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Report of
The Determination of the Components
of the Reverse Current Flowing
in the Control Grid Circuit
of Negatively Biased Transmitting Tubes

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ABSTRACT

The performance of a vacuum tube and, in general, its state or condition at any one time, may be indicated by the negative or reverse current flowing in the control grid circuit when this grid is at a negative potential with respect to the cathode. This is of particular importance with transmitting tubes since the amount of reverse grid current, an important component of which is due to gas, is also an indication of the life expectancy of such tubes.

The importance of these facts has been recognized by the Bureau and a problem was assigned to the Laboratory for investigation and study. This report is intended to give the results of this investigation.

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INTRODUCTION

(a) Authorization

1. This work was authorized by Revision of Navy Specifications RE 13A 600A and Bureau of Engineering Problems V1-4 and V2-4.

(b) Statement of Problem

2. The problem is to determine all possible sources of grid current and to separate and evaluate the components making up this current. Operating conditions are to be simulated as far as possible. The separation and determination of the components are to be made as near as possible at the operating temperature of the tube.

(c) Known Facts Bearing on the Problem

3. The 1933 report of the standards committee of the Institute of Radio Engineers gives certain methods for determining the reverse grid current components.

4. The Navy Specifications, RE 13A 600A, give one method for the determination of the gas component.

(d) Theoretical Considerations

5. In order that the results obtained be of maximum usefulness and the conclusions drawn from the data derived from the tests be seen in their proper perspective without ambiguity or doubt, a brief but sufficiently comprehensive theoretical treatment of what constitutes the reverse grid current appears to be in order.

6. Consider, for example, the case of a three-electrode vacuum tube with normal potentials applied. A meter in the grid circuit will generally indicate grid current. This current will consist of the components listed below, some of which are of considerably greater importance than others.

- (a) Electrons from the cathode which reach the grid by virtue of contact potentials and initial velocities.
- (b) Positive ions emitted by the filament.
- (c) Electrons emitted from the grid under the influence of light from the filament.
- (d) Electrons emitted from the grid under the influence of the soft X-rays given off by the plate due to its bombardment by the plate current.
- (e) Electrons from other electrodes to the control grid.

- (f) Secondary emission from the control grid.
- (g) Electron emission from the control grid due to its temperature. This is also called primary grid emission.
- (h) Leakage current.
- (i) Ionization current, i.e., positive ions formed by collision between the electrons constituting the plate current and the gas molecules in the space.

7. The grid current originating from the first source is generally negligible for transmitting tubes because the control grid bias is normally at a high level. The effect of the initial velocity of the electrons and of the contact potential difference between control grid and cathode is such as to give an effective, virtual, positive potential to the grid with respect to the cathode, on the supposition this time that all the electrons emerge from the cathode surface with zero velocities. The combined effect is generally less than 2 volts. Consequently, when a tube is biased to greater than -3 volts, the grid electron current due to the initial velocity of the electrons and to the contact potential difference between control grid and cathode is negligible. This is eminently true for transmitting tubes where the bias is high. On the other hand, the effect may be important for receiver tubes.

8. The reason why some electrons are emitted from the cathode with initial velocities is due to the fact that all metal conductors are conceived to contain a huge swarm of free electrons in constant random motion, much like the molecules of a gas. These electrons are normally prevented from leaving the metal by surface forces, called in electrical theory, electrical image forces. An electron cannot leave the metal surface unless it has sufficient energy to overcome these forces. The free electrons move inside the metal in random directions with various velocities. These velocities increase with increase of temperature. Whether the velocity distribution of the free electrons in a metal is Maxwellian, as thought in the past, or is governed by the new quantum statistical principles of Fermi and Dirac, is of academic interest. The important practical point is that under certain favorable conditions the grid, although negatively biased, does have a small current, attributable to the initial velocity of the emitted electrons from the cathode surface.

9. The rate of emission of electrons from different substances, i.e., their work function, or the work performed by an electron due to its kinetic energy as it escapes from the surface, and the contact potential differences are closely related. The contact potential is defined by the difference in the work function of two surfaces. Therefore, it is affected by a change in either surface. In vacuum tubes, under certain conditions, the contact potential difference between cathode and grid is important. This potential depends only upon the materials of the electrodes and their temperature, but not upon size,

shape, or position of the electrodes. The contact difference of potential between cathode and grid, and hence grid current, is greater the greater the difference in temperature between cathode and grid. As has been stated in paragraph 7, the effect of the initial velocities of the electrons and the contact potential difference between cathode and grid is to impart a virtual positive potential to the grid with respect to the cathode. Hence, the grid electron current is positive and opposes the total negative or reversed grid current by that amount. This effect is greater at smaller negative applied control grid potentials and negligible at biases greater than -3 volts, as has been stated in paragraph 7.

10. The grid current due to the sources enumerated in paragraph 6, such as, (b) positive ions emitted by the filament, (c) electrons emitted from the grid under the influence of light from the filament, (d) electrons emitted from the grid under the influence of the soft X-rays given off by the plate due to its bombardment by the plate current, (e) electrons from other electrodes to the control grid, and (f) secondary emission from the control grid, is of considerable interest under certain conditions of operation but is of sufficiently small magnitude for transmitting tubes as to consider these components negligible in this study.

11. The list of sources of grid current given in paragraph 6 is, at this point, reduced to the last three remaining; namely, (g) primary grid emission, (h) leakage current, and (i) ionization current. These components make up the bulk of the negative grid current when the control grid is negatively biased.

12. (g) Primary grid emission is electron emission from the grid due to its temperature. Electron emission from the grid is facilitated by the deposition of active material from the cathode on the grid due to either evaporation or sputtering. If the grid is maintained at a sufficiently high temperature by radiation from the cathode, it will emit an appreciable thermionic electron current which will manifest itself as a reverse or negative grid current. Due to the fact that primary grid emission is dependent on temperature, a test for measuring this component should be made at the operating temperature of the tube.

13. (h) The leakage current, also manifest as a reverse grid current in negatively biased control grid tubes, is due to the fact that the insulation resistance between the various electrodes (in our present case between cathode and grid and between plate and grid) is not infinite. It is obvious that the leakage current is directly proportional to the voltage; the greater the voltage the more leakage. For transmitting tubes which are "double-ended," that is, those in which the grid is at one end and the plate at the other, the problem of leakage is not troublesome. In fact, a number of double-ended transmitting tubes have been found to have very little or negligible leakage between the grid and plate, between which the greatest voltage is normally applied. In those tubes in which the electrodes are supported from the same stem it is possible that due to a rise in temperature electrolysis may occur in the glass pinch, thereby reducing the insulation resistance and, hence, giving rise to leakage between the electrodes. Therefore, a test to measure the component of reverse grid current due to leakage must be made at the operating temperature of the tube and with normal potentials.

14. (i) The greatest source of negative grid current in the majority of transmitting tubes is due to ionization current, or gas in the tube. The gas pressure which will produce a given positive ion current to the control grid depends on the nature of the gas, the magnitude of the electron currents, and the potentials of the electrodes. The reason why a knowledge of the amount of gas in a tube under operating conditions is important is because the life of a tube is directly traceable to the contained gas. Most transmitting tubes have thoriated tungsten filaments for cathodes. These cathodes are extremely sensitive to traces of gas and if the emitting properties of the cathode are destroyed the tube is useless. In order to see how gas affects adversely the thoriated tungsten filament we must give a brief description of how modern theories explain the relatively high emission properties of these cathodes. The electron emission of thoriated tungsten cathodes is due to a monatomic layer of thorium adsorbed on the surface of the tungsten. If a small percentage of thoria is introduced into tungsten, it is found that the electron-emitting properties of tungsten at the proper temperature are altered, the emission increasing a thousand-fold without changing the mechanical properties of tungsten. The explanation of this behavior is that some of the thoria in the tungsten wire is reduced to metallic thorium which diffuses through the wire to the surface where under certain conditions it forms a layer one atom deep. If the filament temperature is high the surface thorium may be lost by evaporation. For any filament temperature there is an equilibrium condition of the surface, a balance between the rate of supply and the rate of loss of thorium. In the presence of gas, the equilibrium conditions are altered. Inert gases such as the rare gases argon, helium and neon may remove atoms of thorium from the surface by sputtering, while a chemically active gas, such as oxygen, water vapor, or carbon dioxide, will rapidly oxidize the surface film, rendering the tube useless by destroying the electron emission properties of the cathode. Gas then has a deleterious effect on the cathode. In addition, the positive ions produced by collision of the electrons with the gas molecules tend to neutralize the space charge and fundamentally alter the characteristics of the tube.

15. Since the absence of gas is so important to the proper operation of vacuum tubes, let us see how gas is developed in operation. The walls of glass bulbs give off large quantities of gas upon heating. This is very largely water vapor with a small admixture of carbon dioxide and nitrogen. It is usual practice for the manufacturer to heat the glass envelope for a considerable time in order to insure that no more gas will be evolved during the life of the tube. If this baking process is not properly carried out, there will be a gradual evolution of gas from the walls of the bulb during the operating life.

16. The metal parts used for electrodes contain large amounts of gas in solution (volume gas) as well as gases adsorbed on the surface (surface gas). These gases are removed in part by treatment before the tube is exhausted and in part by a special procedure during the exhaust. If these treatments are not properly carried out, gas will be evolved during the operating life of the tube.

17. Even though a vacuum tube has been properly exhausted, there always remains a small residual gas. Two methods are in use for reducing the pressure still further, chemical clean-up and electrical clean-up. The chemical clean-up takes place through the agency of a "getter." This is a substance which is usually volatilized on to the surface of the bulb wall just before the tube is sealed from the vacuum system. The getter is effective both in the chemical and in the electrical clean-up. In part, the gas reacts chemically with the getter. This is particularly true in the case of water vapor, oxygen, and carbon dioxide. In part the gases are simply adsorbed and held as a monatomic layer on the surface of the getter. The getter not only functions at the time that it is vaporized, but it continues to take up gases which may be evolved during the life of the tube. On the other hand getters may liberate adsorbed gas when warm, or when directly bombarded by electrons. Electrical clean-up is produced by allowing a certain amount of electron current to be drawn to the anode such as to form ions by collisions between electrons and gas molecules. The ions acquire fairly high velocities and are actually driven into the walls of the bulb or the metal electrodes. While this can take place in well-exhausted tubes where no getter is present, it is greatly facilitated by the presence of a getter on the exposed surfaces. The ions formed also react chemically with the getter.

18. Everything that has been said up to this point is to show that the operation of a thermionic tube is greatly affected by the presence of gas. The effect of the gas on the cathode is most important. The most noticeable feature of the bombardment of the cathode by positive ions is the cathode sputtering. The positive ions, owing to their high values of kinetic energy, are able to knock off small particles of the cathode and so cause its disintegration. This cathode sputtering must not be confused with vaporization of the cathode due to the heat of bombardment. Small particles consisting of aggregates of many molecules are actually torn from the cathode by the action of the ions. The size of the particles depends upon the conditions of voltage, gas pressure, nature of the gas and of the cathode surface. Where the bombardment by the gas removes active materials from the surface of the cathode the latter becomes deactivated with a consequent drop in emission.

19. The discussion so far has not only shown the comparative importance of each of the three main sources of negative or reverse grid current in negatively biased tubes; namely, of primary grid emission, leakage, and gas, but that each component must be determined at the operating temperature of the tube. This last condition is important to bear in mind, for the determination of the components at other than the operating temperature of the tube may give results which are misleading.

(e) Narrative of Work done at this Laboratory on the Problem

20. The problem was attacked from a fundamental viewpoint and analyzed as a problem in circuit theory. All possible sources of grid current were theoretically determined and analyzed, and knowing the polarity of the direct voltages applied to the tube, it was a

simple matter to determine the direction of flow and paths of flow of all the components. The experimental procedure followed, as a logical consequence, the theoretical study. In turn, the data obtained showed the soundness of the theoretical approach. The results of this investigation in some places confirm work previously done, as exemplified in the 1933 report of the standards committee of the Institute of Radio Engineers, and in others show the wisdom and necessity of making modifications in past accepted methods.

METHODS

(a) Circuit Diagram

21. Plate 1 shows the circuit diagram employed in the determination of the components.

(b) Description of Experiments

22. Refer to Plate 1. In accordance with Navy Specifications RE 13A 600A, the grid current test for transmitting tubes is made with normal operating voltages and with such bias as to make the plate current and, hence, the plate dissipation from 15 to 60 per cent greater than normal. This increases the operating temperature of the tube by a corresponding amount. This is a more severe test, the purpose of which is to subject the tube to higher than normal temperatures under conditions favorable to the evolution of gas from the glass walls and electrodes of those tubes which have not received proper treatment previous to and during the exhaust process. In the determination of the components of the grid current this higher temperature is kept as near constant as possible.

23. Let switches S_1 , S_2 , and S_3 be closed, and specified potentials applied to the tube for such length of time (ordinarily 5 minutes is sufficient) for the tube to reach steady operating temperature.

(a) Read the grid current with all switches closed. This is the total reverse grid current, or the sum total of all the components. Call this current, I_a .

(b) With S_1 and S_3 closed, open S_2 . The plate current drops to zero, and, therefore, the ionization current drops to such a low value as to be considered negligible. The ionization or gas current depends on the following factors: the quantity of contained gas, the concentration of electrons in motion, and the speed with which these electrons move. The speed is directly a function of the voltage. The first factor is a function of the temperature and may be considered constant at any one time. This makes the mean free path between the molecules of the gas a constant factor. The last factor is also constant, since the voltage imparting motion to the emitted electrons from the cathode is held unchanged during the test. Consequently, at any one time we may say that the ionization current is directly proportional to the concentration of space electrons in motion, or the plate current. Consider the case of the tube in which the plate current, under the specified grid current test conditions, is 400 milliamperes. When either of the three switches, S_1 , S_2 , or S_3 of Plate 1

is opened, the plate current necessarily drops to zero. The only current which may flow in the tube is that due to primary emission, for a very short length of time, and that due to leakage for a much longer length of time. Assume the total current to be 10 microamperes. Then the ionization current, flowing under such conditions is of such a magnitude with reference to the true ionization current, when plate current is flowing, as the ratio of $10/400 \times 10^3$ or 1 to 40,000, which is negligible. The conclusion, then, is that when plate current is not flowing the ionization component may be considered eliminated. With S_2 open, the current read by the grid meter is primary grid emission and leakage between plate and grid. It will be noted that the filament circuit is on so that the tube is very near the operating temperature, as far as radiation from the cathode to the grid is concerned, even though plate dissipation is discontinued by the opening of S_2 . Call this current, I_b .

I_b = primary grid emission + leakage current between plate and grid.

(c) With S_1 and S_3 closed, reclose switch S_2 and allow tube to reach operating temperature. This is so when I_g is again of the same magnitude as in (a).

(d) If leakage between cathode and grid is not negligible: with all switches closed, allow tube to regain its operating temperature by noting when $I_g = I_a$. With S_2 closed, open S_1 and S_3 simultaneously. Ionization current is zero. The grid emission becomes negligible in a very short time. Call this current, I_d .

I_d = leakage current between cathode and grid.

(e) Allow tube to reach operating temperature. With S_2 and S_3 closed, open S_1 . Call this current, I_e . Ionization and primary grid emission components are effectively eliminated in this test. The current read by the grid meter is the sum of the leakage currents in the cathode-grid and plate-grid circuits, or the total leakage.

I_e = leakage current between cathode and grid electrodes
+ leakage current between plate and grid.

= total leakage.

24. The present Navy Specifications RE 13A 600A gas test is a measure not only of the gas content but also the total leakage. The latter may be obtained separately and subtracted from the total value, leaving the pure gas current, I_g' . Call the specification gas test current I_{g1} . Therefore $I_g' = I_{g1} - I_e$. Another independent method for obtaining the pure gas current is by means of the formula below:

$$I_{gas} = I_g'' = I_a - (I_b + I_d)$$

where, as previously explained,

I_a = total grid current (at the steady, operating temperature of the tube).

I_b = primary grid emission + leakage current
between grid and plate.

I_d = leakage current between cathode and grid.

It will be noted that the sum ($I_b + I_d$) represents the total leakage and the total primary grid emission at the operating temperature of the tube. It will be noted from a study of the data shown at the end of this report that I_g' , obtained by one method, and I_g'' , obtained by an entirely different method, check each other to within fairly close limits. This is proof that the theory, as presented in this report, and the experimental data over a large number of representative types of transmitting tubes, check each other satisfactorily.

DATA OBTAINED

(a) Data in Tabular Form

25. The data obtained are shown in tabular form in Table 1.

(b) Statement of Probable Errors

26. The nature of the various experiments tried is such that it was realized at the outset that nothing approaching absolute accuracy may be hoped for. For this reason a large number of transmitting tubes of various sizes, types, and conditions, representing half a dozen manufacturers, were subjected to this investigation. Some of these tubes have been lying idle on the shelf for a number of years. It was hoped that what was lacking in absolute accuracy for each tube, will be made up statistically, as far as general information from which to draw conclusions is concerned, by the employment of a large number of tubes of different previous history and condition. The various components of reverse grid current, singly and collectively, are dependent on the temperature of the tube. In the determination of the various components it is necessary to recreate the same temperature for the various tests for each tube. The temperature was taken to be the same at the instant the total grid current reached a given value determined after the tube was estimated to have reached a steady operating temperature.

CONCLUSIONS AND RECOMMENDATIONS

(a) Conclusions

27. (a) The present specification "gas" test does not give the component of the reverse grid current due solely to gas. It actually measures the sum of the gas current plus the total leakage. The latter component may be obtained by an independent method, as explained in this report, and subtracted from the total, thereby obtaining the required gas current component alone.

(b) The gas current may also be obtained by another independent method, as explained in this report. The primary grid emission and total leakage are obtained semi-independently and subtracted from the total reversed grid current giving the gas component alone.

(c) The total leakage component may be obtained alone and entirely independent of primary grid emission and ionization current.

(d) Knowing gas current component and total leakage, the grid emission may be obtained by subtraction from the total.

(e) The gas component measured by method (a) checks that obtained by method (b) in the great majority of tubes tested.

(b) Recommendations

28. It is recommended that, in view of the data obtained in this investigation in respect to the separation of the components comprising the total reverse grid current in negatively biased transmitting tubes, the Navy Specifications RE 13A 600A be modified accordingly.

Appendix

(a) Symbols employed in this report:

I_{gm} = maximum total reverse grid current at any time during operation.

I_a = total reverse grid current.

I_b = primary grid emission + leakage current between grid and plate.

I_d = leakage current between cathode and grid.

I_e = leakage current between cathode and grid + leakage current between plate and grid

= total leakage current.

$(I_b + I_d)$ = total primary grid emission + total leakage.

I_{g1} = present specification gas test current.

I_{g2} = primary grid emission.

I_g' = pure gas current (from present specification gas test method)

I_g'' = pure gas current (from determination of primary grid emission and total leakage).

Formulas employed in this report:

$$I_g' = I_{g1} - I_e \quad (1)$$

$$I_g'' = I_a - (I_b + I_d) \quad (2)$$

$$I_{g2} = (I_b + I_d) - I_e \quad (3)$$

(b) Symbols used in this report to identify manufacturers of tubes used in this investigation:

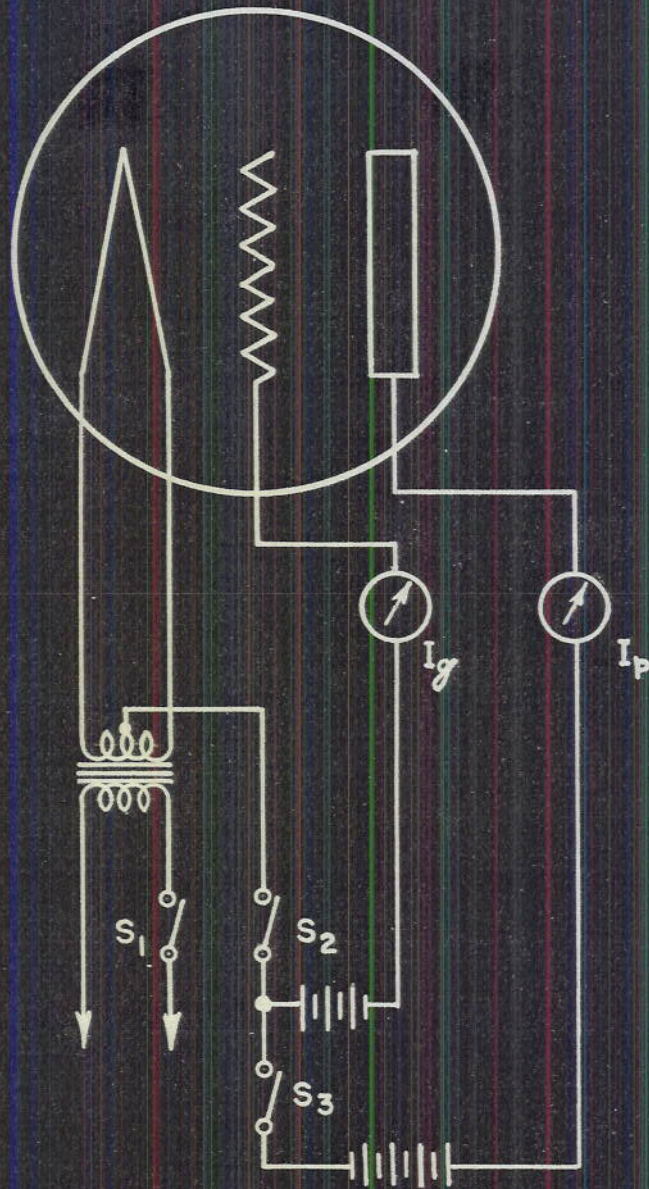
Symbols	Manufacturer
A	Sylvania
B	Amperex
C	RCA
D	Westinghouse
E	General Electric
F	Western Electric

(c) Bibliography.

1. 1933 Report of the Standards Committee of the Institute of Radio Engineers.
2. Navy Specifications RE 13A 600A.
3. E. L. Chaffee, "Theory of Thermionic Vacuum Tubes."
4. L. R. Koller, "Physics of the Electron Tube."
5. A. L. Reimann, "Thermionic Emission."

Table 1

No. of Tubes Tested	Type of Mfr. Tube	Type of Ser. No.	Type of Plate	I _{gm} (ua)	I _a (ua)	I _b (ua)	I _d (ua)	I _e (ua)	I _{g1} (ua)	(I _b +I _d) (ua)	I _{g'} (ua)	I _{g''} (ua)	I _{g2} (ua)
1	A	38151	1008	25	25	4.5	-	3	14.5	6	11.5	19	3
2	B	38149	405	35	12	10.5	-	10	11	10.5	1	1.5	0.5
3	C	38149	10284	110	15	1.5	-	1.5	23	2.2	21.5	12.8	0.7
4	A	38149	1003	21	16.5	3.5	-	3.0	15.5	5	12.5	11.5	2
5	A	38104	1134	16.5	3.5	1.25	-	1.0	3	1.75	2.0	1.7	0.75
6	D	38104	26	16	4.5	0.25	-	0.25	8	0.37	7.75	3.88	0.12
7	D	38161	27668	3.1	3.1	0.15	-	0.1	2.9	0.2	2.8	2.9	0.1
8	E	38161	15210	10	2.6	0.2	-	0.2	2.9	0.3	2.7	2.3	0.1
9	D	38161	27719	3	1.5	0.3	-	0.3	1.3	0.45	1.0	1.05	0.15
10	D	38160	30098	1.6	1.2	0.0	-	0.0	1.1	0.0	1.1	1.2	0.0
11	A	38160	1920	9	7.1	0.1	-	0.1	6.1	0.15	6.0	6.95	0.05
12	C	38160	6337	3.9	1.2	0.1	-	0.1	1.6	0.15	1.5	1.05	0.05
13	C	38145	22401	2.5	1.4	1.4	0.78	1.0	1.2	2.18	0.2	0.0	1.18
14	C	38145	46174	-	0.75	0.65	0.18	0.52	0.65	0.83	0.13	0.0	0.31
15	F	38145	326619	3.6	2.9	0.58	0.35	0.75	2.1	0.93	1.35	1.97	0.18
16	C	38111A	29507	4.2	2.0	1.0	-	0.8	1.4	1.4	0.6	0.6	0.6
17	A	38111A	1463	7.1	1.45	1.2	-	0.83	0.95	1.62	0.12	-0.22	0.79
18	B	38111A	8580	45	45	44	0.0	10	10	-	0.0	1	-
19	E	38111A	70730	28	6.3	3.1	0.42	3.6	5.7	3.52	2.1	2.78	0
20	C	38103	46709	1.42	1.42	4.5	-	4.2	1.7	-	-2.5	-3.25	-
21	A	38103	2509	3.0	1.15	0.05	-	0.05	1.05	0.1	1.0	1.05	0.05
22	B	38103	1	1.9	1.65	0.8	0.05	0.8	1.65	0.85	0.85	0.75	0.05
23	D	38103	27856	3.0	2.15	1.55	-	1.45	1.85	1.6	0.4	0.55	0.15
24	F	38103	101	48	22	29	-	27.5	25	-	-2.5	-7	-
25	C	38152	70749	5.5	3.6	0.05	-	0.05	3.2	0.1	3.15	3.5	0.05
26	A	38152	-	4.3	1.5	0.05	-	0.05	1.4	0.1	1.35	1.4	0.05
27	D	38152	25748	5	2.4	0.05	-	0.05	2.3	0.1	2.25	2.3	0.05
28	C	38150	31158	4.9	1.05	0.3	-	0.25	0.85	0.35	0.60	0.65	0.10
29	C	38150	1	110	55	26	-	23.5	55	26	21.5	29	2.5



CIRCUIT FOR THE DETERMINATION OF COMPONENTS OF REVERSE GRID CURRENT FOR NEGATIVE BIAS TUBES AT THE OPERATING TEMPERATURE.