Direct Conversion of Heat to Electricity

edited by
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Preface

The age-old dream of devising a box, with no moving parts, which converts heat directly into electricity has become a reality in the laboratory. This new development in the art of producing electricity is presently being studied in many parts of the world, and engineers are striving to perfect it for industrial and home consumers. Probably the first small conversion devices which attain practicality will be utilized for exotic space and military applications, but commercial applications are also stimulating considerable interest and research in this new field.

On the one hand, the field of direct energy conversion is so new that practically no trained or experienced personnel are available. On the other hand, the demands by educational, governmental, and industrial groups for engineering talent to work in the general area of direct energy conversion is so large that a significant time lag will occur before this demand is met with adequately trained personnel. Furthermore, no single or concentrated source of reference material exists today to aid new workers in this field to gain a foothold on the varied theories and concepts involved. In view of these facts, a Special Summer Program was offered by the Department of Mechanical Engineering of the Massachusetts Institute of Technology, from July 6 to 17, 1959, on "Direct Conversion of Heat to Electricity." The individual papers presented at this Special Summer Program represented the latest advances in several general areas of research on direct conversion of heat to electricity. On the basis of the excellent attendance and the spirit of this Special Summer Program, we felt it was a privilege not only to be able to partake in the research areas of this new field but also to be able to arrange for such an exchange of information and cross-fertilization of ideas through this Special Summer Program.

One of the unexpected results of this Special Summer Program at M.I.T. was the very large demand from all parts of the world for copies of the notes used therein. Although we had originally planned to transform these notes into a book in a somewhat leisurely fashion, it became evident that such a book would be of immediate interest to many research groups and others, since no comparable collection of new material existed or was foreseen in the immediate future. For this reason, the present volume has not been designed primarily as a text. The editors have not attempted to criticize the work of the contributors or to combine and reorganize the papers into one homogeneous story. Nevertheless, the editors believe that the papers are significant and are basic in the various fields. This book has been designed to get a wealth of available material into the hands of the practicing engineer at the earliest moment, even with the knowledge of incomplete coverage of the subject.

This book has been divided into five general areas as follows:

Section A: Thermionic Engines—High Vacuum
Section B: Thermionic Engines—Low Pressure
Section C: Magnetohydrodynamic Converters
Section D: Semiconductor Devices
Section E: Fuel Cells

Thus the present volume is an edited collection of papers which includes fundamental discussions of thermoelectric energy conversion (the thermocouple), thermionic energy conversion (the vacuum tube and gaseous tube), magnetohydrodynamic conversion (the separation of the positive and negative charges in a gas), and fuel cells (the separation of positive and negative charges during chemical reaction). Discussions of the practical applications and problems associated with each type of conversion scheme are given. We believe that this book will stimulate many fertile minds.

We wish to thank the various authors of the individual papers for their contributions and permission to use them in this volume. We wish to acknowledge permission to reprint some of the papers contained herein from the Institute of Radio Engineers, American Institute of Physics, American Society of Mechanical Engineers, American Institute of Electrical Engineers, Nucleonics, RCA Reviews, and the individual organizations.

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CHAPTER I

Analysis and Experimental Results of a Diode Configuration of a Novel Thermoelectron Engine

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SUMMARY

The direct conversion of heat into useful electrical work without utilization of moving mechanical parts has been successfully achieved in a novel device called the thermoelectron engine. This device is a heat engine in the thermodynamic sense because the working fluid, an electron gas, receives heat at a high temperature, rejects heat at a lower temperature, and delivers useful electrical work to an external load. This heat engine is also a thermionic device in that the electron gas is produced by emission from a hot cathode in a vacuum and by absorption or condensation of the electrons on a colder anode at a higher negative potential.

The basic principle underlying this heat engine is that a calculable fraction of electrons emitted from a hot cathode possess sufficiently high values of emission velocity to overcome a retarding electrostatic potential barrier between cathode and anode in a vacuum. Thus these electrons can transform their high initial value of kinetic energy into useful potential energy at the colder anode; this potential energy can then be utilized by connecting cathode and anode externally through a matched impedance in the form of a load. Hence, this engine utilizes a selection process which results in a large value of output voltage per unit cell compared with the output of a thermoelectric generator per unit thermocouple.

The important engineering aspects of this successful heat engine comprise, first, the use of emissive surfaces which can be machined carefully to high tolerances and thus permit very small

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spacing between cathode and anode, of the order of 0.001 inch or less, and secondly, the heat-transfer designs which can greatly reduce unnecessary heat losses at the required high temperatures.

A brief analysis of the diode configuration of a thermoelectron engine is given to predict the performance of several models. Out of a total of ten successful models of the diode configuration, the experimental results for one model have been selected for presentation here. A thermal efficiency of between 12 to 13 per cent has been attained based on measured power output and calculated values of heat input. Power outputs of the order of 1 watt/cm^2 of emissive surface have been measured with this small feasibility model.

If the theory and the presently available data are used as a basis of extrapolation it appears that thermal efficiencies greater than 15 per cent may be attained. The power output might reach values of the order of 10 to 30 watts/cm^2 of emissive surface. Multiplate designs also indicate the attainability of fairly large values of power output per total volume or per total weight of equipment.

INTRODUCTION

A method for the efficient conversion of heat directly into useful electrical work without the utilization of moving mechanical parts, which shows promise of becoming a practical engineering device, has been successfully tested. The conversion device to be described is the result of a basic research program started about four years ago at M.I.T. in the Research Laboratory of Heat Transfer in Electronics. Several different types of conversion devices have been analyzed and feasibility models have been constructed and tested. All are, in reality, heat engines which employ electrons or an "electron gas" as a working fluid undergoing a cyclic process. These conversion devices, which are based on thermionic emission, are labelled herein "thermoelectron engines" to distinguish them from conversion devices utilizing thermocouples in the form of well-known thermoelectric generators. Although several diverse forms of thermoelectron engines have been analyzed, designed, constructed, and tested, only one particular form, namely the diode configuration, will be described herein.

Briefly, the thermoelectron engine is a true heat engine in the customary thermodynamic sense, and is comparable with the steam power plant as a heat engine. In both heat engines, heat is supplied to a working fluid at high temperature, producing a vapor or gas capable of delivering useful work to the surroundings. Heat is rejected from this working fluid at a lower temperature, and then the fluid completes the cyclic process, being finally pumped to the part of the device supplying heat at the high temperature. In the case of the thermoelectron engine, the working fluid is the electron gas. Initially, this electron gas is in the metallic cathode which is heated to maintain it at a high temperature, T_1. The electron gas is then evaporated or boiled out of the cathode and passed through a vacuum to the colder anode. It is then condensed on the anode which is cooled to maintain it at a lower temperature, T_2. The electron gas delivers useful work to the surroundings as a result of its passage through a retarding electrostatic field in the vacuum between cathode and anode. This useful work is, in fact, the electrical work delivered to the external load.

The use of the Edison effect for the conversion of heat into electric power has often been mentioned in the literature on thermionic devices. Champeix[1] in 1951 gave a qualitative discussion of one such method and concluded that this method was impractical. The first detailed electronic and thermodynamic study on the subject was given by one of the authors in 1956,[2] who analyzed the use of close spacings and of a crossed electric and magnetic field for controlling the effects of space charge. His diode analysis was based on the approximate Childs-Langmuir equation. Subsequently Moss[3] in 1957 analyzed the diode by means of the exact solution of the Poisson's equation.

OBJECTIVES

The objectives of this report are mainly twofold:

1) An analysis of the diode configuration of a novel thermoelectron engine is given in detail.

2) The experimental results obtained with a feasibility model of the diode configuration are given and discussed briefly.

ANALYSIS OF THE DIODE CONFIGURATION

The analysis of this thermionic device operating as a heat engine is based on the laws of thermodynamics, statistical mechanics, and electrical phenomena, including the results available from quantum mechanics. A brief description of this analysis will be given first to acquaint the reader with the basic assumptions used.

Consider a hot plane cathode opposite to a cold plane anode, each being made from the same emissive material. The distribution of electron velocities and energies inside each metal is assumed given by Fermi-Dirac statistics. As the electrons are evaporated from the hot cathode, at say 2500°F, it is assumed that they have a Maxwellian distribution of velocity and energy in the vacuum just beyond the cathode surface. If a negative retarding potential is supplied to the anode, then a calculable fraction of the emitted electrons possess sufficient kinetic energy to overcome this retarding potential barrier in the vacuum between cathode and anode, including the space-charge barrier formed by the electron cloud just beyond the cathode surface. It is evident that a selection process will then occur, in that not all the emitted electrons will pass through this retarding potential, but only those which possess a sufficiently high value of emission velocity normal to the cathode. All those electrons which overcome this retarding potential barrier

[1] Superscripts refer to references at end of chapter.

condense on the colder anode surface, if it is assumed that the reflection coefficient for electrons arriving at the anode is zero; this assumption is not quite true if the quantum-mechanical model of electrons is used.

In addition to the emission of electrons from the hot cathode directed towards the anode, there is also an emission of electrons from the colder anode directed towards the cathode. As in the case of the electrons emitted from the cathode, only a calculable fraction of electrons emitted from the anode will possess a sufficiently high value of emission velocity to overcome the retarding potential barrier from anode to cathode; this barrier is, in general, smaller than that from cathode to anode. Again, it is assumed that the reflection coefficient of electrons reaching the cathode is zero. Hence the net electron flow between cathode and anode is the difference of the two streams described above.

When the cathode and anode are connected by an external circuit through a load, useful electrical work is delivered to this load. In effect, those high-energy electrons which overcome the retarding potential barrier between cathode and anode transform their kinetic energy into useful potential energy at the anode. The output current through the load depends on the temperatures of the cathode and anode, the properties of the emissive materials used, and the spacing between cathode and anode. The thermal efficiency is dependent on these same quantities and also on the heat losses due to radiation and conduction processes.

The analysis of the operation of the diode configuration of the thermoelectron engine is presented briefly.

OUTPUT CURRENT

Consider two parallel plates of emissive material, placed in a vacuum and separated by a distance y, as shown in Fig. 1-1. For steady-state operation, the cathode is maintained at a temperature, T_1, by a steady input of heat flux, q_1, and the anode is maintained at a lower temperature, T_2, by a steady removal of heat flux, q_2. The potential distribution from cathode to anode is illustrated in Fig. 1-2, wherein ϕ_1 is the potential barrier for electrons within the cathode relative to its surface, or its work function, δ is the space-charge barrier, ϕ_2 is the work function of the anode, and V_o is the output voltage obtained when the cathode and anode are connected externally through a load.

The saturation current density of electrons emitted from either cathode or anode in a vacuum is given by the well-known Richardson equation,

$$J_S = AT^2 \exp(-\phi/kT), \qquad (1)$$

wherein it is assumed that the surfaces emit electrons uniformly so that nonuniformities based on patch effects are ignored.

The fraction of the cathode saturation current which reaches the anode is equal to the product of the saturation current and that

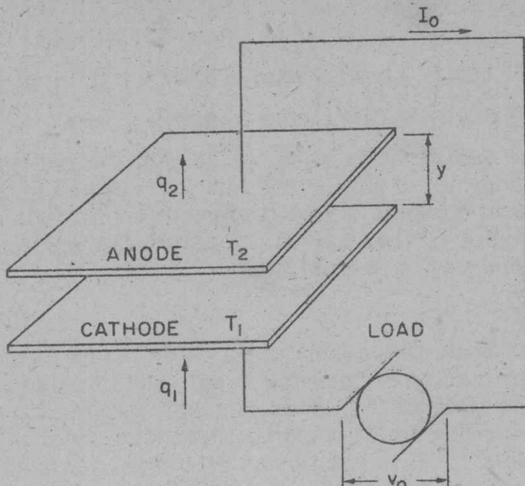

Fig. 1-1. Thermoelectron engine diode configuration.

fraction of emitted electrons which have sufficient initial velocities to overcome the retarding potential barrier of $(\delta + \phi_2 + V_o - \phi_1)$; i.e.,

$$J_{1\to 2} = A_1 T_1^2 \exp(-\phi_1/kT_1) \cdot \exp[-(\delta + \phi_2 + V_o - \phi_1)/kT_1]$$
$$= A_1 T_1^2 \exp(-\phi_2/kT_1) \exp(-\delta/kT_1) \exp(-V_o/kT_1). \quad (2)$$

Likewise, the fraction of the anode saturation current which reaches the cathode is equal to the product of the saturation current and that fraction of emitted electrons which have sufficient initial velocities to overcome the retarding potential barrier equal to δ; i.e.,

$$J_{2\to 1} = A_2 T_2^2 \exp(-\phi_2 kT_2) \exp(-\delta/kT_2). \quad (3)$$

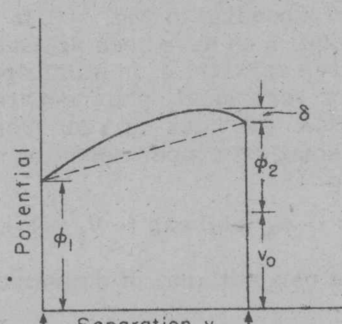

Fig. 1-2. Schematic representation of potential barrier including space charge.

Hence the net current density from cathode to anode is given by

$$\begin{aligned} J_o &\equiv J_{1\to2} - J_{2\to1} \\ &= A_1 T_1^2 \exp(-\phi_2/kT_1) \exp(-\delta/kT_1) \exp(-V_o/kT_1) \\ &\quad - A_2 T_2^2 \exp(-\phi_2/kT_2) \exp(-\delta/kT_2). \end{aligned} \tag{4}$$

The physical significance of eq. (4) is that the net flux of electrons from cathode to anode, or the net current per unit area of emissive surface, depends on the temperatures of cathode and anode, on the space-charge barrier δ and on the work function of only the cold anode ϕ_2, provided that

$$\delta + \phi_2 + V_o > \phi_1.$$

The net current density is independent of the work function of the hot cathode; this rather surprising result has been known for a long time for the case of the anode current collected from a hot cathode in a retarding field, when the retarding field is sufficiently great (see Becker[4]). This result has also been verified experimentally by Davisson in 1924.[5]

Analysis of the space-charge barrier shows that its effects could be controlled for practical purposes, for a given value of the net current, and for the case of plane cathode and anode, as in Fig. 1-1, if the plate separation, y, is made very small, of the order of 0.001 inch. However, the many difficulties of obtaining smooth and uniform emissive surfaces with oxide coatings precluded any practical solution to obtaining such small plate separations. In the last few years, a new engineering emissive material has been developed by the Philips concern in Holland, namely the L cathode. This material can be machined to very close tolerances, handled in a rough fashion compared with the delicate and meticulous handling required for oxide coated cathodes, and activated after machining, cleaning, etc., in a fairly straightforward fashion. With this new emissive material we have been successful, after many arduous efforts, in producing engineering models corresponding to Fig. 1-1, in which plate separations of less than 0.001 inch have been achieved.

If the space-charge barrier, δ, is eliminated from eq. (4), as a result of the use of very small plate separation, and if, as a further approximation, the back current from anode to cathode is made negligibly small by proper selection of T_1 and T_2, then eq. (4) is reduced to

$$J_o = A_1 T_1^2 \exp(-\phi_2/kT_1) \exp(-V_o/kT_1). \tag{5}$$

The power output per unit area of emissive surface is then given by

$$P_o = J_o V_o - P_1, \tag{6}$$

where P_1 is the ohmic loss in the external electrical leads per unit area of emissive surface.

THERMAL EFFICIENCY OF DIODE

The thermal efficiency of a true heat engine is defined by the ratio of net power output to total heat supplied and, for this case of a diode configuration, by

$$\eta \equiv (J_o V_o - P_1)/\Sigma q_i, \tag{7}$$

where Σq_i represents the sum of all heat inputs to the cathode per unit area of emissive surface required to maintain it at temperature, T_1. For the small feasibility model of the diode configuration, which was used to obtain the measured output voltage and current, an accurate measurement of this heat input was most difficult. Hence, the thermal efficiencies given herein are based on measured output voltage and output current and on a calculated value of the heat input on the cathode using the following analysis.

Consider a well-designed engineering model of a multiplate diode configuration of the thermoelectron engine, illustrated schematically in Fig. 1-3.

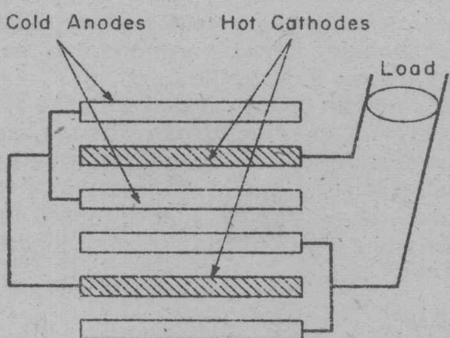

Fig. 1-3. Multiplate diode configuration of thermoelectron engine.

Such a design can be used as a basis for accurate estimation of the total heat inputs to the hot cathodes. Furthermore, it is evident that such a multiplate design, operating in a vacuum, reduces all unnecessary heat losses to a minimum, since each hot cathode is opposed by two cold anodes. An additional advantage of such a design is that almost any combination of voltages and currents becomes possible by using different ways of electrically connecting cathodes and anodes.

For the engineering model represented by the multiplate design of Fig. 1-3, the total heat inputs to the cathodes can be given by

$$\Sigma q_i = J_o \phi_1 + J_o (\phi_2 + V_o + \delta - \phi_1 + 2kT_1) + q_r + q_c, \tag{8}$$

where $J_o\phi_1$ stands for the heat flux corresponding to the latent heat of evaporation of the electrons from the cathodes;

$$J_o(\phi_2 + V_o + \delta - \phi_1 + 2kT_1)$$

represents the heat flux corresponding to the kinetic energy of that selected fraction of electrons which can overcome the retarding potential between cathode and anode; q_r represents the thermal radiation flux between each cathode and the pair of adjacent anodes; q_c represents the thermal conduction flux between each cathode and pair of corresponding anodes due to heat conduction along the necessary electrical leads. It should be remembered that the average kinetic energy of all electrons emitted from the cathode surface is $2kT_1$, but only a selected fraction have a kinetic energy sufficient to overcome the retarding potential equal to $(\phi_2 + V_o + \delta - \phi_1)$.

The thermal radiation flux can be shown, for the geometry of two parallel metallic plates, to be given by

$$q_r = \sigma(T_1^4 - T_2^4)(1/\epsilon_1 + 1/\epsilon_2 - 1)^{-1}, \qquad (9)$$

where the emissivities of the cathode, ϵ_1, and of the anode ϵ_2, are to be evaluated at temperatures, T_1 and $\sqrt{T_1 T_2}$, respectively. The geometric mean temperature is used for determination of ϵ_2 rather than the anode temperature because the metallic surfaces of the cathode and anode are not gray bodies.

The conduction flux can be calculated with the aid of the Fourier rule and the geometry of the electrical leads between cathodes and anodes, and the resistivity of these leads. It was found analytically that for maximum efficiency, the cross section of the electrical leads should be selected so that the ohmic losses in these leads equal approximately one-tenth of the thermal conduction losses in the internal electrical leads.

EXPERIMENTAL RESULTS

General Description of the Diode. The experimental results presented here are based on the diode configuration described schematically in Fig. 1-4. Although ten successful models of this configuration have been constructed and tested in this research program, the preliminary data from only one of them will be given here. In this feasibility model, the cathode and anode were mounted on hollow molybdenum cylinders about 1/8 inch in diameter.

The base of each cylinder was impregnated tungsten, and only these bases of the cylinders, facing each other, were used for electron emission and absorption. Each cylinder was fitted carefully with a separate indirect electric heater, wound to eliminate any magnetic fields. The use of indirect electric heaters permitted us to obtain true equipotential cathodes and anodes. Each cylinder could be used interchangeably with the other as cathode or anode, and each could be heated separately to a given steady temperature.

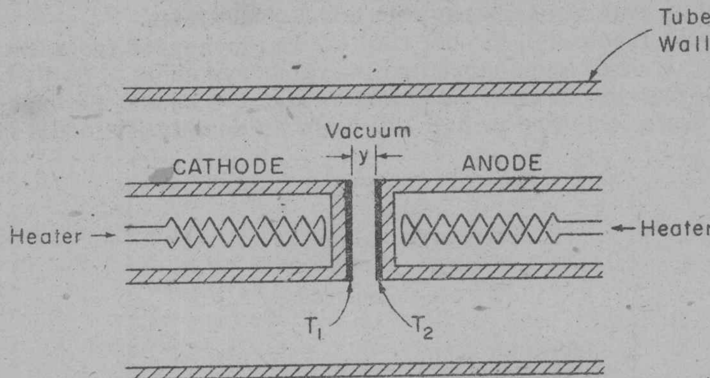

Fig. 1-4. Details of feasibility model of diode configuration of thermoelectron engine.

Hence the reproducibility of the test results could be examined by simply interchanging the roles of the two cylinders. The cylinders were mounted on supports, which are not indicated in Fig. 1-4, so that the separation between the emissive surfaces could be varied carefully and accurately during operation of the diode and without breaking the vacuum.

The results given here are based on use of the same emissive material for cathode and anode. This material is made from tungsten which has been impregnated with various combinations of oxides of barium, aluminum, and calcium. The activation process to get this material to emit at high temperatures is fairly straightforward and requires only that it be heated to temperatures higher than those used in the final tests.

The output voltage and current were measured separately. The output voltage was also examined for ac components or ripples with the aid of an oscilloscope, but ac components were not present during the measurements reported here.

The temperature of the surface of the hot cathode was measured with an optical pyrometer which was calibrated against a standard source and which was carefully corrected experimentally for the deviations for nonblack body emission of the molybdenum cylinder by actually bringing both cathode and anode up to the source temperature in a series of auxiliary experiments. The temperature of the surface of the colder anode was usually too low to use this optical pyrometer for an accurate measurement; hence, its surface temperature was estimated in this feasibility model from known values of the thermal emissivities of the cathode and anode and the view factor for radiative transfer between them, including the conduction along the leads. Since the temperature of the colder anode is of secondary importance here, this estimation method sufficed for this model.

The distance of separation of the two plates was measured with the aid of an optical comparator in some of the tests.

The work function of the hot cathode was measured from auxiliary tests on saturation currents; its value was about 1.7 volt.

Output Current Density vs Voltage. Fig. 1-5 shows the experimental results obtained in Run 17B from the feasibility model of

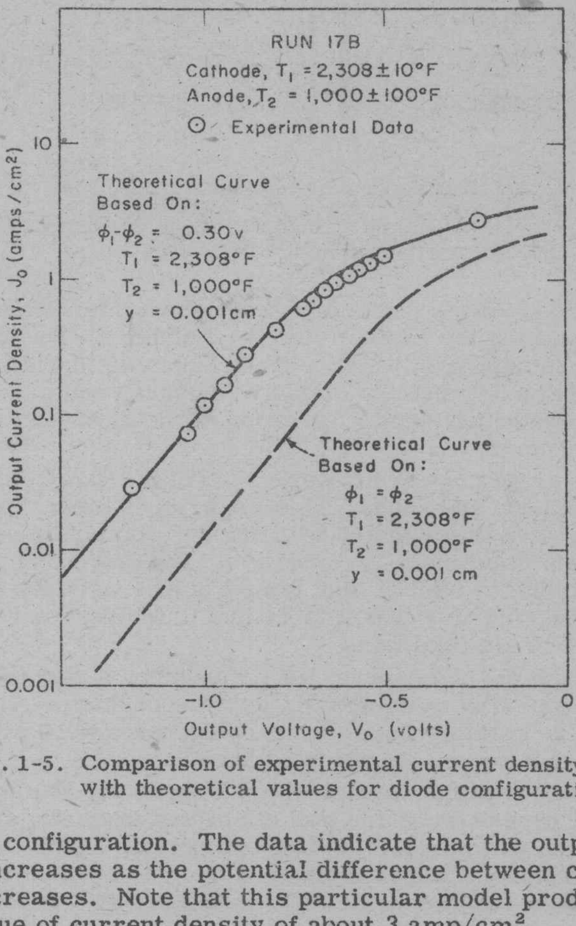

Fig. 1-5. Comparison of experimental current density with theoretical values for diode configuration.

the diode configuration. The data indicate that the output current density increases as the potential difference between cathode and anode decreases. Note that this particular model produced a maximum value of current density of about 3 amp/cm^2.

Fig. 1-5 also shows two theoretical values of current density. The dashed curve was computed for the measured temperature of the cathode of 2308°F, the estimated value of the anode temperature of 1000°F, for equal values of work function of cathode and anode, and for a value of separation of the two plates, y, which was obtained from the tabular values of the solution of the space-charge problem. This solution is found in Kleynen's article.[6] The theoretical dashed curve falls considerably below the experimental points. During the course of testing this model, it was found that the change of work function with temperature of this emissive material could be estimated fairly easily and the results agreed roughly with variations of work function in the literature; see review by Herring and Nichols[7] and Nottingham.[8] Hence these variations were included in the computation of a second theoretical curve, represented by the solid line in Fig. 1-5.

In this second theoretical prediction of current density, the same values of temperature and of plate separation were used, but the work function of the cold anode was assumed to be less by 0.30 volt. This reduction agreed with both our own estimates and with estimates of change of work function with temperature found in the literature.[7,8] The solid line in Fig. 1-5 shows excellent agreement with experimental data. Furthermore, the slope of the asymptote of both the solid and dashed curves, i.e., the linear portion extending to high voltages, can be shown to be equal to $(1/kT_1)$. The value of the cathode temperature deduced from this asymptotic slope for the experimental data points agreed with the measured value of T_1 within $\pm 30°F$. These same data are treated also by W.B. Nottingham in Chapter 2. Excellent agreement is attained between his predictions and these data.

Output Power vs. Voltage. Fig. 1-6 shows the experimental results for Run 17B for power output vs. voltage for the same temperatures as in Fig. 1-5. The data indicate a maximum exists for a voltage of about 0.5 volt. The optimum impedance matching of internal and external load characteristics will be discussed later in a separate publication. (See Chapter 4.) Likewise the theoretical predictions for comparison with the experimental data are omitted.

Thermal Efficiency vs. Voltage. For simplicity of construction of the experimental models tested, there were no provisions made, such as radiation shields and proper geometric design, to reduce the heat input to a minimum. Hence the thermal efficiencies given here were based on the measured voltage and current and on a calculated heat input as explained previously. Fig. 1-7 shows a typical set of data for thermal efficiency vs. output voltage. For this diode configuration a maximum value of thermal efficiency of about 13 per cent was attained for the cathode temperature of 2308°F. Comparison of Figs. 1-6 and 1-7 illustrates that the maximum values of thermal efficiency and power output do not occur at the same value of output voltage. Analysis has also shown that the optimum voltage for thermal efficiency does not coincide with the optimum voltage for power output.

CONCLUSIONS

The analyses presented herein demonstrate that the behavior of the diode configuration of a thermoelectron engine can be predicted accurately. The experimental results show that an engineering model of such a diode configuration is feasible and that values of the thermal efficiency greater than 10 per cent are now