PERFORMANCE OF CESIUM THERMIONIC DIODES OPERATED IN SERIES-PARALLEL CIRCUITS

J.W. HOLLAND*

Atomics International, Canoga Park, Calif.

Abstract

Electrical power degradation from the operation of many series-parallel circuited cesium diodes in a thermionic reactor must be considered when a nonflattened nuclear power distribution exists over the volume of the reactor core. In this experiment the loss of power and efficiency due to unequal heat inputs to series- or parallel-connected diodes is measured and the operating characteristics of a multiple-diode system are studied. The results are applied to a specific thermionic reactor configuration with a ratio of maximum to minimum diode heat input of 1.85. The minimum degradation of power and efficiency was found to be 41 and 19%, respectively, at optimized operating conditions.

I. Introduction

The purpose of this experiment is to determine the loss of electrical power output due to operating many unequally heated cesium diodes, connected in series and parallel circuits. The problem arises in the thermionic reactor application, where unequal heating is the result of a spacial nonuniformity of nuclear power production caused by neutron leakage.

Subjects covered in this paper on in-circuit diodes include 1) the verification of the actual and predicted performance degradation due to unequal heating; 2) the optimization of operating variables for maximum performance; and 3) the exploration of operational problem areas. The

Presented at the ARS Space Power Systems Conference, Santa Monica, Calif., September 25-28,1962. Work performed under U.S. Atomic Energy Commission Contract AT-11-1 GEN-8.
* Senior Research Engineer, Atomics International Division of North American Aviation, Inc.

results of the experiment should be valuable in determining the importance of nuclear power flattening, and to the understanding of the operational behavior of in-circuit diodes.

II. Experimental Apparatus and Procedures

The apparatus consists of three identically prepared cylindrical-geometry diodes and the necessary instrumentation required to test two diodes simultaneously in either independent, series, or parallel circuits. Figure 1 shows a cross section of the diode configuration and a list of the materials and dimensions of importance. The emitter temperature is limited arbitrarily to a maximum value of 1800°C. This will allow a reasonable diode lifetime, and yet permit a relatively high performance level.

In the first part of the experiment, the three diodes were tested independently to obtain data for 1) computing the performance of series and parallel diode circuits, and 2) comparing their performances to determine whether diodes can be manufactured with the same operating characteristics. Then two of the diodes were tested in series and parallel circuits to 1) determine whether the actual and the computed performances agree, and 2) investigate likely operational problem areas.

III. Performance of Individual Diodes

A. Maximizing Power and Efficiency

The maximum performance is determined on the basis of the maximum allowable emitter temperature of 1800°C. Experimentally, the maximum power is obtained by adjusting the operating variable of cesium reservoir temperature, collector temperature, load resistance, and emitter heat input until the power output (P) maximizes while the emitter temperature is maintained at 1800°C. Figures 2 and 3 show the results of this maximization process.

The values of the variables which maximize the performance are termed optimum. The collector temperature (T_C) and cesium reservoir temperature (T_{Cs}) are shown, in Fig. 2, to optimize at 750 and 375°C. Actually, these optima are determined for maximum power in Fig. 2, but the values are also optimum for maximum efficiency. The load is varied in Fig. 3, while holding T_C and T_{Cs} at their optimum values to find the optimum load conditions. The current per emitter area (J) is used as the maximizing variable, which is shown to optimize at 6.6 amp/cm^2 for maximum power and at 5.8 amp/cm^2 for maximum efficiency.

The maximum value of the power output at 4.75 w/cm^2 is designated as P_M and is used hereafter as a factor to normalize the power output. The resulting dimensionless normalized power is used later as an indicator of power degradation. Since the efficiency maximum is 10.0%, the normalization is not necessary for an indication of degradation.

The extreme sensitivity of the power out to a variation of the cesium reservoir temperature is evident in Fig. 2. The most sensitive region is on the low side of the optimum T_{Cs}, where the power falls to zero from the maximum value in 25°C. It will be found later, however, that this sensitivity is diminished in an unequal power input multidiode system. The collector temperature is shown to be a relatively insensitive variable. A departure from the optimum collector temperature, by 150°C, results in only a 15% decrease in the power.

B. Performance vs Power Input

For the purposes of this experiment, it is most convenient to obtain data in the form of voltage output (V) vs power input (Q), for constant values of J or T_{Cs}. Data were obtained in this form, for the purpose of calculating the performance of multiple diode circuits with unequal power inputs. From a preliminary experiment, not covered in this paper, a suitable range of values for the data was determined which would enable optimization of J and T_{Cs} for the unequal input multidiode circuits. These ranges are

$$2 \leq J \leq 10 \text{ amp/cm}^2$$

$$350 \leq T_{Cs} \leq 400°C$$

$$20 \leq Q \leq 50 \text{ w/cm}^2$$

In the next section, the collector temperature is shown to have little effect on the optimization of a multidiode circuit.

The diode voltage (V) is shown, in Fig. 4, as a function of power input (Q) at $T_C = 750°C$ and $T_{Cs} = 375°C$, for integral values of J between 2 and 10 amp/cm^2. The emitter temperature parameter is shown to indicate its variance and the limitation of the applicable power range below

1800°C. The value of the voltage that gives the maximum obtainable power (P_M) is indicated on the 1800°C curve.

Figures 5 - 7 show V vs Q at $T_C = 750°C$ and $J = 5, 6$, and 7 amp/cm^2 for the parameter T_{Cs} ranging between 350 and 400°C. The emitter temperature at 1800°C is shown, to indicate the applicable operating range. In these figures, an interesting result is observed for the $T_{Cs} = 350°C$ curves. There, the voltage is seen to peak and then fall to zero as the power input is increased. This evidently is caused by the sensitivity of the power output to T_{Cs}. The value of Q, where the voltage maximizes on the $T_{Cs} = 350°C$ curve, is the optimum Q for the given value of J.

A moderate degree of instability in the power output was observed when the diode was operating at $T_{Cs} = 350°C$ and at $T_E = 1800°C$. It is noted, in Fig. 7, that the $T_{Cs} = 350°C$ curve is almost vertical near $T_E = 1800°C$, which would cause the voltage to vary markedly with slight variations in Q. In the experiment, the power input is controlled automatically; so apparently the slight resulting perturbations caused the observed instability.

C. Collector Temperature Effects

The power output is shown, in Fig. 8, as a function of the collector temperature, with Q the parameter at $T_{Cs} =$ 375°C. The $Q = 48.6$ w/cm^2 curve is at $T_E = 1800°C$ and $J =$ 6.6 amp/cm^2. The other three curves were made at optimum load conditions for maximum power output.

The optimum value for the collector temperature shows very little dependence on Q; and it could, for intensive purposes, be considered constant at 750°C, for $27 \leq Q \leq 48.6$ w/cm^2. A lower loss in power output is observed for T_C values removed from optimum at the low values of Q.

Since the optimum T_C changes very little with variation of Q in the region of interest, it makes it unnecessary to optimize T_C for the multidiode circuit, because the optimum will be nearly the same as for one diode. This feature makes the entire optimization of an unequal input multidiode circuit much easier.

D. Performance Comparison of the Three Diodes

One of the secondary objectives of the experiment was to determine the degree of performance reproducibility in manufacturing diodes. This is accomplished by comparing the characteristic volt-amp curves for diodes 1,2,and 3 at T_E = 1800°C, T_{Cs} = 375°C, and T_C = 750°C, as shown in Fig. 9. The resulting curve falls within the estimated errors. The errors are based on the assumed emitter temperature error of ± 15°C, as reflected in the variation of the voltage.

A more thorough comparison of the performances of diodes 1 and 2 is shown in Fig. 10. It is evident from Fig. 10 that the performances are very nearly identical. These two diodes were tested in the actual series and parallel circuit tests since their performances were close enough so that the output could be compared easily to the calculated performance based on individual diode data.

IV. Performance of Two Diodes in Series and Parallel Circuits

A. Conditions of Operation

When two diodes are operated in-circuit (Fig. 11) with power inputs Q_1 and Q_2 but $Q_1 \neq Q_2$, and the cesium pressure is optimized, the maximum performance will be obtained if one diode operates at its maximum allowable emitter temperature. In this study, diode 1 is assigned to operate at $(T_E)_{max}$ = 1800°C and to have a power input of Q_1, the value of which is a variable and dependent on the operating parameters. Diode 2 operates with an input Q_2, and an emitter temperature less than 1800°C. In this paper, the applicable range of operation for diode 2 is $0.5Q_1 \leq Q_2 \leq Q_1$.

The ratio Q_2/Q_1 is the parameter used to indicate the variance of Q_2 from Q_1. The ratio $(Q_1 + Q_2)/2Q_1$ is shown also, which is a measure of the average value of Q_1 and Q_2 normalized by Q_1.

The power output of the two in-circuit diodes is shown in this study, as the sum of P_1 and P_2 divided by twice the value of P_M. The resulting quantity, $(P_1 + P_2)/2P_M$, is the power output of the two diodes normalized by the maximum power obtainable. One minus this ratio gives the fractional power degradation experienced in operating under nonoptimum conditions.

The collector temperature (T_C) is held invariant at 750°C which is the optimum value corresponding to the maximum power output (P_M). It has been shown that the power output is affected only slightly by changes in T_C near the optimum value, and also that $(T_C)_{opt}$ is only slightly dependent on Q. An actual attempt to optimize T_C for the two in-circuit diodes is not made, then, because of its very small dependence.

B. Computed Performance

The expected performances of the multidiode circuits are calculated from the individual diode data, using the basic electrical laws governing series and parallel circuits; namely, additive voltages for the series-connected diodes and additive currents for the parallel-connected diodes. The results of the calculation are shown graphically in Figs. 12 - 14. The normalized power output and the efficiency vs the operating variables J and T_{Cs} for the series circuit and vs V for the parallel circuit is given. The variation of T_{Cs} for the parallel circuit is not given, because of less emphasis being placed on the parallel part of the experiment.

Not only is the performance computed for purposes of comparison with the actual data, but also to determine the maximum power output for a given Q_2/Q_1 and the associated optimum cesium reservoir temperature and load conditions. These optimized operating points are listed in Table 1. In order to establish more clearly the power or efficiency degradation trends indicated in Table 1, these results are plotted in Fig. 15.

Two important trends are observed 1) parallel operation of two diodes is less degrading than series operation at the same value of Q_2/Q_1, and 2) the efficiency is reduced to a lesser extent than the power output for a given Q_2/Q_1.

The calculated results also show the expected lowering of the optimum values of J and T_{Cs}, for values of $Q_2/Q_1 < 1$. Another observation is for the graphs of power output and efficiency vs T_{Cs}; it is noted that the knees in the curves are less sharp for the lower values of J. This means that, as T_{Cs} is reduced past the optimum value for the J = 7 case, the power is reduced much more abruptly than for J = 5. The implication here is that it may be more desirable, from an operational viewpoint, to operate at lower values of J. This, of course, is in harmony with the reduction of other operational problems; that of lowering electrical resistance losses in external circuitry, and the production of higher voltage power with the subsequently more efficient inversion, if necessary.

The curves also indicate a desirability of operating on the high side of the optimum T_{Cs}, in order to prevent operation in the extremely sensitive low T_{Cs} region.

C. Actual Performance

In short, the actual and predicted performances were found to agree in all of the operating regions explored, which includes the computed areas of performance shown in Figs. 12 - 14. A sampling of the actual performance is compared with the calculated results, in Figs. 16 and 17, where the power output is shown as a function of Q_2/Q_1, at values of J for series operation and at values of V for parallel operation. The in-circuit data agree within the experimental errors.

Some extremely sensitive operating regions were found, however, as would be predicted from the calculated results. By sensitive, it is meant that slight variations of the input variables, Q and T_{Cs}, cause very large changes in the power output, with a resulting unstable operation.

The worst situation is caused by operating with a low cesium pressure. It is noted, in Fig. 12, that the power output is extremely sensitive to a change in T_{Cs}, at around 350 to 360°C. When operating in this region, the slight changes in T_{Cs}, caused by the T_{Cs}-controlling action, causes either oscillations or, in some cases, instigates a runaway in emitter temperature. These unstable reactions did not cause damage to the diodes in the experimental arrangement, because of a built-in safety mechanism in the diode power supplies which limited the plate current of the electron bombardment heaters.

V. Application of Results to a Space Thermionic Reactor

The power and efficiency losses are now computed for a small fast thermionic reactor,[1] designed for space auxiliary power, which contains about 1000 series-connected thermionic diodes. For this case, each diode has identical geometry, fuel loading, and potential power output (P_M). The ratio of maximum to minimum power input to the diodes (Q_{max}/Q_{min}) is 1.85 ($Q_{min}/Q_{max} = 0.54$). No control perturbations are considered.

In this calculation, it is assumed that all 1000 diodes operate at the same cesium reservoir temperature. This assumption is not necessarily for calculational convenience.

[1] Smith, C.K., Holland, J.W., Hirsch, R., "Design Study of a Thermionic Reactor Power Plant for Space Applications (Title unclassified)," NAA-SR-6077, United States Atomic Energy Commission Report (May 1, 1961).

It is found in thermionic reactor design studies that large numbers of diodes should be operated with a common reservoir for simplicity and reliability. Several reasons back up this decision. The first reason lies in the extreme sensitivity of the performance to the cesium reservoir temperature, so that a high degree of control is essential, which probably would require a sizable piece of equipment. If each diode had to have a separately controlled reservoir, the resulting weight added to the system would be prohibitive. In addition, the reliability of many series-connected diodes, each with its own reservoir, would be reduced; because, if the reservoir of one diode failed, the entire series in effect would be inoperative.

The power and efficiency are computed for the nonflattened power distribution of the reactor, using the single-diode data to determine the optimum values of J and T_{Cs} and the maximum power and efficiency. The results of this calculation are presented in Figs. 18 and 19, where the performance is shown as a function of J and T_{Cs}. The power is normalized by the factor P_M times the number of diodes in the reactor. For purposes of comparison, the power and efficiency are shown for the same reactor, but with a flat power distribution ($Q_{max}/Q_{min} = 1.0$). A summary of the power and efficiency degradation and the corresponding optimum values of current and cesium reservoir temperature is listed in Table 2.

The minimum power and efficiency degradation for the nonflattened ouput is 41 and 19%, respectively. It is noted that the optimum values of both J and T_{Cs} are reduced by the nonflattened power distribution. The amount they are reduced is relatively small, however. This effect also was found for the two-diode system.

Another significant observation is the reduction of performance sensitivity to low cesium reservoir temperatures of the nonflattened case. The reason for the reduction in sensitivity is explained by the high fraction of diodes in the system which are operating at values of Q which are more optimum for the lower values of T_{Cs}.

VI. Conclusions

It has been shown that thermionic diodes can be manufactured with equal performances, and that the performance of two in-circuit diodes can be computed from the data of one diode. It seems a reasonable assumption, then, that the performance of any number of diodes in a circuit can be computed.

The trend of power and efficiency degradation has been established for operating a multidiode plant where there are unequal power inputs; the efficiency degrades less than the power, and the performance of parallel-circuited diodes degrades less than for diodes in a series circuit.

The optimized values of J (or V) and T_{Cs} for a nonflattened power input multidiode system do not vary much from the optimum values that are observed for one diode operating at its maximum allowable emitter temperature. Operation of two series-connected diodes at T_{Cs} values 10 to 20°C below the optimum value is unstable and should be avoided. It is noted, however, when comparing the performance of the two-diode system to the 1000-diode system, that the low cesium pressure has much less effect on the latter system. Near the optimum value for the collector temperature, the effect on the performance of a variation in the collector temperature is very small. The optimum values of the collector temperature were nearly the same for one diode at its maximum emitter temperature and for a multidiode system with a nonflattened input.

The degradation in power and efficiency, for the space thermionic reactor with an unflattened input, was 41 and 19%. These losses, of course, are reduced to zero, if it is possible to obtain a flat power distribution. Other conceivable methods of reducing the losses include 1) variation of emitter area to optimize the current throughout the core, and 2) variation of the cesium pressure to groups of the diodes, to obtain a more optimum operation. The degradation caused by control perturbations has not been considered, but should be given more attention in the future.

The data presented in this experiment may be useful to the systems designer, for estimating performance degradations of other multiple-diode power plants on a relative basis. Some care must be excercised, however, if the level of performance does not coincide fairly closely with that reported herein. It is probable that the diodes with a different potential performance will give different degradation results.

Table 1 Maximized power and efficiency for two diodes in series and parallel circuits

Q_2/Q_1	Q_1/Q_2	$\frac{Q_1+Q_2}{2Q_1}$	Series operation: Power: $\frac{P_{max}}{2P_M}$	Series operation: Power: J_{opt} $\left[\frac{amp/cm^2}{diode}\right]$	Series operation: Power: $(T_{Cs})_{opt}$, °C	Series operation: Efficiency: η_{max}, %	Series operation: Efficiency: J_{opt} $\left[\frac{amp/cm^2}{diode}\right]$	Series operation: Efficiency: $(T_{Cs})_{opt}$, °C	Parallel operation: Power: $\frac{P_{max}}{2P_M}$	Parallel operation: Power: V_{opt}, v	Parallel operation: Efficiency: η_{max}, %	Parallel operation: Efficiency: V_{opt}, v
1.0	1.0	1.0	1.00	6.6	375	10.0	5.8	375	1.00	0.72	10.0	0.80
0.9	1.11	0.95	0.93	6.6	373	9.7	5.7	372	0.94_5	0.71	9.8	0.78
0.8	1.25	0.90	0.83_5	6.5	371	9.3_5	5.5	370	0.87_5	0.68	9.5	0.76
0.7	1.43	0.85	0.72_5	6.1	370	8.6	5.2	369	0.79	0.65	9.1	0.73
0.6	1.67	0.80	0.59	5.5	370	7.6	4.5	368	0.71	0.62	8.5	0.70
0.5	2.0	0.75	0.44_5	4.3	369	6.6	3.7	367	0.62	0.60	7.9_5	0.69

Table 2 Summary of the minimum degradation in power and efficiency of a thermionic reactor design [a]

Power distribution	Nonflattened	Flattened
Q_{max}/Q_{min}	1.85	1.00
Maximum power (normalized)	0.59	1.00
Power degradation, %	41	0
Optimum J, (amp/cm^2)/diode	5.6	6.6
Optimum T_{Cs} (°C)	370	375
Maximum efficiency, %	8.1	10
Efficiency degradation, %	19	0
Optimum J, (amp/cm^2)/diode	5	5.8
Optimum T_{Cs} (°C)	365	375

[a] NAA-SR-6077 (U.S. Atomic Energy Commission classified report, May 1, 1961)

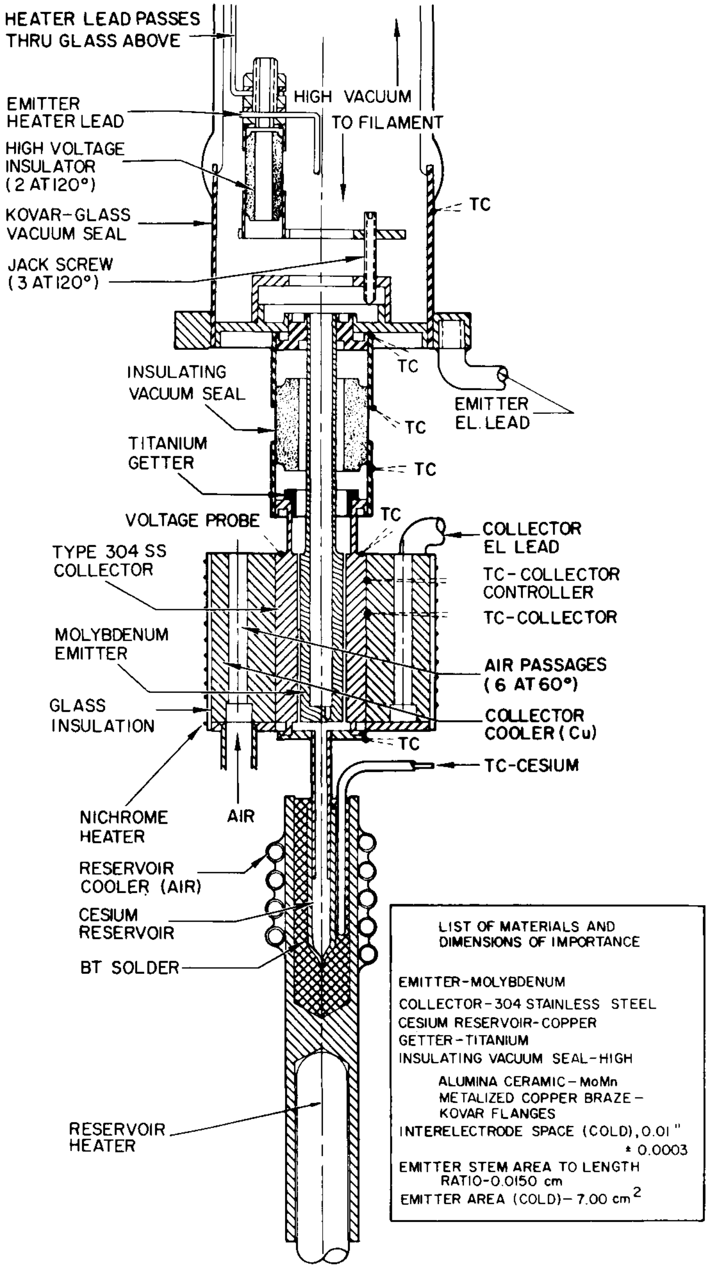

Fig. 1 Diode configuration

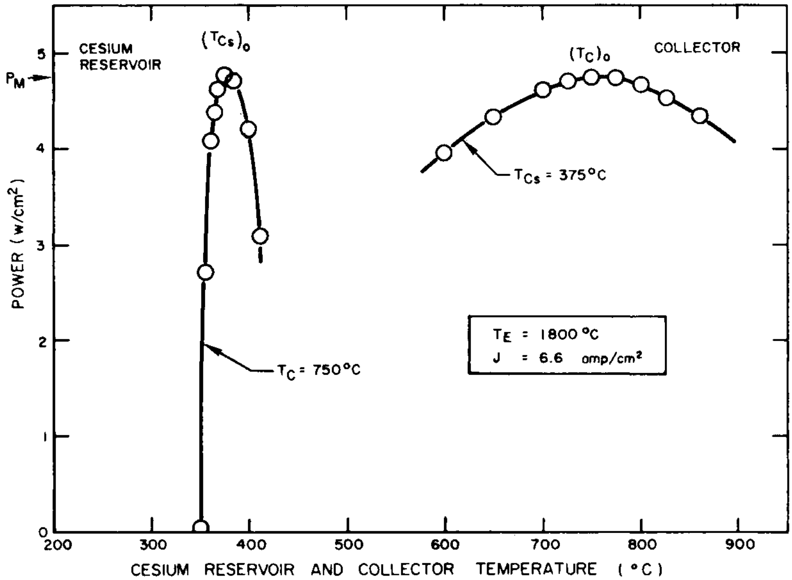

Fig. 2 Optimization of cesium reservoir and collector temperature

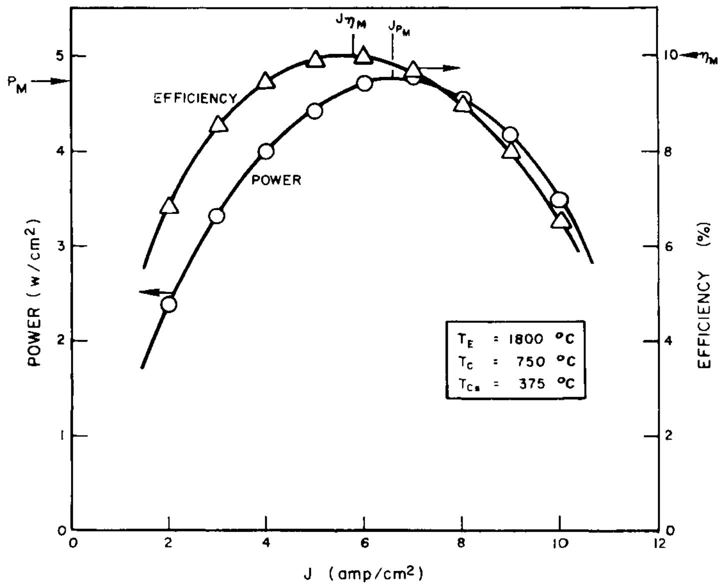

Fig. 3 Maximization of power and efficiency and the optimum values of J

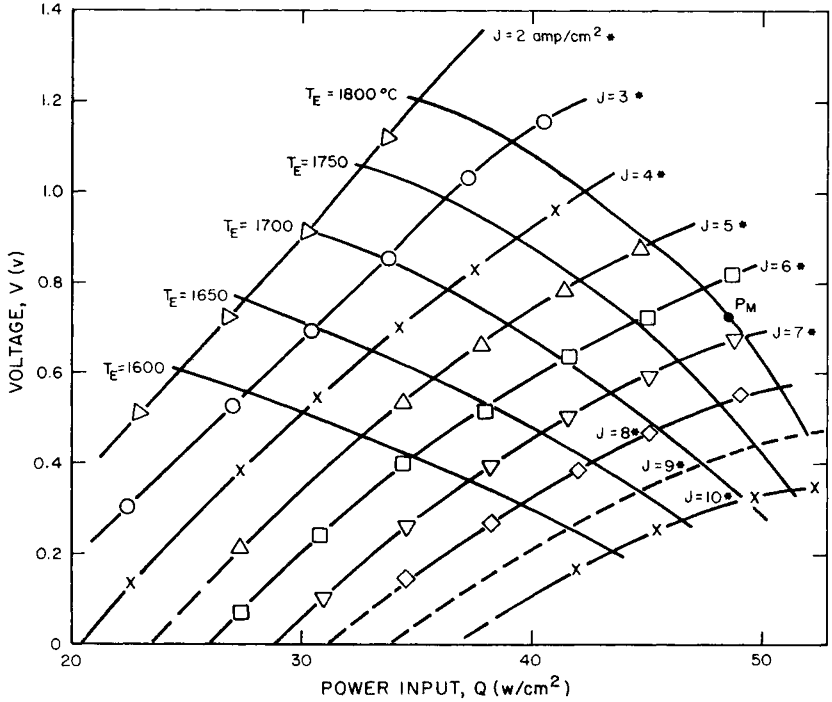

Fig. 4 Voltage vs power input at T_C = 750°C and T_{Cs} = 375°C

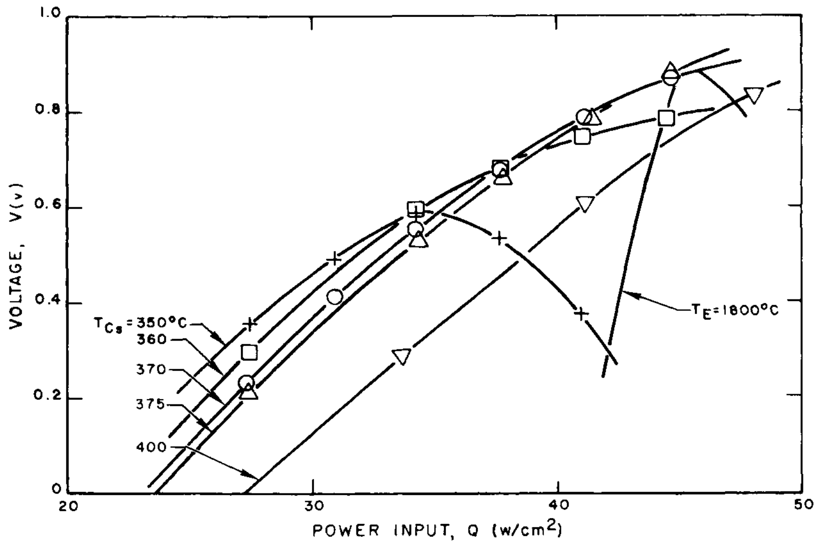

Fig. 5 Voltage vs power input at J=5 amp/cm^2 and T_C = 750°C

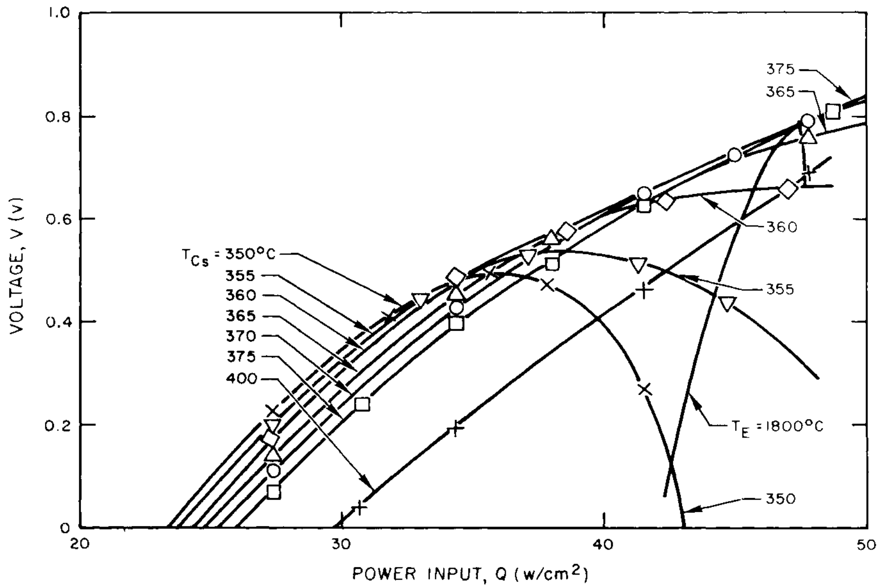

Fig. 6 Voltage vs power input at J = 6 amp/cm^2 and T_C = 750°C

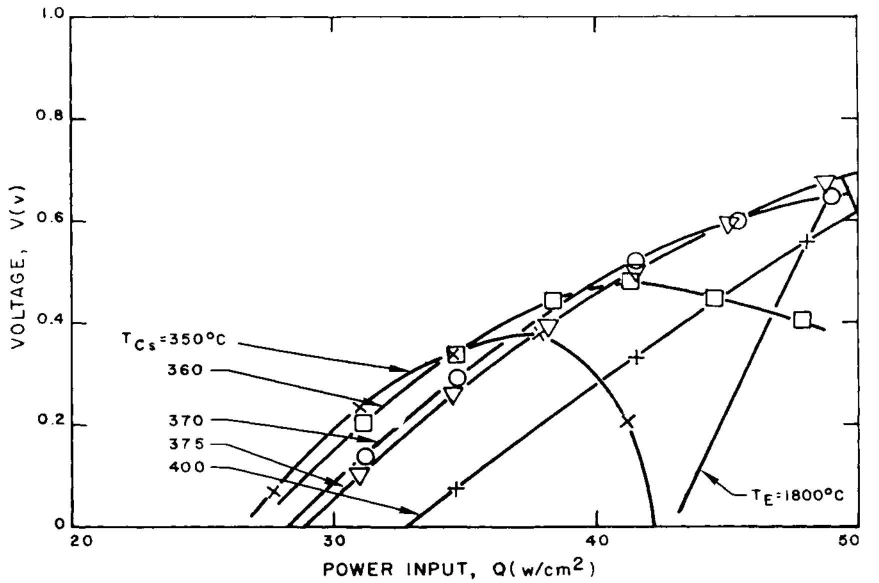

Fig. 7 Voltage vs power input at J = 7 amp/cm^2 and T_C = 750°C

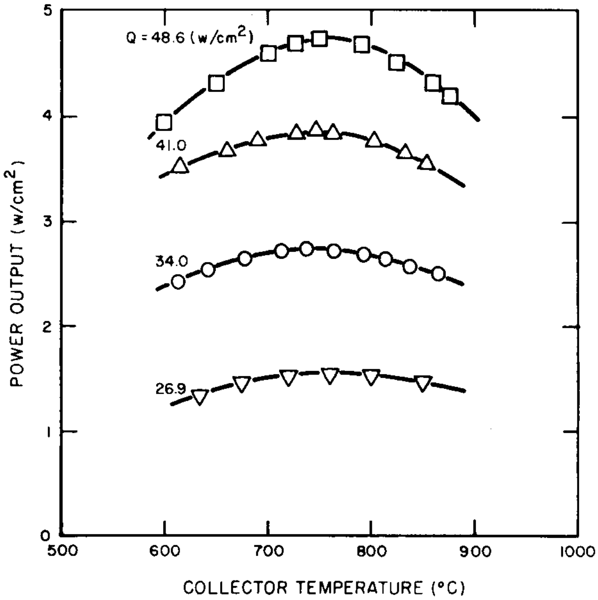

Fig. 8 Effect of collector temperature on power output at $T_{Cs} = 375°C$

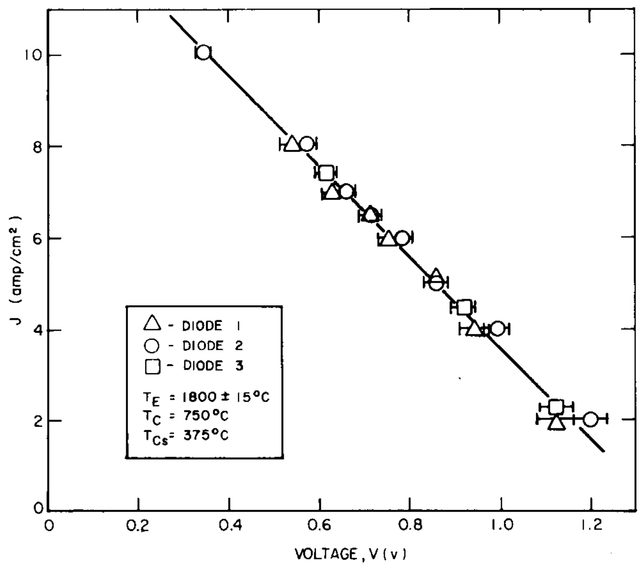

Fig. 9 Comparison of the individual performances of the three diodes at $T_E = 1800 \pm 15°C$

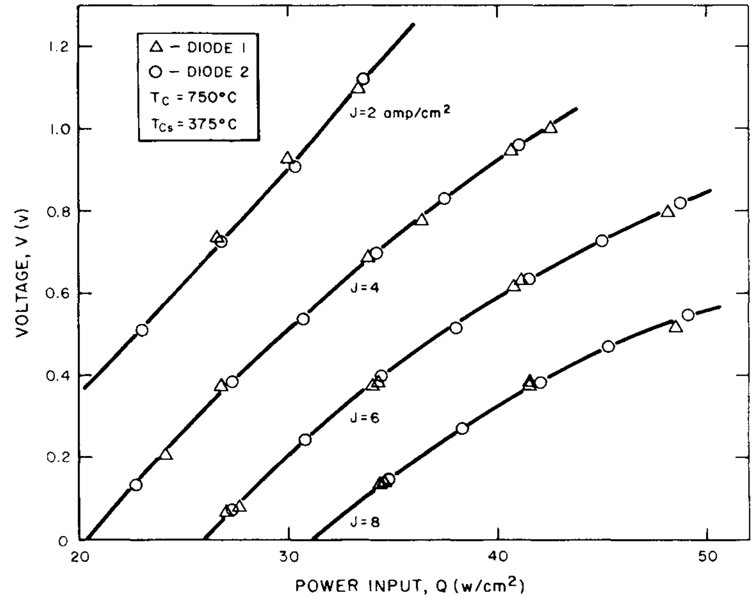

Fig. 10 Comparison of diodes 1 and 2 at $T_{Cs} = 375°C$ and $T_C = 750°C$. (These two diodes are tested in series and parallel circuits)

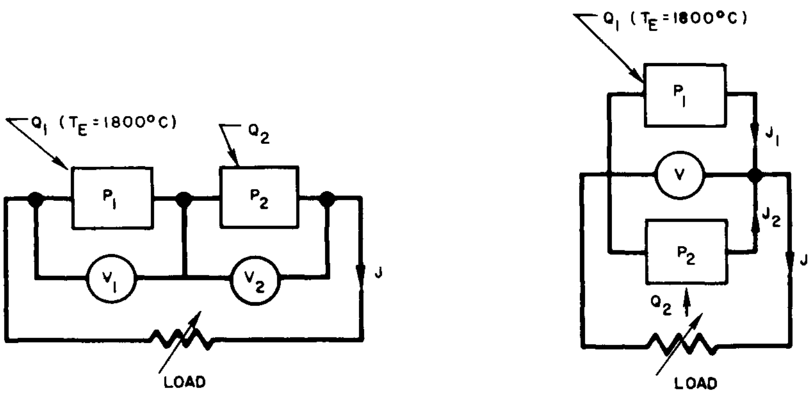

Fig. 11 Circuit diagrams. a) Two diodes in series; b) two diodes in parallel

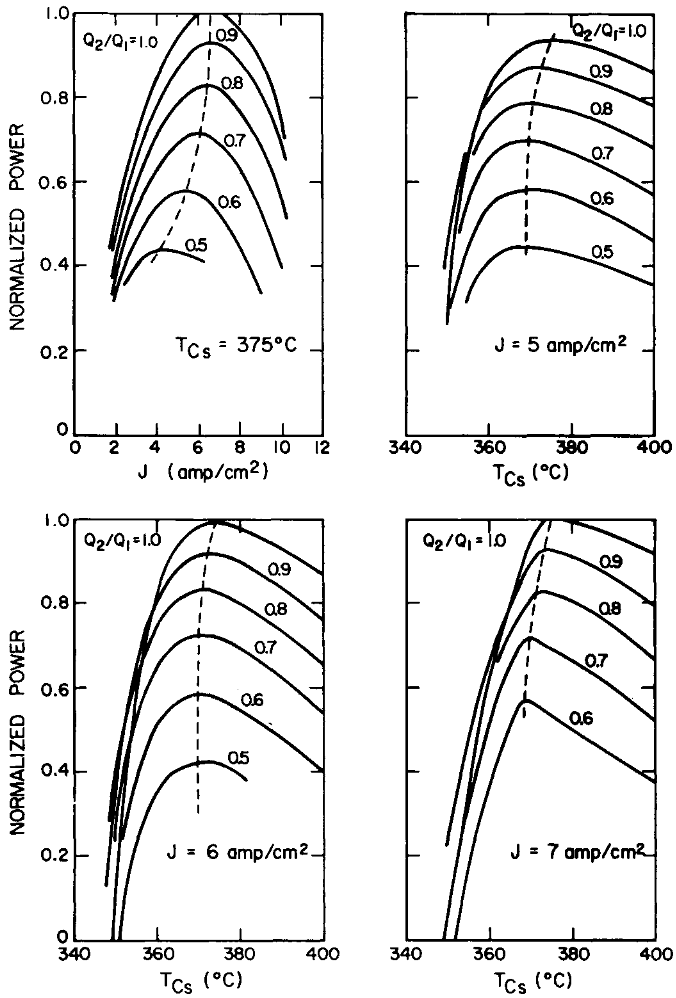

Fig. 12 Normalized power output of two diodes in a series circuit with power inputs Q_1 and Q_2. (Q_1 is the power input at T_E = 1800°C)

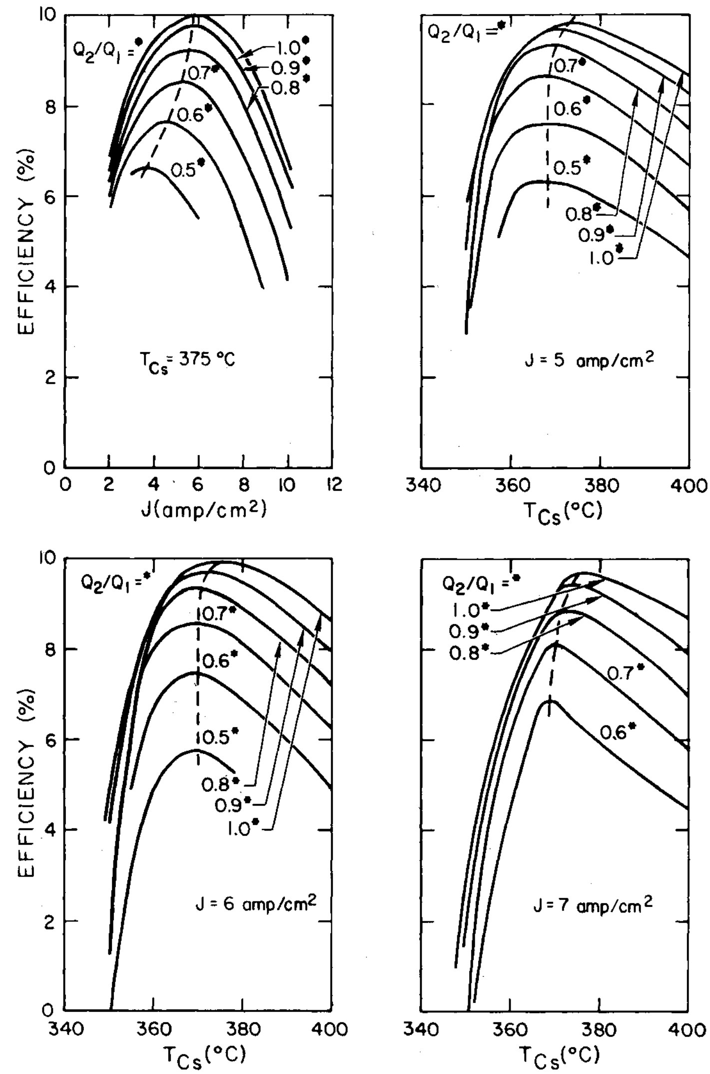

Fig. 13 Efficiency of two diodes in a series circuit with power inputs Q_1 and Q_2. (Q_1 is the power input at $T_E = 1800°C$)

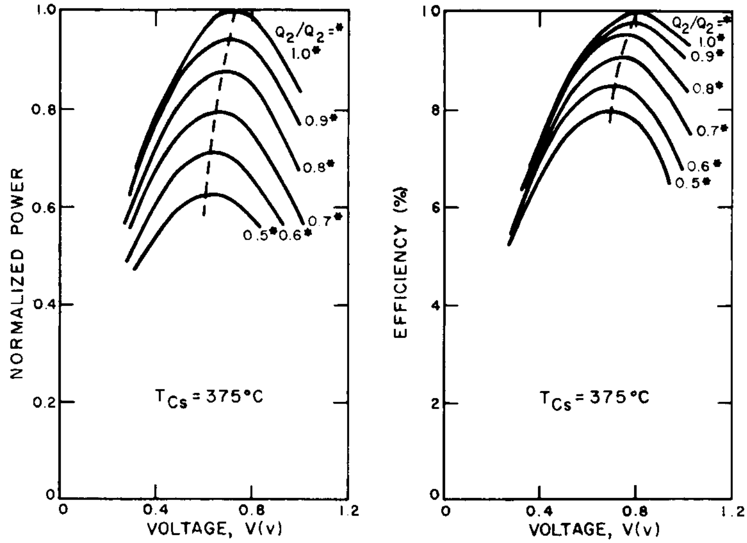

Fig. 14 Normalized power output and efficiency of two diodes in a parallel circuit with power inputs Q_1 and Q_2. (Q_1 is the power input at T_E = 1800°C)

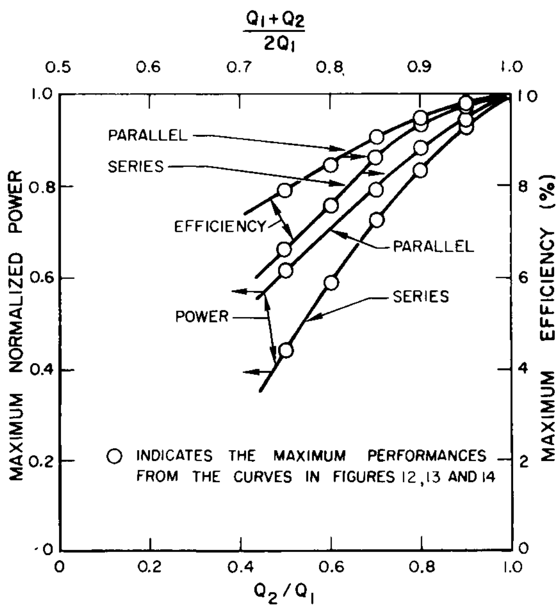

Fig. 15 Maximized power and efficiency of two diodes in series and parallel circuits vs Q_2/Q_1

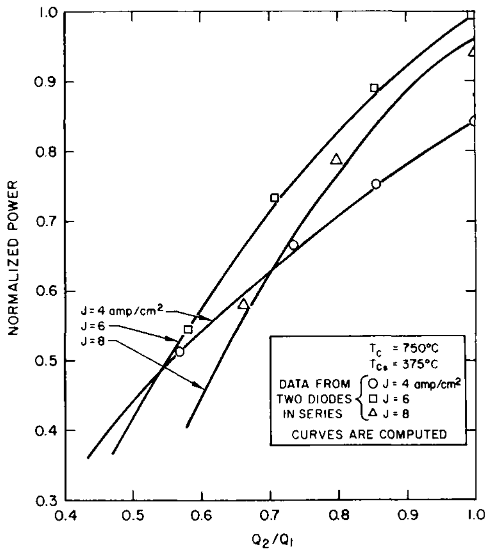

Fig. 16 Operating data for series-connected diodes with power inputs Q_1 and Q_2. (Q_1 is the power input at T_E = 1800°C)

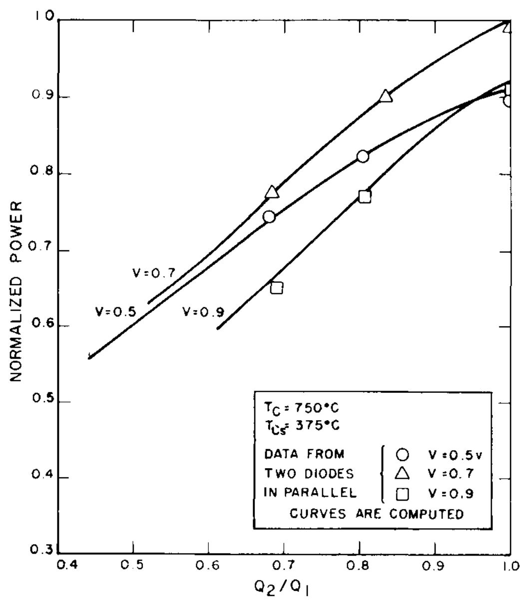

Fig. 17 Operating data for parallel-connected diodes with power inputs Q_1 and Q_2. (Q_1 is the power input at T_E = 1800°C)

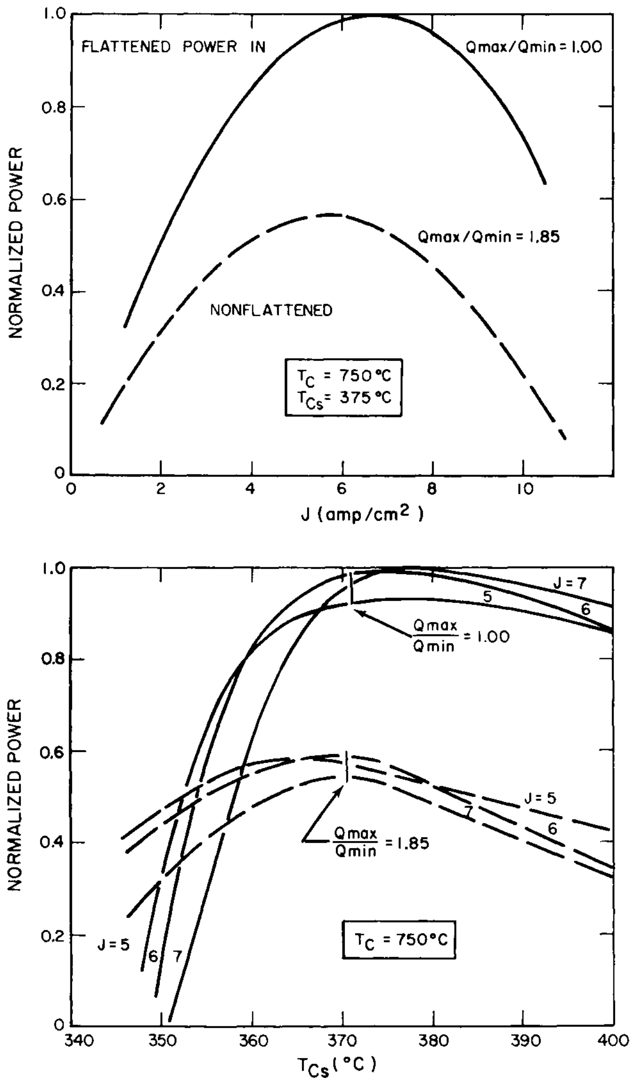

Fig. 18 Normalized power output of a thermionic reactor with 1000 series-connected diodes

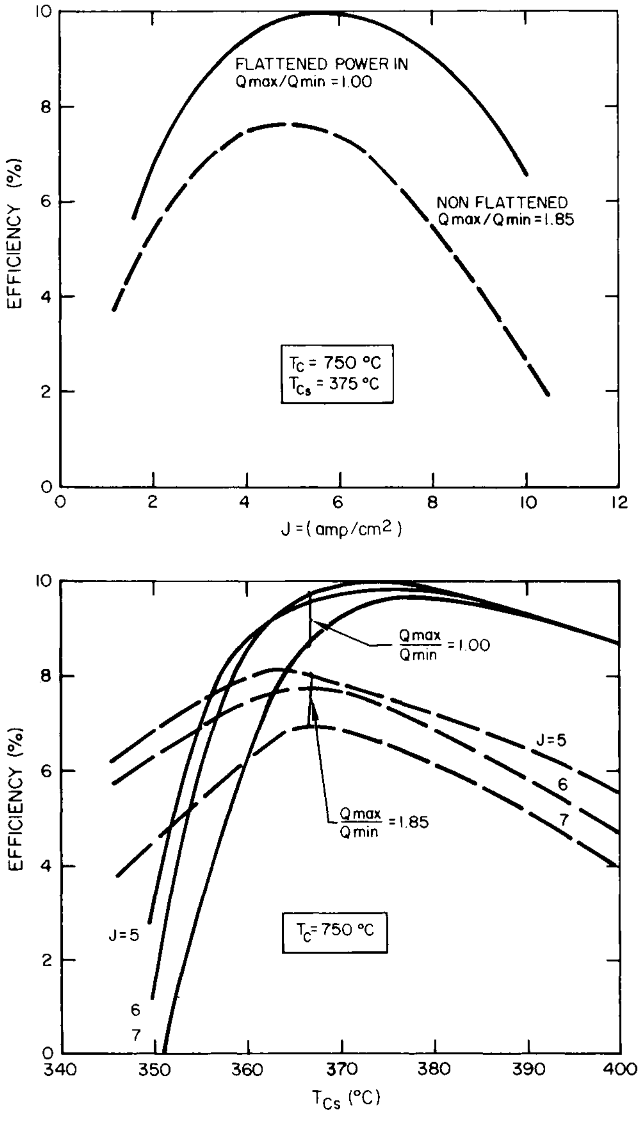

Fig. 19 Efficiency of a thermionic reactor with 1000 series connected diodes