MC 241
Box 2 Folder 29

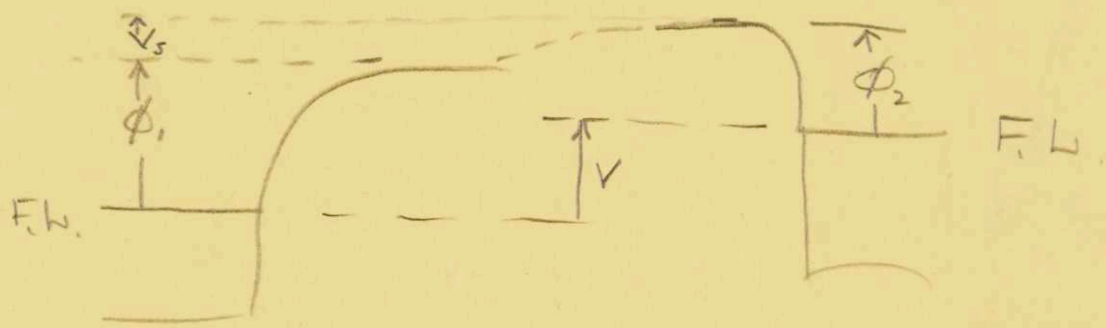
Heat to Electric Power Transducer, 1958

July 23 58

(1)

Analysis of
"Thermo-electron Engine"

Ref: "Measured Thermal Efficiencies of a Diode Configuration of a Thermo Electron Engine"
G.H. Hatsopoulos & J. Kaye
J. Appl. Phys. 29, 1124 (1958)



$\phi' \equiv \phi_1 + V_s$

at the critical condition of onset of space charge at collector with $V_s \Rightarrow V_{T_1}$ the current flow is given by 51.1 or

$$I_m = 7.729 \times 10^{-12} \frac{T^{3/2}}{w^2}$$

or

$$I_m = 9.664 \times 10^{-6} \frac{V_T^{3/2}}{w^2} \quad 51.1$$

These are the same as. 7/23/58 ②

58.1 or 58.2 corrected for w^2

The condition that this current density is flowing is

$$i = AT^2 e^{-\frac{\phi'}{V_{T_1}}} = AT^2 e^{-\left(\frac{\phi_1}{V_{T_1}}+1\right)}$$

$$= Ae^{-1} T_1^2 e^{-\frac{\phi_1}{V_{T_1}}}$$

$$i = i_0 e^{-1}$$

If the applied potential is greater than the critical one then

$$i' = i_0 e^{-1} e^{-\frac{\Delta V}{V_T}}$$

or

$$\Delta i = i - i_1' = i_0 e^{-1}\left(1 - e^{-\frac{\Delta V}{V_T}}\right)$$

for very small values of ΔV we have

$$\Delta i = i_0 e^{-1} \frac{\Delta V}{V_T}$$

and $\frac{\Delta V}{\Delta i} = \frac{V_T}{i_0 e^{-1}}$ this is the

internal resistance of the

7/23/58 ③

generator and should be matched by the external load to get max power out

$$R_e = \frac{V_T \quad \omega^2}{a\,9.664\times10^{-6} V_T^{3/2}} = \frac{1}{a}\,\frac{\omega^2}{9.664\times10^{-6} V_T^{1/2}}$$

For the example of H & K

$T = 1550\,°K$ | $T^2 = 2.4\times10^6$ | $T^4 = 5.77\times10^{12}$

$V_T = .1336$

$\omega^2 = (2.54\times10^{-5})^2 = 6.45\times10^{-10}$

$V_T^{1/2} = .3655$

$V_T^{3/2} = .04883$

$$R_e = \frac{6.45\times10^{-10}}{a\,9.664\times10^{-6}\times .3655} = \frac{1.88\times10^{-4}}{a}$$

area used by H K was.

$$\left(\frac{2.54\times10^{-2}}{8\times2}\right)^2 \pi = 7.91\times10^{-6} = a$$

$$R_e = \frac{1.88\times10^{-4}}{.791\times10^{-5}} = 23.8\,\omega$$

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Current would be

$$i = 7.91\times10^{-6} \times \frac{9.66\times10^{-6}\times 4.88\times10^{-2}}{6.45\times10^{-10}}$$

$$= 5.8 \times 10^{-3}$$

$$V = 5.8\times10^{-3}\times 23.8 = .138 \doteqdot V_T$$

Since

$$\frac{\Delta V}{a\Delta i} = \text{internal resistance} = \frac{V_T}{a i_0 e^{-1}}$$

and

$P = I^2 R$ in load if work function were equal.

$$P = \frac{a^2(i_0 e^{-1})^2 V_T}{a(i_0 e^{-1})} = a\, i_0 e^{-1} V_T$$

$$= a\,\frac{9.664\times10^{-6}\, V_T^{3/2}}{\omega^2}\left(V_T + \phi_1 + V_T - \phi_2\right)$$

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Returning to the Fig 1

assume that

$$i' = 1.20\times10^{6} \times 2.4\times10^{6}\, e^{-\frac{\phi'}{.1336}} =$$

$$= 7.3\times10^{2}$$

2.864

$$\begin{array}{r} 6.079 \\ 6.38 \\ \hline 12.459 \\ 2.864 \\ \hline 9.595 \end{array} = \quad \phi' = 2.95$$

$.1336 \quad .4343 \qquad .13$

$$\phi_1 = 2.82$$

Take $\phi_2 = 1.4$

$$V = 1.55$$

$$R = \frac{1.55}{7.3\times10^{2} \times 7.91\times10^{-6}} = 2.7\times10^{2}$$

$$= 270^{\omega}$$

$270^{\omega} \times 5.8\times10^{-3} = 1.56^{V}$ to check.

$P_0 = 9\times10^{-3}$ watts.

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Power lost by radiation at surface:

$$H_r = 5.65 \times 10^{-8} T^4 a \times (\varepsilon r)$$

$$= 3.26 \times 10^5 a \times (\varepsilon r)$$

take $\varepsilon r = .2$

$$a = 7.9 \times 10^{-6}$$

$P_r = .515$ watt

$$\gamma = \frac{.9 \times 10^{-2}}{.515} = 1.75 \times 10^{-2}$$

---

a change in voltage applied by $2V_T$ would increase the current by ~ 2.5 so that taking a

$$V_0 = 1.56 - .26 = 1.3$$

gives $(1.3 \times 2.5 \times 5.8 \times 10^{-3}) = 18.9 \times 10^{-3}$ watt

and $\gamma = \dfrac{1.89 \times 10^{-2}}{.515} = 3.66 \times 10^{-2}$

This would be the limit for a cathode of this ϕ, value

$$R_L = \frac{1.3}{.58 \times 10^{-2}} = 224^{\omega}$$

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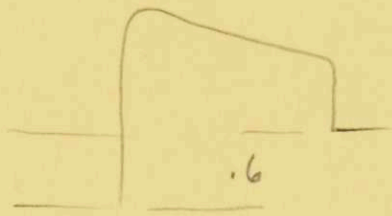
assume an out put voltage

of 0.6



To have an efficiency of

.13

$i \cdot .6 = .13 \cdot .515$

$i = .112$

$I = \dfrac{.112 \times}{.0791 \times 10^{-4}} = 1.41 \times 10^{4}$

$= 10^{4.048}$

See p 5

$$\begin{array}{r} 12.459 \\ 4.048 \\ \hline 8.411 \end{array} \times .307 = 2.58$$

The value of ϕ' must be 2.58 for this current to flow at this temp but for this amount of current which is $\dfrac{.112}{5.8 \times 10^{-3}} = u^2 = 19.3$ then $s \doteq 14$

ru $14 \times .133 = 1.86$

$.6 + 1.86 = 2.46$

$$\begin{array}{r} 2.58 \\ 2.40 \\ \hline .18 \end{array}$$ would have to be ϕ_2 which is impossible.

let R_L = load resistance

$$IR_L = V$$

$$\frac{IR_L}{V_T} = S_0'$$

$$\cancel{\frac{I/I_m R_L}{V_T} = S_R}$$

$$I^2 R_L = P = I S_0' V_T$$

$$\frac{IR_L}{V_T} = S_0'$$

$$\cancel{\frac{I/I_m R_L}{V_T} = S_R}$$

$$\cancel{\frac{I}{I_0} = \frac{S_0'}{S_R}}$$

$$P = \cancel{\frac{I^2 S_R}{I_m} V_T = I a^2 S_R V_T}$$

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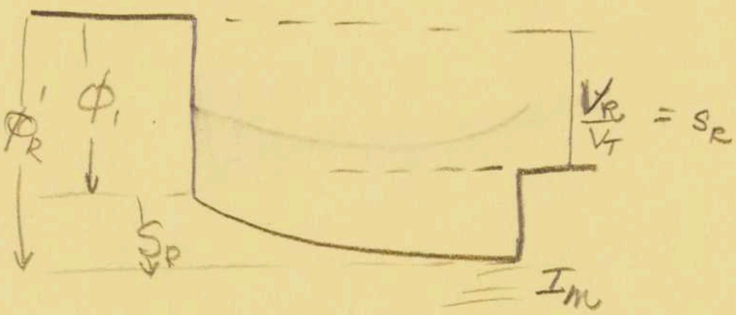
$$\phi' = \phi_1 + S_R$$

$$\phi' - \phi_2 = s_R = \frac{V_R}{V_T}$$ — applied pot for space charge at collector

Plot as in theor. sm.



Power under crit cond

$$P_m = V_R I_m$$

$$P_W = VI$$

as V decrease I increase

and P is max when

$$\frac{dP}{dV} = I + \frac{dI}{dV}V = 0$$

$$I = \frac{dI}{dV}V \qquad \frac{d(\ln I)}{d(\ln V)} = 1$$

$$\cancel{dV = \frac{dI}{I}}$$

$$\frac{d(\ln I)}{d(\ln S)} = \cancel{\frac{d\left(\frac{\ln I}{V_T}\right)}{dS}} = 1$$

$$V = SV_T$$

$$\ln V = \ln S + \ln V_T$$

$$d(\ln V) = d(\ln S) + 0$$

$$\cancel{\frac{d \ln I}{dS} = V_T}$$

~~assume $V_T = .1$~~

~~For $\Delta S = 1$~~

~~$\Delta \ln I = .1$~~

~~$\frac{I_1}{I_2} = e^{.1} = 1.105$~~

This would indicate that $\ln \frac{I}{I_R}$ be plotted as function of $\ln(S)$ to find 45° points.

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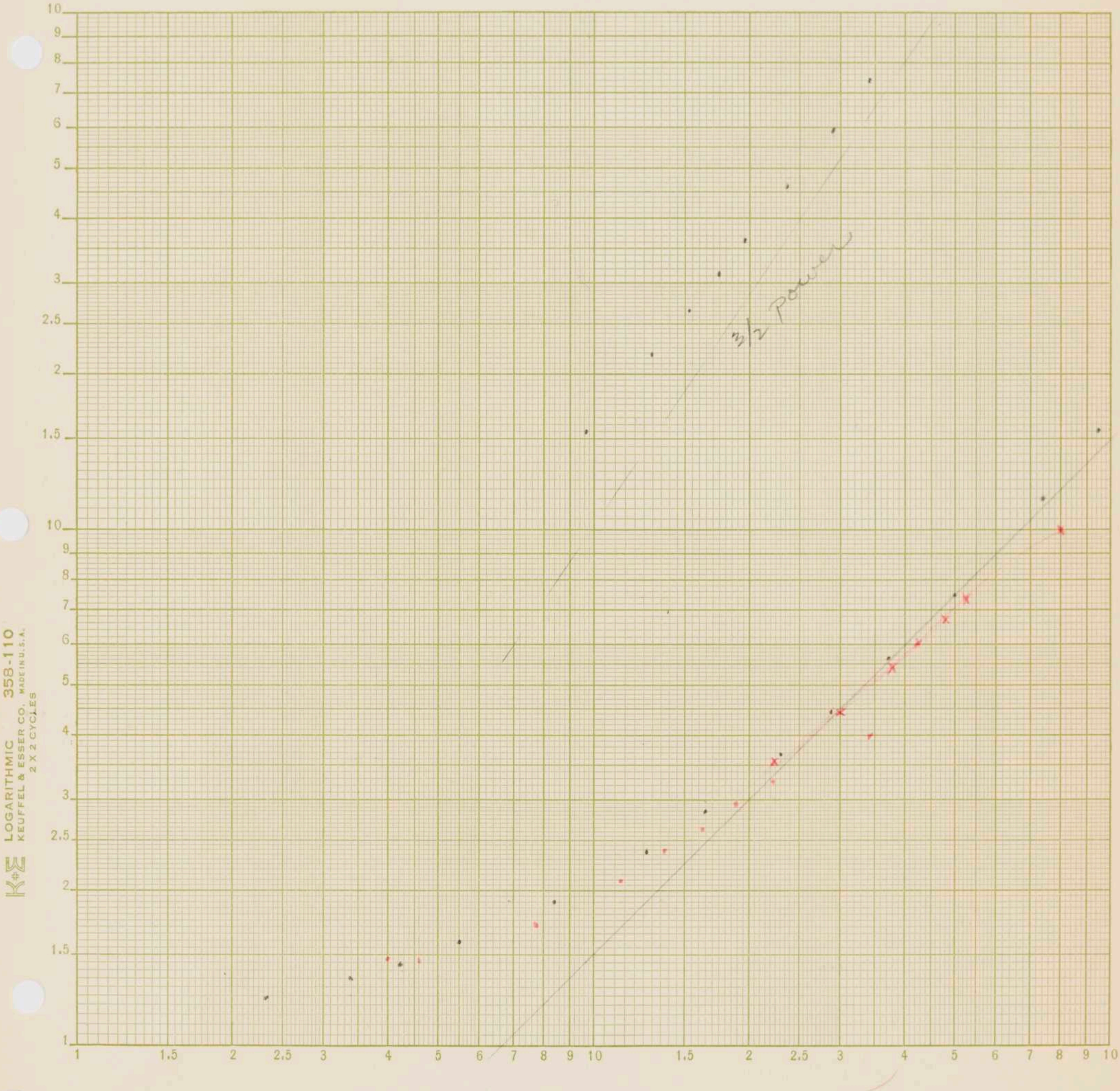
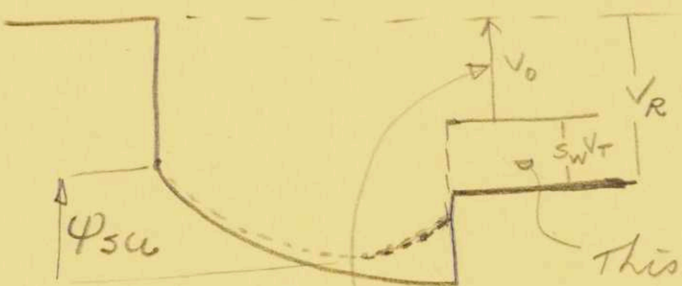


$u_0^2 = 10$

slope of 1

at $(5 \cdot V_T)$

Log-log plot shows that rise in current with decrease in reverse voltage Balances (slope 1) at $5 \cdot V_T$. The difficulty is that this plot cannot apply as is because the change that should be plotted is not correctly taken care of.



This is change being plotted

Is this V_0 that determines the power.

$$V_0 + S_W V_T = V_R$$

$$dV_0 + V_T\, dS_W = 0$$

$$\frac{dV_0}{V_0} = -\frac{V_T\, dS_W}{V_0}$$

$$P = I V_0$$

$$dP = I\, dV_0 + V_0\, dI$$

$$\frac{dP}{dV_0} = I + V_0 \frac{dI}{dV_0}$$

assume that $\varphi_{su} > V_T$
then curve $u_0 = \infty$ applies.
Under the critical space charge cond
Current is I_m and potential is V_R.
This condition is satisfied by

$$I_m = 9.664 \times 10^{-6} \frac{V_T^{3/2}}{\omega^2} = AT^2 e^{-\frac{\phi'}{V_T}}$$

under the condition that
ϕ' of this equation is $\phi_1 + nV_T$
with $n \gg 1$.
The applied potential is then

$V_{OR} = \phi' - \phi_2$
and the power is
$V_R I_m = P_R$
With $0 < V_0 < V_R$ power will increase
to a max. as shown in general
curves of p 14. for various values
of V_R from $6V_T$ to $18V_T$. At $V_{om} = V_R - S_m V_T$
power out will be max. $\frac{V_{om}}{V_T} = \frac{V_R}{V_T} - S_m$

See p 15

general eqn. for power to load.

$$\cancel{P = I_m V_T \left(\frac{V_R}{V_T} \right.}$$

$$P = I V_T \frac{V}{V_T}$$

$$\frac{V_R - V}{V_T} = \Sigma \qquad \frac{V_R}{V_T} - \Sigma = \frac{V}{V_T}$$

$$I = U^2 I_m$$

$$P = I_m V_T \; U^2 \left(\frac{V_R}{V_T} - \Sigma \right)$$

$$= I_m V_T \left[U^2 \left(\frac{V_R}{V_T} - \Sigma \right) \right]$$

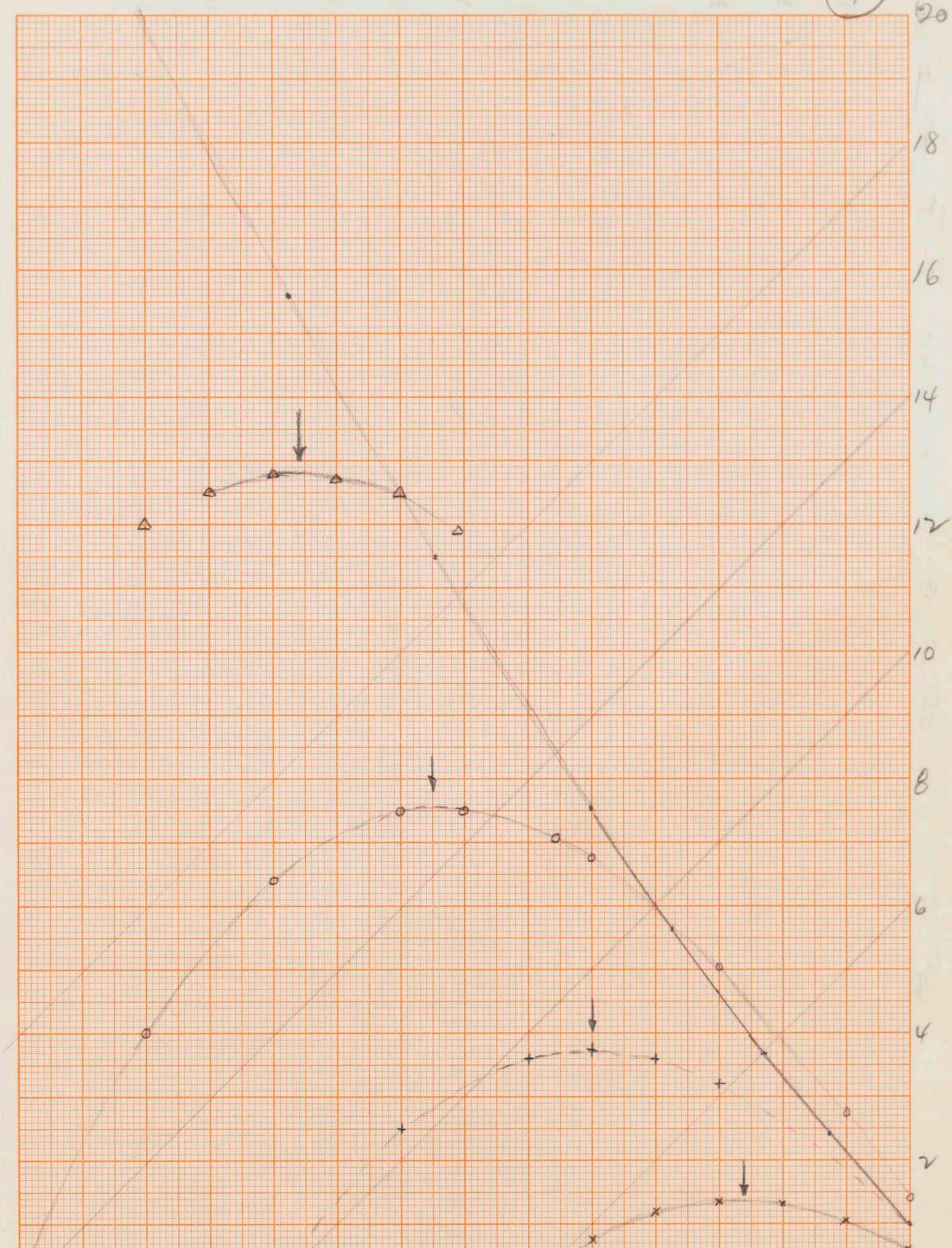
when $\Sigma = 0$

$$P_R = I_m V_R$$

when $\Sigma = \frac{V_R}{V_T}$

$$P = 0$$

$$\frac{P}{I_m V_T} = \left(\frac{I}{I_m} \right) \left(\frac{V_R}{V_T} - \Sigma \right)$$


20
18
16
14
12
10
8
6
4
2
0
14
12
10
8
6
4
2
0

5

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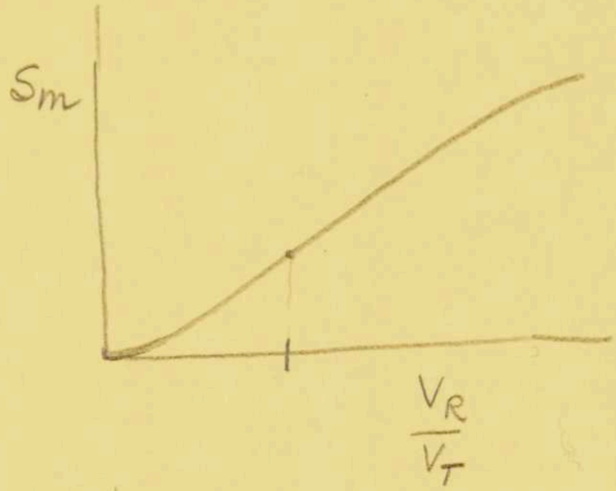
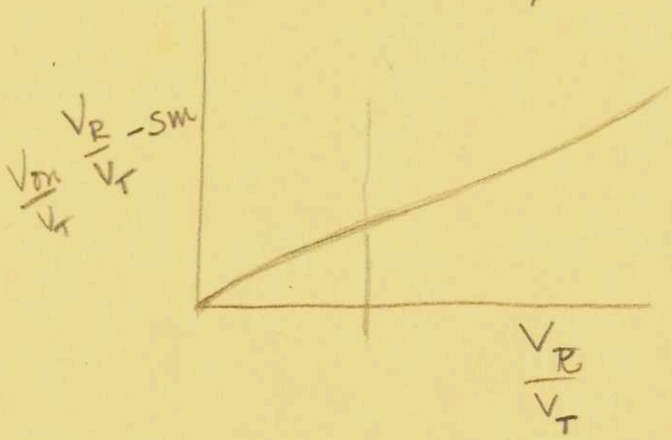
16

From p 13





with V_R known S_m is known

and $U_m^2 = I/I_m$

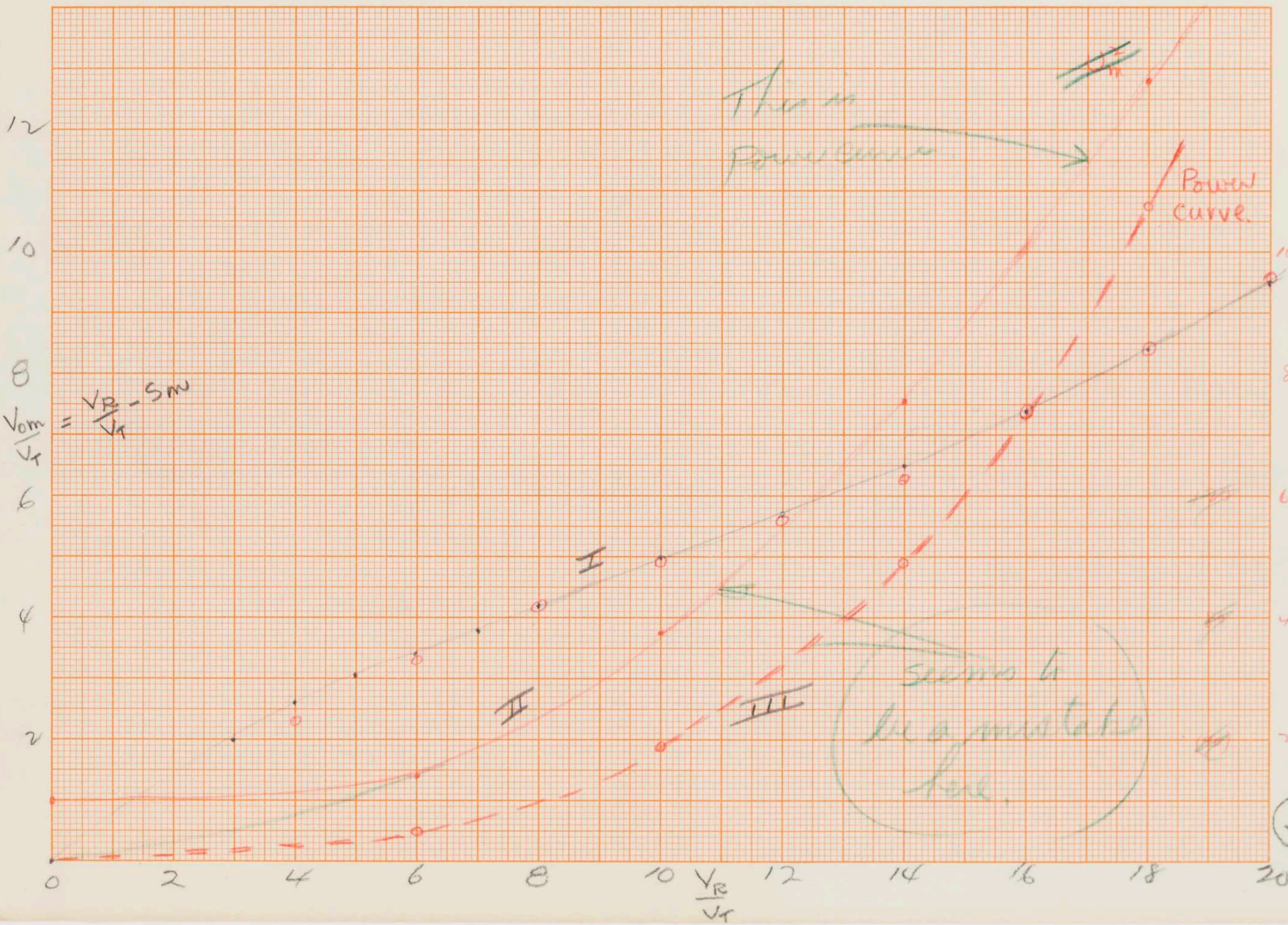
or $I = I_m U_m^2$

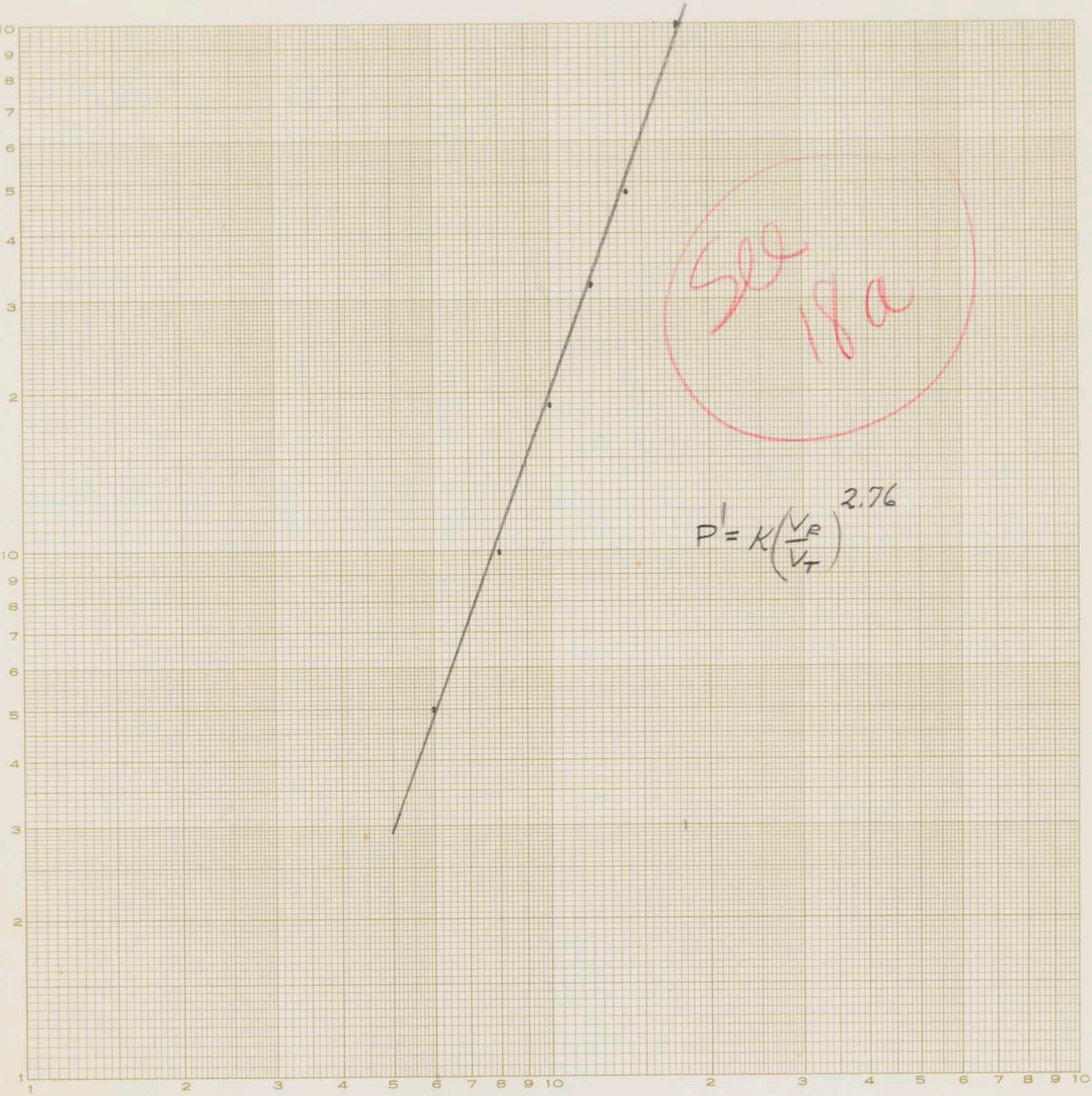
V_{om} is known and

$$P = I_m U_m^2 V_{om} = I_m U_m^2 (V_R - S_m V_T)$$

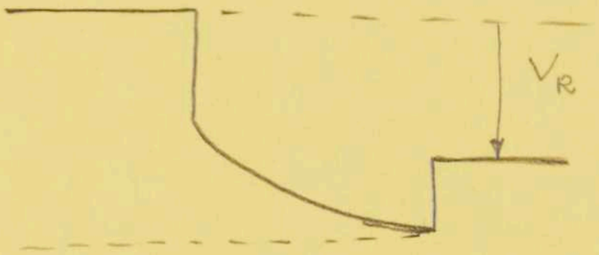
$$P = I_m U_m^2 V_R - I_m U_m^2 S_m V_T$$

$$= I_m V_T \underbrace{\left(\frac{U_m^2 V_R}{V_T} - U_m^2 S_m \right)}_{\text{This is a function of } \frac{V_R}{V_T}} = I_m V_T \left[U_m^2 \frac{V_{om}}{V_T} \right]$$


$\frac{V_{om}}{V_T} = \frac{V_R}{V_T} - 5m$
This is Power curve
Power curve.
Seems to be a mistake here.
I
II
III
$\frac{V_R}{V_T}$
0 2 4 6 8 10 12 14 16 18 20
2 4 6 8 10 12
20 40 60 80 100


See 18a
$P' = K\left(\frac{V_R}{V_T}\right)^{2.76}$
1
2
3
4
5
6
7
8
9
10

Review of development to here.



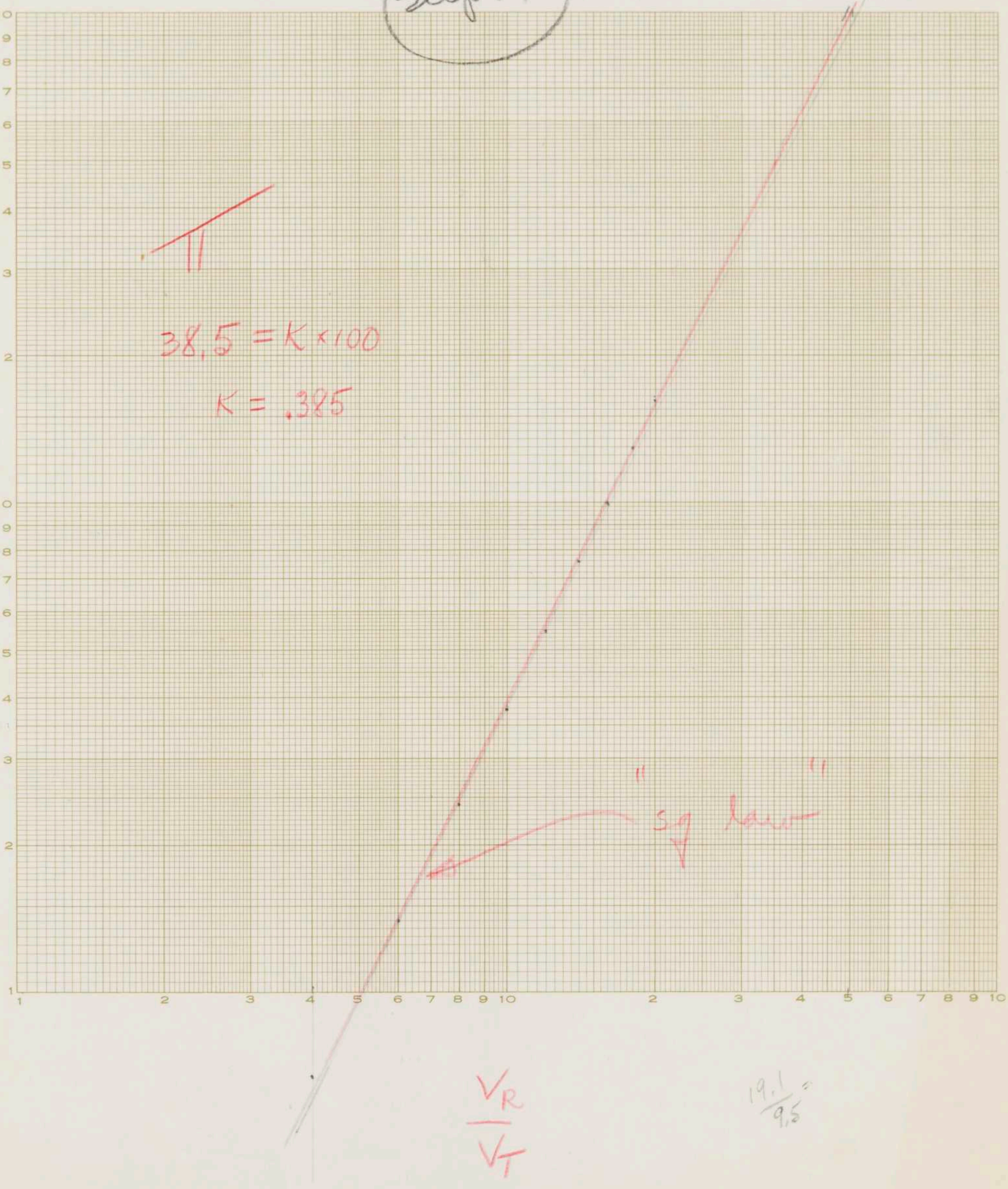
For a given cathode temp and collector work-function there is a critical V_R for zero space charge at col. surface. This condition is obtained if R_R is in the external circuit.

$$R_{LR} = \frac{V_R}{I_m} \quad \text{and power } P_R = V_R I_m$$

As R_L is reduced, the current increases and the power is $I^2 R_L$; the output volts $(I R_L) = V_0$ and power $I V_0$.
There is a particular value of I_{mx} and V_{om} and $\therefore$ R_{Lm} which gives the maximum power into the load.
The larger the value of (V_R/V_T) the larger the V_{om} as shown by curve I of 17

18 a

see p 24



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For each value of $\frac{V_R}{V_T}$ there is a particular value of U^2 at the max. of power output

This is shown by curve II

The power out is

$$P = I_m V_T \left[U^2_{mx} \frac{V_{om}}{V_T} \right]$$

This mult. factor is shown as III

Thus if $\frac{V_R}{V_T} = 10$

The optimum value of $\frac{V_{om}}{V_T} = \cancel{5}$ 4.9

The resulting " " $U^2_m = \cancel{3.75}$ 7.7

and " " " $[\;] = \cancel{18.75}$ 37.8

Fig 18a shows that this $[\;] \equiv P'$

$$P' = K \left(\frac{V_R}{V_T} \right)^{2.76} = 1$$

$$\overset{37.8}{\cancel{18.75}} = K \cdot 10^{2.06}$$

$$K = \frac{\cancel{18.75}}{\cancel{575}} = \cancel{3.26 \times 10^{-2}}\ .378$$

$$P_{max} = I_m V_T\ \overset{.378}{\cancel{3.26 \times 10^{-2}}} \left(\frac{V_R}{V_T} \right)^{2.\cancel{76}}$$

$$I_m = 9.664 \times 10^{-6} \frac{V_T^{3/2}}{\omega^2}$$

$$P_{max} = \frac{\overset{3.72}{\cancel{3.14}} \times 10^{\cancel{-7}\,-6}}{\omega^2} \frac{V_T^{2.5}}{V_T^{2.\cancel{76}}} \cdot V_R^{2.\cancel{76}}$$

$$= \overset{3.72 - 6}{\cancel{3.14 \times 10^{-7}}} V_T^{\overset{.5}{\cancel{-0.26}}} \frac{V_R^{2.\cancel{76}}}{\omega^2}$$

---

assume $V_R = 1^v$ and $V_T = 10^{-1}$ $V_T^{+.5} = .316$

$\cancel{V_T^{-.26} = 10^{.26} = 1.82}$

$$P_{max} = \frac{\overset{3.72 \times 10^{-6}}{\cancel{3.14 \times 10^{-7}}} \times \overset{.316}{\cancel{1.82}} \times 1}{6.45 \times 10^{-10}} = 18\cancel{00} \text{ watts}/m^2$$

Radiation power (see 6)

$\cancel{3.26 \times 10^5 \times (Er) \text{ watts}}$

$$M_T = 5.65 \times 10^{-8} \times (1{,}160)^4 \times (Er)$$

$$= 5.65 \times 1.81 \times 10^4 \times .3$$

$$= 3.07 \times 10^4$$

$$\gamma = \frac{18.88 \times \cancel{10^2}}{3.07 \times 10^4} = \cancel{2.9}\% \quad 5.9\%$$

If V_R can be increased over 1v

$\cancel{\gamma = 2.9 \times V_R^{2.76}}$ $\rightarrow V_R = 1.5$

to get 13% $\cancel{V_R = 1.725}$

The thermionic diode as a heat-to-electrical power transducer.

Introduction:

Requirements
1) Low-w.f. col.
2) Small spacing
3) Sufficient temp. difference

Interest without full consideration of fundamentals. Examples H. + K.

Purpose - present basic relations, details in T.E. not applied to specific application.

Diode properties:
Qualitative discussion
Energy diagram:

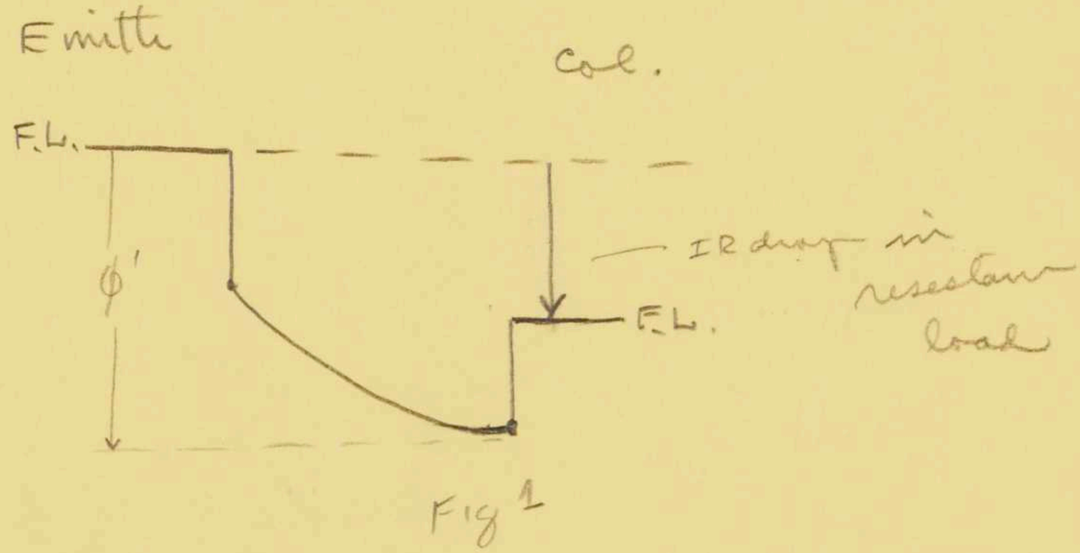
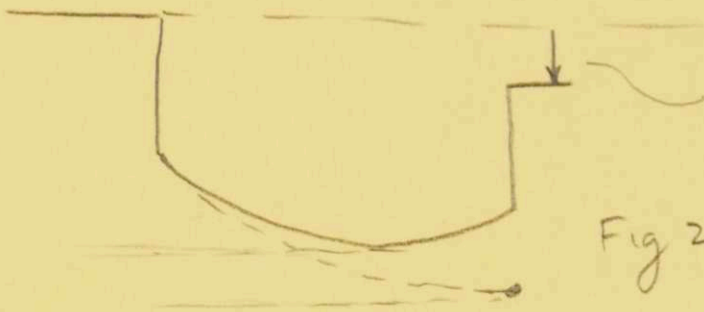


Fig 1



lowers R increases I

Fig 2

quantitative relations:

Discussion of efficiency:—

computations for Table 2

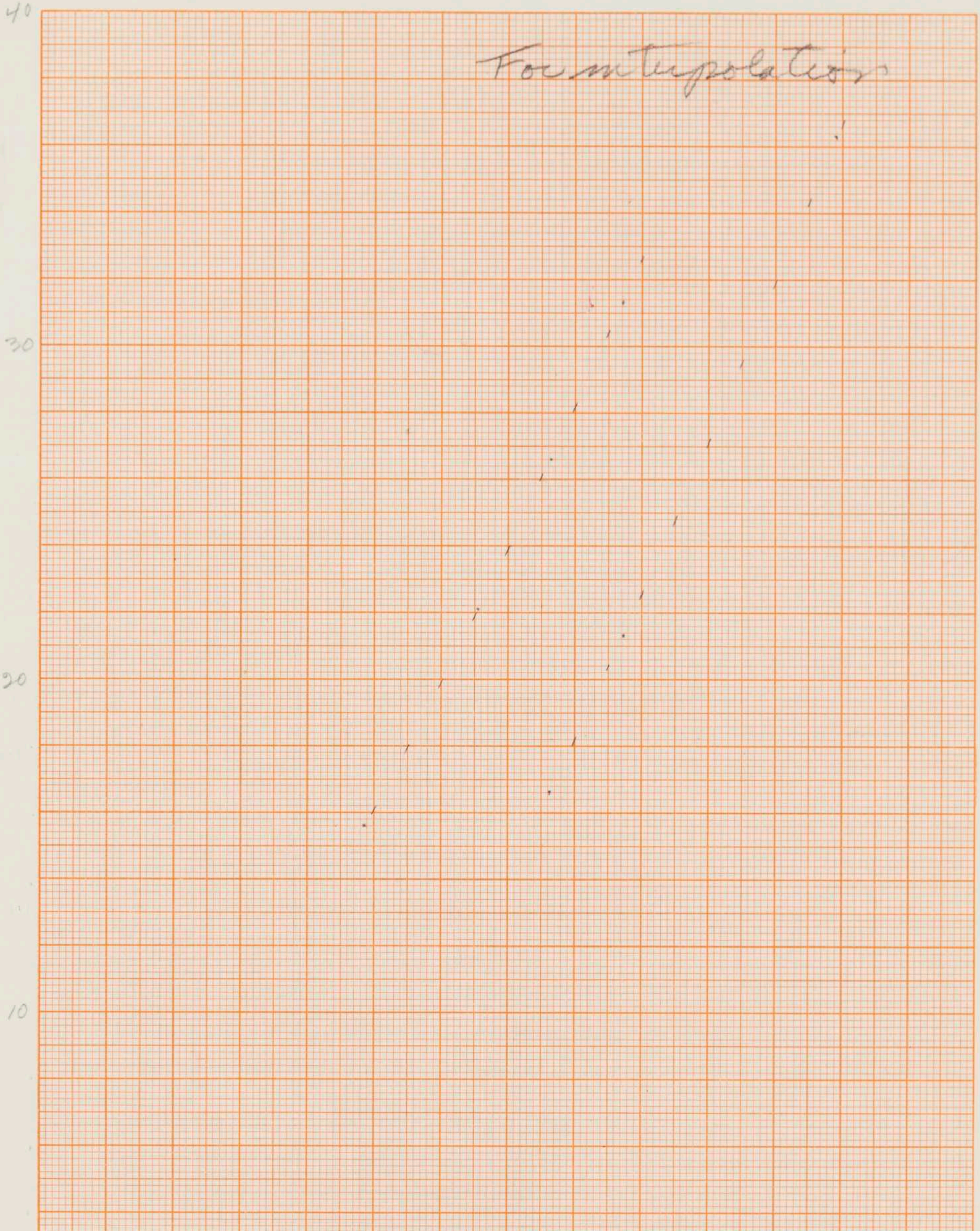
$\left(\frac{V_R}{V_T}-\Sigma\right)$

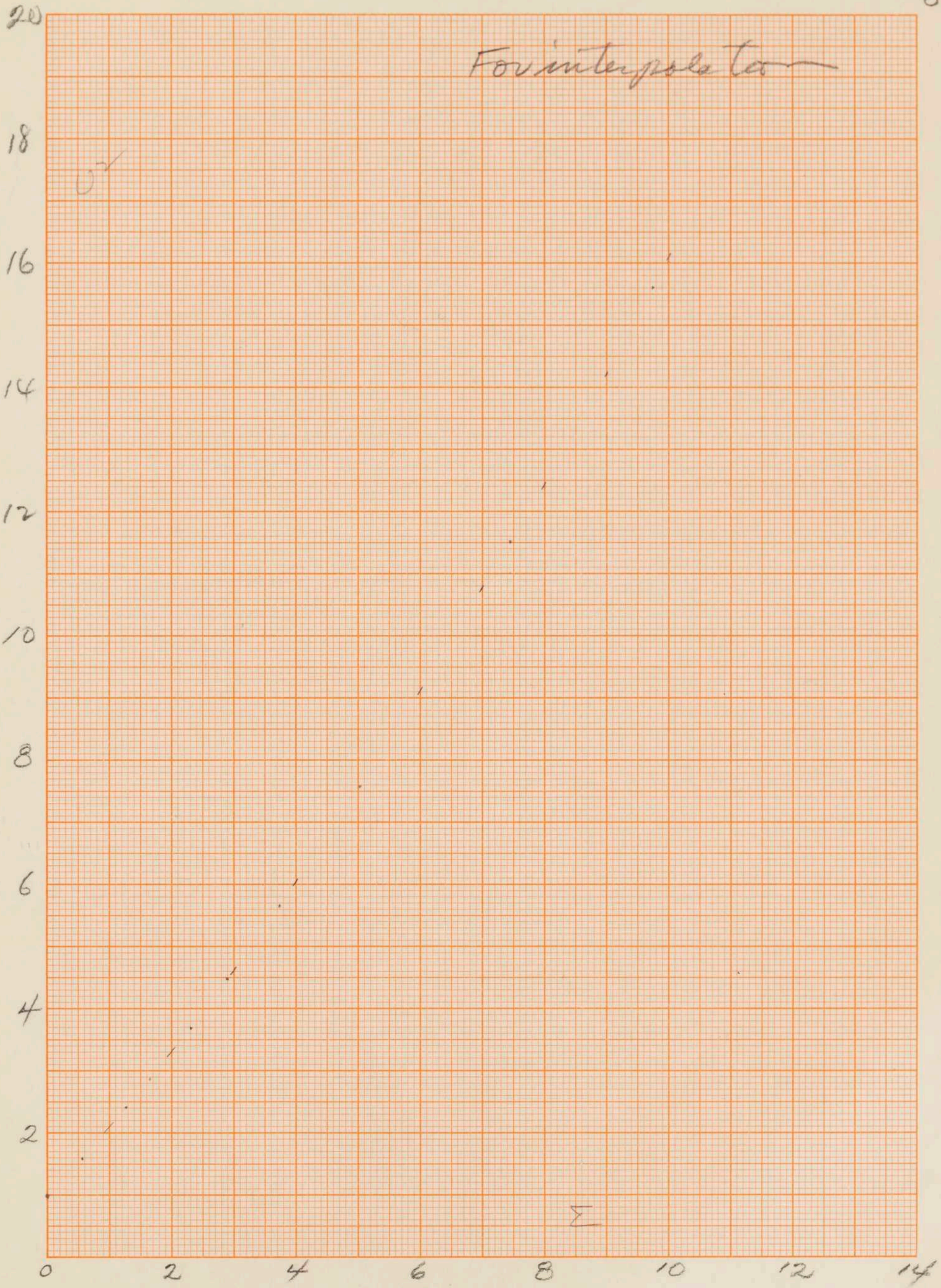
$U^2\left(\frac{V_0}{V_T}-\Sigma\right)$

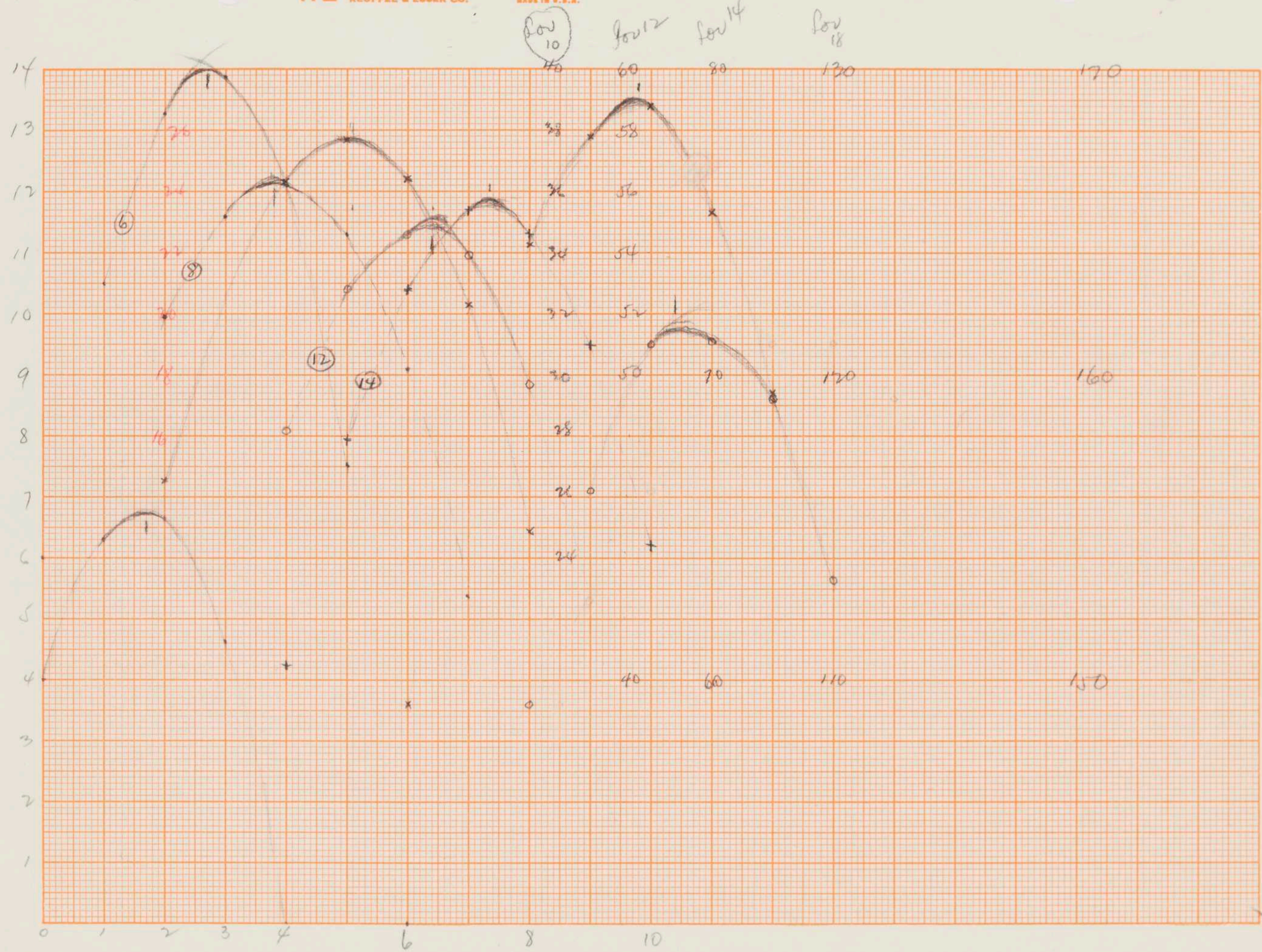
Σ	U^2	for 4	for 6	8	10	12	14	16	18	20
0	1	4	6	8	10	12	14	16	18	20
1	2.10	6.3	10.5	14.7	18.9	23.1	27.3	31.5	3.57	39.9
2	3.32	6.64	13.28	19.92	26.56	33.2	39.8	46.5	53.1	59.8
3	4.63	4.63	13.89	23.15						
4	6.05	0	12.1	24.2	36.3	48.2	60.5	72.6	84.7	96.8
5	7.54		7.54	22.62	37.7	52.8	67.9	82.9		
6	9.10		0	18.2	36.4	54.6	72.8	91.0	109.2	127.4
7	10.77			10.77	32.3	53.9	75.4			
8	12.43			0	24.9	49.7	74.6	99.4	124.3	149.2
9	14.2				14.2	42.6	71.0	99.4	127.8	156.2
10	16.1				0	32.2	64.4	96.6	128.8	161.0
11	17.9					17.9	53.7	89.5	125.3	161.1
12	19.9					0	39.8	79.6	119.4	159.2
13	21.9						21.9	65.7	109.5	153.3
14	23.9						0	47.8	95.6	143.4
15	26.05							26.05	78.2	130.3
16	28.15							0	56.3	112.6
17	30.4								30.4	91.2
18	32.5								0	65.0
19	34.7									34.7
20	37.1									0

V_R/V_T	Π	Σ_{max}	~~Σ_{max}~~	~~approx $\frac{V_R}{V_T}-\Sigma$~~	good	U^2
0	0	0	~~1.7~~	~~0~~	0	1
4	6.72	1.7	~~2.7~~	~~2.3~~	2.30	2.92
6	14.0	2.72	~~3.8~~	~~3.28~~	3.28	4.27
8	24.4	3.80	~~5.1~~	~~4.2~~	4.20	5.78
10	37.8	5.05	~~6.4~~	~~4.9~~	4.95	7.64
12	55.0	6.3	~~7.7~~	~~5.6~~	5.7	9.78
14	75.7	7.4	~~8.6~~	~~6.6~~	6.6	11.5
16	99.5	8.60		~~7.4~~	7.40	13.45
18	129.0	9.60		~~8.4~~	8.40	15.3
20	161.4	10.42		~~9.64~~	9.58	16.85

make new log plot.


For interpolation
40
30
20
10
0
2
4
6
8
10
12
14
16
18
20
22
24
26


For interpolation
v^2
Σ
0
2
4
6
8
10
12
14
16
18
20


fov 10
fov 12
fov 14
fov 18
40
60
80
130
170
58
56
54
52
50
70
120
160
40
60
110
150
6
8
12
14
0
1
2
3
4
6
8
10

Derivation for Eq(9)

set

$$7.729\times10^{-12}\,\frac{T^{3/2}}{\omega^2} = AT^2 e^{-\frac{\phi_R'}{V_T}}$$

$$1 = \frac{A\omega^2 T^{1/2}}{7.729\times10^{-12}}\, e^{-\frac{\phi_R'}{V_T}}$$

See Sect 50 for

$$a = A_\nu e^{\nu} T_0^{\nu}$$

$$\Phi = \phi_\nu + \nu V_T$$

$$a = \frac{A \quad e^{1/2}}{7.729\times10^{-12}}\,\omega^2 T_0^{1/2}$$

$$\Phi = \phi_R' + \frac{1}{2}V_T$$

$e^{1/2} = 1.649$

1.20×10

$$\left[\frac{\overset{1.9788}{1.2\times10^6\cdot1.649}}{\underset{2.56\times10^{17}}{7.729\times10^{-12}}}\right] = 10^{17.408}$$

$$= e^{40.09}$$

$$40.09 + 2\ln w + \frac{1}{2}\ln T_0 = \frac{\phi_R'}{V_T} + \frac{1}{2}$$

$$\frac{T}{11600} = V_T = \frac{\phi_R'}{40.09 + \frac{1}{2}\ln T_0 + 2\ln W - .5}$$

assume $T_0 \approx 1500°K$ 1000

$\ln T_0 = 7.3$

$\frac{1}{2}\ln T_0 = 3.65$ 3.45

$$\begin{array}{r} 3.65 \\ \underline{40.09} \\ 43.74 \\ \underline{.5} \\ 43.24 \end{array}$$

43.

$$V_T = \frac{\phi_R'}{43.2 + 4.6\log_{10} W}$$

assume $T_0 = 1000$

$$V_T = \frac{\phi_R'}{43.0 + 4.6\log_{10} W}$$

Temperature of collector

Collector emission should be about $e^{-3} \times I_1 = \left(\frac{I_1}{20}\right)$

$$\phi_2 = \phi_R' - V_R$$

$$I_2 = A T_2^2 e^{-\frac{\phi_R' - V_R}{V_{T_2}}}$$

$$I_1 = I_m e^{x}$$

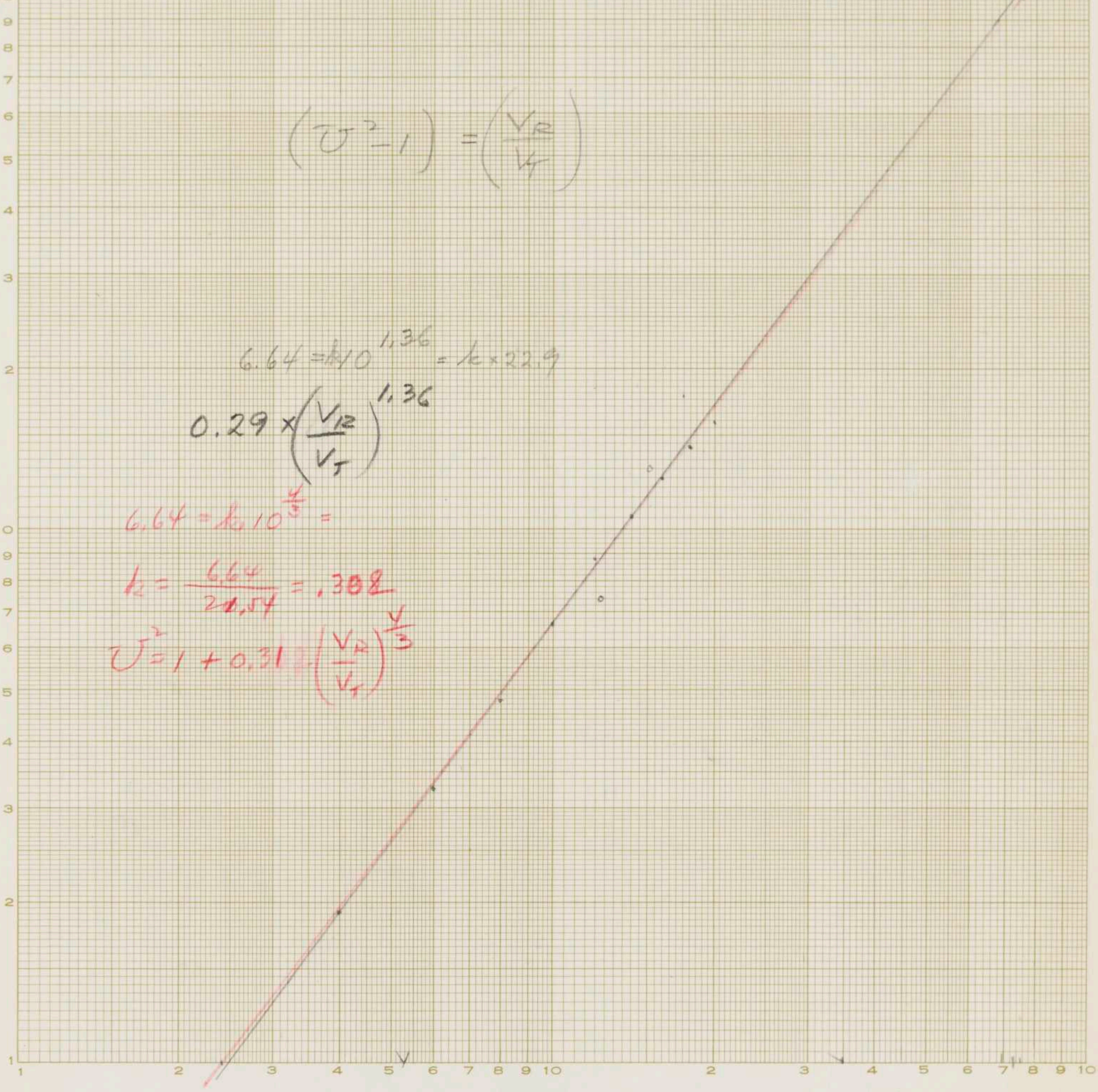
$$I_m e^{x} = 7.729 \times 10^{-12} \frac{T_1^{3/2}}{\omega^2} e^{x} = A T_2^2 e^{-\left[\frac{\phi_R' - V_R}{V_{T_2}} + 3\right]}$$

$$7.729 \times 10^{-12} \frac{T_1^{3/2}}{\omega^2} e^{x} = A e^{-3} T_2^2 e^{-\frac{\phi_R' - V_R}{V_T}}$$

Plot on 31

shows $\left(\frac{I}{I_m}\right)_{max} = 1 + 0.29\left(\frac{V_R}{V_T}\right)^{1.36}$

$$9.664 \times 10^{-6} \frac{V_T^{1.5}}{\omega^2} \cdot \left[1 + 0.29\left(\frac{V_R}{V_T}\right)^{1.36}\right] = A T_2^2 e^{-3} e^{-\frac{\phi_R' - V_R}{V_T}}$$



$$(U^2-1) = \left(\frac{V_R}{V_T}\right)$$

$$6.64 = k\,10^{1.36} = k \times 22.9$$

$$0.29 \times \left(\frac{V_R}{V_T}\right)^{1.36}$$

$$6.64 = k\,10^{\frac{4}{3}} =$$

$$k = \frac{6.64}{21.54} = .308$$

$$U^2 = 1 + 0.31\left(\frac{V_R}{V_T}\right)^{\frac{4}{3}}$$

$$U^2 = 1 + 0.29\left(\frac{V_R}{V_T}\right)^{1.36}$$

$$\frac{19.1}{14.05} = 1.36$$

$$\frac{19.1}{7.8}$$

$$\frac{1.20 \times 10^{\cancel{8}\,4}}{20 \times 9.66 \times 10^{-6}} = 6.2\ 10^{9}$$

$$= 10^{9.794}$$

$$V_{T2} = \frac{\phi_R' - V_R}{22.56 + 2\ln T_2 + 2\ln w - 1.5\ln V_T - \ln\left[1 + .29\left(\frac{V_R}{V_{T1}}\right)^{1.36}\right]}$$

T_2 assumed as 1020

Example.

Take $\phi_R' - V_R = 1.2$

$$V_{T_2} = \frac{1.2}{22.56 + 14 - 21.14 + 3.06 - 1.47}$$

$$w = 2.54 \times 10^{-5} = 10^{-4.595} = e^{-10.57}$$

$V_T = .13$ Take $\frac{V_R}{V_T} = 6$

$$\ln[1 + \quad] = 1.47$$

$$V_{T_2} = \frac{1.2}{17.} = .0707 \text{ or } T_2 = 820\,°K$$

with T_2 at 820

$$V_{T2} = \frac{1.2}{16.4} = .073$$

or 850°K

<u>840 is best value.</u>

$$\frac{\phi_2 + V_T 2}{V_T} = N$$

$N V_T \qquad (N-2) V_T = \phi_2$

$$V_{T2} = \frac{\phi_2}{22.56 + \underbrace{2 \times \ln 1000}_{13.82} + 2 \ln\left(\frac{T_2}{1000}\right)}$$

$$\begin{array}{r} 22.56 \\ 13.82 \\ \hline 36.38 \end{array}$$

2

$$V_{T2} = \frac{\phi_2}{36.38 + 2 \ln\left(\frac{T}{1000}\right) + 2 \ln W + 1.5 \ln(V_T^{-1}) - \ln[\quad]}$$

Numerical example.

$T = 1510°K$ $\quad \ln T = 7.3$ $\quad \frac{1}{2}\ln T = 3.65$

$V_T = .13$ $\quad V_T^{1/2} = .361$ $\quad V_T^{3/2} = .0469$ ✓

$V_T^{-1} = 7.7$ $\quad \log_{10} 7.7 = .8865$

$w = 2.54 \times 10^{-5}$ $\quad \log_{10} w = -4.595$

$w^2 = 6.45 \times 10^{-10}$

$2 \ln w = -21.15$

$$\begin{array}{r} 39.59 \\ 3.65 \\ \hline 43.24 \\ 21.15 \\ \hline 22.09 \end{array}$$

$22.09 \times .13 = \phi_R' = 2.87$

$2.87 - \underset{\phi_2}{1.57} = 1.3 = V_R$

$$\frac{V_R}{V_T} = 10.$$

$$P_{max} = \frac{3.67 \times 10^{-6} \times .361 \times 1.69}{6.45 \times 10^{-10}} = 3,470 \text{ Watts}/m^2$$

$\cancel{I = \frac{3,470}{1.3} = 2,670\ a/m}$

$\phi' = 2.87 - .13 \cdot 2.04$
$.27$
$= 2.6$

Electron cooling

$2.6 \times 5,426$
$= 14.1 \times 10^3$

$$I_m = \frac{9.66 \times 10^{-6}}{6.45 \times 10^{-10}} \cdot 4.69 \times 10^{-2} = 702$$

$I = 702 \times 7.73 = 5,426\ a/m^2$

To get an increase in current of

7.73 pot max must change

$2.04\ V_T = .267$ ✓

and $\bar{V}$ is $\overset{5.1}{5.05}$ or V changes .656

thus $1.3 - .66 = .64 = V_0$

$\frac{3470}{.644} = 5400$ a/m² as current,

~~Radiation power 3×10^4 w/m²~~

See (21)

$\cancel{\gamma = \frac{3.47 \times 10^3}{3 \times 10^4} = .116}$

$$T_c^4 = \frac{11600 \times 1.57}{36.38 - 4.6 \times 4.6 + 3.45 \times .887 + 2.3 [\cancel{4.6} \times + .885]}$$

36.38
3.06
2.03
41.49
21.17
20.30

$V_c = .773$

$T_c = 920\,°K.$

In calculating Power loss on face of emitter.

Electron cooling

we have

$$N_T = 5.65 \times 10^{-8} \left((1510)^4 - (920)^4 \right) \epsilon r \quad .28$$

$$\begin{array}{l} (1.51)^4 \times 10^{12} \\ - (.92)^4 \times 10^{12} \end{array} \quad = \quad \begin{array}{r} 5.20 \\ \underline{.72} \\ 4.48 \end{array}$$

Radiation

71×10^3
14×10^3

$$= 7.1 \times 10^4$$

for .25 = ϵr
$N_r = 6.3 \times 10^4$

$$\eta \quad \frac{.347 \times 10^4}{7.1} = 4.9\%$$

$$\text{Cathode w.f.} < \left(V_R - V_T \left[\ln \frac{I}{I_m} + 1 \right] \right)$$

$$\begin{array}{r} 2.87 - 1.26 \\ \cancel{1.26} \\ \hline .39 \\ \hline 2.48 \end{array}$$

$$\phi_1 < 2.48$$

$$\begin{array}{r} 71 \\ \underline{14} \\ 85 \end{array}$$

Rad 83% +
El. 17% −

3.086 2nd Numerical Example

$T = 1219°K$. $\ln T = 7.107$ $\frac{1}{2} \ln T = 3.5535$

$V_T = .105$ $V_T^{1/2} = .324$ $V_T^{3/2} = .0340$

$V_T^{-1} =$

$\omega = 2.54 \times 10^{-5}$

$$\begin{array}{r} 39.59 \\ 3.55 \\ \hline 43.14 \\ 21.15 \\ \hline 22.00 \end{array}$$

$22 \times .105 = \phi_R' = 2.31$

$2.31 - 1.57 = .74 = V_R$

$$\frac{V_R}{V_T} = 7.05$$

$$P_{max} = \frac{3.67 \times 10^{-6} \times .324 \times .547}{6.45 \times 10^{-10}} = 1{,}010 \text{ watts/m}^2$$

$$I_m = \frac{9.66 \times 10^{-6} \cdot 3.4 \times 10^{-2}}{6.45 \times 10^{-10}} = 509 \text{ a/m}^2$$

$$I/I_m^* = 1 + .29 \times \underset{14.2}{(7.05)^{1.36}} = 5.12$$

$I = 2600 \text{ a/m}^2$

$$T_c = \frac{11600 \times 1.57}{36.38 - 4.6 \times 4.6 + 3.45 \times .885 + 2.3 \times .71}$$

3.06

$$\begin{array}{r} 36.38 \\ 3.06 \\ 1.63 \\ \hline 41.07 \\ 21.57 \\ \hline 19.50 \end{array}$$

$\cancel{.45}$

Take $T_c = 800$

$V_{Tc} = 0806$

$T_c = 850°K$

$$P_r = 5.65 \times 10^{-8} (2.21 \times 10^{12} \times -$$

.28

$$\begin{array}{r} 2.21 \\ .52 \\ \hline 1.79 \times \end{array}$$

22.4

$$P_r = 5.68 \times 1.7 \times .25 \quad 10^4$$
$$= 2.41 \times 10^4$$

$$\delta = \frac{1.010 \times 10^3}{.241 \times 10^3 \times 10^2} = 4.2\%$$

$$\phi_1 \ll 2.31 - 2.64 \times .105 =$$

$$\begin{array}{r} 2.31 \\ .28 \\ \hline 2.03 \end{array}$$

Workout case for 1740°K

$V_T = .15$

$T = 1740$ $\quad \ln T = 7.46$ $\quad \frac{1}{2}\ln T = 3.73$

$\log_{10} T = 3.24$

$V_T = 1.5$ $\quad V_T^{1/2} = .387$ $\quad V_T^{3/2} = .058$

$V_T^{-1} = 6.67$ $\quad \log_{10} 6.67 = .824$

$$\begin{array}{r} 39.59 \\ 3.73 \\ \hline 43.32 \\ 21.15 \\ \hline 22.17 \end{array}$$

$22.17 \times .15 = 3.33 = \phi_R$

$$\begin{array}{r} 1.57 \\ \hline 1.78 \end{array} = V_R$$

$\frac{V_R}{V_T} = 11.87$ $\quad V_R^2 = 3.17$

$$P_{max} = \frac{3.67 \times .387 \times 3.17 \times 10^4}{6.45} = 6,980$$

$$I_m = \frac{9.66 \times 10^{-6} \times 5.8 \times 10^{-2}}{6.45 \times 10^{-10}} = 870 \text{ a/m}^2$$

$\left(\frac{V_R}{V_T}\right)^{4/3} = 27.1$ $\quad 27.1 \times .31 + 1 = 9.4 = U^2$

$2.3 \log_{10} U^2 = 2.24$

$I_{max} = 8180 \text{ a/m}^2$

$V_0 = .854$

$3.24 \times .15$

$$T_c = \frac{11600 \times 1.57}{36.38 - 4.6 \times 4.6 + 3.45 \times .824 + 2.24}$$

$$\begin{array}{r} 36.38 \\ 2.84 \\ 2.24 \\ \hline 41.46 \\ 21.17 \\ \hline 20.3 \end{array}$$

$V_{Tc} = .78$ ✓

$T_e = 920$ ✓

$$\begin{array}{r} 3.33 \\ \cancel{.49} \\ \hline \end{array}$$

$\phi_1 = 2.84$

$$T^5 = \begin{array}{r} 15.9 \times 10^{15} \\ .7 \\ \hline 15.2 \end{array}$$

$$P_r = 1.4 \times 10^{-12} \times 15.2 \times 10^{16} = 2.13 \times 10^5$$

$$\frac{6.98 \times 10^3}{2.13 \times 10^5} = .0328 \qquad 3.3\%$$

---

use this formula, (16) for

$T = 1510$ $\qquad T_c = 920$

$$T^5 = \begin{array}{r} 7.87 \times 10^{15} \\ .7 \\ \hline 7.17 \times 10^{15} \end{array} \qquad P_r = 10 \times 10^4$$

$$\delta = \frac{3470}{10} = 3.5\%$$

$T = 1220$ $\qquad T_c = 850$

$$T^5 = \begin{array}{r} 2.7 \times 10^{15} \\ .44 \\ \hline 2.26 \end{array}$$

$$P_r = 3.16 \times 10^4$$

$$\delta = \frac{1010}{316} = 3.2\%$$

analysis applied to Hatsopoulos + Kaye ①

Stefan-Boltzmann law.

$\sigma = .5668 \times 10^{-4}$ erg cm^{-2} deg^{-4} sec.

10^7 erg/sec = 1 watt

$.5668 \times 10^{-11}$ watts / cm^2 deg^4

$.5668 \times 10^{-7}$ " / m^2 / deg.^{4}

$\underline{5.668 \times 10^{-8}}$ ✓

$T = 1510°K$

$T^4 = (1.51)^4 \times 10^{12}$ ✓

$= 5.2 \times 10^{12} \times 5.6 \times 10^{-8}$

$= 29.1 \times 10^4$ watts

assume $\varepsilon_1 = \varepsilon_2 = .4$

$(2.5 + 2.5 - 1)^{-1} = .25$

$29.1 \times 10^4 \times .25 = 7.3 \times 10^4$

$= \underline{73 \times 10^3}$

H+K (2)

Take $(V_0)_{max} = .6$ ✓

$V^{1/2} = .365$

$1550 \Rightarrow V_T = .1335$ ✓ $V_T^{3/2} = .0488$

assume $W = 2 \times 10^{-5}$ m. (?)

$\log W = -4.7$

$\ln W = 10.8$

$2 \ln W = -21.6$?

$\ln T = 7.34$ ✓

$\frac{1}{2} \ln T = 3.67$ ✓

$$\begin{array}{r} 39.59 \\ 3.67 \\ \hline 43.26 \\ 21.6 \\ \hline 21.66 \end{array}$$

$\phi_R' \lesssim .1335 \cdot (21.66)$

$\lesssim 2.89$

Take $V_R \doteq 1.1$ $\quad \frac{V_R}{V_T} = 8.25$

with $\frac{V_R}{V_T} = 9$ $\quad V_R = 1.2$ ✓

$P_{max} = 3.7 \times 10^{-6} \times .366 \times \frac{1.44}{4 \times 10^{-10}}$

$= .49 \times 10^{4}$

$= 4.9 \times 10^{3}$

$V_0 = .6$

$I_{max} = 8150$

H×K 3

with I_{max} 8150

$$I_m = \frac{\cancel{9}.66 \times \cancel{10}^{-6} \times 4.88 \times 10^{-2}}{4 \times 10^{-10}}$$

$= 1180$ OK

$$\upsilon^2 = \frac{8.15}{1.18} = 6.9$$

$1 + .31 \times (9)^{4/3} = 6.85$ formula (11)

2×10^{-5}

Since $I_m = 1180$

$$\phi_R' = V_T\left(14 + \overset{2\ln T}{14.7} - 7.55\right)$$

$$\ln \frac{1180}{T^2} = \ln A - \frac{\phi_R'}{V_T}$$

$$\begin{array}{r} 28.7 \\ 7.55 \\ \hline 21.15 \end{array}$$

$\phi_R' = 2.72$

$V_R = 1.2$

$\phi_2 = 1.52$ ✓

$\phi' = \underset{.26}{2.72} - .1335 \cdot 1.93$

$\phi' = 2.46$

H&K 4

Election cooling power,

$$8150\,(2.46 + .267) = 2.22 \times 10^4 \ \mathrm{w/m^2}$$

$$\begin{array}{r} 2.46 \\ .27 \\ \hline 2.73 \end{array}$$

assuming this loss.

$$\text{Eff} = \frac{4.9 \times 10^3}{.222 \times 10^5} = \underline{22\%}$$

H. & K show 13%

Since eff $\propto$

at 1550 With $W = 2.54 \times 10^{-5}$ and $\phi_2 = 1.57$

$$P_{max} = 3750 \ \mathrm{w/m^2}$$

$$\frac{3750}{3.7 \times 10^{-6} \times .365} = \frac{V_R^2}{W^2} = \underline{2.78 \times 10^9}$$

With $\frac{3750}{.6} = I_{max} = \underline{6250 \ \mathrm{a/m^2}}$

$$\phi' = .1335\,(28.7 - 8.74) = 2.66$$

$$\begin{array}{r} 2.66 \\ .27 \\ \hline 2.93 \end{array}$$

$\phi_2 + V \ln \frac{I_{max}}{I_m} = 2.06$

$\begin{array}{r} 1.57 \\ \hline .5 \end{array}$

this gives

$\ln \frac{I_{max}}{I_m} = 3.85$. which is not poss.

Election cooling

$$3750\,(2.66 + .267) = .11 \times 10^5$$

11,000

H&K 5

Radiation from ①

$$\begin{array}{r} .73 \times 10^5 \\ .11 \\ \hline .84 \end{array}$$

$$\frac{3.750 \times 10^3}{.84} = 4.5\%$$

$$\frac{3.750 \times 10^3}{13 \times 10^{-2}} = \underline{.289 \times 10^5}$$

loss taking less H&K

~~? A this was made~~

---

assume $P_{max} = 4200$

$I_{max} = 7000$

$\phi' = .1335(28.7 - 8.85) = 2.52$

$2.52 + .267 = 2.79$

$2.79 \times 7000 = .195 \times 10^5$

$$\frac{4.200 \times 10^3}{.195 \times 10^5} = 21.5\%$$

$$\cancel{I_{max}}\, 0.6 = P_{max} = .13 \times \cancel{I_{max}} (\phi_E' + .27)$$

$$\phi' + .27 = 4.61$$

$$\phi' = 4.3$$ which is

<u>impossibly high</u>

In calculating $eff_{max} = 13\%$ H&K must have used other losses in addition to $I_{max}(\phi' + .27)$ electron cooling but did not use the radiation power loss.

Questions:-

1) Are the temperatures quoted <u>true</u> temp or brightness temp? How Measured?
2) What was the observed current at max?
3) What values of σ, ε_1 and ε_2 in eq. 7 were used?
4) How do they justify statement that elec. cooling is main term of Eq (6.)
5) How do they prove Eq (7)?

The Thermionic Diode As a Heat-to-Electrical-Power Transducer *

W. B. Nottingham

Department of Physics and the Research Laboratory of Electronics

Massachusetts Institute of Technology

Cambridge, Massachusetts

Abstract

The high-vacuum thermionic diode is shown to be capable of converting heat to electric power. For this purpose, a low work-function collector, a small spacing, and sufficient temperature difference between the emitter and the collector are necessary. A detailed understanding of both thermionic emission and space-charge phenomena are needed for evaluating the effectiveness of this transducer. With V_R defined as the critical bias potential that gives zero potential gradient at the collector, the maximum available power is given by the relation $3.7 \times 10^{-6}\, V_T^{1/2}\, (V_R^2/w^2)$ watts/m^2. Here, V_T is the voltage equivalent of the temperature T/11,600. In the range of emitter temperature from 1200°K to 1700°K, the most optimistic conversion efficiency lies between 3 and 4 per cent for a diode of 0.001 inch spacing. With a suitable choice of emitter inhomogeneity, the introduction of cesium vapor should improve the efficiency of this device.

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INTRODUCTION

It has been known since the earliest experiments on thermionic diodes that heat can be converted into electric power by this device. Three requirements must be satisfied for it to yield a significant amount of power: (1) a low work-function collector; (2) a small spacing between the emitter and the collector; and (3) a sufficient temperature difference between the emitter and the collector.

Hatsopoulos and Kaye[1] have given a brief discussion of the physical phenomena involved, but they have omitted so much that is basic to the understanding of the problem that a more detailed analysis is justified. It is the purpose of this paper to summarize the fundamental relations that were developed and published under the title of "Thermionic Emission,"[2] referred to below as T. E. The requirements that must be satisfied for the device to have its highest efficiency will be developed by means of these theories.

DIODE PROPERTIES

Although the equations used in this paper apply strictly to the plane-parallel structure, the methods by which they can be applied to a concentric cylindrical structure are given in Sections 60 and 61 of T. E.

If the collector surface potential of a diode structure is made very negative with respect to the emitter, the electron flow is not inhibited by space charge. As the collector potential is made less and less negative, the presence of space charge creates a critical situation for which the potential gradient at the surface of the collector is <u>exactly zero</u>. Under this condition there is no net charge on the surface of the collector, whereas at the surface of the emitter there is a positive surface charge equal to that of the total number of electrons in transit between the emitter and the collector.

The potential distribution under this critical condition is illustrated by Fig. 1. Some of the symbols that are used in the following equations are also defined in this figure. The "true work-function" of a surface is the energy difference for an electron at the Fermi level (FL) within the conductor as compared with its energy in the immediate neighborhood of the surface of the conductor in the absence of an externally applied field. This work-function is not a constant; it varies with the temperature and the surface condition. It should not be confused with the "Richardson work-function," which is often misidentified with the true work-function.

In Fig. 1 the true work-functions of the emitter and of the collector are shown as ϕ_1 and ϕ_2, respectively. The Fermi levels are separated by the potential, indicated by V_R. Note that this <u>critical</u> energy separation applies to the present problem when the potential gradient at the collector is exactly zero. This quantity (V_R) becomes the determining factor in establishing the effectiveness of the device as an energy transducer. If the energy difference ϕ_R' is greater than the work-function ϕ_1 by at least V_T, as defined by Eq. (1), the current that flows across the diode is independent of the emitter work-function.

$$V_T = \frac{k}{q} T = \frac{T}{11600} , \qquad (1)$$

where k is Boltzmann's constant, the value of the electronic charge is q, and the temperature (in degrees Kelvin) is T. The equation that was derived in Section 43 of T. E. to relate the maximum current flow to the spacing, w, and the temperature is given as

$$I_m = 7.729 \times 10^{-12} \frac{T^{3/2}}{w^2} = 9.664 \times 10^{-6} \frac{V_T^{3/2}}{w^2} . \qquad (2)$$

The simplest circuit arrangement for delivering electric power to an external load resistance is shown in Fig. 2. For an emitter of area A, there is a critical value for the external load resistance (R_{LR}) which will bring about the potential distribution illustrated in Fig. 1. This load resistance must satisfy

$$R_{LR}\ I_m\ A = V_R. \tag{3}$$

If a resistance (R_L) is used smaller than this critical value, the current density flowing across the diode will be greater than I_m, and the energy difference between the Fermi levels will be less than V_R. As the resistance decreases, the voltage across it decreases but the current increases more rapidly at first until an optimum resistance is reached. The product VI therefore comes to a maximum and more power is delivered to the load when a space-charge minimum exists between the emitter and the collector. The potential distribution under this condition is illustrated by Fig. 3, in which the dotted lines represent a superposition of Fig. 1 on Fig. 3. The fact that the drop in potential over the load resistance has been decreased is shown by the difference between V_R and V_O. The space-charge minimum at ϕ' is lower than that at ϕ_R'. The increase in the current that flows around the circuit is determined quantitatively by this change as exp $(\phi_R' - \phi')/V_T$. The method of determining the optimum load conditions will now be discussed.

QUANTITATIVE EVALUATION OF DIODE PROPERTIES

The detailed analysis that is given here is subject to the condition that ϕ' exceeds ϕ_1 by at least V_T. (See Table 9 of T. E. for data on the special, and rather unusual, case in which the difference $(\phi' - \phi_1)$ is less than V_T). The basic table (Table 8 of T. E.) upon which the correct analysis of the problem depends is given here in a shorter form as Table 1. The data of Table 1 are plotted as curve 1 in Fig. 4.

The power delivered to the load for any value of current that is greater than I_m, and for any value of V/V_T that is less than V_R/V_T is expressed by

$$P = I_m V_T \left[\frac{I}{I_m} \left(\frac{V_R}{V_T} - \Sigma \right) \right] = I_m V_T \Pi . \tag{4}$$

The quantity Σ is defined as $(V_R - V)/V_T$. For an arbitrary set of values of V_R/V_T between 4 and 20, the quantity within the square brackets (Π) has been computed, and corresponding curves are plotted as a function of Σ in Fig. 4. The curves are to be used for determining the value of Σ which is associated with the maximum of each curve, and for illustrating that deviations from the maximum of from 10 to 20 per cent do not result in much loss in operational efficiency. Table II summarizes the relations between the significant quantities at the several maxima. The quantity Π_{max} is defined as

$$\Pi_{max} = \frac{P_{max}}{I_m V_T} \tag{5}$$

The output voltage is V_0, at the maximum of the curve.

Curves I and II of Fig. 5 represent the data for Σ_{max} and (I_{max}/I_m) of Table II in graphical form for easy interpolation. Figure 6 shows the relation between Π_{max} and V_R/V_T. A logarithmic plot of these data is used to illustrate how Π_{max} is related to the important parameter (V_R/V_T). The equation for the straight line is given by

$$\Pi_{max} = 0.385 \left(\frac{V_R}{V_T} \right)^2 \tag{6}$$

MKS units are used in all of the equations that are given above, current densities are expressed in amperes/m^2, and the power is expressed in watts/m^2.

DISCUSSION OF RESULTS

The combination of Eqs. 5 and 6 yields

$$P_{max} = 3.7 \times 10^{-6} \, V_T^{1/2} \, \frac{V_R^2}{w^2} \, . \tag{7}$$

Although V_R is dependent upon temperature through its relation to ϕ_R', it is clearly shown in Fig. 1 that the work-function of the collector ϕ_2 and the spacing w are the most important controllable factors.

The design procedure that must be used is outlined in the following steps:

1. Choose the smallest possible value of the spacing w which is consistent with the reliable fabrication of the diode.

2. Specify the necessary power per unit area of the emitter for the device to be useful.

3. Assume an approximate value for $V_T^{1/2}$ of 0.35 to 0.4 and compute the value of V_R.

4. Estimate the lowest possible collector work-function ϕ_2 that can be realized in the diode and determine the value of ϕ_R' from

$$\phi_R' = \phi_2 + V_R \, . \tag{8}$$

5. Use the following equation as a means of determining the minimum emitter temperature that can be used to satisfy the requirements:

$$\frac{T}{11600} = V_T = \frac{\phi_R'}{39.59 + \frac{1}{2}\ln T + 2\ln w} \tag{9}$$

A simplified form of Eq. (9) that applies if the emitter temperature is close to $1500^{o}K$ is

$$T = \frac{11600\ \phi'_R}{43.2 + 4.6\ \log_{10} w} \tag{10}$$

If a specific application depends on having an emitting source at a specified temperature, then the reverse of these steps can be followed; that is, ϕ'_R is first determined from Eq. (9) or Eq. (10). Equation (8) determines V_R and Eq. (7) the maximum power that can be delivered to the load.

Once (V_R/V_T) is known, the diode current density (I_{max}) at the maximum power output can be determined by

$$\frac{I_{max}}{I_m} = U^2_{max} = 1 + 0.31\left(\frac{V_R}{V_T}\right)^{4/3} \tag{11}$$

With the maximum power output P_{max} known from Eq. (7), the optimum load resistance for an emitter of area A becomes

$$R_{LO} = \frac{P_{max}}{I^2_{max}\ A} . \tag{12}$$

Since minimizing the collector work-function results in a greater power output, it is necessary to maintain the collector at a sufficiently low temperature so that its saturation electron emission will be small compared with the electron current that it receives from the high-temperature emitter. The following formula serves as a means of evaluating this maximum temperature in terms of quantities already determined by the previous analysis and based on the assumption that the emission from the collector will be approximately 5 per cent of the electron current received from the emitter.

$$T_c = \frac{11600\ \phi_2}{36.38 + 4.6\ \log_{10} \frac{T_c}{1000} + 4.6\ \log_{10} w + 3.45\ \log_{10} V_T^{-1} + 2.3\ \log_{10} U_{max}^2} \quad (13)$$

NUMERICAL EXAMPLES

In order to illustrate the use of the aforementioned equations, two of the critical quantities will be taken arbitrarily. These are 1.57v, for the true work-function of the collector, and 0.001 inch, as the spacing between the emitter and the collector. The values of the assumed emitter temperatures are given in Table III, together with the derived results.

If the area of the emitter is actually 1 sq. cm. and the temperature is 1510°K, then these results show that it is possible to deliver to a load resistance of 1.2 ohm electric power of 0.35 watt. The natural question to ask is "What is the efficiency of this conversion of heat to electric power?" In answering, we note that the absolute maximum of efficiency would occur if there were no losses except radiation losses from the emitter to the collector. It is obvious that in any practical application there will be other losses such as radiation losses to heat shields, and the electron cooling of $I(\phi' + 2V_T)$, which will reduce the actual operating efficiency below the most optimistic figure. The radiation loss from the emitter to the collector can be estimated by using

$$P_r = 5.65 \times 10^{-8}\ (T^4\ \overline{\epsilon}\ \overline{r} - T_c^4\ \overline{\epsilon_c}\ \overline{r_c})\ \text{watts/m}^2. \quad (14)$$

In Eq. (14), $(\overline{\epsilon}\ \overline{r})$ is closely related to the "total emissivity" of the emitter and to the reflectivity of the surface. It is not independent of

See new "p 9" + "p 10"

temperature. The determination of $\overline{\epsilon}\ \overline{r}$ involves a problem of multiple reflection between two surfaces of different spectral emissivity, and hence a very complex integration is needed to determine it. The same difficulty is associated with the quantity $\overline{\epsilon_c}\ \overline{r_c}$ as it applies to the collecting surface. For a limited range of temperature, it will be assumed that

$$\overline{\epsilon}\ \overline{r} = 2.5 \times 10^{-4}\ T. \tag{15}$$

With these approximations we have

$$P_r = 1.4 \times 10^{-11}\ (T^5 - T_c^5)\ \text{watts/m}^2. \tag{16}$$

~~This formula was used to calculate P_r and $(\text{eff})_{max}$ of Table III.~~ Omit

Should put in eq for el. cooling.

CONCLUSIONS

This analysis has shown that a conversion of heat energy to electric power is quite possible in a high-vacuum diode, although many technical difficulties stand in the way of creating an efficient power transducer of this kind. The calculations show that the maximum efficiency is almost independent of the temperature, since V_R increases approximately as $T^{2.3}$. Equation (7) would then give the maximum power as proportional to $T^{5.1}$. Since the radiation power also increases almost proportionally to T^5, the efficiency remains constant. The efficiency of 3.5 per cent that is given here is undoubtedly optimistic by at least a factor of two. All other things being approximately equal, the reduction of the emitter-to-collector spacing a factor of three increases the efficiency by almost a tenfold factor. This decrease in spacing would be extremely difficult to accomplish, since it would indicate a spacing of 0.0003 inch. The diode power transducer not only involves a proper application of the theories of thermionic emission but also the theory of space charge.

Some of the difficult technical problems could be relieved by the design of a diode containing cesium vapor. Cesium atoms, as they come in contact with the emitter at a temperature higher than $1200^{o}K$, become ionized[3], leave the emitter and then flow into the electron space-charge region. To use this type of ionization and still have an average emitter work-function of less than 2.5 v would demand a "controlled" inhomogeneity on the surface. With such an emitter many electrons are permitted to go to the collector that could not otherwise do so. Furthermore, the presence of cesium on the cooler collector reduces its work-function and makes it a favorable electron receiver for a power transducer. The basic facts for predicting in detail the efficiency of this device are not available at this time.

REFERENCES

1. G. N. Hatsopoulos and J. Kaye, J. Appl. Phys. 29, 1124 (1958).

2. W. B. Nottingham, "Thermionic Emission," Handbuch der Physik, Vol. 21, 1, (1956), Springer Verlag, Berlin-Gottingen-Heidelberg.

3. I. Langmuir and K. H. Kingdon, Proc. Roy. Soc. (London) A107, 61 (1925).

Table I

The Diode Characteristic With $\Sigma \equiv (V_R - V)/V_T$*

Σ	I/I_m	Σ	I/I_m
0	1	5.02	7.57
0.565	1.59	7.44	11.51
1.28	2.41	9.75	15.6
1.65	2.86	13.10	22.1
2.31	3.69	15.28	26.6
2.90	4.48	17.44	31.3
3.73	5.65	23.84	46.3

*Abridged from Table 8 of "Thermionic Emission."

		Drawn or typed	Proof read		Slides
1		✓	✓		
2		✓	✓		
3		✓	✓		
4		✓	✓		
5		✓	✓		
6		✓	✓		
7		✓	✓		✓
8		✓	✓		
9		✓	✓		
10		✓	✓		
11		✓	✓		
12		✓	✓		
13		✓	✓		
14	a	✓	✓		
	b	✓	✓		
15					
16		✓	✓		
17					

Table II

Dat~~e~~a Derived from the Maxima of Curves in Fig. 4

$\frac{V_R}{V_T}$	Σ_{max}	Π_{max}	$\frac{I_{max}}{I_m}$	$\frac{V_R}{V_T} - \Sigma_{max}$	$\ln \left(\frac{I_{max}}{I_m}\right)$
	curve I Fig. 5	Fig. 6	curve II Fig. 5	(V_0/V_T)	
0	0	0	1	0	0
4	1.70	6.72	2.92	2.3	1.07
6	2.70	14.0	4.24	3.3	1.44
8	3.80	24.4	5.80	4.2	1.76
10	5.05	37.8	7.73	4.95	2.05
12	6.30	55.0	9.70	5.7	2.27
14	7.40	75.8	11.5	6.6	2.44
16	8.6	99.5	13.45	7.4	2.60
18	9.6	129.0	15.35	8.4	2.73
20	10.4	161.4	16.80	9.6	2.82

Table III

Calculations for Diode: $w = 2.54 \times 10^{-5}$ m; $\phi_2 = 1.57$ v; area A.

V_T	.105	.13	.15	
T	1220	1510	1740	Units $^{\circ}K$
ϕ'_R	2.31	2.87	3.33	volt
V_R	0.74	1.3	1.78	volt
V_R/V_T	7.0	10	11.9	
P_{max}	1000	3470	7000	watt/m^2
I_m	509	702	870	a/m^2
	5.12	7.7	9.4	
I_{max}	2600	5400	8200	a/m^2
V_0	0.385	0.64	0.854	volt
R_{LO}	$1.5 \times 10^{-4}/A$	$1.2 \times 10^{-4}/A$	$1.04 \times 10^{-4}/A$	ohm
T_c	850	920	920	$^{\circ}K$
$(\phi_1)_{max}$	2.0	2.5	2.8	volt
P_r	3.16×10^4	10×10^4	21.3×10^4	watt/m^2
$(eff)_{max}$	3.2	3.5	3.3	per cent
	(2.6)	(3.0~~4~~)	(2.9~~5~~)	
P_e	~~.557~~ $\times 10^4$	1.41×10^4	~~2.45~~ $\times 10^4$	
	.77	1.67	2.75	
ϕ'	2.14	2.605	2.99	

$$\begin{array}{r} 2.31 \\ .17 \\ \hline 2.14 \end{array} \qquad \begin{array}{r} 2.87 \\ .265 \\ \hline 2.605 \end{array} \qquad \begin{array}{r} 3.33 \\ .34 \\ \hline 2.99 \end{array}$$

$$\begin{array}{r} 3.16 \\ .77 \\ \hline 3.93 \end{array} \qquad 11.67 \qquad 24.0$$

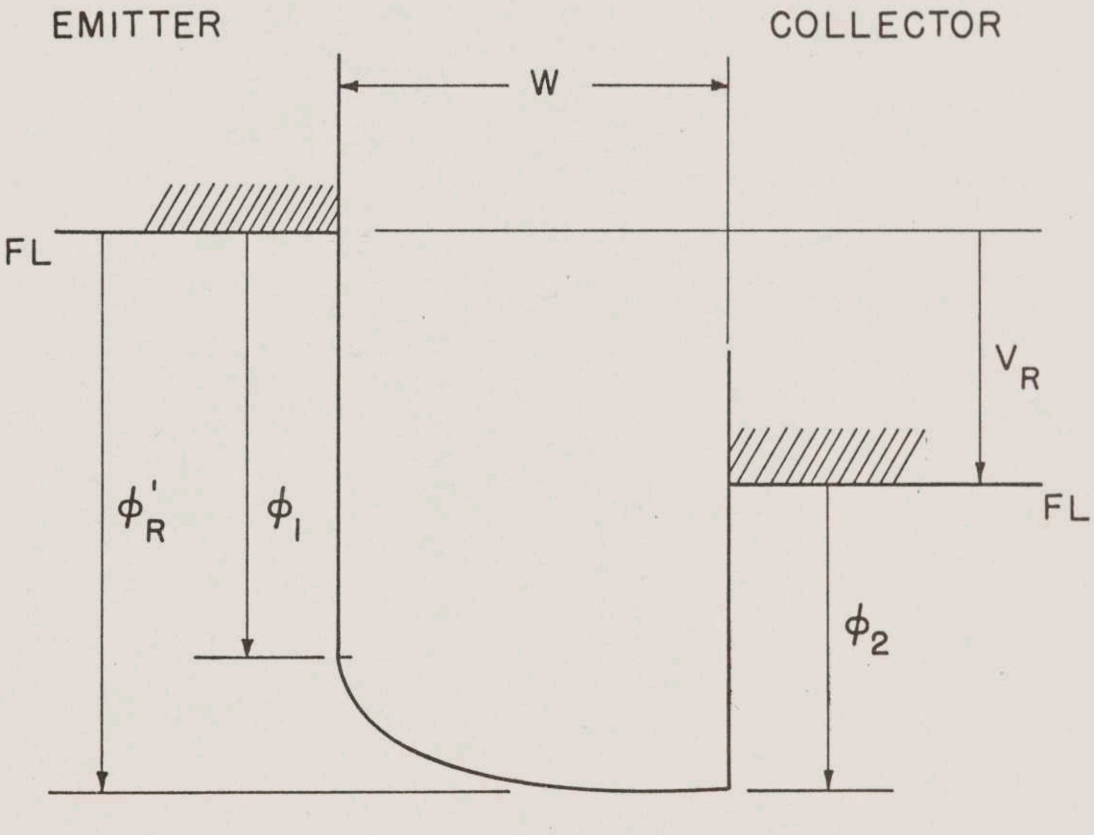

Fig. 1

Potential distribution with critical condition of zero gradient at the collector.

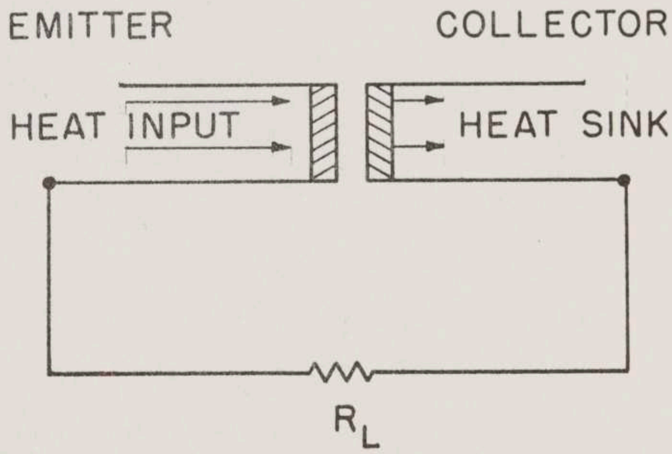

Fig. 2

Transducer circuit.

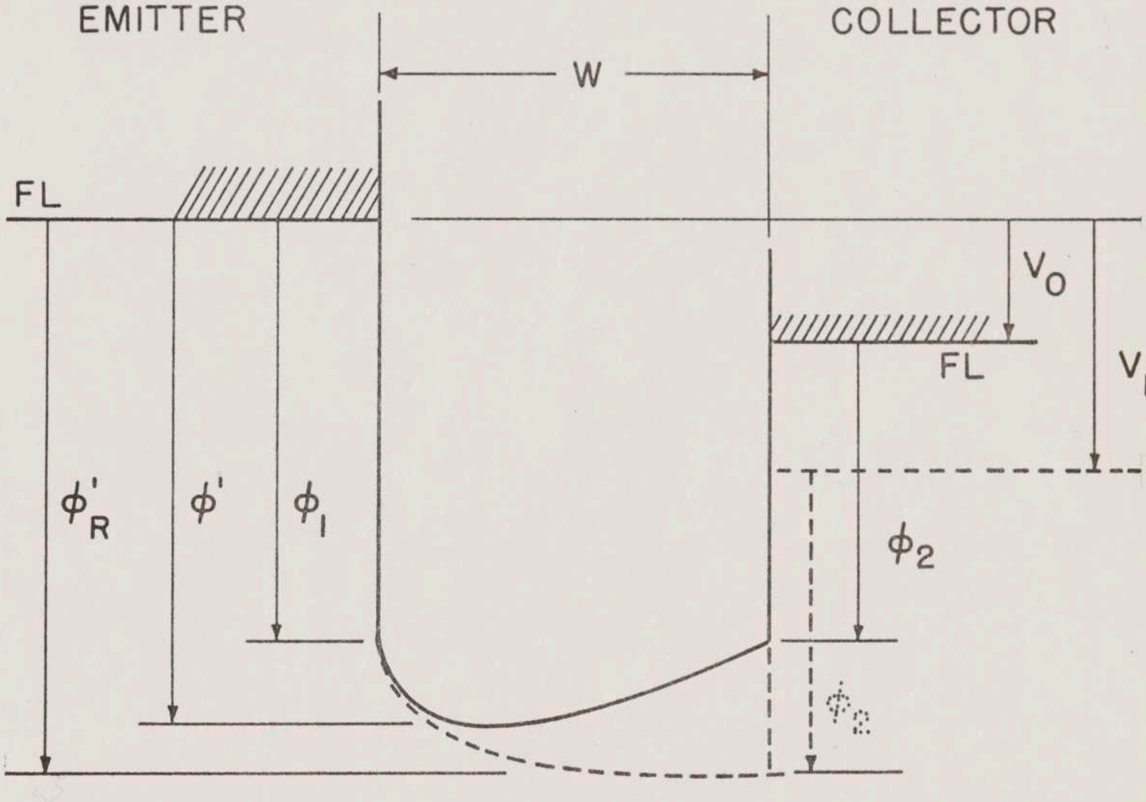

Fig. 3.

Potential distribution with maximum power in load.

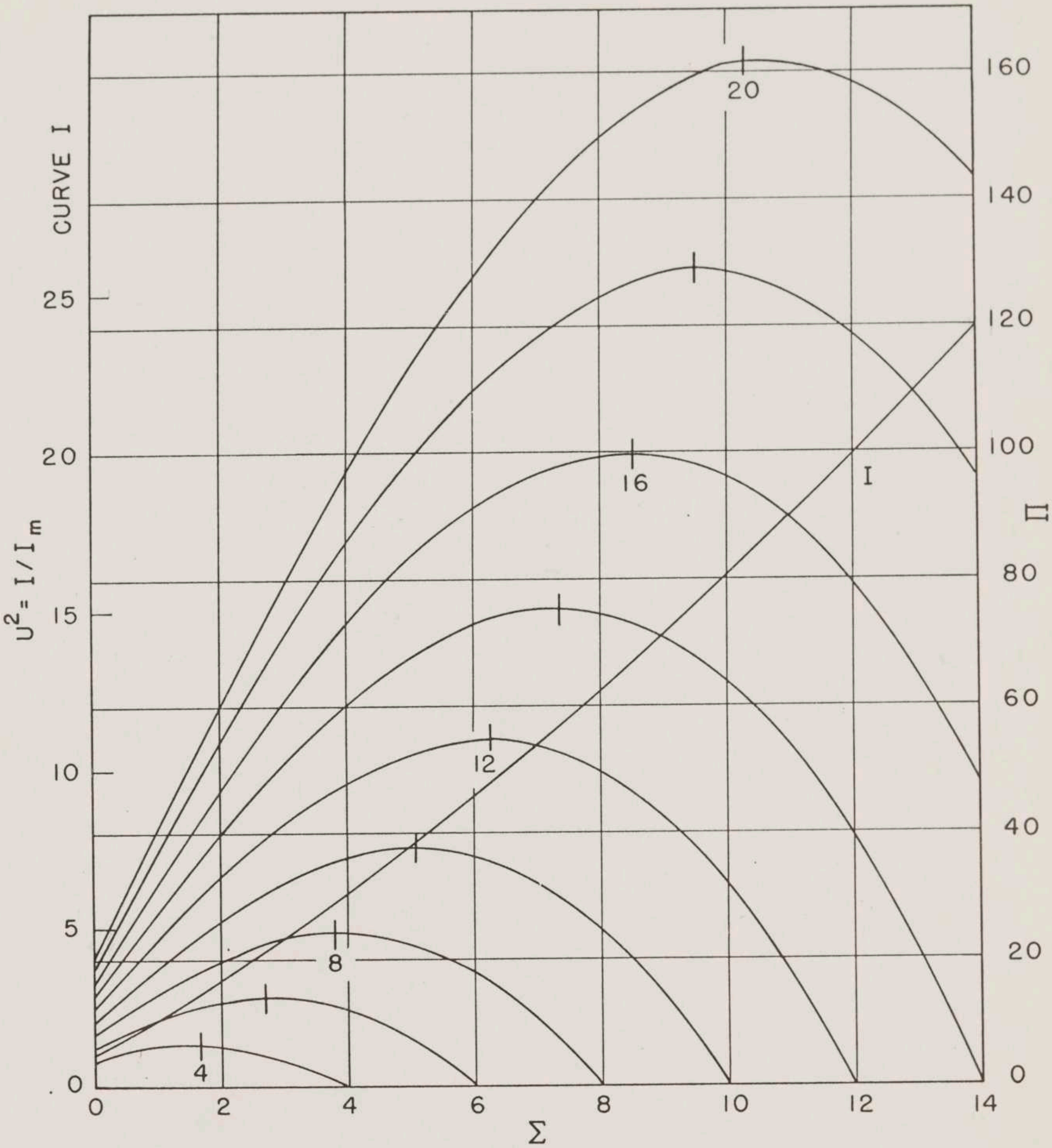

Fig. 4

Values of Π as a function of Σ for selected values of (V_R/V_T) of 4 to 20 and curve I is (I/I_m) of Table I.

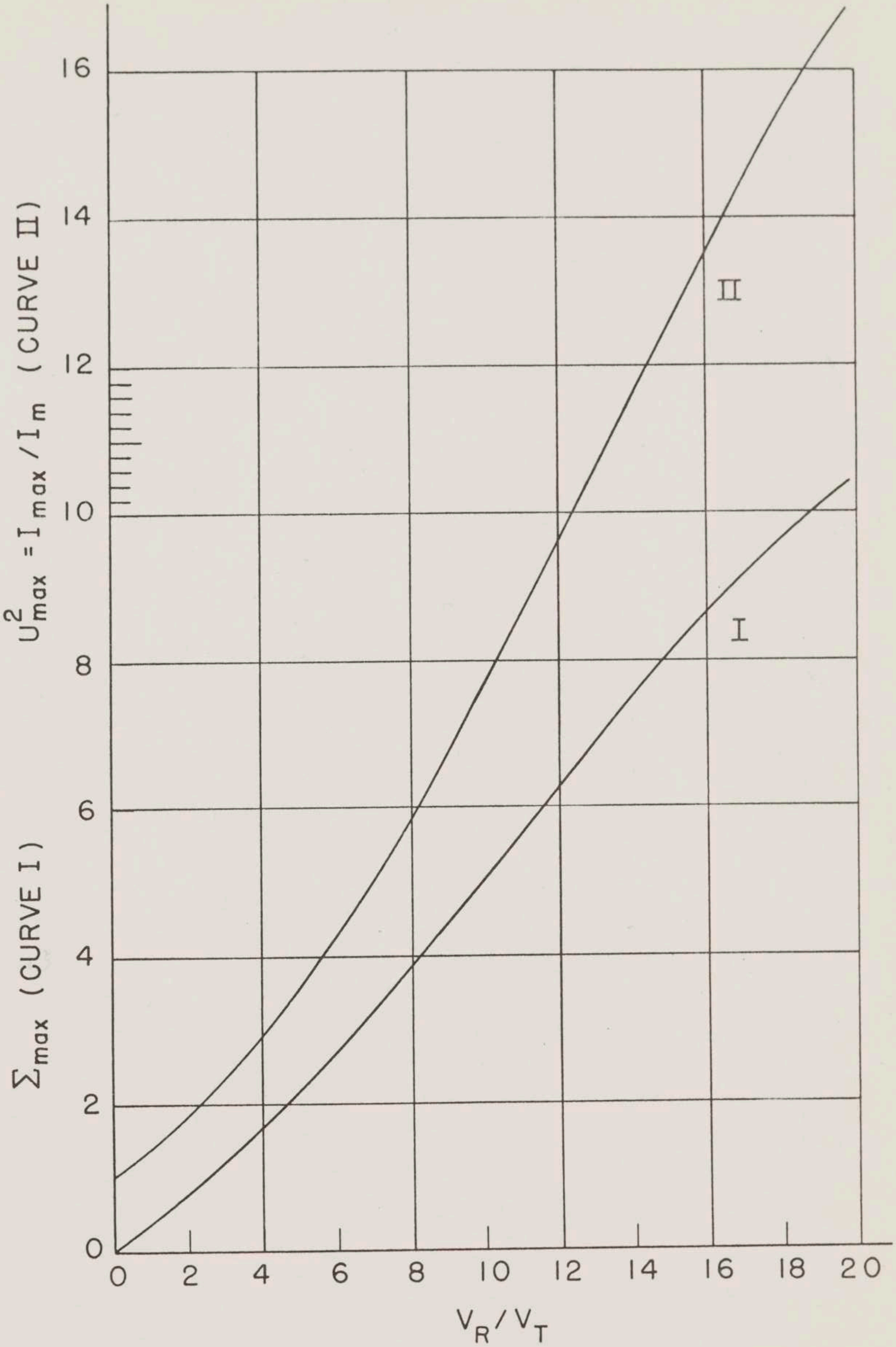

Fig. 5

Values of Σ_{max} and U^2_{max} as functions of V_R/V_T (see Table II).

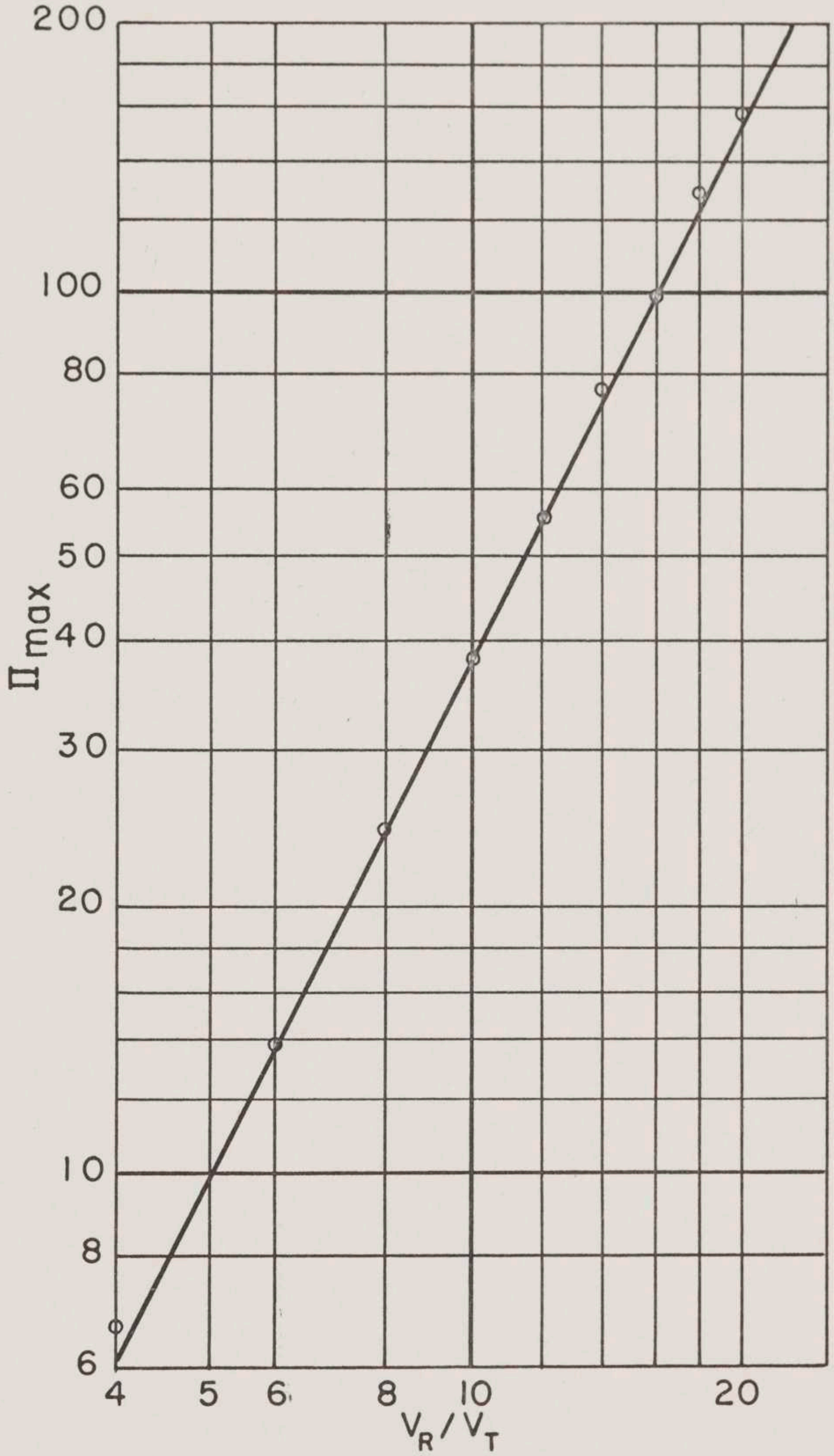

Fig. 6.

Values of Π_{max} as a function of V_R/V_T. The straight line representation of the data is Eq. (6).

Calculations on data in

H + K — IRE paper.

$V_R = .79$ $\boxed{\text{for } 1538^\circ K}$

$V_T = .1325$ $V_T^{1/2} = .364$ $V_T^{3/2} = 48 \times 10^{-3}$

$$I_m = \frac{9.66 \times 10^{-6} \times 48 \times 10^{-3}}{10^{-10}} = .464 \times 10^4$$

I m observed $.465 \times 10^4$

or $w = .0010$ cm

~~assum 1538°K as given by H + K~~

~~$V_T = .1325$ $V_T^{1/2} = .366$ $V_T^{3/2} = 49$~~

~~cal. $I_m = \frac{9.66 \times 49 \times 10^{-9}}{10^{-10}} \times 10^4 = .475 \times 10^4$~~

~~or $w = .00101$ cm~~ $\left| \frac{V_R}{V_T} = 5.95 \rightarrow \left(\frac{V_R}{V_T}\right)^{4/3} = \right.$

$I_{max} = .47 \times 10^4 (1 + .31 \times 10.7) = .47 \times 10^4 \times 4.3$ ✓ Eq 11

$= 2.02 \times 10^4$ ✓

$$P_{max} = \frac{3.7 \times 10^{-6} \times .364 \times (.79)^2}{10^{-10}} = .84 \times 10^4$$ ✓

.624

$V_0 = .416$ ✓

Table 5

Collector Region Potential and Its Relation to Emitter Properties and Current Flow. (Use with Eq. 46-2 and related equations.)

ψ_c	χ_c^2	$\left[F(\psi_c)\right]$	$\left[F(\psi_c)\right]^{3/4}$	$\left[F(\psi_c)\right]^{3/2}$
.01	.02074	.08849	.16227	.02633
.02	.04215	.1420	.23132	.05351
.03	.06396	.1875	.28494	.08119
.04	.08602	.22846	.33045	.1092
.05	.1084	.26654	.37094	.1376
.06	.1311	.3025	.40792	.1664
.07	.1540	.3369	.44215	.1955
.08	.1772	.3698	.47424	.2249
.09	.2004	.4015	.50438	.2544
.10	.2240	.4324	.53320	.2843
.15	.3441	.5757	.66091	.4368
.20	.4680	.7067	.77078	.5941
.25	.5951	.8295	.86914	.7554
.30	.7251	.9462	.95937	.9204
.35	.8578	1.0584	1.0436	1.089
.40	.9930	1.1672	1.1229	1.261
.45	1.130	1.2716	1.1975	1.434
.50	1.270	1.3748	1.2696	1.612
.60	1.555	1.5736	1.4050	1.974
.70	1.847	1.7649	1.5312	2.345
.80	2.146	1.9542	1.6505	2.724
.90	2.455	2.1334	1.7652	3.116
1.00	2.766	2.3101	1.8738	3.511
1.10	3.084	2.4840	1.9786	3.915
1.20	3.408	2.6550	2.0799	4.326
1.40	4.072	2.9896	2.2735	5.169
1.60	4.757	3.3163	2.4574	6.039
1.80	5.457	3.6338	2.6319	6.927
2.00	6.180	3.9482	2.8009	7.845
2.20	6.917	4.2560	2.9631	8.780
2.40	7.667	4.5583	3.1196	9.732
2.60	8.433	4.8559	3.2711	10.70
2.80	9.217	5.1538	3.4205	11.70
3.00	10.011	5.4463	3.5651	12.71
3.20	10.824	5.7367	3.7068	13.74
3.40	11.649	6.0243	3.8453	14.79
3.60	12.482	6.3072	3.9799	15.84
3.80	13.330	6.5908	4.1134	16.92

(Continued on next page)

Eq 9

$$\phi_R' = .1325\left(39,59 + \frac{7.35}{2} + 2(-11,5)\right)$$

$$\begin{array}{r} 39.59 \\ 3.68 \\ \hline 43.27 \\ 23.0 \\ \hline 20.27 \times .1325 = 2.7 \end{array}$$

$\phi_2 = 2.7 - .79 = \underline{1.91}$ ✓

See

Heat Transmission

W. H. McAdams

See Chapt 4 by Hottel p 55

Formula for grey bodies

$$q_{1 \rightleftarrows 2} = A_1 \sigma (T_1^4 - T_2^4) \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

by infinite series

Calculation —

Table 4 (Continued)

Emitter Region Potential and Its Relation to Emitter Properties and Current Flow. (See Sections 43 and 44 and Fig. 9.)

ψ_s	z	z^2	u_o	u_o^2	$(I_o/I_m)^{1/2}$	I_o/I_m
3.0	.8749	.7654	4.482	20.09	3.922	15.38
3.1	.8804	.7751	4.712	22.20	4.148	17.21
3.2	.8870	.7868	4.953	24.53	4.393	19.30
3.3	.8920	.7957	5.207	27.11	4.644	21.57
3.4	.8976	.8057	5.474	29.96	4.913	24.14
3.5	.9031	.8156	5.755	33.12	5.197	27.01
3.6	.9075	.8236	6.050	36.60	5.490	30.14
3.8	.9164	.8398	6.686	44.70	6.127	37.54
4.0	.9247	.8551	7.389	54.60	6.833	46.69
4.2	.9319	.8684	8.166	66.69	7.610	57.91
4.4	.9380	.8798	9.025	81.45	8.465	71.66
4.6	.9441	.8913	9.974	99.48	9.416	88.67
4.8	.9496	.9017	11.023	121.51	10.47	109.6
5.0	.9546	.9113	12.18	148.4	11.63	135.2
5.5	.9646	.9304	15.64	244.7	15.09	227.7
6.	.9723	.9454	20.09	403.4	19.53	381.4
6.5	.9784	.9573	25.79	665.1	25.23	636.7
7.	.9834	.9671	33.12	1096.6	32.57	1060.5
7.5	.9873	.9748	42.52	1808.	41.98	1762.4
8	.9900	.9801	54.60	2981.	54.05	2921.7
9	.9939	.9878	90.02	8103.	89.47	8004.
10	.9961	.9922	148.4	22026.	147.8	21854.
12	.9983	.9966	403.4	$.16275 \times 10^6$	402.7	$.1622 \times 10^6$
14	.9994	.9988	1096.6	1.2026×10^6	1096.	1.201×10^6
16	.9994	.9988	2981.	8.8861×10^6	2979.	8.875×10^6

Note 1. ψ_s and χ_s from Table 3E.

$z = (\chi_s/\chi_m)$ from Eq. 43-7.

$u_o^2 = I_o/I_R = e^{\psi_s}$ from Eq. 43-5.

$(I_o/I_m) = z^2 \, e^{\psi_s}$ from Eq. 43-6.

Statement on p 78

α_{12} conbo rep. by $g T_1^m T_2^n$

and refers to 62

See problem 2 on p 79

Ref. fr Sieber, W.

Z. tech Phys. 130-135 (1941)

Table 4

Emitter Region Potential and Its Relation to Emitter Properties and Current Flow. (See Sections 43 and 44 and Fig. 9.)

ψ_s	z	z^2	u_o	u_o^2	$(I_o/I_m)^{1/2}$	I_o/I_m
.02	.1078	.01162	1.0100	1.0202	.1089	.01185
.025	.1201	.01442	1.0126	1.0253	.1216	.01478
.03	.1312	.01721	1.0151	1.0305	.1332	.01773
.04	.1507	.02271	1.0202	1.0408	.1538	.02364
.05	.1676	.02809	1.0253	1.0513	.1718	.02953
.06	.1828	.03342	1.0304	1.0618	.1884	.03549
.07	.1967	.03869	1.0356	1.0725	.2037	.04150
.08	.2095	.04389	1.0408	1.0833	.2181	.04755
.09	.2214	.04902	1.0460	1.0942	.2316	.05364
.10	.2326	.05410	1.0513	1.1052	.2445	.05979
.15	.2807	.07879	1.0779	1.1618	.3026	.09154
.2	.3199	.1023	1.1052	1.2214	.3534	.1249
.25	.3535	.1250	1.1331	1.2840	.4006	.1605
.3	.3833	.1469	1.1619	1.3499	.4453	.1983
.35	.4095	.1677	1.1913	1.4191	.4879	.2380
.4	.4338	.1882	1.2214	1.4918	.5299	.2808
.45	.4561	.2080	1.2523	1.5683	.5711	.3262
.5	.4765	.2270	1.2840	1.6487	.6118	.3743
.55	.4957	.2457	1.3165	1.7333	.6526	.4259
.6	.5137	.2639	1.3499	1.8221	.6935	.4809
.7	.5466	.2988	1.419	2.014	.7758	.6018
.8	.5753	.3310	1.492	2.226	.8584	.7368
.9	.6024	.3629	1.568	2.460	.9448	.8927
1.0	.6262	.3921	1.649	2.718	1.032	1.066
1.1	.6484	.4204	1.733	3.004	1.124	1.263
1.2	.6689	.4474	1.822	3.320	1.219	1.485
1.3	.6877	.4729	1.915	3.669	1.317	1.735
1.4	.7049	.4969	2.014	4.055	1.420	2.015
1.5	.7209	.5197	2.117	4.482	1.526	2.329
1.6	.7364	.5423	2.226	4.953	1.639	2.686
1.7	.7508	.5637	2.340	5.474	1.757	3.086
1.8	.7641	.5838	2.460	6.050	1.879	3.532
1.9	.7763	.6026	2.586	6.686	2.007	4.029
2.0	.7879	.6208	2.718	7.389	2.142	4.587
2.1	.7996	.6394	2.858	8.166	2.285	5.221
2.2	.8095	.6553	3.004	9.025	2.432	5.914
2.3	.8195	.6716	3.158	9.974	2.588	6.699
2.4	.8289	.6871	3.320	11.023	2.752	7.574
2.5	.8378	.7019	3.490	12.18	2.924	8.549
2.6	.8455	.7149	3.669	13.46	3.102	9.623
2.7	.8533	.7281	3.857	14.88	3.292	10.834
2.8	.8610	.7413	4.055	16.44	3.491	12.19
2.9	.8682	.7538	4.263	18.17	3.701	13.70

(Continued on next page)

$\frac{2308}{\frac{32}{2276}}$

$\frac{1265}{\frac{273}{1538}}$

Calculation of radiation power using Hottel formula - grey ~~surfaces~~

$$P = A\sigma(T_1^4 - T_2^4)\frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

$T_1 = 1538°K$ $\quad T_1^4 = (1.54)^4 \times 10^{12} = 5.6 \times 10^{12}$

$T_2 = 810°K$ $\quad = (.81)^4 \times 10^{12} = .43$

$\frac{968}{\frac{537}{\frac{273}{810}}}$

$T_{12} = \sqrt{810 \times 1538} = 1120$

$\varepsilon_1 = .2$ $\quad \varepsilon_{12} = .127$

$\frac{1}{\varepsilon_1} = 5$ $\quad \frac{1}{\varepsilon_{12}} = 7.9$

$\frac{5}{12.9}$ $\quad \frac{1}{11.9} = .084$

$(T_1^4 - T_2^4) = 5.2 \times 10^{12} \times .084 = .437 \times 10^{12}$

$\sigma = 5.65 \times 10^{-8}$

$P = 2.47 \times 10^4$ watts/m^2

$= 2.47$ watts/cm^2

$\phi_R' = 2.7$ $\quad \frac{I_{max}}{I_m} = \frac{2.02}{.464} = 4.35$

$.1325 \ln 4.35 = .195$

$\phi_R = 2.5$

Electron cooling $= 2.02 \times 2.5 \times 10^4 = 5 \times 10^4$

Eff at Power max $= \frac{.84}{7.47} = 11.2\%$

Table 3E (Emitter Space) (Continued)

Numerical Solution[1] to the Langmuir Equation for Space Charge in the Emitter Space (Eq. 36-1).

ψ_s	χ_s	χ_s/χ_m	$(\chi_s/\chi_m)^2$
8.0	1.788	.9900	.9802
9.0	1.795	.9939	.9878
10.0	1.799	.9961	.9921
12.0	1.803	.9983	.9967
14.0	1.805	.9994	.9989
16.0	1.805	.9994	.9989

1 Based on tables computed by P. H. J. A. Kleynen, Philips Res. Rep. 1, 81 (1946).

Note 1. See Eqs. 37-1; 37-3; 37-5 and 37-6 for empirical equations for these data and the means for extrapolation.

Note 2. The limiting value of χ_s is $\chi_m = 1.806$.

Note 3. Definitions: $\psi_s = V_s/V_T = qV_s/kT$ and $\chi_s^2 = (x_s/x_1)^2$ with $(x_1)^2$ given by Eq. 35-2.

ϕ_1 should be $\ll (2.5 - .133) = 2.37$ ev

Since ϕ_2 is shown to be 1.91

it is to be expected that $\phi_1 < 1.91$

and condition above is satisfied

H & K show max eff at

$V_0 = .623^v$

See table I at $\Sigma = 2.31$ $\frac{I}{I_m} = 3.69$

$2.31 \times .1325 = .306$ which is change in

voltage from 2.7 $\therefore V_{out} = (2.39 - 1.91) = .48$

Current is

$3.69 \times .465 = 1.71 \times 10^4$ a/m²

Power is $(.48 \times 1.71 \times 10^4) = 0.82 \times 10^4$

compared with 0.84×10^4

$\phi' = 2.39$ and el. cooling is 4.08×10^4 w/m²

$$eff = \frac{.82}{2.47 + 4.08} = 12.5\%$$

Table 3E (Emitter Space) (Continued)

Numerical Solution[1] to the Langmuir Equation for Space Charge in the Emitter Space (Eq. 36-1).

ψ_s	χ_s	χ_s/χ_m	$(\chi_s/\chi_m)^2$
1.1	1.171	.6484	.4203
1.15	1.189	.6584	.4335
1.2	1.208	.6689	.4473
1.25	1.225	.6783	.4602
1.3	1.242	.6877	.4731
1.35	1.258	.6966	.4853
1.4	1.273	.7049	.4970
1.45	1.288	.7132	.5086
1.5	1.302	.7209	.5197
1.6	1.330	.7364	.5424
1.7	1.356	.7508	.5638
1.8	1.380	.7641	.5837
1.9	1.402	.7763	.6028
2.0	1.423	.7879	.6208
2.1	1.444	.7996	.6392
2.2	1.462	.8095	.6552
2.3	1.480	.8195	.6714
2.4	1.497	.8289	.6871
2.5	1.513	.8378	.7018
2.6	1.527	.8455	.7150
2.7	1.541	.8533	.7282
2.8	1.555	.8610	.7413
2.9	1.568	.8682	.7539
3.0	1.580	.8749	.7652
3.1	1.590	.8804	.7751
3.2	1.602	.8870	.7867
3.3	1.611	.8920	.7956
3.4	1.621	.8976	.8057
3.5	1.631	.9031	.8155
3.6	1.639	.9075	.8235
3.8	1.655	.9164	.8398
4.0	1.670	.9247	.8551
4.2	1.683	.9319	.8683
4.4	1.694	.9380	.8799
4.6	1.705	.9441	.8913
4.8	1.715	.9496	.9017
5.0	1.724	.9546	.9112
5.5	1.742	.9646	.9305
6.0	1.756	.9723	.9455
6.5	1.767	.9784	.9572
7.0	1.776	.9834	.9670
7.5	1.783	.9873	.9746

(Continued on next page)

V	V/V_T	I_o	J_o
.241	1.815	.204	2.79
.502	3.78	.111	1.52
.540	4.07	.099	1.36
.570	4.30	.089	1.22
.595	4.49	.081	1.11
.618	4.66	.075	1.03
.638	4.81	.070	.96
.670	5.05	.061	.836
.701	5.29	.051	.699
.732	5.52	.046	.630
.800	6.04	.032	.438
.885	6.66	.020	.274
.945	7.12	.012	.164
1.00	7.54	.0086	.118
1.05	7.92	.0051	.070
1.2	9.05	.0020	.027

area $\frac{(.125\times 2.54)^2\,\pi}{4} = .079\,cm^2$

used area of .073

Recalculation

$T = 1540°K$

$V_T = 0.1325 \qquad V_T^{1/2} = 0.364$

$$V_T^{3/2} = 48 \times 10^{-3}$$

$I_{m(obs.)} = 0.42 \times 10^4 \ a/m^2 \quad \Big| \quad \frac{V_R}{V_T} = 6.2$

$V_R = .82$

$$W^2 = \frac{9.66 \times 10^{-6} \times 48 \times 10^{-3}}{.42 \times 10^4} = 1.105 \times 10^{-10}$$

$W = 1.05 \times 10^{-5} m$

$$I_{max} = 0.42 \times 10^4 \underbrace{\left[1 + 0.31 \times 11.4\right]}_{4.53}$$

$$= 1.90 \times 10^4$$

$$P_{max} = 3.7 \times 10^{-6} \times .364 \times \frac{(.82)^2}{1.10 \times 10^{-10}}$$

$$= 0.82 \times 10^4 \ n/m^2$$

$V_{out} = \frac{.82}{1.9} = 0.42$

$$= \frac{.383 \times 6.2 \times .82}{4.53} = .43$$

Table 11 (Continued)

The Fermi Level and Its Temperature Coefficient for Selected Donor Concentration and Energy Level. (Section 64.)

$N_o = 3 \times 10^{21}$

V_T^{-1}	μ'	E = -.6 μ	E = -.8 μ	E = -.9 μ	E = -1.0 μ	E = -1.1 μ	E = -1.2 μ	E = -1.4 μ	E = -1.6 μ
8	1.511	-1.425	-1.425	-1.426	-1.428	-1.433	-1.441	-1.478	-1.543
10	1.175	-1.107	-1.110	-1.117	-1.130	-1.152	-1.184	-1.265	-1.357
12	.957	- .901	- .917	- .939	- .972	-1.012	-1.056	-1.152	-1.250
14	.804	- .761	- .802	- .840	- .883	- .930	- .979	-1.077	-1.177
16	.691	- .666	- .733	- .778	- .826	- .874	- .924	-1.024	-1.124
18	.604	- .603	- .686	- .734	- .783	- .833	- .883	- .983	-1.083
20	.536	- .560	- .652	- .701	- .751	- .801	- .851	- .951	-1.051
22	.480	- .529	- .625	- .675	- .725	- .775	- .825	- .925	-1.025
24	.435	- .505	- .603	- .653	- .703	- .753	- .803	- .903	-1.003
26	.397	- .486	- .585	- .635	- .685	- .735	- .785	- .885	- .985

V_T^{-1}	$\frac{d\mu'}{dV_T}$	E = -.6 $\frac{d\mu}{dV_T}$	E = -.8 $\frac{d\mu}{dV_T}$	E = -.9 $\frac{d\mu}{dV_T}$	E = -1.0 $\frac{d\mu}{dV_T}$	E = -1.1 $\frac{d\mu}{dV_T}$	E = -1.2 $\frac{d\mu}{dV_T}$	E = -1.4 $\frac{d\mu}{dV_T}$	E = -1.6 $\frac{d\mu}{dV_T}$
8	13.589	-12.889	-12.850	-12.785	-12.638	-12.333	-11.784	-10.041	-8.413
10	13.254	-12.521	-12.215	-11.693	-10.776	- 9.640	- 8.603	- 7.281	-6.693
12	12.981	-12.092	-10.682	- 9.360	- 8.190	- 7.381	- 6.877	- 6.395	-6.228
14	12.750	-11.298	- 8.546	- 7.455	- 6.807	- 6.446	- 6.251	- 6.090	-6.029
16	12.550	- 9.877	- 7.117	- 6.520	- 6.218	- 6.069	- 5.996	- 5.943	-5.932
18	12.373	- 8.316	- 6.389	- 6.082	- 5.947	- 5.887	- 5.860	- 5.844	-5.840
20	12.215	- 7.180	- 6.006	- 5.860	- 5.801	- 5.762	- 5.768	- 5.762	-5.761
22	12.072	- 6.479	- 5.800	- 5.730	- 5.704	- 5.695	- 5.691	- 5.690	-5.689
24	11.941	- 6.061	- 5.674	- 5.641	- 5.630	- 5.626	- 5.625	- 5.624	-5.624
26	11.821	- 5.806	- 5.587	- 5.571	- 5.566	- 5.565	- 5.564	- 5.564	-5.564

(Continued on next page)

$\phi'_R = .1325(39.59 + 3.67 -$

$$\begin{array}{r} 3.67 \\ \hline 43.26 \\ 23.08 \\ \hline 20.16 \end{array}$$

$.0\cancel{8}$

$(11.54)2 =$

23.08

$= 2.67$

$\phi_2 = 2.67 - .82 \quad = \quad 1.85$

$\phi' = 2.67 - .1325 \ln 4.53$

$.2$

$\phi' = 2.47$

$2.47 \cancel{8} + .265$

$$\begin{array}{r} .265 \\ \hline \cancel{2.6} \\ 2.735 \end{array}$$

$2.735 \times 1.9 \times 10^4$

Cooling 5.2×10^4 W/m2

$\cancel{.26}$ $2.67 - .306 = 2.364$

$$\begin{array}{r} 1.85 \\ \hline .51 \end{array}$$ Vout

Pout = .79 W

Current is $3.69 \times \cancel{4}.2 = 1.55$

Table 11 (Continued)

The Fermi Level and Its Temperature Coefficient for Selected Donor Concentration and Energy Level. (Section 64.)

$N_o = 10^{21}$

		E = -.6	E = -.8	E = -.9	E = -1.0	E = -1.1	E = -1.2	E = -1.4	E = -1.6
V_T^{-1}	μ'	μ	μ	μ	μ	μ	μ	μ	μ
8	1.648	-1.562	-1.562	-1.562	-1.563	-1.565	-1.568	-1.587	-1.634
10	1.285	-1.216	-1.218	-1.220	-1.226	-1.238	-1.260	-1.328	-1.415
12	1.048	- .991	- .998	-1.010	-1.033	-1.067	-1.107	-1.199	-1.296
14	.882	- .835	- .858	- .888	- .927	- .972	-1.019	-1.117	-1.216
16	.759	- .724	- .774	- .815	- .861	- .909	- .959	-1.058	-1.158
18	.665	- .646	- .719	- .766	- .814	- .864	- .913	-1.013	-1.113
20	.591	- .594	- .680	- .729	- .778	- .828	- .878	- .978	-1.078
22	.530	- .557	- .650	- .700	- .750	- .800	- .850	- .949	-1.049
24	.481	- .530	- .626	- .676	- .726	- .776	- .826	- .926	-1.026
26	.439	- .508	- .606	- .656	- .706	- .756	- .806	- .906	-1.006

		E = -.6	E = -.8	E = -.9	E = -1.0	E = -1.1	E = -1.2	E = -1.4	E = -1.6
V_T^{-1}	$\frac{d\mu'}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$
8	14.688	-13.992	-13.979	-13.956	-13.903	-13.777	-13.518	-12.232	-10.220
10	14.353	-13.646	-13.534	-13.304	-12.766	-11.797	-10.563	- 8.542	- 7.543
12	14.080	-13.318	-12.605	-11.485	-10.033	- 8.794	- 7.955	- 7.128	- 6.840
14	13.848	-12.849	-10.546	- 9.011	- 7.918	- 7.302	- 6.965	- 6.686	- 6.608
16	13.648	-11.887	- 8.498	- 7.498	- 6.979	- 6.722	- 6.596	- 6.505	- 6.484
18	13.471	-10.285	- 7.324	- 6.809	- 6.576	- 6.471	- 6.425	- 6.396	- 6.390
20	13.313	- 8.696	- 6.735	- 6.482	- 6.379	- 6.338	- 6.321	- 6.312	- 6.311
22	13.171	- 7.596	- 6.431	- 6.309	- 6.264	- 6.248	- 6.242	- 6.239	- 6.239
24	13.040	- 6.928	- 6.260	- 6.202	- 6.183	- 6.176	- 6.174	- 6.174	- 6.173
26	12.920	- 6.531	- 6.153	- 6.125	- 6.117	- 6.114	- 6.114	- 6.113	- 6.113

(Continued on next page)

$\phi' = 2.67$

$$\begin{array}{r} .173 \\ \hline 2.50 \end{array}$$

Cooling $\begin{array}{r} 2.5 \\ .306 \\ \hline 2.806 \end{array} \times 1.55 = 4.35$

$$\frac{.79}{6.82} = 11.6\%$$

$$\begin{array}{r} 2.47 \\ 4.35 \\ \hline 6.82 \end{array}$$

at max power.

$$\frac{.82}{7.67} = 10.7\%$$

$$\begin{array}{r} 2.47 \\ 5.2 \\ \hline 7.67 \end{array}$$

Table 11 (Continued)

The Fermi Level and Its Temperature Coefficient for Selected Donor Concentration and Energy Level. (Section 64.)

$N_o = 10^{20}$

V_T^{-1}	μ'	E = -.6 μ	E = -.8 μ	E = -.9 μ	E = -1.0 μ	E = -1.1 μ	E = -1.2 μ	E = -1.4 μ	E = -1.6 μ
8	1.936	-1.850	-1.850	-1.850	-1.850	-1.850	-1.850	-1.853	-1.864
10	1.516	-1.446	-1.446	-1.447	-1.447	-1.449	-1.454	-1.482	-1.546
12	1.240	-1.182	-1.183	-1.185	-1.190	-1.204	-1.228	-1.302	-1.395
14	1.046	-.997	-1.001	-1.011	-1.032	-1.066	-1.107	-1.201	-1.299
16	.903	-.861	-.876	-.902	-.940	-.985	-1.032	-1.130	-1.230
18	.793	-.758	-.795	-.835	-.880	-.928	-.978	-1.077	-1.177
20	.706	-.680	-.742	-.788	-.836	-.886	-.936	-1.036	-1.136
22	.635	-.624	-.704	-.753	-.802	-.852	-.902	-1.002	-1.102
24	.577	-.585	-.675	-.724	-.774	-.824	-.874	-.974	-1.074
26	.528	-.556	-.651	-.701	-.751	-.801	-.851	-.951	-1.051

V_T^{-1}	$\frac{d\mu'}{dV_T}$	E = -.6 $\frac{d\mu}{dV_T}$	E = -.8 $\frac{d\mu}{dV_T}$	E = -.9 $\frac{d\mu}{dV_T}$	E = -1.0 $\frac{d\mu}{dV_T}$	E = -1.1 $\frac{d\mu}{dV_T}$	E = -1.2 $\frac{d\mu}{dV_T}$	E = -1.4 $\frac{d\mu}{dV_T}$	E = -1.6 $\frac{d\mu}{dV_T}$
8	16.990	-16.297	-16.295	-16.293	-16.288	-16.274	-16 242	-16.243	-15.018
10	16.656	-15.961	-15.949	-15.923	-15.846	-15.634	-15.118	-12.708	-10.187
12	16.382	-15.682	-15.590	-15.344	-14.645	-13.253	-11.543	-9.208	-8.308
14	16.151	-15.424	-14.837	-13.552	-11.608	-9.966	-8.946	-8.073	-7.824
16	15.951	-15.107	-12.857	-10.694	-9.198	-8.399	-8.002	-7.715	-7.647
18	15.774	-14.493	-10.372	-8.859	-8.130	-7.800	-7.663	-7.562	-7.544
20	15.616	-13.172	-8.794	-8.006	-7.681	-7.549	-7.496	-7.467	-7.462
22	15.473	-11.282	-7.997	-7.614	-7.471	-7.420	-7.401	-7.391	-7.390
24	15.342	-9.644	-7.600	-7.416	-7.355	-7.335	-7.328	-7.325	-7.325
26	15.222	-8.574	-7.390	-7.302	-7.276	-7.268	-7.266	-7.265	-7.265

(Continued on next page)

$T = 1510$

$V_T = .13 \qquad = 1.3 \times 10^{-2}$

$V_T^{3/2} = \cancel{1.482}\ 47 \times 10^{-3}$

$\omega = 10^{-5}$

$$I_m = \frac{9.66 \times 47 \times 10^{-3} \times 10^{-6}}{10^{-10}} = 4.53 \times 10^{+3}\ a/m^2$$

$$\phi_R' = \frac{1510\left(43.2 + 4.6 \times (-5)\right)}{11600} \qquad \begin{matrix} 230 \end{matrix}$$

$.13 \times 20.2$

$= 2.63$

$\cancel{\phi_R}$

$V_R = 2.63 - 1.57 = 1.06$

$\frac{V_R}{V_T} = 8.16$

$I_{max} = 6 \times 4.53 \times 10^{-2} = 27.18 \times 10^{+3}$

$\phi' = 2.63 - .23 = 2.4$

Cooling power $= 2.4 \times 27 \times 10^3 = 65 \times 10^3 / m^2$

$$P_{max} = \frac{3.7 \times 10^{-6}}{10^{-10}} \cdot .36 \times \cancel{.576}\,(1.06)^2 = \cancel{87.2}\ 1.5 \times 10^4\ w/m^2$$

eff $=$

$$\frac{\cancel{87.2}\ 1.5}{6.56 + 10.\cancel{1} + \cancel{87.2}\ \cancel{18}} = \frac{1.5}{\cancel{31.5}\ 16.56} = 9.1\%$$

$$\frac{1.5}{6.56} = \frac{1.5}{11.5} = 13\%$$

$11.5 - 6.56 = 5$ for radiation

CALENDAR FOR WEEK OF OCTOBER 6 - OCTOBER 10, 1958

PHYSICS

HARVARD UNIVERSITY AND MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Monday, October 6

Harvard University

4:00 p.m. - Tea served in the Library of the Jefferson Laboratory.

4:45 p.m. - Large Lecture Hall, Jefferson Laboratory
Physics and Applied Science Colloquium
"Ice"
Professor Bruce Chalmers

Wednesday, October 8

Harvard University

3:45 p.m. - Applied Mechanics Colloquium
Pierce Hall, Room 209
"Sloshing of Liquids in Circular Canals and Spherical Tanks"
Professor Bernard Budiansky
Harvard University
Coffee will be served after the colloquium.

Thursday, October 9

Harvard University

4:00 p.m. - Tea served in the Harvard College Observatory Library.

4:30 p.m. - Harvard Astronomical Colloquium, Harvard College Observatory Library
"An Outline of a Physical Theory of Galactic Structure and Evolution"
Professor K. F. Ogorodnikov
Leningrad University Observatory

Massachusetts Institute of Technology

* 3:30 p.m. - Tea will be served in the Cafeteria of Lincoln Laboratory.

4:00 p.m. - Physics Colloquium, Cafteria of Lincoln Laboratory
"Recent Developments in the Theory of Superconductivity"
Professor John Bardeen
University of Illinois

* NOTE

Transportation will be provided to Lincoln for the Colloquium of October 9. There will be busses at the entrance of the Main Parking Lot on Massachusetts Avenue at 3:00 p.m. Transportation will also be provided back to Harvard Square and M.I.T. from Lincoln at the end of the Colloquium.

Will those people who need transportation tell Miss Phillips, Room 6-306, Extension 877, by Monday, October 6.


7.6
.4
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(2.8)
U^2
From table 8
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2.4
2.8
3.2
3.6
4.0
4.4
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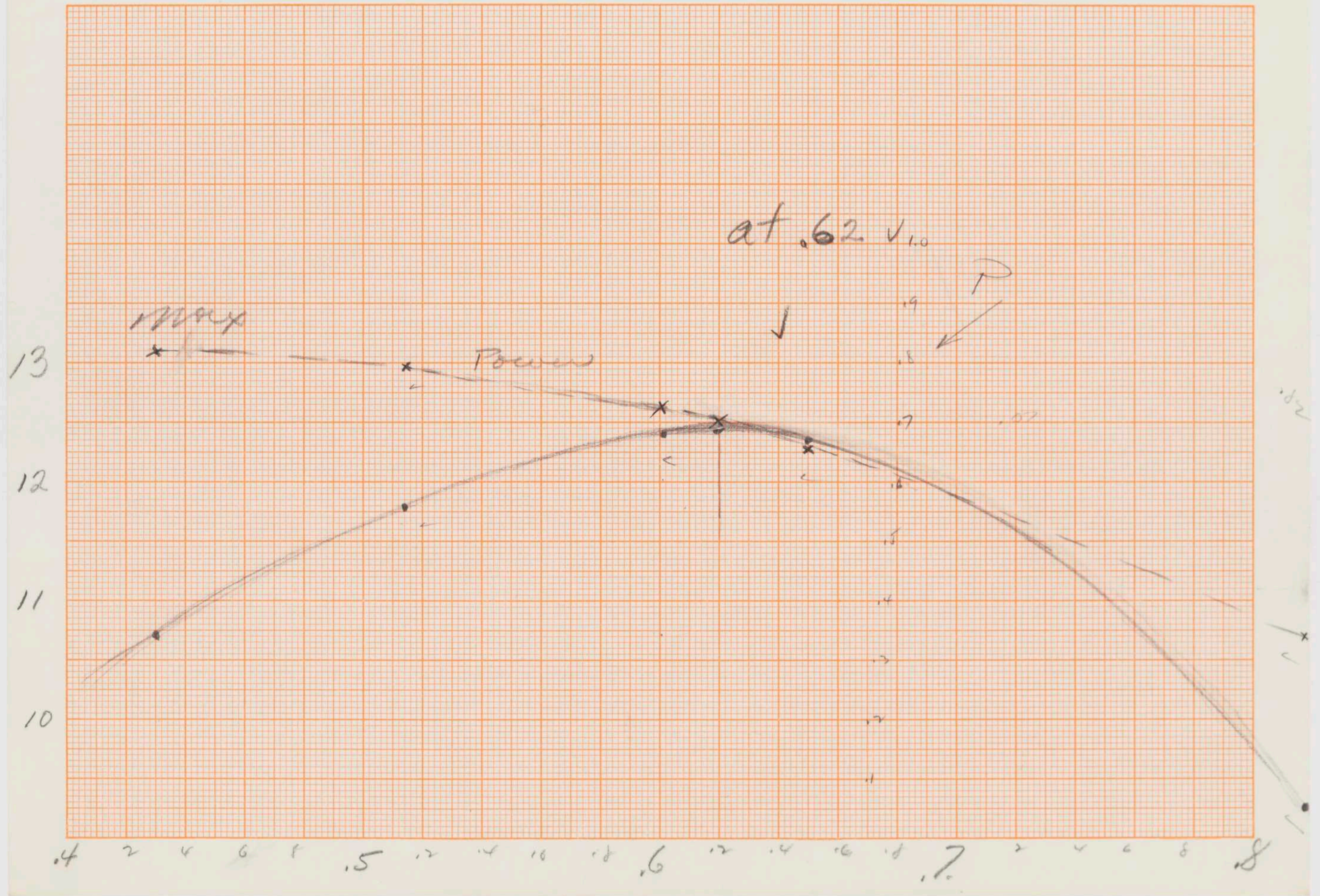
K+E 10 X 10 TO THE 1/2 INCH KEUFFEL & ESSER CO. 359-11 MADE IN U.S.A.



See p 28

a check on Eg 9

$$0 = \frac{1}{2}\ln T + 2\ln W + \ln \frac{120\times 10^{4}}{7.729\times 10^{-12}} - \frac{\phi_R'}{V_T}$$

$$\phi_R' = V_T($$

$$\frac{120}{7.729} = 15.56$$

$$\ln 10^{17.192} = 39.55$$

39.59 was used which is ok

When $I_{\cancel{max}} = I_M = 0.42$

$\frac{1}{2}\ln T$ $\quad 2\ln W$

$$P_e = .1325(41.59 + 3.67 - 22.90) \times .42$$

$$\begin{array}{r} 3.67 \\ \hline 45.26 \\ 22.90 \\ \hline 22.36 \end{array}$$

$$.42 \times (.265 + .82)$$

$$\begin{array}{r} 2.67 \\ \hline 2.935 \end{array}$$

$$P_e = 1.24 = 1.235$$

$$eff = \frac{.82\times .42}{(2.47 + 1.24)} = \frac{3.44}{3.71} = 9.28\%$$

Table 11 (Continued)

The Fermi Level and Its Temperature Coefficient for Selected Donor Concentration and Energy Level. (Section 64.)

$N_o = 3 \times 10^{20}$

		E = -.6	E = -.8	E = -.9	E = -1.0	E = -1.1	E = -1.2	E = -1.4	E = -1.6
V_T^{-1}	μ'	μ	μ	μ	μ	μ	μ	μ	μ
8	1.799	-1.712	-1.712	-1.712	-1.713	-1.713	-1.714	-1.722	-1.746
10	1.406	-1.336	-1.337	-1.338	-1.340	-1.344	-1.356	-1.404	-1.482
12	1.149	-1.091	-1.093	-1.098	-1.111	-1.134	-1.167	-1.252	-1.347
14	.968	- .919	- .929	- .948	- .979	-1.019	-1.064	-1.160	-1.260
16	.835	- .794	- .824	- .858	- .901	- .948	- .997	-1.096	-1.196
18	.732	- .702	- .757	- .801	- .848	- .897	- .947	-1.047	-1.147
20	.651	- .636	- .712	- .760	- .809	- .858	- .908	-1.008	-1.108
22	.585	- .590	- .678	- .727	- .777	- .827	- .877	- .977	-1.077
24	.531	- .557	- .652	- .701	- .751	- .801	- .851	- .951	-1.051
26	.486	- .532	- .630	- .680	- .729	- .779	- .829	- .929	-1.029

		E = -.6	E = -.8	E = -.9	E = -1.0	E = -1.1	E = -1.2	E = -1.4	E = -1.6
V_T^{-1}	$\frac{d\mu'}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$
8	15.892	-15.198	-15.194	-15.187	-15.170	-15.131	-15.039	-14.431	-12.729
10	15.557	-14.860	-14.825	-14.748	-14.536	-14.025	-13.052	-10.438	- 8.726
12	15.284	-14.569	-14.309	-13.718	-12.485	-10.897	- 9.551	- 8.087	- 7.563
14	15.052	-14.260	-12.946	-11.209	- 9.567	- 8.494	- 7.886	- 7.378	- 7.235
16	14.852	-13.745	-10.550	- 8.916	- 7.993	- 7.525	- 7.295	- 7.129	- 7.184
18	14.675	-12.638	- 8.678	- 7.756	- 7.332	- 7.141	- 7.057	- 7.004	- 6.993
20	14.517	-10.892	- 7.686	- 7.227	- 7.039	- 6.963	- 6.932	- 6.915	- 6.913
22	14.374	- 9.252	- 7.192	- 6.970	- 6.888	- 6.858	- 6.847	- 6.842	- 6.841
24	14.244	- 8.143	- 6.934	- 6.828	- 6.793	- 6.781	- 6.777	- 6.776	- 6.775
26	14.124	- 7.475	- 6.787	- 6.737	- 6.722	- 6.717	- 6.716	- 6.715	- 6.715

(Continued on next page)

Take $\upsilon^2 = 2.86$

$\Sigma = 1.65$

$\Delta V = 1.65 \times .1325 = .2185$

$V_{out} = .82 - .22 = .6015$

$I = 2.86 \times .42 = 1.2\ a/cm^2$

$P_{out} = \underline{.721\ w/cm^2}$

$\phi' = 2.67 - \cancel{tw}\ .1325\ ln\ 2.86$ 1.05

$\underline{.139}$

$2.531 = \phi'$

$\underline{.265}$

2.796

$P_e = 2.796 \times 1.2 = 3.35$

$\underline{2.47}$

5.82

$eff\ \frac{.721}{5.82} = 12.4\ \cancel{10.59}\ \%$

$\upsilon^2 = 3.69$

$\Sigma = 2.31 \qquad \Delta V = .306$

$V_{out} = .82 - .306 = .514$

$I = 1.55\ a/cm^2 \qquad P_{out} = .797$

$\phi' = 2.67 - .1325 \times 1.305$

$\underline{.173}$

2.497

$\underline{.265}$

2.762

$P_e = 4.29$

2.47

6.76

$eff = 11.8\%$

Table 11 (Continued)

The Fermi Level and Its Temperature Coefficient for Selected Donor Concentration and Energy Level. (Section 64.)

$N_o = 10^{20}$

		E = -.6	E = -.8	E = -.9	E = -1.0	E = -1.1	E = -1.2	E = -1.4	E = -1.6
V_T^{-1}	μ'	μ	μ	μ	μ	μ	μ	μ	μ
8	1.936	-1.850	-1.850	-1.850	-1.850	-1.850	-1.850	-1.853	-1.864
10	1.516	-1.446	-1.446	-1.447	-1.447	-1.449	-1.454	-1.482	-1.546
12	1.240	-1.182	-1.183	-1.185	-1.190	-1.204	-1.228	-1.302	-1.395
14	1.046	- .997	-1.001	-1.011	-1.032	-1.066	-1.107	-1.201	-1.299
16	.903	- .861	- .876	- .902	- .940	- .985	-1.032	-1.130	-1.230
18	.793	- .758	- .795	- .835	- .880	- .928	- .978	-1.077	-1.177
20	.706	- .680	- .742	- .788	- .836	- .886	- .936	-1.036	-1.136
22	.635	- .624	- .704	- .753	- .802	- .852	- .902	-1.002	-1.102
24	.577	- .585	- .675	- .724	- .774	- .824	- .874	- .974	-1.074
26	.528	- .556	- .651	- .701	- .751	- .801	- .851	- .951	-1.051

		E = -.6	E = -.8	E = -.9	E = -1.0	E = -1.1	E = -1.2	E = -1.4	E = -1.6
V_T^{-1}	$\frac{d\mu'}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$
8	16.990	-16.297	-16.295	-16.293	-16.288	-16.274	-16 242	-16.243	-15.018
10	16.656	-15.961	-15.949	-15.923	-15.846	-15.634	-15.118	-12.708	-10.187
12	16.382	-15.682	-15.590	-15.344	-14.645	-13.253	-11.543	- 9.208	- 8.308
14	16.151	-15.424	-14.837	-13.552	-11.608	- 9.966	- 8.946	- 8.073	- 7.824
16	15.951	-15.107	-12.857	-10.694	- 9.198	- 8.399	- 8.002	- 7.715	- 7.647
18	15.774	-14.493	-10.372	- 8.859	- 8.130	- 7.800	- 7.663	- 7.562	- 7.544
20	15.616	-13.172	- 8.794	- 8.006	- 7.681	- 7.549	- 7.496	- 7.467	- 7.462
22	15.473	-11.282	- 7.997	- 7.614	- 7.471	- 7.420	- 7.401	- 7.391	- 7.390
24	15.342	- 9.644	- 7.600	- 7.416	- 7.355	- 7.335	- 7.328	- 7.325	- 7.325
26	15.222	- 8.574	- 7.390	- 7.302	- 7.276	- 7.268	- 7.266	- 7.265	- 7.265

(Continued on next page)

at ~~.64 out~~

$V^2 = 241 \quad \Sigma = 1.28 \quad \Delta V = .1695$

$$\begin{array}{r} .82 \\ .17 \\ \hline .65 \end{array}$$ — V_{out} $I = 1.01$

$P_{out} = .656$

$.1325 \ln 241 = .88 \times .1325 = .1162$

$$\begin{array}{r} 2.67 \\ .116 \\ \hline 2.554 \\ .265 \\ \hline 2.819 \end{array}$$ $\times 1.01 = 2.84 = P_e$

$$\begin{array}{r} 2.47 \\ \hline 5.31 \end{array}$$

$\frac{.656}{5.31} = 12.35$

$P_{out} = .7$ at $.62$ V

$I = 1.13$

$\frac{I}{I_m} = 2.69$

$.1325 \ln 2.69 = .131$

.99

$$\begin{array}{r} 2.67 \\ .131 \\ \hline 2.54 \\ .265 \\ \hline 2.805 \end{array}$$ $\times 1.13 = P_e = 3.17$

$$\begin{array}{r} 2.47 \\ \hline 5.64 \end{array}$$

$\frac{.7}{5.64} = 12.4\%$

Table 7

The Universal Limiting Curve of Figs. 16 and 17 is a Plot of u_o^2 as a Function of S'. (See Section 57.)

			u_o	$u_o \chi_{sR}$		u_o^2	S'
ψ_{sR}	χ_{sR}	$\psi_{sR}/2$	$e^{(\psi_{sR}/2)}$	χ_{co}	ψ_{co}	$e^{\psi_{sR}}$	$\psi_{sR} + \psi_{co}$
.02	.1947	.01	1.0101	.1967	.0180	1.0202	.038
.04	.2721	.02	1.0202	.2776	.0362	1.0408	.076
.06	.3302	.03	1.0305	.3403	.0533	1.0618	.113
.08	.3783	.04	1.0408	.3937	.0703	1.0833	.150
.10	.4201	.05	1.0513	.4417	.0871	1.1052	.187
.15	.5070	.075	1.0779	.5465	.1322	1.1618	.282
.20	.5777	.10	1.1052	.6385	.1750	1.2214	.375
.25	.6385	.125	1.1332	.7235	.223	1.2840	.473
.30	.6923	.15	1.1618	.8043	.270	1.3499	.570
.40	.7835	.2	1.2214	.9570	.372	1.4918	.772
.50	.8605	.25	1.2840	1.1049	.483	1.6487	.983
.60	.9277	.3	1.3499	1.252	.605	1.8221	1.205
.693	.985	.347	1.414	1.393	.732	2	1.425
.80	1.039	.4	1.4918	1.550	.883	2.226	1.683
1.00	1.131	.5	1.6487	1.865	1.22	2.718	2.220
1.099	1.169	.549	1.732	2.025	1.382	3	2.481
1.2	1.208	.6	1.8221	2.201	1.627	3.320	2.827
1.386	1.267	.693	2.000	2.534	2.068	4	3.454
1.4	1.273	.7	2.014	2.564	2.110	4.055	3.51
1.6	1.330	.8	2.226	2.961	2.690	4.953	4.29
1.792	1.375	.896	2.449	3.369	3.33	6	5.12
1.8	1.380	.9	2.460	3.395	3.37	6.050	5.17
2.0	1.423	1.0	2.718	3.868	4.19	7.389	6.19
2.079	1.439	1.040	2.828	4.071	4.55	8	6.63
2.303	1.480	1.151	3.162	4.680	5.69	10	7.99
2.4	1.497	1.2	3.320	4.970	6.28	11.023	8.68
2.773	1.550	1.386	4.000	6.200	8.92	16	11.69
2.8	1.555	1.4	4.055	6.306	9.15	16.44	11.95
2.996	1.580	1.498	4.472	7.065	10.91	20	13.91
3.2	1.602	1.6	4.953	7.935	13.09	24.53	16.29
3.6	1.639	1.8	6.050	9.916	18.40	36.60	22.00
3.689	1.645	1.844	6.325	10.40	19.77	40	23.46
4.0	1.670	2.0	7.389	12.34	25.59	54.60	29.59
4.094	1.675	2.047	7.746	12.98	27.56	60	31.6
4.4	1.694	2.2	9.025	15.288	35.0	81.45	39.4
4.605	1.704	2.303	10.000	17.04	41.0	100	45.6

(Continued on next page)

at $\Sigma = 1.65$

$\frac{I}{I_m} = 2.86$

$$\begin{array}{r} .82 \\ 1.85 \\ \hline 2.67 \end{array}$$

$1.65 \times .1325 = .2185$

$$\begin{array}{r} 2.67 \\ .22 \\ \hline 2.45 \end{array} = \phi'$$

$$\begin{array}{r} .26+ \\ \hline 2.71+ \end{array} = 2V_T$$

$I = 2.86 \times .42 = 1.20$

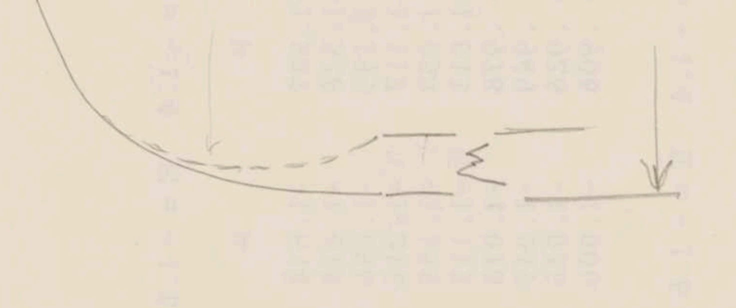
$\underline{P_e = 2.67 \times 1.2 = 3.2 \ w/cm^2}$

$V_{out} =$

$\frac{V}{V_T} \doteq 4.5 \quad V = .596$

$$\begin{array}{r} 1.85 \\ \hline 2.446 \end{array}$$ surface of col.

$4.7 \times .1325 = v$



$\phi_R' = 2.67$

Table 11 (Continued)

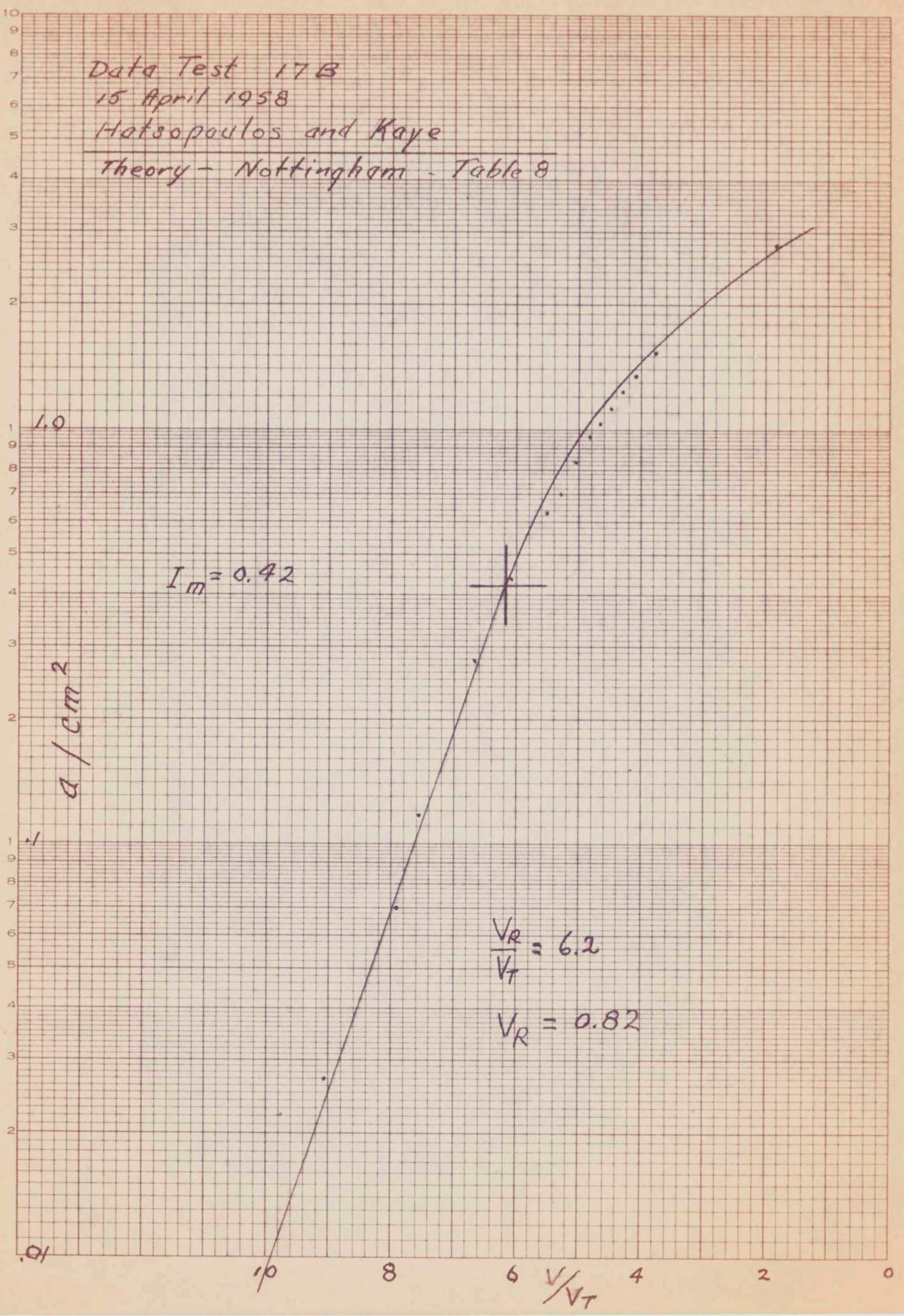
The Fermi Level and Its Temperature Coefficient for Selected Donor Concentration and Energy Level. (Section 64.)

$N_o = 10^{21}$

V_T^{-1}	μ'	E = -.6 μ	E = -.8 μ	E = -.9 μ	E = -1.0 μ	E = -1.1 μ	E = -1.2 μ	E = -1.4 μ	E = -1.6 μ
8	1.648	-1.562	-1.562	-1.562	-1.563	-1.565	-1.568	-1.587	-1.634
10	1.285	-1.216	-1.218	-1.220	-1.226	-1.238	-1.260	-1.328	-1.415
12	1.048	- .991	- .998	-1.010	-1.033	-1.067	-1.107	-1.199	-1.296
14	.882	- .835	- .858	- .888	- .927	- .972	-1.019	-1.117	-1.216
16	.759	- .724	- .774	- .815	- .861	- .909	- .959	-1.058	-1.158
18	.665	- .646	- .719	- .766	- .814	- .864	- .913	-1.013	-1.113
20	.591	- .594	- .680	- .729	- .778	- .828	- .878	- .978	-1.078
22	.530	- .557	- .650	- .700	- .750	- .800	- .850	- .949	-1.049
24	.481	- .530	- .626	- .676	- .726	- .776	- .826	- .926	-1.026
26	.439	- .508	- .606	- .656	- .706	- .756	- .806	- .906	-1.006

V_T^{-1}	$\frac{d\mu'}{dV_T}$	E = -.6 $\frac{d\mu}{dV_T}$	E = -.8 $\frac{d\mu}{dV_T}$	E = -.9 $\frac{d\mu}{dV_T}$	E = -1.0 $\frac{d\mu}{dV_T}$	E = -1.1 $\frac{d\mu}{dV_T}$	E = -1.2 $\frac{d\mu}{dV_T}$	E = -1.4 $\frac{d\mu}{dV_T}$	E = -1.6 $\frac{d\mu}{dV_T}$
8	14.688	-13.992	-13.979	-13.956	-13.903	-13.777	-13.518	-12.232	-10.220
10	14.353	-13.646	-13.534	-13.304	-12.766	-11.797	-10.563	- 8.542	- 7.543
12	14.080	-13.318	-12.605	-11.485	-10.033	- 8.794	- 7.955	- 7.128	- 6.840
14	13.848	-12.849	-10.546	- 9.011	- 7.918	- 7.302	- 6.965	- 6.686	- 6.608
16	13.648	-11.887	- 8.498	- 7.498	- 6.979	- 6.722	- 6.596	- 6.505	- 6.484
18	13.471	-10.285	- 7.324	- 6.809	- 6.576	- 6.471	- 6.425	- 6.396	- 6.390
20	13.313	- 8.696	- 6.735	- 6.482	- 6.379	- 6.338	- 6.321	- 6.312	- 6.311
22	13.171	- 7.596	- 6.431	- 6.309	- 6.264	- 6.248	- 6.242	- 6.239	- 6.239
24	13.040	- 6.928	- 6.260	- 6.202	- 6.183	- 6.176	- 6.174	- 6.174	- 6.173
26	12.920	- 6.531	- 6.153	- 6.125	- 6.117	- 6.114	- 6.114	- 6.113	- 6.113

(Continued on next page)



Data Test 17B
15 April 1958
Hatsopoulos and Kaye
Theory - Nottingham - Table 8
$I_m = 0.42$
$\frac{V_R}{V_T} = 6.2$
$V_R = 0.82$
a / cm²
V/V_T
1.0
.1
.01
10
8
6
4
2
0

Addendum Remarks on a
Diode Configuration of a Thermo-Electron Engine
by

Wayne B. Nottingham, George N. Hatsopoulos, and Joseph Kaye
Massachusetts Institute of Technology
Cambridge, Massachusetts

Three contributions to the literature have been made by us. The first two[1,2] by Hatsopoulos and Kaye presented the results of experimental studies made on a very close-spaced parallel plane diode~~s~~ designed for the purpose of showing in a quantitative manner the conversion of heat to electric power. The paper by Nottingham is a theoretical analysis of this problem, by means of which the design factors are quantitatively related and the physics of the design explained in fundamental terms. Superficially there seems to be a conflict between the first two papers and the third. There are two reasons for this apparent conflict. The first results from a natural misinterpretation of the text material since most of the readers including W. B. Nottingham are likely to interpret the data as though they applied to studies with a diode spacing of 0.001 inch, whereas in fact they applied to a diode of spacing 0.001 cm. The second point of disagreement is related more specifically to the interpretation of the data presented in the two papers in that the authors state[2]: "Analysis of the space-charge barrier shows that its effects could be completely eliminated for practical purposes, for a given value of the net current, and for the case of plane cathode and anode, as in Fig. 1 (of ref 2), if the separation, y, is made very small, of the order of ~~0100~~ 0.001 inch." This statement leads the reader to believe that their results apply to a diode in which space charge has been "eliminated", whereas the experimental results shown in the papers indicate clearly that space charge is playing a very important role in the actual operation of the experimental tube. It is the purpose of this ~~letter~~ note to point out as briefly as possible that the theory presented by W. B. Nottingham[3] is in very exact agreement with the experimental results presented in the second paper[2]. ¶ Figure 1 shows the experimental determination of current density carried across the diode as a function of the voltage difference between the emitter and the collector. The theoretical curve shown was computed directly from the universal-diode data given in Table 8 of "Thermionic Emission".[4] The interpretation that ~~the~~ theory places on these data is that the critical value of (V_R/V_T) is 5.95 and the critical applied potential V_R is 0.79 volt. This potential is critical because for larger values of negative voltage the current flow across the diode is not inhibited by space charge, whereas for voltages less negative than this, a space-charge minimum exists between the emitter and the collector. At this critical voltage, the potential gradient at the collector is exactly zero. Equation 1 is a theoretical equation which relates the current density that can flow under this condition to the two parameters, namely, the spacing, w, and the voltage equivalent of the temperature V_T.

$$I_m = 7.729 \times 10^{-12} \frac{T^{3/2}}{w^2} = 9.664 \times 10^{-6} \frac{V_T^{3/2}}{w^2} \text{ ; amp/m}^2. \qquad (1)$$

For the~~se~~ data, shown in Fig. 1, the emitter was operated at 1540°K and the corresponding voltage equivalent of temperature is 0.1325. With a spacing $w = 10^{-5}$m, the current density calculated is in exact agreement with the current density observed.[3] ¶ Under the condition that maximum power is being delivered to the external load ~~when~~ the current flow is given by ~~Eq. 2~~

$$I_{max} = I_m \left[1 + 0.31 \left(\frac{V_R}{V_T} \right)^{4/3} \right]. \qquad (2)$$

> Insert A

? sentence

The maximum power that can be delivered is given by ~~Eq. 3~~

$$P_{max} = 3.7 \times 10^{-6} \; V_T^{1/2} \left(\frac{V_R}{w}\right)^{\cancel{4/3}\,2} . \qquad (3)$$

The output voltage of the device is given by ~~Eq. 4~~

$$V_{out} = \frac{0.383 \left(\frac{V_R}{V_T}\right) V_R}{1 + 0.31 \left(\frac{V_R}{V_T}\right)^{4/3}} . \qquad (4)$$

Although the maximum power depends strongly on the spacing, it is of interest to note that the voltage output under the condition of maximum power is independent of the spacing.

It is of engineering interest to answer questions concerning the efficiency of this device. The test model was obviously very inefficient and the calculated efficiencies given by Hatsopoulos and Kaye[1,2] were based on the assumption that an advanced engineering design would ultimately reduce the necessary power input to a minimum. For that design the dominating losses would ~~then~~ be the radiation loss from the emitter to the collector and the "electron cooling" of the emitter. The electron cooling can be calculated with accuracy from the experimental data given and the theoretical ~~treatments~~ analyses of W. B. Nottingham[3,4]. Hatsopoulos and Kaye used a radiant heat transfer equation developed by Hottel[5] and emissivity data of Forsyth and Watson[6] to compute a radiation loss of 2.47 watts per square centimeter. With an external resistance adjusted to give an output voltage of 0.48v, the computed electron cooling is 4.08 watts per square centimeter and the power delivered to the load is 0.82 watts per square centimeter thus giving an "optimistic" figure of 12.5 per cent as the efficiency of conversion assuming that all other

Insert B

losses can be reduced to negligible proportions.

It is hoped that these addendum remarks will clear up misunderstandings and establish the fact that there is no basic disagreement between the experimental data presented by Hatsopoulos and Kaye and the theoretical analysis by Nottingham.

Inserts

Insert A

Furthermore these data serve to give an accurate value to the true work-function to the collector. The current flow equation establishes the fact that the surface of the collector under the condition of zero field at the collector is 2.7 volts negative with respect to the Fermi level within the interior of the emitter. Since the observed applied potential for this condition was 0.79 volt, the true work-function of the collector is the difference between these numbers, namely, 1.91 volts. Further analysis shows that the results are completely independent of the work-function of the emitter if its value is less than ~~0~~2.37 volt. ~~Since in general~~ For dispenser cathodes the emitter work-function is generally less than the collector work-function, and therefore this condition ~~may~~ was ~~be~~ satisfied for the emitters used. ~~subject, of course, to the maintenance of suitable vacuum conditions.~~

that face each other

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The equation used by Nottingham[3] to calculate the power radiated

by the emitter is more conservative than that used by Hatsopoulos and Kaye

to include some correction for the porosity and the non-ideal nature of

since it attempted ~~on~~ the emissivity and the absorbtivity of the surfaces used

in the experiment. The calculated radiation using the Hottel formula

assumption that the surfaces are ideal "grey" and on the

depends to a large extent on the applicability of experimental results obtained

with polished, pure tungsten surfaces completely free from porosity.

can be made

Additional research is needed before accurate predictions concerning the

ultimate efficiency of these energy converters.

References

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4. W. B. Nottingham, "Thermionic Emission", Handbuch der Physik, 21, 1, (1956) Springer-Verlag, Berlin, Germany.

5. H. C. Hottel, Chap. 4 of "Heat Transmission" by W. H. McAdams, McGraw-Hill, 3rd edition, 1954.

6. W. E. Forsythe and E. M. Watson, Jour. Opt. Soc. of America, 24, 114, April (1934).


Langmuir
Ct
Langmuir + Jones XI
Forsythe + Watson
J.O. Soc. 24, 114 (1934)
19.05
3.35
= 5.69
from F+W
Ct
Jones-Lang
Hottel theory
for polished tungsten
(No porosity)
300
1000
2000

°K	E_T	W/cm²
800	074	.1730
900	089	.333
1000	.105	.600
1100	.121	1.01
1200	.138	1.63
1300	.156	2.54
1400	.174	3.82
1500	.192	5.54
1600	.207	7.74
1700	.222	10.58
1800	.236	14.15
1900	.248	18.45
2000	.259	23.65

536.33

Nielsen radiant heat
transfer among surfaces
separated by
non-abs. media
MIT Rio 1951 65p.

Hottel + McAdams

660.61

M41

24 1934 p 154

Table 11 (Continued)

The Fermi Level and Its Temperature Coefficient for Selected Donor Concentration and Energy Level. (Section 64.)

$N_o = 10^{21}$

		E = -.6	E = -.8	E = -.9	E = -1.0	E = -1.1	E = -1.2	E = -1.4	E = -1.6
V_T^{-1}	μ'	μ	μ	μ	μ	μ	μ	μ	μ
8	1.648	-1.562	-1.562	-1.562	-1.563	-1.565	-1.568	-1.587	-1.634
10	1.285	-1.216	-1.218	-1.220	-1.226	-1.238	-1.260	-1.328	-1.415
12	1.048	- .991	- .998	-1.010	-1.033	-1.067	-1.107	-1.199	-1.296
14	.882	- .835	- .858	- .888	- .927	- .972	-1.019	-1.117	-1.216
16	.759	- .724	- .774	- .815	- .861	- .909	- .959	-1.058	-1.158
18	.665	- .646	- .719	- .766	- .814	- .864	- .913	-1.013	-1.113
20	.591	- .594	- .680	- .729	- .778	- .828	- .878	- .978	-1.078
22	.530	- .557	- .650	- .700	- .750	- .800	- .850	- .949	-1.049
24	.481	- .530	- .626	- .676	- .726	- .776	- .826	- .926	-1.026
26	.439	- .508	- .606	- .656	- .706	- .756	- .806	- .906	-1.006

		E = -.6	E = -.8	E = -.9	E = -1.0	E = -1.1	E = -1.2	E = -1.4	E = -1.6
V_T^{-1}	$\frac{d\mu'}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$	$\frac{d\mu}{dV_T}$
8	14.688	-13.992	-13.979	-13.956	-13.903	-13.777	-13.518	-12.232	-10.220
10	14.353	-13.646	-13.534	-13.304	-12.766	-11.797	-10.563	- 8.542	- 7.543
12	14.080	-13.318	-12.605	-11.485	-10.033	- 8.794	- 7.955	- 7.128	- 6.840
14	13.848	-12.849	-10.546	- 9.011	- 7.918	- 7.302	- 6.965	- 6.686	- 6.608
16	13.648	-11.887	- 8.498	- 7.498	- 6.979	- 6.722	- 6.596	- 6.505	- 6.484
18	13.471	-10.285	- 7.324	- 6.809	- 6.576	- 6.471	- 6.425	- 6.396	- 6.390
20	13.313	- 8.696	- 6.735	- 6.482	- 6.379	- 6.338	- 6.321	- 6.312	- 6.311
22	13.171	- 7.596	- 6.431	- 6.309	- 6.264	- 6.248	- 6.242	- 6.239	- 6.239
24	13.040	- 6.928	- 6.260	- 6.202	- 6.183	- 6.176	- 6.174	- 6.174	- 6.173
26	12.920	- 6.531	- 6.153	- 6.125	- 6.117	- 6.114	- 6.114	- 6.113	- 6.113

(Continued on next page)

Hilary Moss. - (1)

J. El. + Control

Vol 2, 305, Jan 1957

impedance matching ?

" upper limits of available power on the assumption that the space charge barrier is non-existent"

p. 306. Explains the influence of the anode and cathode work-function"

Moss's eqns (2) and (3) serve to confuse the issue by expressing the anode w-f. so indirectly.

Analysis of p 308

Takes current density

$$I = AT^2 e^{-\frac{qV}{V_T}}$$ (my notation)

Which means $V = IR + \phi_a$

IR = output volts and power in res. is $I^2R = IV_0$ This the area in the diagram NPMX

R is the total ohmic resistance in the circuit - Talk about "bulk res of the coating

Table 5 (Continued)

Collector Region Potential and Its Relation to Emitter Properties and Current Flow. (Use with Eq. 46-2 and related equations.)

ψ_c	χ_c^2	$\left[F(\psi_c)\right]$	$\left[F(\psi_c)\right]^{3/4}$	$\left[F(\psi_c)\right]^{3/2}$
4.00	14.190	6.8708	4.2438	18.01
4.50	16.394	7.5657	4.5618	20.81
5.00	18.662	8.2486	4.8672	23.69
5.50	21.004	8.9243	5.1633	26.66
6.00	23.406	9.5926	5.4507	29.71
6.50	25.867	10.255	5.7306	32.84
7.00	28.388	10.911	6.0033	36.04
7.50	30.958	11.559	6.2690	39.30
8.00	33.594	12.205	6.5299	42.64
9.00	39.000	13.483	7.0363	49.51
10.0	44.622	14.749	7.5260	56.64
11.0	50.424	16.002	8.0006	64.01
12.0	56.400	17.241	8.4611	71.59
13.0	62.552	18.473	8.9107	79.40
14.0	68.857	19.696	9.3493	87.41
15.0	75.342	20.914	9.7796	95.64
16.0	81.957	22.115	10.198	104.0
18.0	95.648	24.516	11.018	121.4
20.0	109.83	26.885	11.807	139.4
25.0	147.87	32.782	13.700	187.7
30.0	188.79	38.587	15.482	239.7
35.0	232.26	44.294	17.170	294.8
40.0	278.22	49.966	18.794	353.2
45.0	326.89	55.637	20.372	415.0
50.0	377.52	61.236	21.891	479.2
60.0	484.88	72.357	24.809	615.5
70.0	600.25	83.426	27.604	762.0
80.0	722.53	94.400	30.285	917.2
90.0	850.89	105.26	32.863	1080.1
100.0	985.96	116.16	35.378	1252.
150.0	1745.6	169.97	47.074	2216.
200.0	2626.6	223.44	57.741	3334.
300.0	4692.3	328.57	77.175	5956.
400.0	7103.1	433.22	94.958	9017.
500.0	9808.9	537.20	111.58	12451.
600.0	12783.	640.95	127.39	16227.
700.0	16002.	744.48	142.52	20313.
800.0	19432.	847.43	157.06	24667.
900.0	23074.	950.20	171.14	29290.
1000.0	26929.	1053.3	184.89	34184.

(Continued on next page)

Hilary Moss. -

(1)

J. El. + Control

Vol 2, 305, Jan 1957

impedance matching?

"upper limits of available power on the assumption that the space charge barrier is non-existent"

p. 306. Explains the influence of the anode and cathode work-function

Moss's eqns (2) and (3) serve to confuse the issue by so indirectly expressing the anode w-f.

Analysis of p 308

Takes current density

$$I = AT^2 e^{-\frac{qV}{V_T}}$$ (my notation)

Which means $V = IR + \phi_a$

IR = output volts and power in res. is $I^2R = IV_0$ This the area in the diagram NPMX

R is the total ohmic resistance in the circuit - Talk about "bulk res of the coating and the "interface layer" does not bring out the point clearly

---

All of Moss's 1st analysis applies only if the zero field emission of the cathode is less than I_m of my equation (2)

$$I_m = 9.66 \times 10^{-6} \frac{V_T^{3/2}}{W^2}$$

Under this condition it is quite likely that $V_{out} = V_T$ his eq (4) (Max power)

---

his Sec 2,2

talks about a value of $1 a/cm^2 = 10^4 a/m$ at $V_T =$ ~~1160~~ 0,1 or (1160 °K)

Use above and solve for W,

$$W^2 = \frac{6.66 \times 10^{-10} \times}{10^{3/2}}$$

$$\doteq 2 \times 10^{-10}\ m^2$$

$$\text{or } 14 \times 10^{-6}\ m$$

---

or 14μ and uses an oxide coated cathode.

Table 5

Collector Region Potential and Its Relation to Emitter Properties and Current Flow. (Use with Eq. 46-2 and related equations.)

ψ_c	χ_c^2	$\left[F(\psi_c)\right]$	$\left[F(\psi_c)\right]^{3/4}$	$\left[F(\psi_c)\right]^{3/2}$
.01	.02074	.08849	.16227	.02633
.02	.04215	.1420	.23132	.05351
.03	.06396	.1875	.28494	.08119
.04	.08602	.22846	.33045	.1092
.05	.1084	.26654	.37094	.1376
.06	.1311	.3025	.40792	.1664
.07	.1540	.3369	.44215	.1955
.08	.1772	.3698	.47424	.2249
.09	.2004	.4015	.50438	.2544
.10	.2240	.4324	.53320	.2843
.15	.3441	.5757	.66091	.4368
.20	.4680	.7067	.77078	.5941
.25	.5951	.8295	.86914	.7554
.30	.7251	.9462	.95937	.9204
.35	.8578	1.0584	1.0436	1.089
.40	.9930	1.1672	1.1229	1.261
.45	1.130	1.2716	1.1975	1.434
.50	1.270	1.3748	1.2696	1.612
.60	1.555	1.5736	1.4050	1.974
.70	1.847	1.7649	1.5312	2.345
.80	2.146	1.9542	1.6505	2.724
.90	2.455	2.1334	1.7652	3.116
1.00	2.766	2.3101	1.8738	3.511
1.10	3.084	2.4840	1.9786	3.915
1.20	3.408	2.6550	2.0799	4.326
1.40	4.072	2.9896	2.2735	5.169
1.60	4.757	3.3163	2.4574	6.039
1.80	5.457	3.6338	2.6319	6.927
2.00	6.180	3.9482	2.8009	7.845
2.20	6.917	4.2560	2.9631	8.780
2.40	7.667	4.5583	3.1196	9.732
2.60	8.433	4.8559	3.2711	10.70
2.80	9.217	5.1538	3.4205	11.70
3.00	10.011	5.4463	3.5651	12.71
3.20	10.824	5.7367	3.7068	13.74
3.40	11.649	6.0243	3.8453	14.79
3.60	12.482	6.3072	3.9799	15.84
3.80	13.330	6.5908	4.1134	16.92

(Continued on next page)

The trouble with the Moss analysis is that he used the wrong parameters and could not make use of the Langmuir space charge theory easily.

Statement:

"It is now apparent that we may attain reasonable efficiency only by employing cathodes yielding high saturated emission densities, together with very small cathode-anode spacing." (Note no mention here of anode w.f.) and no means of calculating what is meant by ("high sat. emiss.")

1) Moss uses inappropriate parameters.
2) Does not use good eqns to relate experimental factors.
3) applies calculations to oxide cathodes. not generally useful
4) Does not show independence of cathode w.f. and dependence on anode w.f.

Table 4 (Continued)

Emitter Region Potential and Its Relation to Emitter Properties and Current Flow. (See Sections 43 and 44 and Fig. 9.)

ψ_s	z	z^2	u_o	u_o^2	$(I_o/I_m)^{1/2}$	I_o/I_m
3.0	.8749	.7654	4.482	20.09	3.922	15.38
3.1	.8804	.7751	4.712	22.20	4.148	17.21
3.2	.8870	.7868	4.953	24.53	4.393	19.30
3.3	.8920	.7957	5.207	27.11	4.644	21.57
3.4	.8976	.8057	5.474	29.96	4.913	24.14
3.5	.9031	.8156	5.755	33.12	5.197	27.01
3.6	.9075	.8236	6.050	36.60	5.490	30.14
3.8	.9164	.8398	6.686	44.70	6.127	37.54
4.0	.9247	.8551	7.389	54.60	6.833	46.69
4.2	.9319	.8684	8.166	66.69	7.610	57.91
4.4	.9380	.8798	9.025	81.45	8.465	71.66
4.6	.9441	.8913	9.974	99.48	9.416	88.67
4.8	.9496	.9017	11.023	121.51	10.47	109.6
5.0	.9546	.9113	12.18	148.4	11.63	135.2
5.5	.9646	.9304	15.64	244.7	15.09	227.7
6.	.9723	.9454	20.09	403.4	19.53	381.4
6.5	.9784	.9573	25.79	665.1	25.23	636.7
7.	.9834	.9671	33.12	1096.6	32.57	1060.5
7.5	.9873	.9748	42.52	1808.	41.98	1762.4
8	.9900	.9801	54.60	2981.	54.05	2921.7
9	.9939	.9878	90.02	8103.	89.47	8004.
10	.9961	.9922	148.4	22026.	147.8	21854.
12	.9983	.9966	403.4	$.16275 \times 10^6$	402.7	$.1622 \times 10^6$
14	.9994	.9988	1096.6	1.2026×10^6	1096.	1.201×10^6
16	.9994	.9988	2981.	8.8861×10^6	2979.	8.875×10^6

Note 1. ψ_s and χ_s from Table 3E.

$z = (\chi_s/\chi_m)$ from Eq. 43-7.

$u_o^2 = I_o/I_R = e^{\psi_s}$ from Eq. 43-5.

$(I_o/I_m) = z^2 e^{\psi_s}$ from Eq. 43-6.

See L.W. Kerr on Non Magnetic Mass Spect. J Electron 2, 179 Sept 1956

Thermionic Energy Converter.

K.G. Hernqvist
M. Kanefsky
F.H Norman

RCA Rev
Vol XIX, 244 June 1958

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p 244 – statement (1) that high cathode w.f. is needed for eff. is wrong.

2) Meaning of "overcome space charge" very vague.

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245 Statement "When the external circuit between - - - -" is very wrong.

Max output volt $\phi_C - \phi_A$ wrong.

p 246 Efficiency eq(2) neglects $2V_T$ and does not the radiation problem justice

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Theoretical back ground lacking

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attributes "resonance ionization" idea as applied to cesium to A.V. Engel + M Steenbeck – Elecktrische Gasentladungen – Springer 1932 (p 130) not to Langmuir Kingdon.