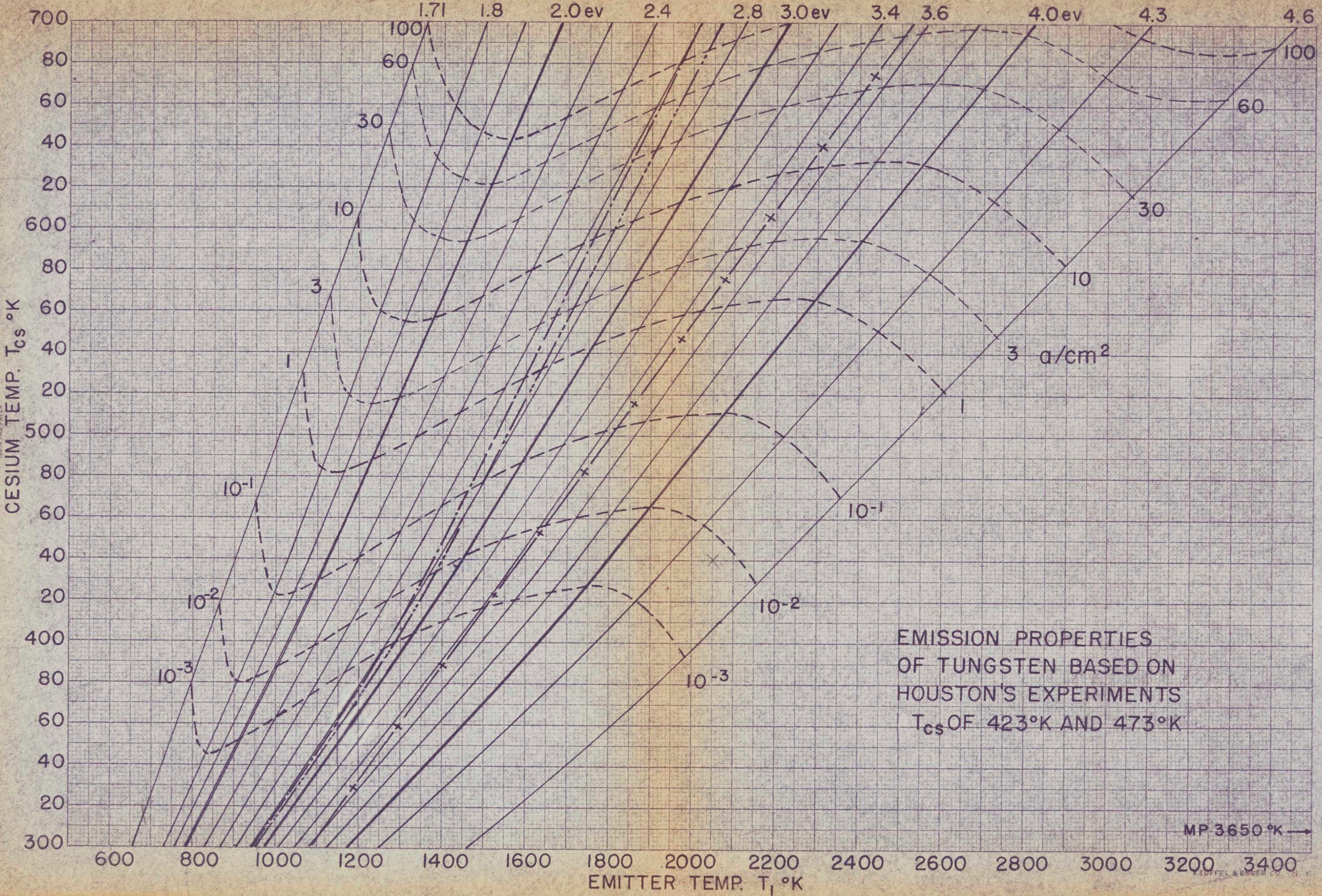
Fig. 5 Voltage-current curves from Houston[1] observed with a tantalum emitter of area 6.5 cm^2.

Fig. 6 Motive diagrams applicable to Houston's voltage-current curve taken at 1530°K.
Curve A for applied potential of - 0.7 for which surface potential of collector at s_2 is practically equal to the surface potential of the emitter at s_1.
Curve B: applied potential +0.7 with collector surface potential moved more positive 1.4 volts.
Curve C: emitter ion sheath formed after critical point is reached.

Fig. 7 Voltage current curves supplied by TEE. See Table 1 for identification of conditions in terms of A through I.
Emitter temperature constant at 1843°K.
Area: 4.25 cm^2
Spacing: 3.2×10^{-3} cm.

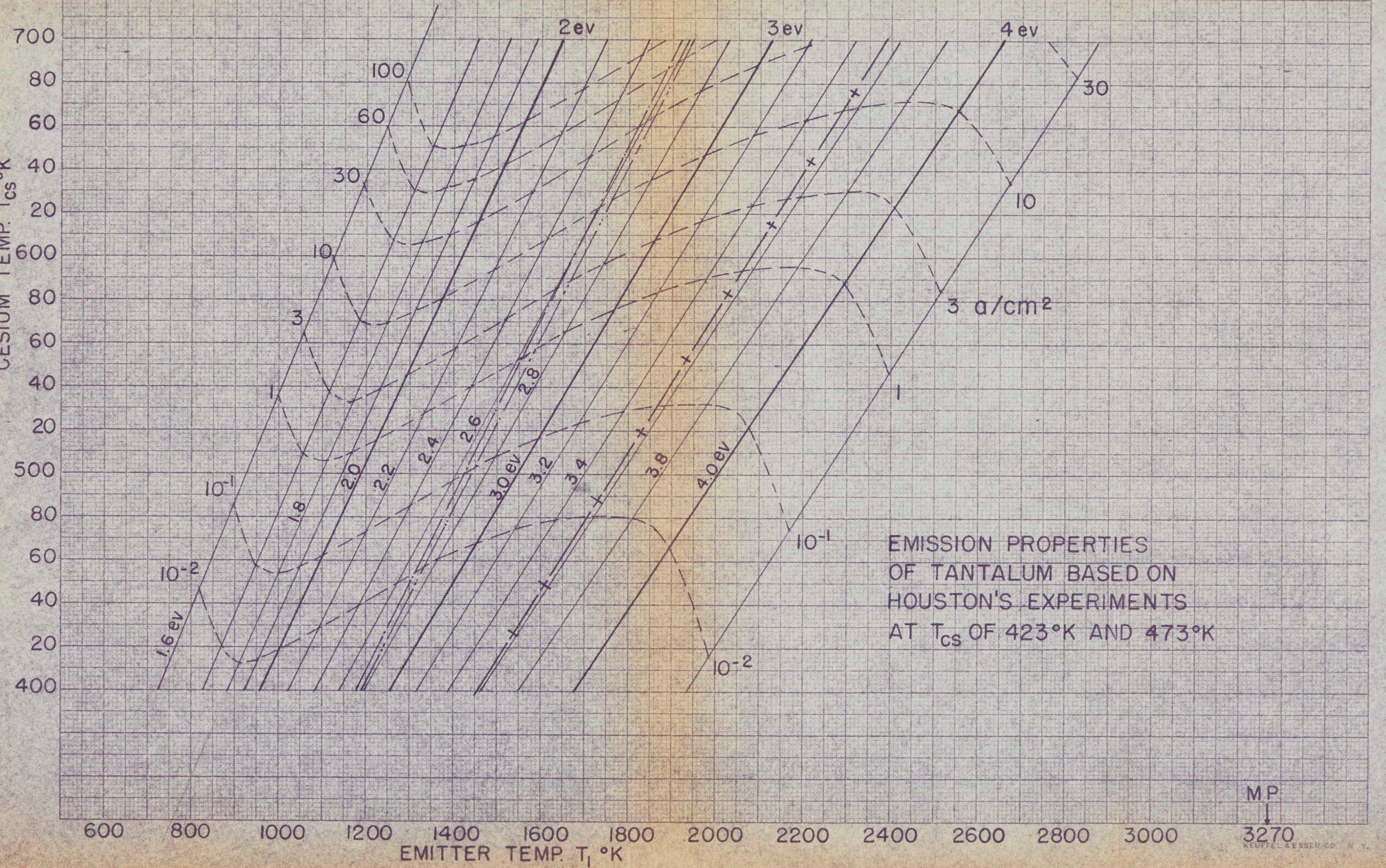
Fig. 8 Motive diagram applicable to curve C of Fig. 7.
Curve 1: applied voltage - 0.8
Curve 2: applied voltage - 0.2. Note development of increased injection sheath at the emitter.
Curve 3: strong injection sheath with a reduction of surface work-function.

Fig. 9 Motive diagram applicable to curve G of Fig. 7.
Curve 1: space-charge-limited emission at applied voltage of -0.36 before plasma formation.
Curve 2: after plasma formation with applied voltage of - 0.35.
Curve 3: high electron emission with small, positive potential applied.



EMISSION PROPERTIES
OF TUNGSTEN BASED ON
HOUSTON'S EXPERIMENTS
T_{CS} OF 423°K AND 473°K

Fig 1



EMISSION PROPERTIES
OF TANTALUM BASED ON
HOUSTON'S EXPERIMENTS
AT T$_{CS}$ OF 423°K AND 473°K

Fig. 2