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Report

of

Correct Capacitance Measurement Procedure on Metal Base Shell Vacuum Tubes.

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ABSTRACT

The importance of the correct and accurate measurement of the direct inter-electrode capacitances of vacuum tubes needs no special emphasis. The Naval Research Laboratory has been making such measurements over a number of years in connection with work pertaining to tubes submitted for Navy type approval. The results of the measurements at this Laboratory were, on occasion, at variance with some of the tube manufacturers. One manufacturer in particular has submitted a number of transmitting tubes with capacitance data specially obtained for comparison. Part of the data obtained at this Laboratory was again at variance with that submitted. The difference between the two sets of data was considerable and disturbing because on the surface, at least, it appeared unaccountable. However, a careful study of the problem and careful measurements have indicated what is considered to be the correct method of measuring the direct inter-electrode capacitances of vacuum tubes, in particular those of the transmitting type that have metallic base shells.

This report contains a detailed analysis of the problem, develops a theory to account for the causes of disagreement, and presents data showing most excellent agreement between theory and experiment. Finally, what is considered to be the proper method of measurement, which this report proves and advocates, is recommended for adoption.

INTRODUCTION

(a) Authorization

1. This work was authorized by Bureau of Engineering letter S67/38/L5 (9-11-W8) of 13 November 1936.

(b) Statement of Problem

2. The problem is to determine the cause of the disagreement between the data obtained by the Naval Research Laboratory and those of a specific manufacturer on transmitting tubes submitted by him for comparison purposes. Two of the three types submitted, in which the disagreement occurred, had metallic base shells. In the third type, which had a bakelite base, the agreement was excellent.

(c) Theoretical Considerations

3. Consider a Navy type 38103 tube. This is a transmitting type of tube containing a metallic base shell and having a maximum rating for plate dissipation of 100 watts.

4. When this tube is inserted in the proper adaptor socket of the Naval Research Laboratory Capacitance Measuring Equipment for measuring the tube's direct inter-electrode capacitances, an equivalent electrical network representing the tube is set up in the measuring circuit. Consider the case when the metallic base shell is left floating electrically. The equivalent electrical circuit representing this condition is shown in Figure 1, Plate 1. In the case illustrated, the direct capacitance desired is that between the plate and cathode electrodes.

5. It will be noted that the floating shell, represented by the letter S, produces by electric induction a network of capacitances to ground and to the various electrodes of the tube as shown in Figure 1.

C_1 is the capacitance between the shell and the plate electrode.
C_2 is the capacitance between the shell and cathode.
C_3 is the capacitance between the shell and grid.
C_s is the capacitance between the shell and ground.

The following measurements were then made:

(a) With shell floating:

$$C_{(P-K)_1} = 4.78 \ \mu\mu f. \qquad (1)$$

(b) With shell grounded:

$$C_{(P-K)_2} = 3.78 \ \mu\mu f. \qquad (2)$$

This is to be construed as the true direct capacitance between the plate and cathode electrodes, as this report definitely proves.

(c) With shell tied to cathode:

$$C_{(P-K)_3} = 8.13 \ \mu\mu f. \qquad (3)$$

(d) With shell tied to plate:

$$C_{(P-K)_4} = 6.52 \ \mu\mu f. \qquad (4)$$

Hence, C_1 is the difference between equations (3) and (2). That is,

$$C_1 = 8.13 - 3.78 = 4.35 \ \mu\mu f. \qquad (5)$$

Similarly,

$$C_2 = 6.52 - 3.78 = 2.74 \ \mu\mu f. \qquad (6)$$

6. Another more direct method for obtaining C_1, C_2, and also C_3 is given in Figures 4, 5 and 6 (Plates 4, 5 and 6). The values obtained by direct measurement are as follows:

$$C_1 = 4.25 \ \mu\mu f. \qquad (7)$$

$$C_2 = 2.68 \ \mu\mu f. \qquad (8)$$

$$C_3 = 1.31 \ \mu\mu f. \qquad (9)$$

The close agreement between (5) and (7) and between (6) and (8) may be noted.

7. Referring to Figure 1, it will be noted that the Y-network of capacitances, formed by the floating shell with the ground and the tube electrodes, effectively forms an equivalent capacitance in parallel with the direct plate-cathode capacitance desired of the tube under measurement.

8. In order to calculate this effective equivalent capacitance of the Y-network, we must transform the Y- to a Δ - network.

9. Refer to Figure 7-A and 7-B, Plate 7. The Y-Δ transformation is well known and gives the following equation for Z_3:

$$Z_3 = \frac{Z'Z'' + Z''Z''' + Z'Z'''}{Z'''} \qquad (10)$$

10. Substituting for the Z's the equivalent expressions for the capacitative reactances, we obtain the expression given below:

$$C_{eq.} = \frac{C_1C_2}{C_1 + C_2 + C_3 + C_s} \qquad (11)$$

11. In equation (11), we know C_1, C_2, and C_3, but we do not know C_s. However, by utilizing equations (1), (2) and (11), we obtain C_s as follows:

From equations (1) and (2),

$$C_{eq.} = C_{(P-K)_1} - C_{(P-K)_2}$$

$$= 4.78 - 3.78$$

$$= 1.0 \ \mu\mu f. \qquad (12)$$

Substituting (7), (8), (9) and (12) in (11), we have,

$$1.0 = \frac{(4.25)(2.68)}{4.25 + 2.68 + 1.31 + C_s}$$

$$= \frac{11.39}{8.24 + C_s}$$

$$\therefore C_s = 11.39 - 8.24$$

$$= 3.15 \ \mu\mu f. \qquad (13)$$

12. Equation (13) is the capacitance to ground of the floating shell, employing the socket, shown by its photograph on Plate 8-a. However, the data given in Table 1 were obtained by means of the same socket but having in addition an improvised shield, as shown by its photograph on Plate 8-b, which raised the effective ground and brought it closer to the shell, thus increasing the value of C_s. Consequently, it becomes necessary to use new values of capacitance corresponding to equations (1) and (2). These values are taken from Table 1 for tube No. 55629 and are as follows for the case shown in Figure 1:

$$C_{(P-K)_1} = 4.64\ \mu\mu f. \qquad (1')$$

$$C_{(P-K)_2} = 3.80\ \mu\mu f. \qquad (2')$$

13. Using the above values, we get for the equivalent parallel capacitance formed by the floating shell,

$$C_{eq.} = C_{(P-K)_1} - C_{(P-K)_2}$$

$$= 4.64 - 3.80$$

$$= 0.84\ \mu\mu f. \qquad (14)$$

Substituting (7), (8), (9) and (14) in (11), we have,

$$0.84 = \frac{(4.25)(2.68)}{4.25 + 2.68 + 1.31 + C_s}$$

$$= \frac{11.39}{8.24 + C_s}$$

$$\therefore C_s = \frac{11.39 - 6.92}{0.84} = 5.32\ \mu\mu f. \qquad (15)$$

This is the shell to ground capacitance, using the socket shown in Plate 8-b. It will be noted that the value of C_s has increased by bringing the ground closer to the shell, which is as it should be.

14. Now refer to Figure 2 (Plate 2). In this case the desired capacitance is that between the grid electrode and the cathode. With the shell floating, we get,

$$C_{(G-K)_1} = 5.50\ \mu\mu f. \qquad (16)$$

With the shell grounded, we get,

$$C_{(G-K)_2} = 5.21\ \mu\mu f. \qquad (17)$$

15. We are now in a position to calculate the equivalent parallel capacitance formed by the floating shell, as of Figure 2, since we know C_1, C_2, C_3, and C_s. It will be noted that C_s remains constant with the shell floating for all three of the inter-electrode capacitance measurements.

16. The equation for $C_{eq.}$ now becomes, referring to Fig. 2,

$$C_{eq.} = \frac{C_2C_3}{C_1 + C_2 + C_3 + C_s} \quad (18)$$

Substituting (7), (8), (9) and (15) in (18), we have,

$$C_{eq.} = \frac{(2.68)(1.31)}{4.25 + 2.68 + 1.31 + 5.32}$$

$$= \frac{3.51}{13.56}$$

$$= 0.26 \ \mu\mu f. \quad (19)$$

Subtracting (19) from (16),

$$C_{(G-K)} = 5.50 - 0.26$$

$$= 5.24 \ \mu\mu f. \quad (20)$$

17. It will be noted that (20), obtained by measurement and calculation from the theory of the floating shell effect, checks excellently the value obtained by direct measurement, with the shell grounded, as given by (17).

18. Now refer to Figure 3 (Plate 3). In this instance the capacitance desired is that between the plate and grid electrodes.

With the shell floating, we have,

$$C_{(P-G)_1} = 14.43 \ \mu\mu f. \quad (21)$$

With the shell grounded, we have,

$$C_{(P-G)_2} = 13.98 \ \mu\mu f. \quad (22)$$

19. Again we make a Y-Δ transformation, and obtain for the equivalent parallel capacitance the following expression:

$$C_{eq.} = \frac{C_1C_3}{C_1 + C_2 + C_3 + C_s} \quad (23)$$

Substituting (7), (8), (9) and (15) in (23), we have,

$$C_{eq.} = \frac{(4.25)(1.31)}{13.56} = 0.41 \ \mu\mu f. \quad (24)$$

Subtracting (24) from (21), we have,

$$C_{(P-G)} = 14.43 - 0.41$$

$$= 14.02 \ \mu\mu f. \quad (25)$$

Again, (25) checks excellently the value obtained by direct measurement, as given by (22).

(d) Narrative of Original Work Done at this Laboratory on the Problem.

20. The work done at this Laboratory on the problem was original and came about in an attempt to explain the cause of discrepancies of considerable magnitude existing between capacitance data as obtained by the Laboratory and those submitted by a manufacturer for the specific purpose of checking the facilities and measurement technique existing with each party. The disagreement in the data gave rise to a study of the problem by the Laboratory from a fundamental viewpoint, treating it as an electrical network which ought to be amenable to solution in accordance with well-known principles of electrical circuit theory. The results obtained gave a most excellent agreement between theory and experiment.

METHODS

(a) Circuit Diagram

21. Figures 1, 2 and 3 show the equivalent networks existing when the shell of the transmitting tube under measurement is left floating.

22. Figures 4, 5, and 6 show the correct method to use in measuring directly the capacitances formed by the floating shell with each of the three electrodes of the tube under measurement.

23. Figures 7-A and 7-B give the mathematical expressions for a Y-Δ transformation of impedances.

(b) Description of Experiments

24. The experiments were carried out in a straightforward manner, the equipment employed for the measurements having been completely described in a recent report to the Bureau of Engineering entitled "Description of the Naval Research Laboratory Capacitance Measuring Equipment" having a range of 0.003 to 100 μμf.

DATA OBTAINED

(a) Data in Tabular Form

25. The data obtained with the shell floating and shell grounded are shown in Table 1. The manufacturer's data are also shown for comparison.

26. Table 2 gives some previously obtained data on receiving tubes containing bakelite bases and shows excellent agreement with the manufacturer's data. This is additional proof

that tubes with metal shell bases must have the shell grounded for proper evaluation and measurement of their direct inter-electrode capacitances.

(b) Statement of Probable Errors

27. The equipment employed for the measurement is capable of a high degree of accuracy. See Report No. R-1461, entitled "Description of the Naval Research Laboratory Capacitance Measuring Equipment," previously referred to. The results of the actual measurements checked those of the calculations to better than 1%.

CONCLUSIONS AND RECOMMENDATIONS

(a) Conclusions

28. It is concluded that any transmitting type of vacuum tube, containing a metallic base shell, which is employed in measuring its inter-electrode capacitances, may have its system resolved into each of the electrical equivalent networks represented by Figures 1, 2 and 3, provided the shell is left floating. It is further concluded that the direct inter-electrode capacitances, as defined for vacuum tubes, may be properly measured only if the metallic base shell, used by most transmitting tubes, is grounded.

29. A comparison of the Naval Research Laboratory data, obtained with the shell floating, with those of the manufacturer discloses considerable disagreement. With the shell grounded, the Naval Research Laboratory data check very closely that of the manufacturer in two general cases - with respect to the grid-plate and grid-cathode capacitances. On the other hand, the disagreement for the case of the plate-cathode capacitance still remains, and is in fact increased. It appears that in the two cases the manufacturer took his measurements with the shell grounded. In the third case it is not known how he made his measurements. In every other case considered, however, where the tube had no metallic base shell the agreement was most excellent.

(b) Recommendations

30. It is recommended that, in view of the considerable extraneous effect introduced into inter-electrode capacitance measurements by the floating metallic base shell for those of the transmitting type of tubes that have it, the Bureau of Engineering stipulate that these measurements be made with the base shell grounded.

TABLE 1

Comparison of NRL Data with those of
Manufacturer on Tubes Type 38103,
38111A and 38152 specially sub-
mitted by the latter.

A. Using socket shown on Plate 8-a except for type 38152.
1. Measuring Technique: (a) NRL method, shell floating.
(b) Mfr's method, unknown.

(a) Tube type 38103.

Tube No.	NRL Cg-p (μμf)	Mfr. Cg-p (μμf)	Difference (μμf)
55617	14.17	13.60	-0.57
55622	14.40	13.85	-0.55
55628	14.20	13.70	-0.50
55629	14.51	13.95	-0.56
55632	14.28	13.80	-0.48

Tube No.	NRL Cg-k (μμf)	Mfr. Cg-k (μμf)	Difference (μμf)
55617	5.80	5.50	-0.30
55622	5.52	5.20	-0.32
55628	5.61	5.30	-0.31
55629	5.50	5.20	-0.30
55632	5.84	5.50	-0.34

Tube No.	NRL Cp-k (μμf)	Mfr. Cp-k (μμf)	Difference (μμf)
55617	4.69	5.00	+0.31
55622	4.86	5.10	+0.24
55628	4.92	5.20	+0.28
55629	4.79	5.00	+0.21
55632	5.07	5.30	+0.23

(b) Tube type 38111A

Tube No.	NRL Cg-p (μμf)	Mfr. Cg-p (μμf)	Difference (μμf)
56051	9.93	9.60	-0.33
56058	9.90	9.50	-0.40
56059	9.75	9.30	-0.45
56063	10.07	9.60	-0.47

Tube No.	NRL Cg-k (μμf)	Mfr. Cg-k (μμf)	Difference (μμf)
56051	5.74	5.40	-0.34
56058	5.23	4.90	-0.33
56059	5.19	4.90	-0.29
56063	5.56	5.10	-0.46

Tube No.	NRL Cp-k (μμf)	Mfr. Cp-k (μμf)	Difference (μμf)
56051	5.27	5.40	+0.13
56058	5.09	5.20	+0.11
56059	5.22	5.30	+0.08
56063	5.58	5.60	+0.02

(c) Tube type 38152.

Tube No.	NRL Cg-p (μμf)	Mfr. Cg-p (μμf)	Difference (μμf)
7418	2.42	2.42	+0.0
7435	2.41	2.42	+0.01
7436	2.42	2.40	-0.02
7450	2.42	2.40	-0.02
7451	2.42	2.40	-0.02

Tube No.	NRL Cg-k (μμf)	Mfr. Cg-k (μμf)	Difference (μμf)
7418	1.67	1.60	-0.07
7435	1.62	1.57	-0.05
7436	1.65	1.60	-0.05
7450	1.66	1.60	-0.06
7451	1.70	1.65	-0.05

Tube No.	NRL Cp-k (μμf)	Mfr. Cp-k (μμf)	Difference (μμf)
7418	0.585	0.5	-0.1
7435	0.600	0.5	-0.1
7436	0.570	0.5	-0.1
7450	0.595	0.5	-0.1
7451	0.585	0.5	-0.1

2. Measuring Technique: (a) NRL Method, shell grounded.
(b) Mfr's method, unknown.

(a) Tube type 38103.

Tube No.	NRL Cg-p (μμf)	Mfr. Cg-p (μμf)	Difference (μμf)
55617	13.58	13.60	+0.02
55622	13.82	13.85	+0.03
55628	13.64	13.70	+0.06
55629	13.96	13.95	-0.01
55632	13.73	13.80	+0.07

Tube No.	NRL Cg-k (μμf)	Mfr. Cg-k (μμf)	Difference (μμf)
55617	5.53	5.50	+0.0
55622	5.20	5.20	+0.0
55628	5.30	5.30	+0.0
55629	5.19	5.20	+0.01
55632	5.55	5.50	-0.05

Tube No.	NRL Cp-k (μμf)	Mfr. Cp-k (μμf)	Difference (μμf)
55617	3.70	5.00	+1.30
55622	3.88	5.10	+1.22
55628	3.95	5.20	+1.25
55629	3.77	5.00	+1.23
55632	4.01	5.30	+1.29

(b) Tube type 38111A.

Tube No.	NRL Cg-p (μμf)	Mfr. Cg-p (μμf)	Difference (μμf)
56051	9.37	9.60	+0.23
56058	9.29	9.50	+0.21
56059	9.18	9.30	+0.12
56063	9.48	9.60	+0.12

Tube No.	NRL Cg-k (μμf)	Mfr. Cg-k (μμf)	Difference (μμf)
56051	5.46	5.40	-0.06
56058	4.90	4.90	+0.00
56059	4.87	4.90	+0.03
56063	5.23	5.10	-0.13

Tube No.	NRL Cp-k (μμf)	Mfr. Cp-k (μμf)	Difference (μμf)
56051	4.25	5.40	+1.15
56058	4.06	5.20	+1.14
56059	4.21	5.30	+1.09
56063	4.57	5.60	+1.03

B. Using socket shown on Plate 8-b.

1. Tube type 38103

(a)' Measuring Technique: (a) NRL method, shell floating
(b) Mfr's method, unknown

Tube No.	NRL Cg-p (μμf)	Mfr. Cg-p (μμf)	Difference (μμf)
55617	14.08	13.60	-0.48
55622	14.31	13.85	-0.46
55628	14.12	13.70	-0.42
55629	14.43	13.95	-0.48
55632	14.20	13.80	-0.40

Tube No.	NRL Cg-k (μμf)	Mfr. Cg-k (μμf)	Difference (μμf)
55617	5.80	5.50	-0.30
55622	5.54	5.20	-0.34
55628	5.62	5.30	-0.32
55629	5.50	5.20	-0.30
55632	5.83	5.50	-0.33

Tube No.	NRL Cp-k (μμf)	Mfr. Cp-k (μμf)	Difference (μμf)
55617	4.56	5.00	+0.44
55622	4.78	5.10	+0.33
55628	4.82	5.20	+0.38
55629	4.64	5.00	+0.36
55632	4.93	5.30	+0.33

(b)' Measuring Technique: (a) NRL method, shell grounded.
(b) Mfr's method, unknown.

Tube No.	NRL Cg-p (μμf)	Mfr. Cg-p (μμf)	Difference (μμf)
55617	13.61	13.60	-0.01
55622	13.81	13.85	+0.04
55628	13.64	13.70	+0.06
55629	13.98	13.95	-0.03
55632	13.72	13.80	+0.08

Tube No.	NRL Cg-k (μμf)	Mfr. Cg-k (μμf)	Difference (μμf)
55617	5.53	5.50	-0.03
55622	5.25	5.20	-0.05
55628	5.34	5.30	-0.02
55629	5.21	5.20	-0.01
55632	5.56	5.50	-0.06

Tube No.	NRL Cp-k (μμf)	Mfr. Cp-k (μμf)	Difference (μμf)
55617	3.73	5.00	+1.[illegible]
55622	3.91	5.10	+1.19
55628	3.97	5.20	+1.[illegible]
55629	3.80	5.00	+1.[illegible]0
55632	4.05	[illegible].30	+1.[illegible]

C. Using socket shown on Plate 8-c. This automatically grounds the shell. Mfr's method of measurement unknown.

(a) Tube type 38103.

Tube No.	NRL Cg-p (μμf)	Mfr. Cg-p (μμf)	Difference (μμf)
55617	13.61	13.60	-0.01
55622	13.81	13.85	+0.04
55628	13.63	13.70	+0.07
55629	13.97	13.95	-0.02
55632	13.76	13.80	+0.04

Tube No.	NRL Cg-k (μμf)	Mfr. Cg-k (μμf)	Difference (μμf)
55617	5.56	5.50	-0.06
55622	5.29	5.20	-0.09
55628	5.36	5.30	-0.06
55629	5.26	5.20	-0.06
55632	5.61	5.50	-0.09

Tube No.	NRL Cp-k (μμf)	Mfr. Cp-k (μμf)	Difference (μμf)
55617	3.73	5.00	+1.27
55622	3.92	5.10	+1.18
55628	3.98	5.20	+1.22
55629	3.81	5.00	+1.19
55632	4.06	5.30	+1.24

(b) Tube type 38111A.

Tube No.	NRL Cg-p (μμf)	Mfr. Cg-p (μμf)	Difference (μμf)
56051	9.40	9.60	+0.20
56058	9.30	9.50	+0.20
56059	9.22	9.30	+0.08
56063	9.49	9.60	+0.11

Tube No.	NRL Cg-k (μμf)	Mfr. Cg-k (μμf)	Difference (μμf)
56051	5.50	5.40	-0.10
56058	4.97	4.90	-0.07
56059	4.94	4.90	-0.04
56063	5.28	5.10	-0.18

Tube No.	NRL Cp-k (μμf)	Mfr. Cp-k (μμf)	Difference (μμf)
56051	4.29	5.40	+1.11
56058	4.09	5.20	+1.11
56059	4.24	5.30	+1.06
56063	4.62	5.60	+1.08

TABLE 2

Tube type 38057:

Tube No.	NRL C_{g-k} (μμf)	Mfr. C_{g-k} (μμf)	Difference (μμf)
11	4.8	4.9	+0.1
12	4.8	4.9	+0.1
13	4.7	4.8	+0.1
14	4.7	4.8	+0.1
15	4.8	4.9	+0.1
16	4.6	4.7	+0.1

Tube No.	NRL C_{p-k} (μμf)	Mfr. C_{p-k} (μμf)	Difference (μμf)
11	6.1	6.3	+0.2
12	6.2	6.4	+0.2
13	6.2	6.3	+0.1
14	6.2	6.4	+0.2
15	6.0	6.1	+0.1
16	6.2	6.4	+0.2

Tube No.	NRL C_{g-p} (μμf)	Mfr. C_{g-p} (μμf)	Difference (μμf)
11	0.004	0.003	-0.001
12	0.005	0.004	-0.001
13	0.007	0.004	-0.003
14	0.006	0.004	-0.002
15	0.007	0.006	-0.001
16	0.006	0.004	-0.002

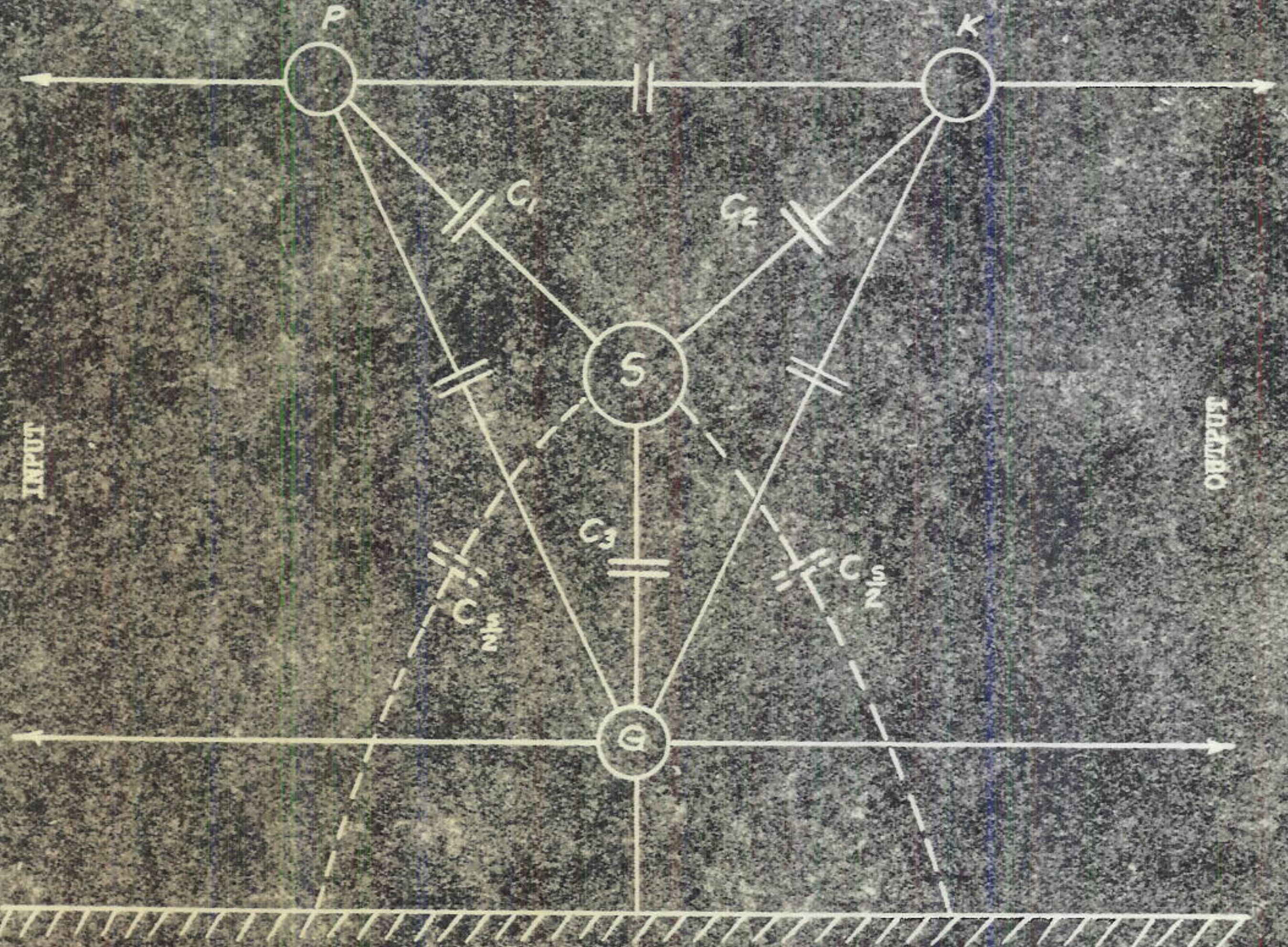


Fig. 1

Equivalent circuit of tube with its metal shell floating. The direct capacitance desired is C_{P-K}.

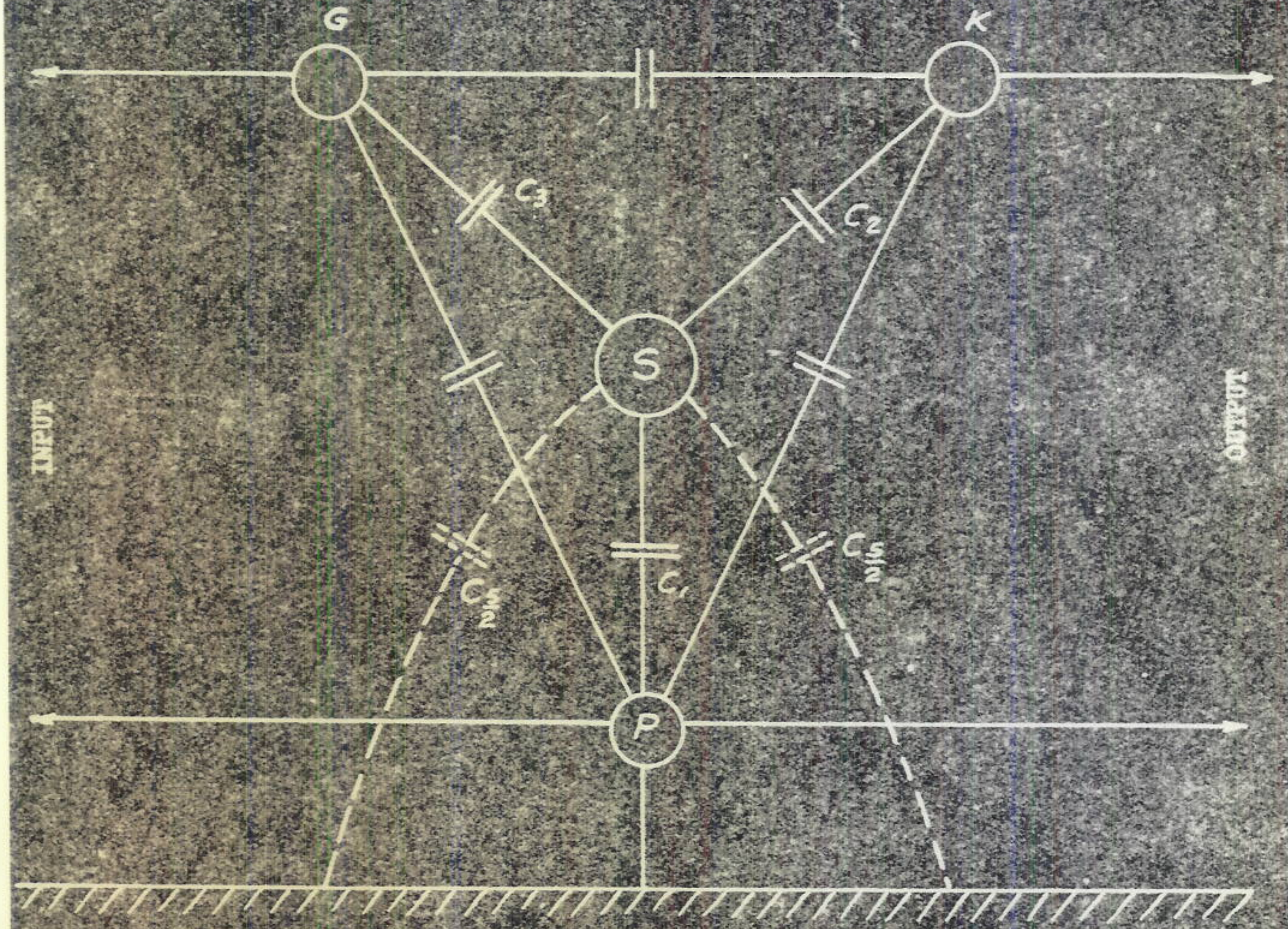


Fig. 2

Equivalent circuit of tube with its metal shell floating. The direct capacitance desired is C_{G-K}.

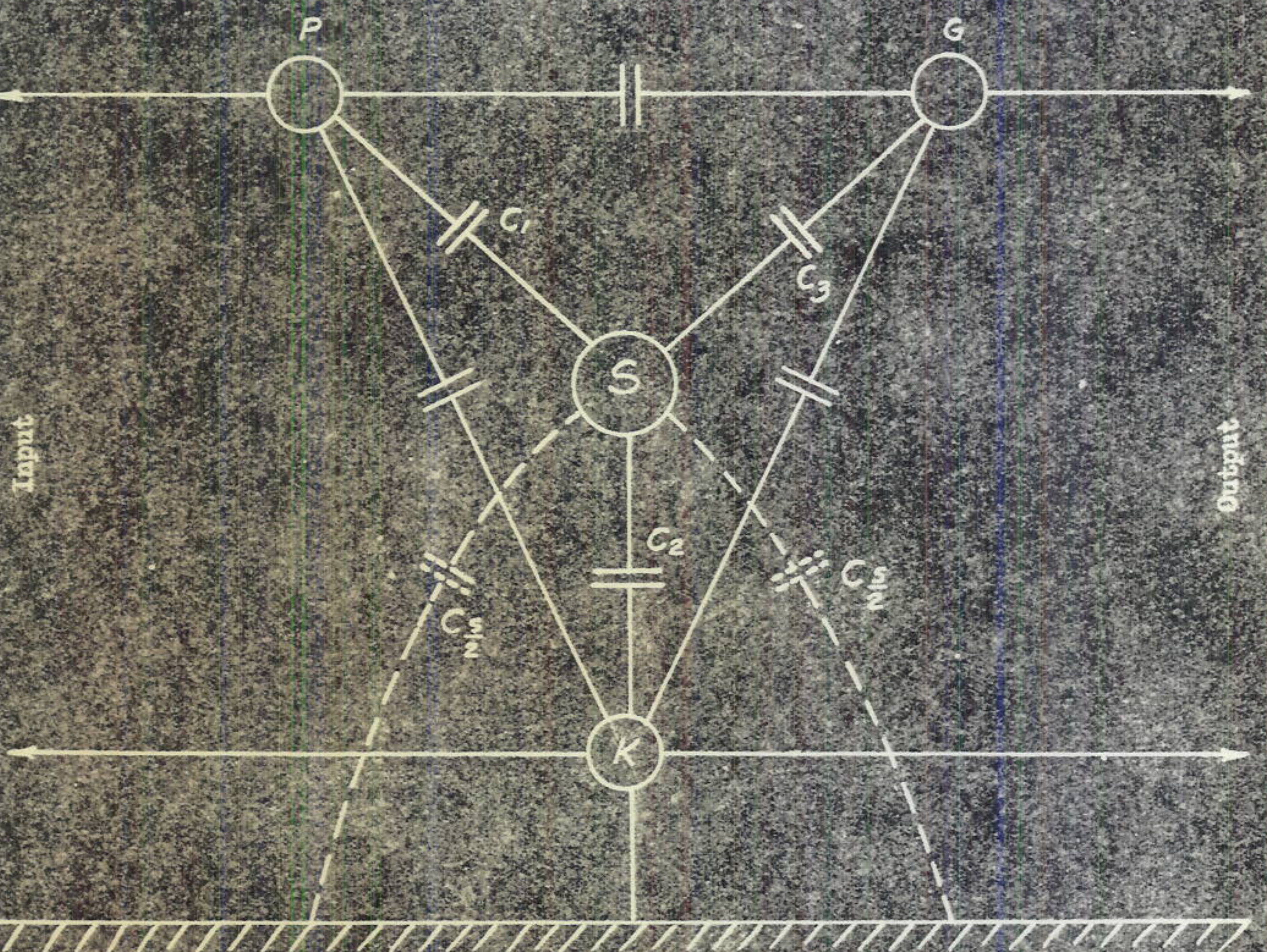


Fig. 3

Equivalent circuit of tube with its metal shell floating. The direct capacitance desired is C_{P-G}.

PLATE 3

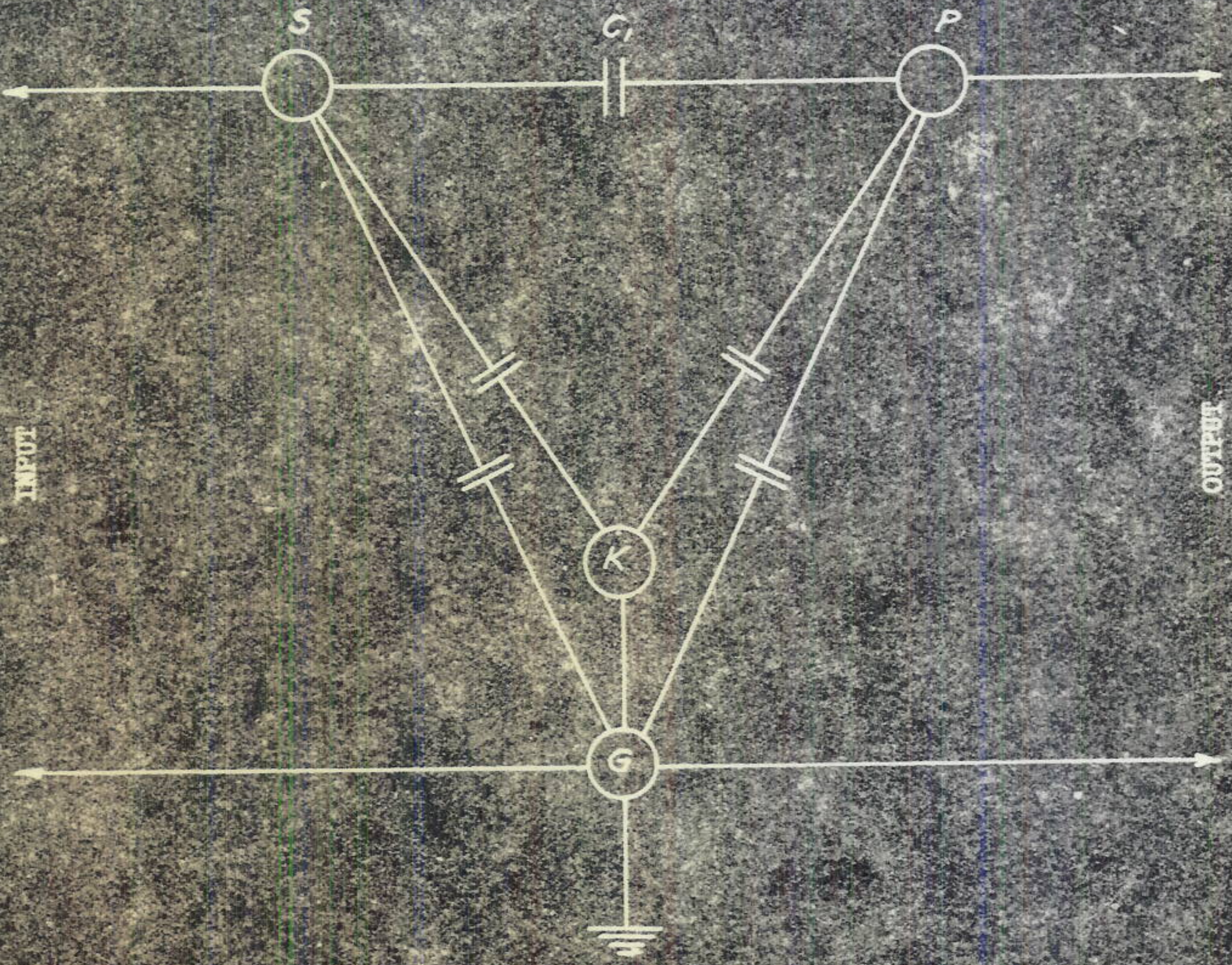


Fig. 4

Circuit for measuring the direct capacitance between shell and plate. The cathode and grid are grounded.

PLATE 4.

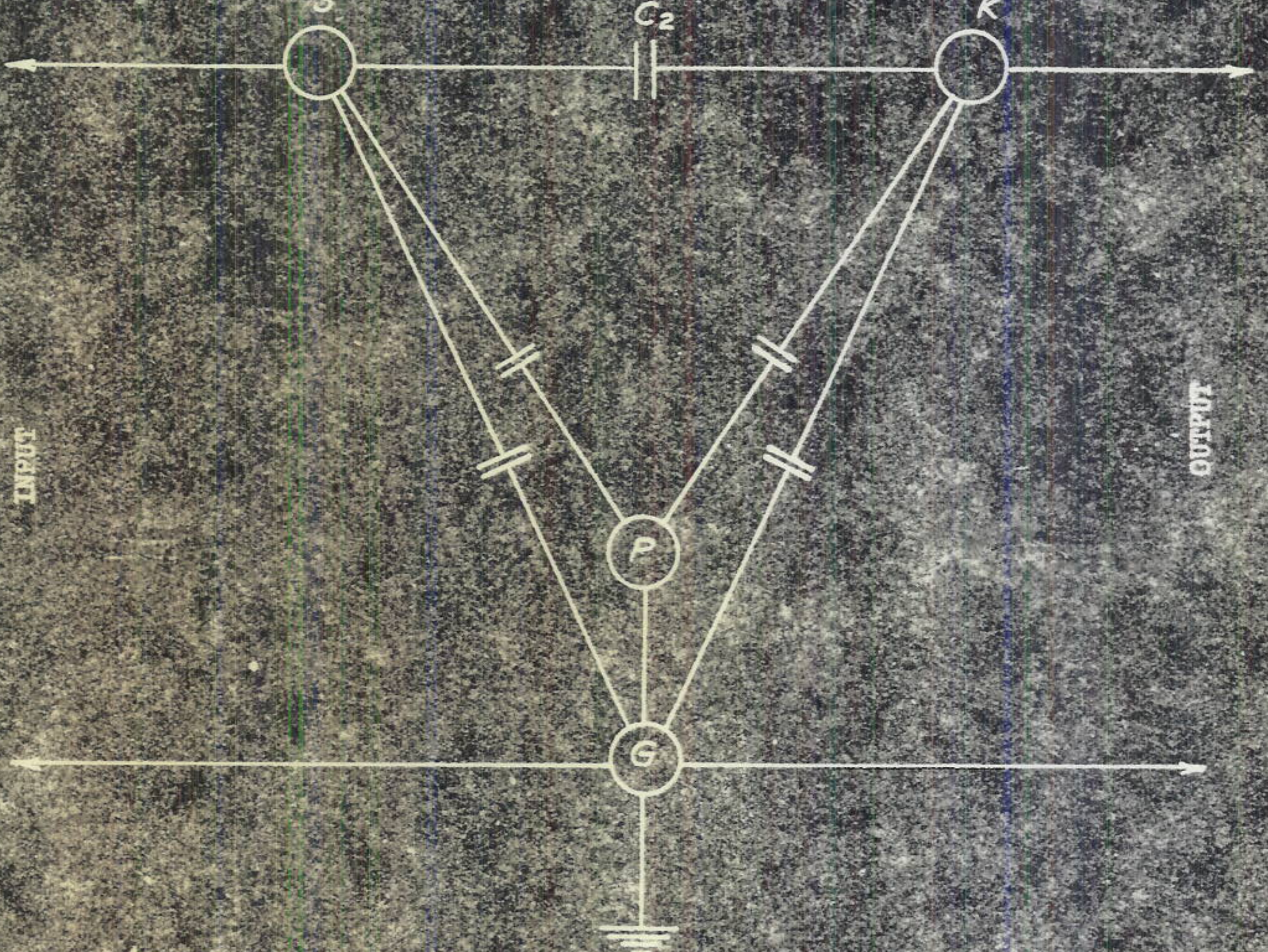


Fig. 5

Circuit for measuring the direct capacitance between shell and cathode. The plate and grid are grounded.

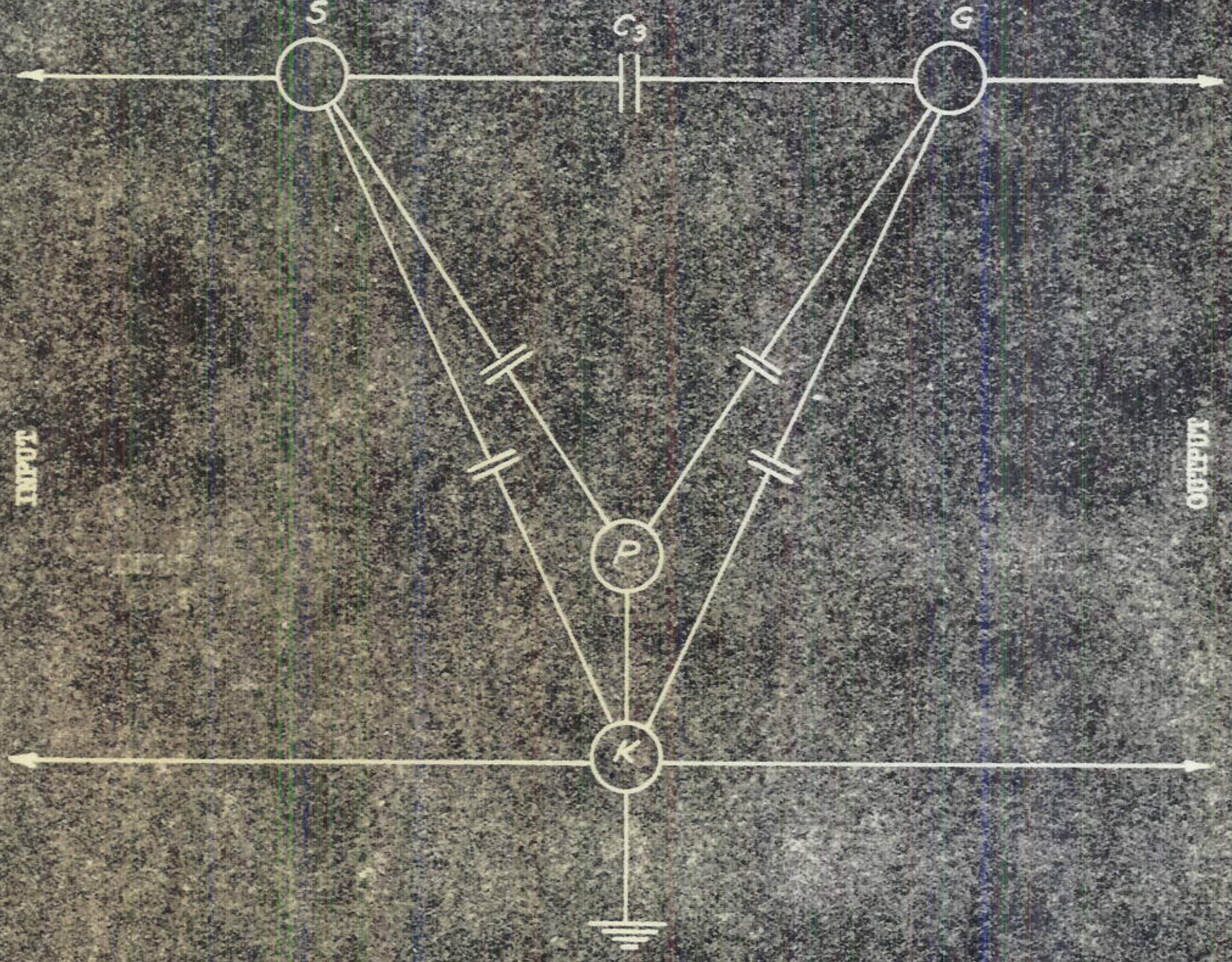
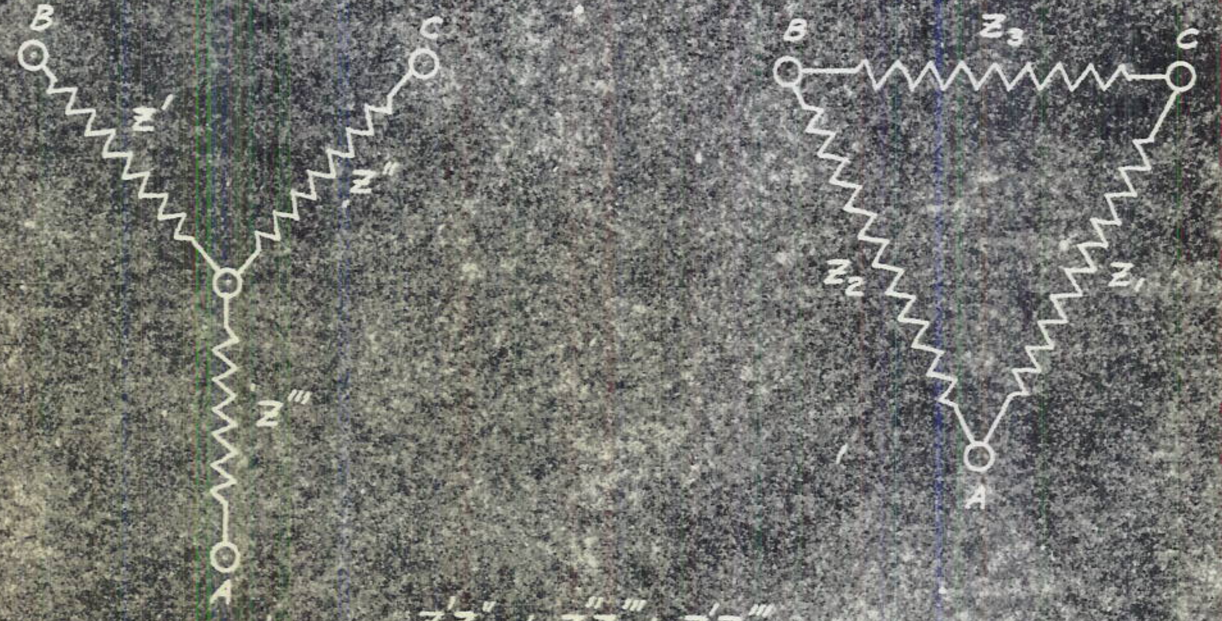


Fig. 6

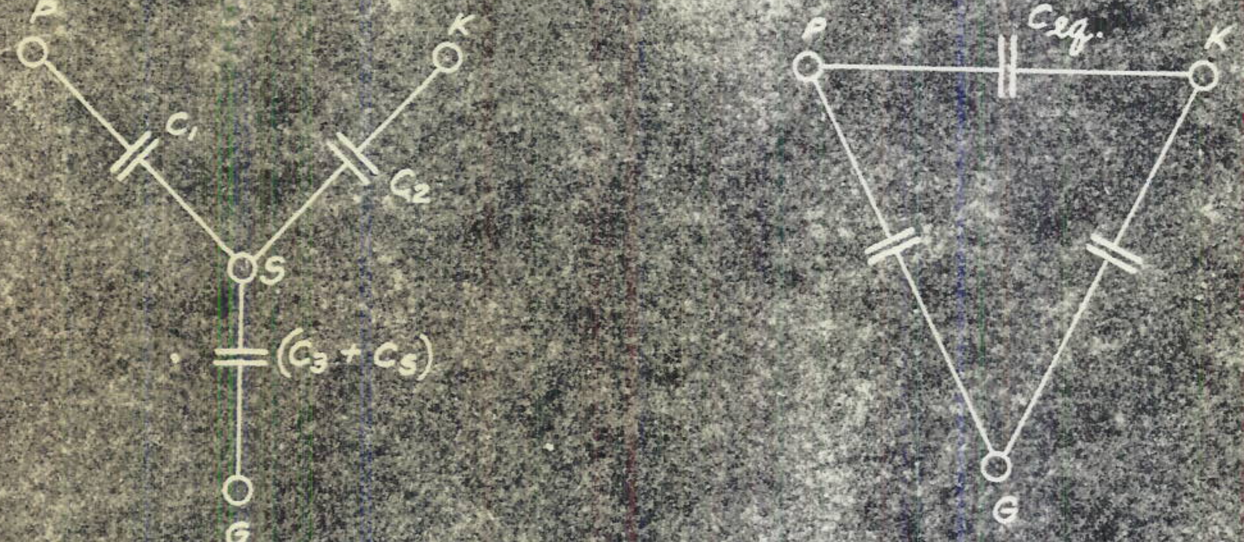
Circuit for measuring the direct capacitance between shell and grid. The plate and cathode are grounded.

Y - Δ Transformation of Impedances.



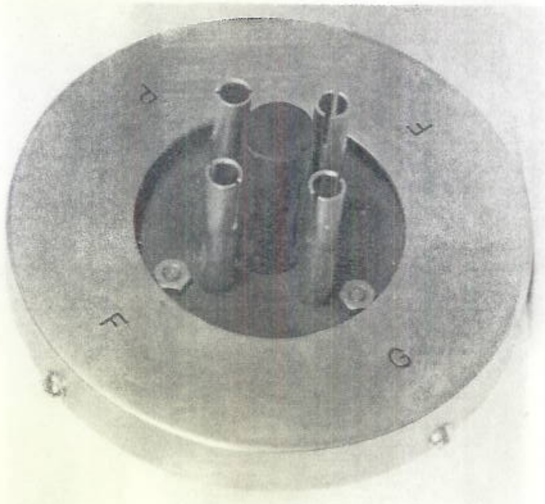
$$Z_3 = \frac{Z'Z'' + Z''Z''' + Z'Z'''}{Z'''}$$

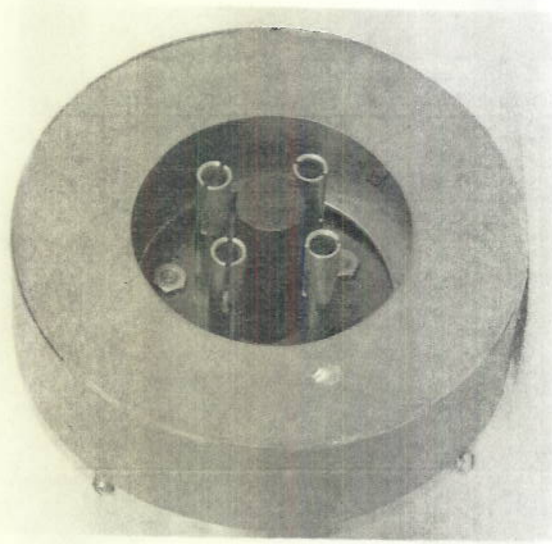
Fig. 7A



$$C_{eq.} = \frac{C_1 C_2}{C_1 + C_2 + C_3 + C_5}$$

Fig. 7B





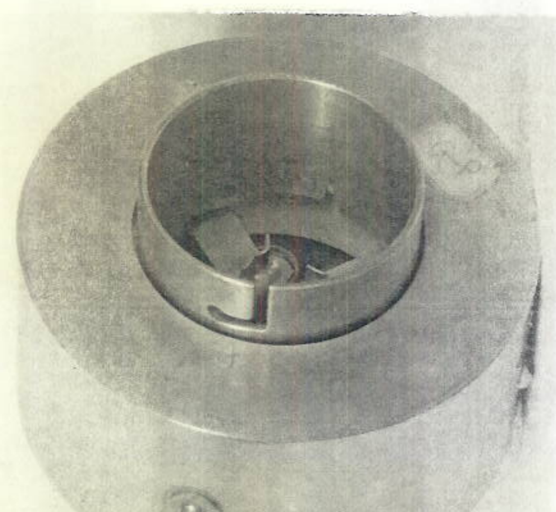


PLATE 8