ADDENDUM REMARKS ON A DIODE CONFIGURATION OF A THERMO-ELECTRON ENGINE by Wayne B. Nottingham et al (undated

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

by

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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 designed for the purpose of showing in a quantitative manner the conversion of heat to electric power. The paper by Nottingham[3] 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[1,2] 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 centimeter. The second point of disagreement results from the statement made by the authors[1,2] that the effects of space charge could be completely eliminated for practical purposes, for a given value of the net current. This statement is true for currents corresponding to large values of the retarding potential, but it is certainly not true for the current that corresponds to the maximum power output, as was apparent from their data. It is the purpose of this 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 data are from Fig. 1 of reference 2. The theoretical curve shown was computed directly from the universal-diode data given in Table 8 of "Thermionic Emission."[4] The interpretation that theory places on these data is that the critical value of (V_R/V_T) is 6.2 and the critical applied potential V_R is 0.82 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 critical 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 data shown in Fig. 1, the emitter was operated at 1540°K and the corresponding voltage equivalent of temperature is 0.1325 v. With a spacing $w = 10.5 \times 10^{-6}$ m, the current density calculated is in exact agreement with the current density observed[2].

Furthermore these data serve to give an accurate value to the true work-function of the collector. The current flow equation establishes the fact that the surface of the collector under the critical condition of zero field at the collector is 2.67 volts negative with respect to the Fermi level within the interior of the emitter. Since the observed applied potential for this condition was 0.82 volt, the true work-function of the collector is the difference between these numbers, namely, 1.85 volts. Further analysis shows that the results are completely independent of the work-function of the emitter if its value is less than 2.37 volts.

Under the condition that maximum power is being delivered to the external load, the current flow is given by

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

The maximum power that can be delivered is given by

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

The output voltage of the device at maximum power output is given by

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

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 actual efficiency of the test model was obviously very low 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 rate of thermal energy input to a minimum. For that ideal design the dominating losses would 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 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 $P_r \approx 2.47\ w/cm^2$. The general expression for the electron cooling when the maximum power is delivered to the load is

$$P_e \approx V_T I_{max} \left\{ 41.59 + \frac{1}{2} \ln T + 2 \ln w - \ln \left[1 + 0.31 \left(\frac{V_R}{V_T} \right)^{4/3} \right] \right\} \quad (5)$$

If the radiation loss of an ideal device is much less than the electron cooling then the load conditions for maximum "efficiency" are not the same as those for maximum power output. For the data of Fig. 1

$$P_{max} \approx 0.82\ w/cm^2;\ I_{max} \approx 1.9\ a/cm^2;\ V_{out} \approx 0.43\ v;$$

$$P_e \approx 5.2\ w/cm^2,\ P_r \approx 2.47\ w/cm^2,$$

Under these conditions the idealized efficiency is 10.7 per cent. The theory shows that an increase in load resistance to give an output voltage of 0.62 v gives $I \approx 1.13\ a/cm^2$; $P_{out} \approx 0.7\ w/cm^2$; $P_e \approx 3.17\ w/cm^2$ and an efficiency of 12.4 per cent is the maximum idealized efficiency for the computed value of $P_r \approx 2.47\ w/cm^2$.

The equation used by Nottingham[3] to calculate the power radiated by the emitter is more conservative than that used by Hatsopoulos and Kaye since it attempted to include some correction for the porosity and the non-ideal nature of the emissivity and the absorptivity of the surfaces used in the experiment. The calculated radiation using the Hottel formula depends on the applicability of experimental results obtained with polished, pure tungsten surfaces completely free from porosity. The Hottel formula is derived on the basic assumption that the surfaces are "grey" and then he assumes a method of emissivity evaluation which corrects to some extent for the deviation from the ideal grey. Additional research is needed before accurate predictions can be made concerning the ultimate efficiency of these energy converters.

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

References

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

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3. W. B. Nottingham, J. Appl. Phys. About March (1959).

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, 3 rd edition, 1954.

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Figure Legend

Fig. 1 Observed diode current density of Test 17B Hatsopoulos and Kaye[2] Solid line is theory of Nottingham[4], Table 8. $T = 1540^{\circ}K$; spacing 10.5×10^{-6} m; area 0.073 cm^2.

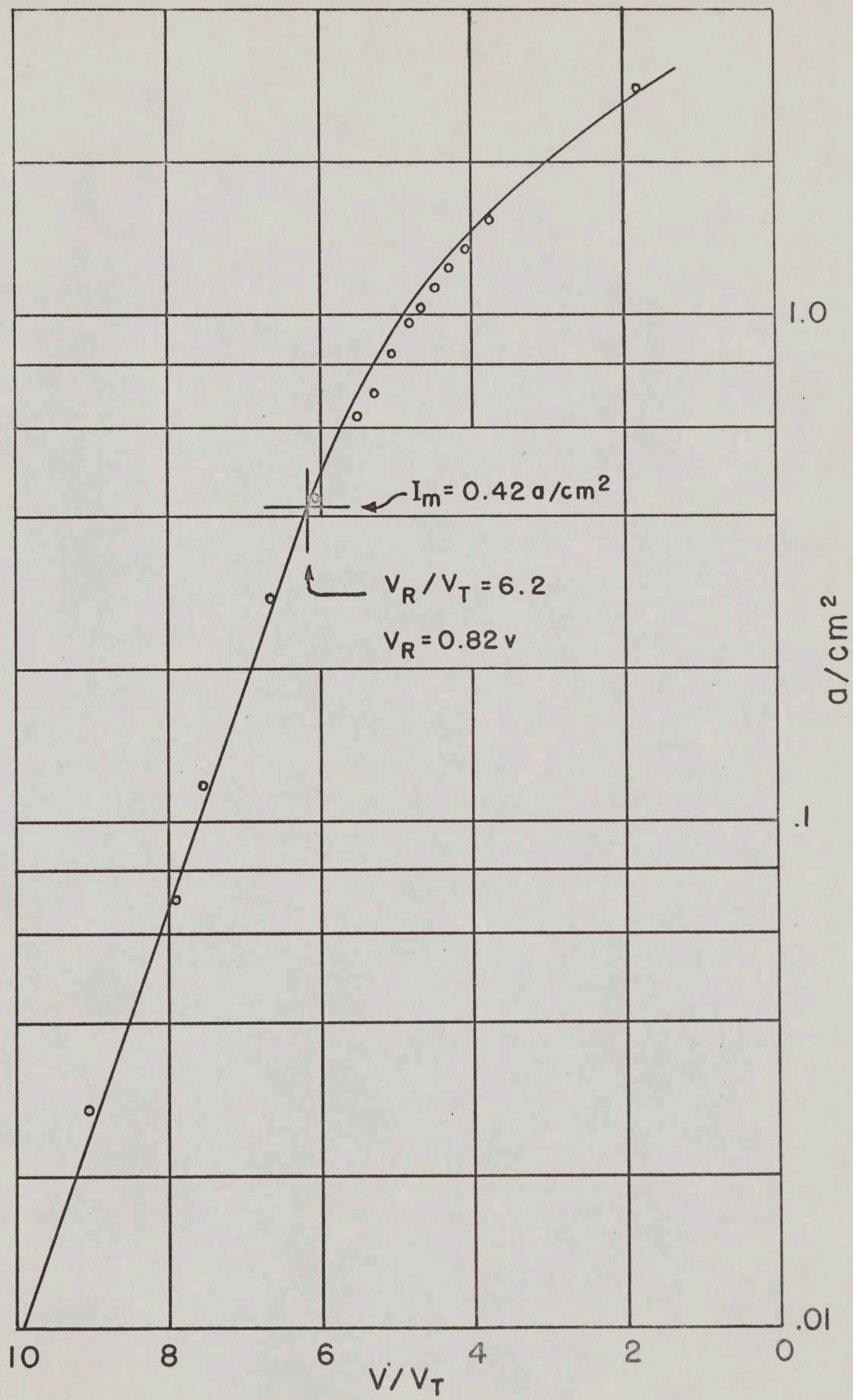

Fig. 1 Nottingham