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PERFORMANCE OF CESIUM THERMIONIC DIODES OPERATED IN SERIES-PARALLEL CIRCUITS

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PERFORMANCE OF CESIUM THERMIONIC DIODES OPERATED IN SERIES-PARALLEL CIRCUITS

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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. This experiment measures the loss of power and efficiency due to unequal heat inputs to series- or parallel-connected diodes, and studies the operating characteristics of a multiple-diode system. 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:

a) The verification of the actual and predicted performance degradation due to unequal heating;

b) The optimization of operating variables for maximum performance, and;

c) The exploration of operational problem areas.

The 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

A. GENERAL

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.

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 performance to determine if diodes can be manufactured with the same operating characteristics. Then two of the diodes were tested in series and parallel circuits to: (1) determine if the actual and the computed performances agree, and (2) investigate likely operational problem areas.

B. THE DIODES

1. Design

Figure 1 shows a cross-section of the cylindrical geometry diode configuration and a list of the materials and dimensions of importance. Arc-cast molybdenum bar and T-304 stainless steel bar were selected for the emitter and collector, respectively, because of previous operating and fabricating experience with these materials. Whether or not these materials represent those which will be used as electrodes in a thermionic reactor is not especially important because the degradation results probably will not be very sensitive to the type of refractory metal emitter or collector.

The cylindrical geometry is the first choice for the electrode configuration since it is the most probable geometry for use in a practical reactor design.[1,2,3] The interelectrode spacing was set at 0.010 ± 0.0003 in. which is a compromise between high performance at small spacings[4] and reliability at larger spacings. Besides, from the consideration of nuclear fuel swelling, which usually accompanies fuel burnup, very small spacings appear an unlikely choice. The emitter area available for power production is 7.00 cm^2 and includes only the outer cylindrical surface. The emitter stem and end are sufficiently removed from the collector that little additional power should be realized from these areas.

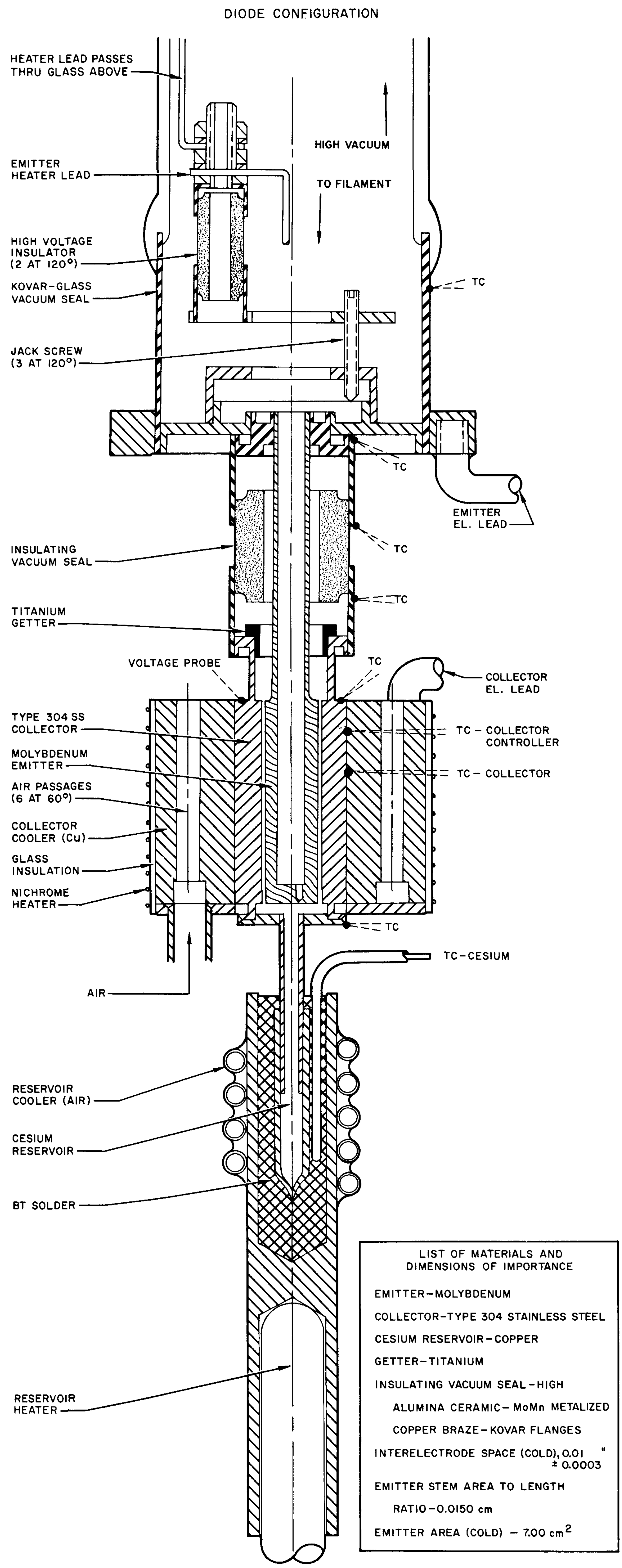

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Figure 1. Diode Configuration

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One of the objectives of the diode design is to produce diodes with equal performances. If this can be accomplished, several advantages are realized; first, the consistency of performance between the diodes will lend to the credibility of the data. Second, in diode production it is of interest to know performance reproducibility in advance. If this is possible, then the performance of a multidiode power plant should be amenable to calculation using the data of a representative diode.

The degree of performance reproducibility depends on many factors which include those of impurity concentration,[5] uniformity of emitter surface with respect to work function,[6] uniformity of electrode temperature profiles, and machining tolerances. The importance of the interelectrode tolerance is acute at very close spacings because of the extreme sensitivity of the performance to spacing changes as zero spacing is approached.[4] The error in the interelectrode spacing of the diodes in this experiment is estimated to be ± 0.0003 in. which is 3% of the spacing. Variable spacing data[4] indicate that this would result in a ± 5% deviation in power output. It is noted that error in spacing is for each diode but that it is entirely possible the error in spacing between the three diodes could be less than ± 3%. All of the previous discussion on spacing assumes an accurate centering of the cylindrical emitter within the collector and perfect cylindrical surfaces. This is, of course, not an exact reality in the experiment but is probably a less important effect.

The uniformity of emitter temperature profiles has an important effect on performance reproducibility because of: (1) performance sensitivity to emitter temperature, and (2) the dependence of the emitter temperature profile on the position of the emitter heater. The importance of impurities can be eliminated if it is possible to prepare extremely "clean" diodes, prepare them by exactly the same method and standards, and use a getter. The emitter crystal orientation effect is reduced by machining all the emitters from the same piece of material, in the same orientation, and by the same machining procedure.

The emitter and its lead are machined from a single piece of arc-cast molybdenum bar. The geometry of the emitter lead, that is, the ratio of the cross-sectional area to the length, is an important design variable. This ratio is optimized for maximum efficiency in the following equation[7] by considering the I^2R power losses and the heat conduction losses in the lead.

$$\frac{A}{L}_{opt} = JA_E\left[\frac{\rho}{\eta K(T_E - T_C)}\right]^{1/2}\left(1 - \frac{\eta}{2}\right)^{1/2}$$

where

J = current/emitter area

A_E = emitter area

L = lead length

ρ = lead electrical resistivity

K = lead thermal conductivity

η = diode efficiency

T_E = emitter temperature

T_C = collector temperature

It is noted that in order to calculate $(A/L)_{opt}$ it is necessary to know the operating variables J, T_C, and T_E. Before the diode is tested, however, these variables are unknown, so it becomes necessary to predict the performance based on the data of earlier diodes. At the time of the diode design the current experiments indicated that in order to reliably achieve a reasonable diode life (hundreds of hours) it was necessary to limit the emitter temperature to about 1650°C. The emitter stem A/L ratio was calculated on this basis at 0.015 cm, which is the A/L on the diodes tested.

By the time the diodes were fabricated and ready for testing, however confidence was established in emitter operation at 1800°C, so this value was used as a maximum allowable temperature for long term operation. Because of the potentially higher values of J obtainable from 1800°C emitter operation, the design value, 0.015 cm, which was then optimum is now smaller than optimum for 1800°C operation. The end result is that the performance is lower than optimum due to an excessive I^2R power loss in the lead.

The diodes are completely welded and brazed containments which have the advantage of operation without mechanical seals such as O-rings. This feature should make the inherent reliability of each diode greater. Particular attention was given to the design of the welding flanges in order to prevent excessive heating of the parts during welding and to obtain few fabrication rejects. During the fabrication of the three diodes, 27 successful welds were made without any rejects.

The insulating vacuum seal is a commercial product (Carborundum Company) made of high alumina content ceramic which is Mo-Mn metalized on the flange areas and then copper-brazed to the Kover flanges. This type of seal was found to be reliable in cesium vapor at temperatures up to ~600°C. In the design the exterior of the seal operates in air, therefore, to prevent oxidation of the Kovar flanges and the copper braze, the seal is nickel- and rhodium-plated after it has been welded to the diode parts. The advantages in having the seal exposed in air are: (1) easy control of the seal temperature may be obtained by adding or removing glass insulating tape, and (2) provides outside connections for the emitter lead, the diode temperature profile thermocouples, and the voltage probes.

A titanium getter is provided to absorb gases evolved into the interdiode volume. The getter is cylindrically shaped and pressed into the inside of the collector top flange. The temperature of the getter is more or less dependent on the collector temperature but it can be adjusted by either heating or cooling the collector flange. In the experiment, the getter operated at about 100°C below the collector temperature.

The emitter heater chamber is made of a standard 1-1/2 in. Kovarglass tubular seal, as shown in Figure 1. The Kovar flange is welded to a stainless steel flange which is in turn welded to a nickel flange. The stainless steel flange, besides forming the bottom end of the heater chamber,also provides a table for positioning the heater filament. The heater filament leads are supported on high-voltage insulators. These insulators are welded to a washer, the position of which is adjusted by three jacking screws located at 120 degrees. The heater filament is then positioned by tilting the washer on which the high voltage insulators are located.

The upper end of the heater chamber (not shown in Figure 1) is connected by way of a side arm to a glass vacuum manifold which accommodates the heater chambers of several diodes. The glass then acts as an insulator between the emitters of the diodes. The manifold is connected to a two-inch, high-vacuum, diffusion pump. An optical window is located directly above the heater chamber for viewing the interior of the emitter.

Both the collector and the cesium reservoir are provided with means for cooling and heating. The collector is fitted with a heavy, Ni-Rh plated, copper sleeve, which is cooled by air flow through drilled passages in its wall as shown in Figure 1. The sleeve is heated on its outside surface by a wound-Nichrome wire. The collector temperature is controlled by regulating the air flow. The cesium reservoir is a pinched-off copper tube potted in silver solder. The pot is air cooled by a spiral tube soldered to its outside surface, and it is heated from the bottom by a 50-w soldering iron. The cesium reservoir temperature is controlled by regulating the power to the heater.

2. Fabrication

The diode parts were prepared by standard vacuum tube techniques.[5,8] The metallic parts in contact with the inter-diode volume were machined without the use of coolants or oils containing sulfur, then individually outgassed, and joined by retort arc welding in an inert atmosphere.[5] Special jigs for maintaining alignments and clearances, as well as chill bars for welding operations were used during assembly.

After the diode was assembled, all the exterior, except the cesium reservoir, was nickel-rhodium plated for oxidation resistance. In order to maintain the desired temperature profile over the length of the diode, glass thermal insulation was applied. The inter-diode space was then connected to a liquid nitrogen trapped high vacuum diffusion pump [manifold pressure 10^{-8} Torr (mm Hg)] via the copper cesium filling tube extending from the bottom of the diode. The diode was instrumented and operated as a vacuum diode with the emitter temperature at about 1800°C. The collector temperature was maintained at 800°C to expel gasses remaining from the handling and fabrication. Operation was continued until the manifold pressure leveled out at 8×10^{-7} Torr.

Cesium (99.99% purity) was loaded into the diode using the "breakoffski" technique,[5] and the filling tube was pinched off. The entire copper cesium reservoir and thermocouple were set in a molten bath of 603 BT solder contained in a nickel thimble and allowed to cool, forming a region of uniform temperature for the cesium reservoir.

C. INSTRUMENTATION

1. Emitter Heater

Each diode emitter was independently heated by an electron bombardment heater. The heater system which consists of a filament, a controlled-current ac power supply, and a 3000-v, 500-milliampere, dc power supply is shown in Figure 2.

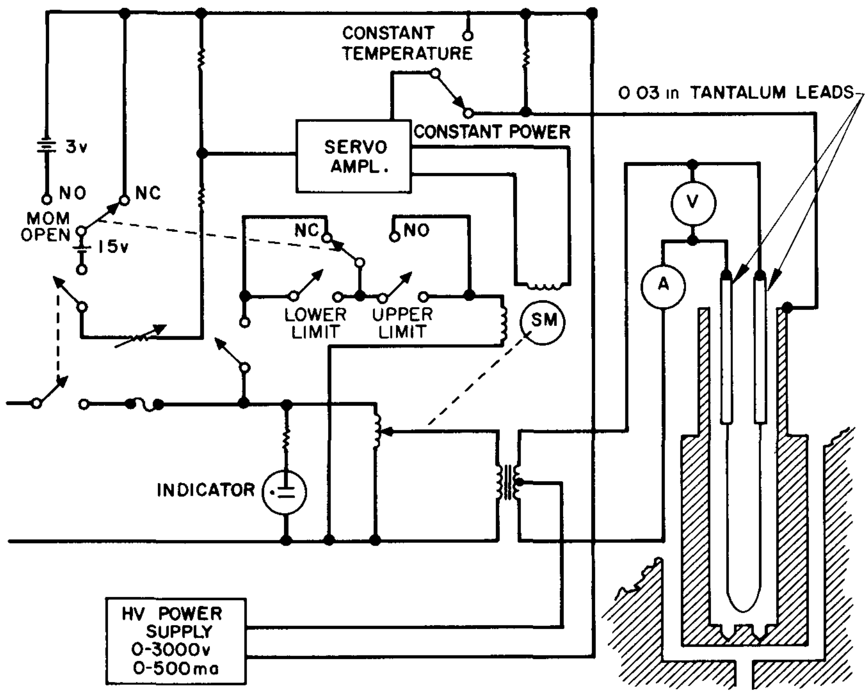

Figure 2. Schematic of Electron Bombardment Heater and Controller

The filament is a 0.010-in. diameter tungsten wire hairpin, spot welded to 0.030-in. diameter tantalum leads. The ac current to the filament is controlled to provide a stable and constant power input to the emitter.

With this type of heating the power input to the emitter is directly determined by the sum of the ac and dc power and can be used for a direct computation of the efficiency. The errors encountered in the power input to the emitters are: (1) the heat conducted away by the filament leads, (2) the radiation lost through the top of the emitter, and (3) instrument errors. The first two errors are inherent to this type of heating, but are small and can be neglected. The instrument errors are estimated as follows.

		Normal Value	Error
Filament	voltage	5 - 7 v	±0.05 v
	current	5 - 7 a	±0.05 a
Plate	voltage	1000 v	±5 v
	current	0 - 400 ma	±2 ma

The propagated errors for the maximum and minimum power inputs used in the experiment are 0.8 and 1.4%, respectively.

2. Temperature Measurement and Control

The emitter temperature is measured by focusing an optical pyrometer on a cavity 0.030-in. in diameter by 0.090-in. deep on the bottom of the emitter heater cavity. The pyrometer and glass optics were calibrated against a standard tungsten filament. The resulting deviations from the true tungsten filament temperatures were the only corrected errors applied to the emitter temperature in this experiment. Another source of error comes from the heater filament radiation which is reflected into the cavity. At the high emitter temperatures, 1500 to 1900°C, investigated in this study, the error is estimated[5] at less than ±10°C. This error is dependent on many variables including the position of the heater filament.

Actually the relative errors between the emitter temperatures of the three diodes are of prime importance instead of the absolute error. To reduce the relative errors to the lowest possible values the same pyrometer is used for the measurements along with optical windows and prisms with equal corrections. The relative emitter error is estimated at ±15°C. The bulk in this error is thought to be due to varying amounts of reflected light into the cavity which is caused by variation of the heater filament position and variation of power input to the filament.

The temperatures of the collector, cesium reservoir, insulating seal, etc. were measured with Chromel Alumel thermocouples. The cesium reservoir thermocouples were of the grounded-shielded type and were calibrated and matched because of the sensitivity of the diode performance to the cesium reservoir temperature. Close regulation of the cesium reservoir temperature was successfully accomplished with a recording position-adjusting type proportional controller which adjusted the cesium reservoir heater voltage. The error in the cesium reservoir temperature is estimated to be ±2°C.

The other diode temperatures were measured with thermocouples spot welded to the part and recorded on a 12-point Brown Recorder. The collector temperature was regulated by the cooling air flow with an on-off type controller. The error in the collector temperature is estimated at ± 10°C.

3. Diode Electrical Output, Control, and Measurement[5]

The circuit used to control and measure the electrical output of the diodes is shown schematically in Figure 3. For operation at positive power

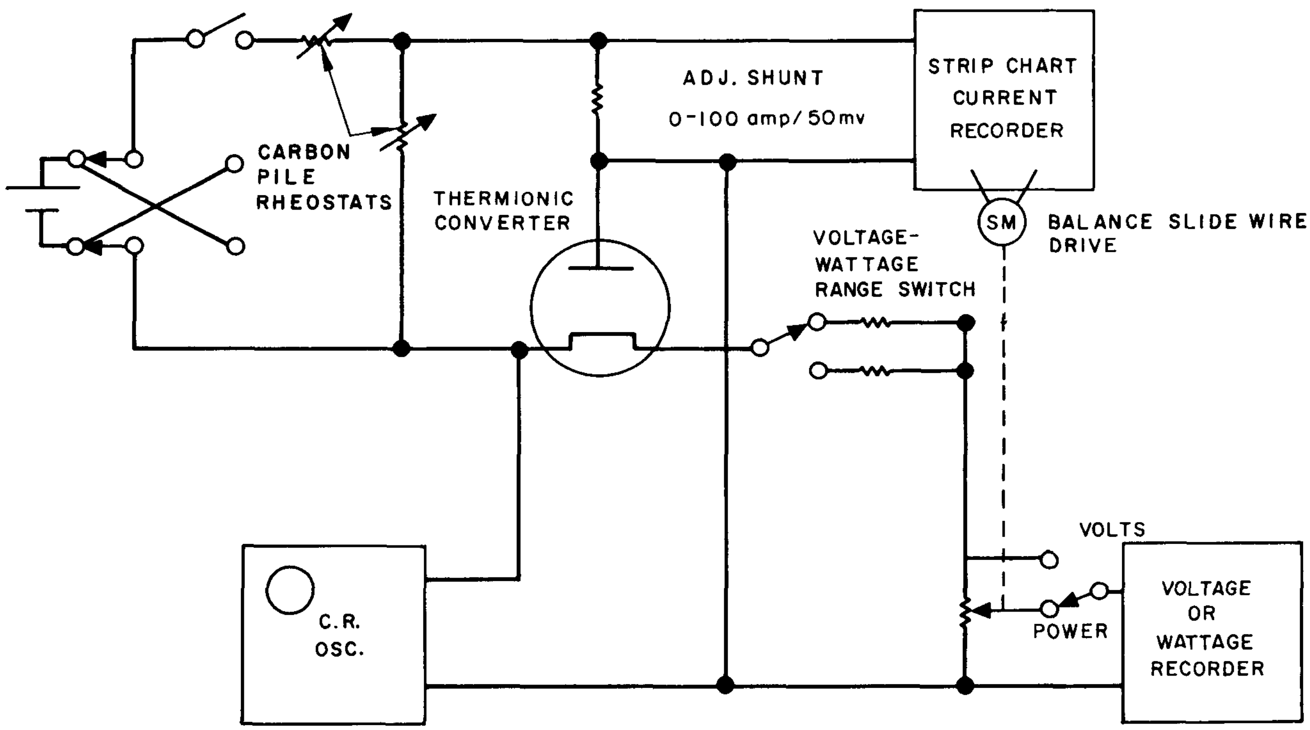

Figure 3. Power Output and Control Measurement Circuits

output, a smoothly variable, high-current resistor (carbon pile rheostat) is used as a load. For reverse current or reverse potential measurements, an externally supplied current, controlled by a similar rheostat, is shunted across the load. Output potential is measured between probes that are spark-welded directly to the collector and to the integral emitter lead, where it emerges from the converter. Output current is determined from the potential drop across a 50 millivolt shunt having seven ranges between 1 and 100 ampere. The current and potential are recorded simultaneously and continuously on a two-pen, strip-chart, recording potentiometer.

The errors in the recorded outputs are estimated at:

Current: ± 0.2 amp (50-amp shunt)
Voltage: ± 0.002 volt

4. Switching Circuit

A switching circuit is used in the experiment for quickly changing the electrical connections of two diodes from independent operation to either series or parallel operation. This is accomplished using six high-current mercury relays which were activated by a three-position rotary switch. The center position is for independent operation where each diode is operating on separate variable loads. By switching to the series or parallel position the diodes are connected to the same two loads either in series or parallel circuits. By rapidly changing the circuitry it is possible to confirm quickly whether the voltages are additive for series operation or the currents are additive for parallel operation.

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 4 and 5 show the results of this maximization process. Here, the maximum values of the output and efficiency are shown at 4.75 w/cm^2 and 10.0%.

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 Figure 4, to optimize at 750 and 375°C. Actually, these optima are determined for maximum power in Figure 4, but the values are also optimum for maximum efficiency. The load is varied in Figure 5, 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 seen 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 Figure 4. 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.

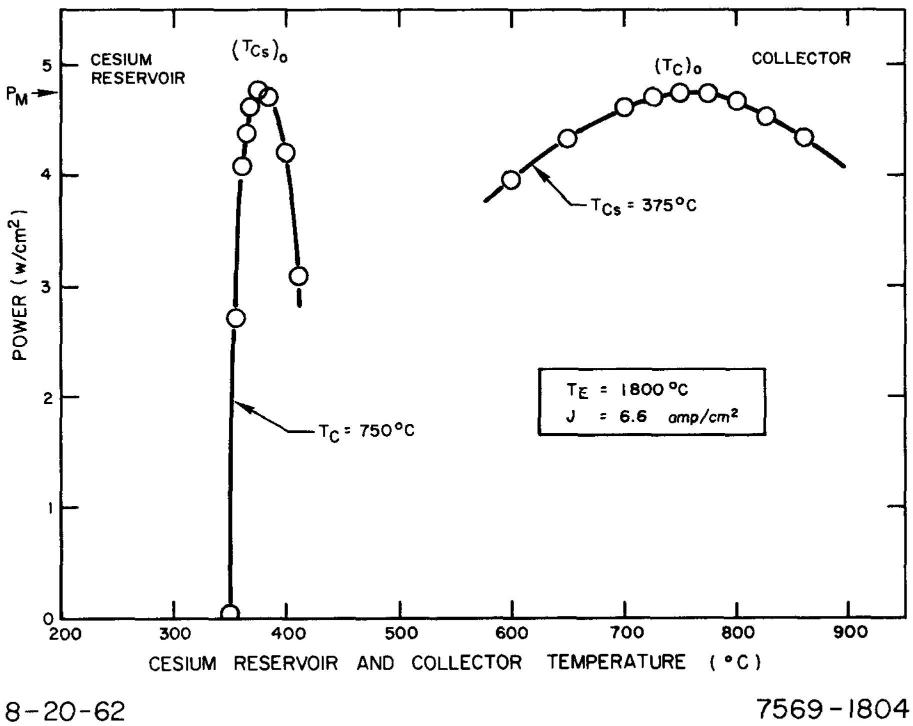

Figure 4. Optimization of Cesium Reservoir and Collector Temperature

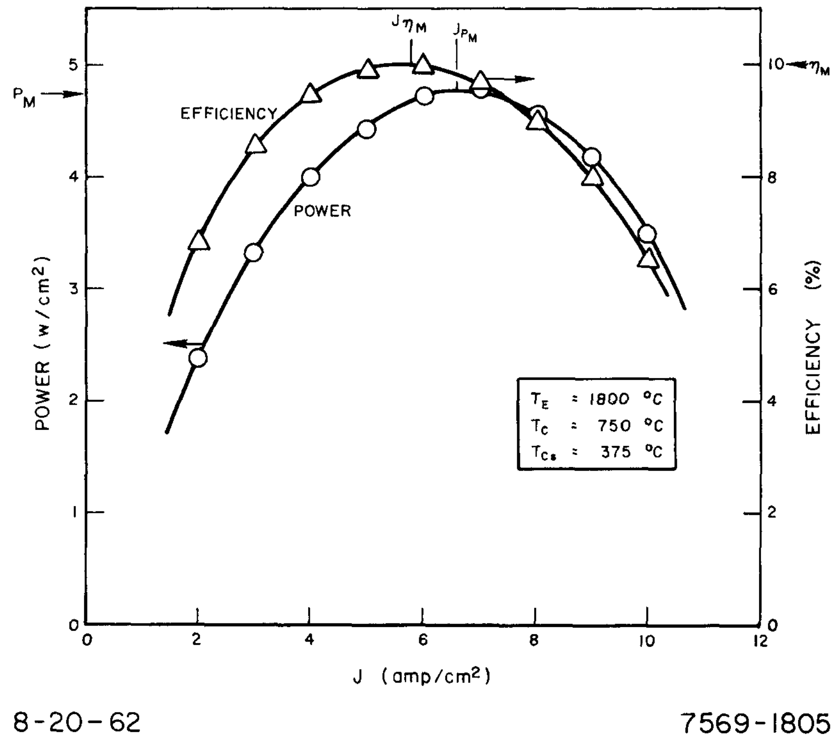

Figure 5. Maximization of Power and Efficiency and the Optimum Values of J

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 Figure 6, 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 which gives the maximum obtainable power (P_M) is indicated on the 1800°C curve.

Figures 7, 8, and 9 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 is evidently caused by the sensitivity of the power output to T_{Cs}. The values of Q, where the voltage maximizes on the T_{Cs} = 350°C curve, is the optimum Q at T_{Cs} = 350°C for the given value of J.

A moderate degree of instability in the power output was observed, when operating the diode at T_{Cs} = 350°C and at T_E = 1800°C. It is noted in Figure 9 that the T_{Cs} = 350°C curve is almost vertical near T_E = 1800°C, which would

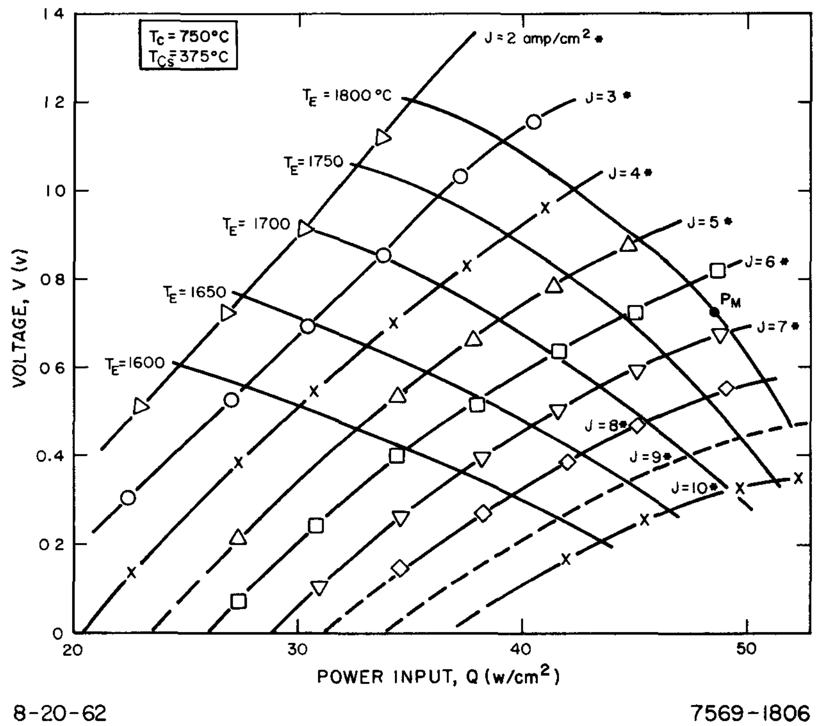

Figure 6. Voltage vs Power Input at T_C = 750°C and $\overline{T}_{Cs}$ = 375°C

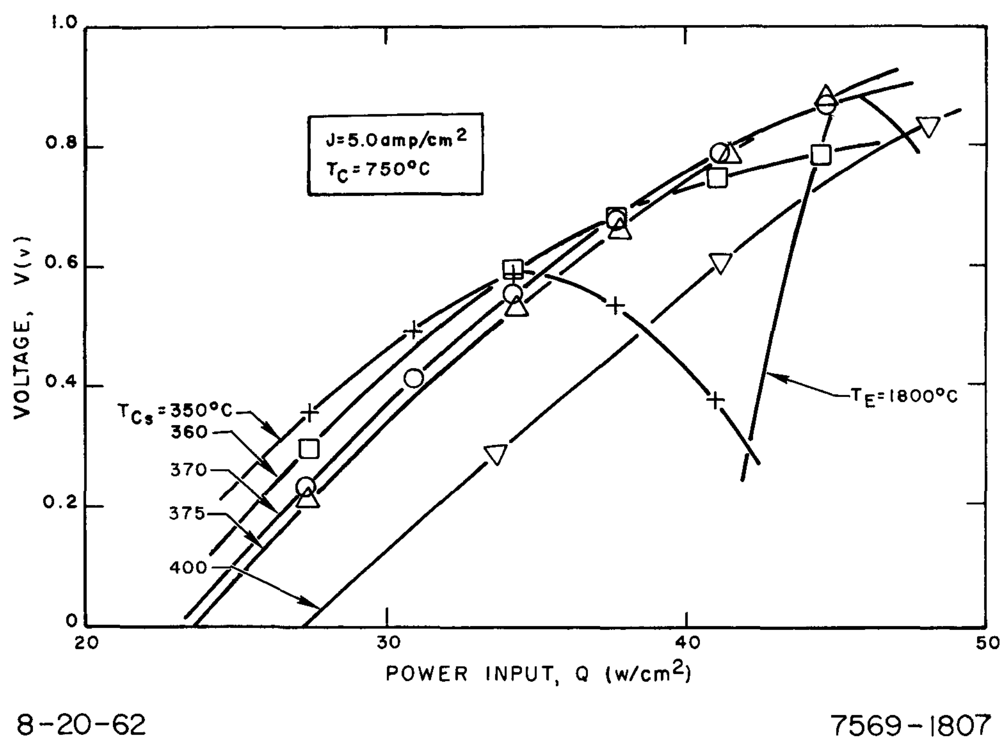

Figure 7. Voltage vs Power Input at J = 5 amp/cm^2 and T_C = 750°C

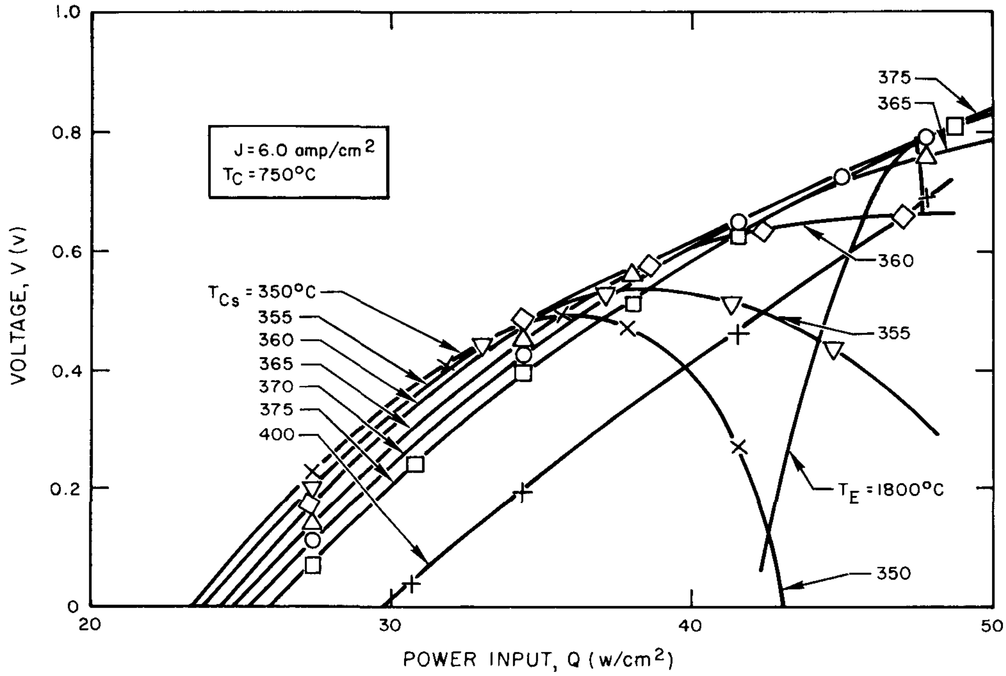

Figure 8. Voltage vs Power Input at
J = 6 amp/cm^2 and T_C = 750°C

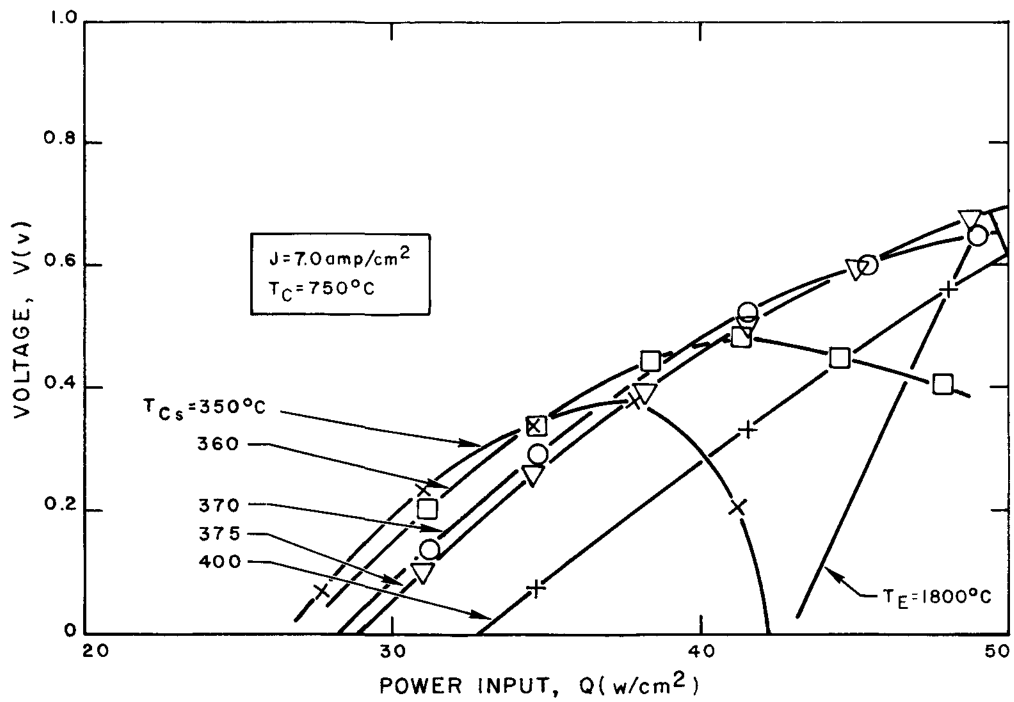

Figure 9. Voltage vs Power Input at
J = 7 amp/cm^2 and T_C = 750°C

cause the voltage to vary markedly with slight variations in Q. In the experiment the power input is automatically controlled; so apparently the slight resulting perturbations caused the observed instability.

C. COLLECTOR TEMPERATURE EFFECTS

The power output is shown, in Figure 10, 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 Figure 11. It is seen that the resulting curve falls within the estimated errors. The errors are based on the assumed emitter temperature error of $\pm 15°C$, as reflected in the variation of the voltage.

A more thorough comparison is made for Diodes 1 and 2; and is shown in Figure 12, where the performance of these two diodes is given as V vs Q for $J = 2$, 4, 6, and 8 amp/cm^2 at $T_C = 750°C$ and $T_{Cs} = 375°C$. As can be seen, their performances are very nearly identical. These two diodes were tested in the actual series and parallel circuit tests, since their performances were close enough that the output could be easily compared to the calculated performance based on individual diode data.

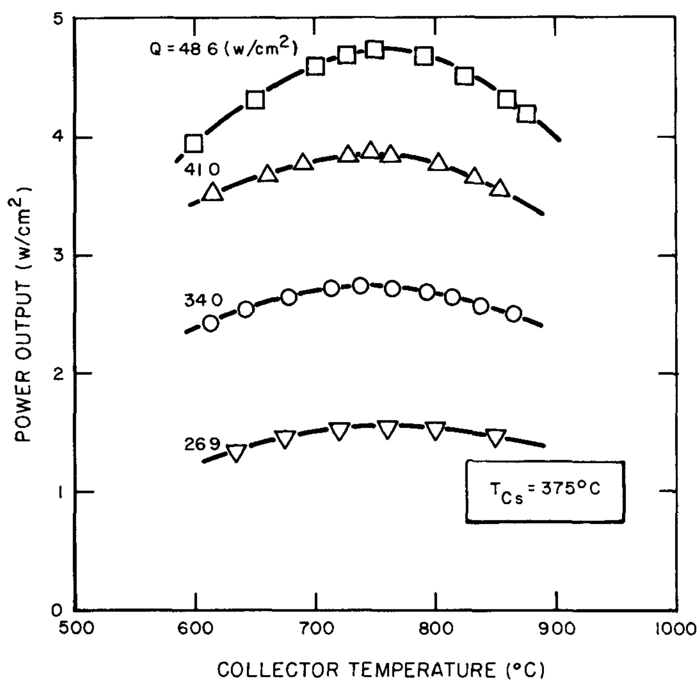

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Figure 10. Effect of Collector Temperature on Power Output at $T_{Cs} = 375°C$

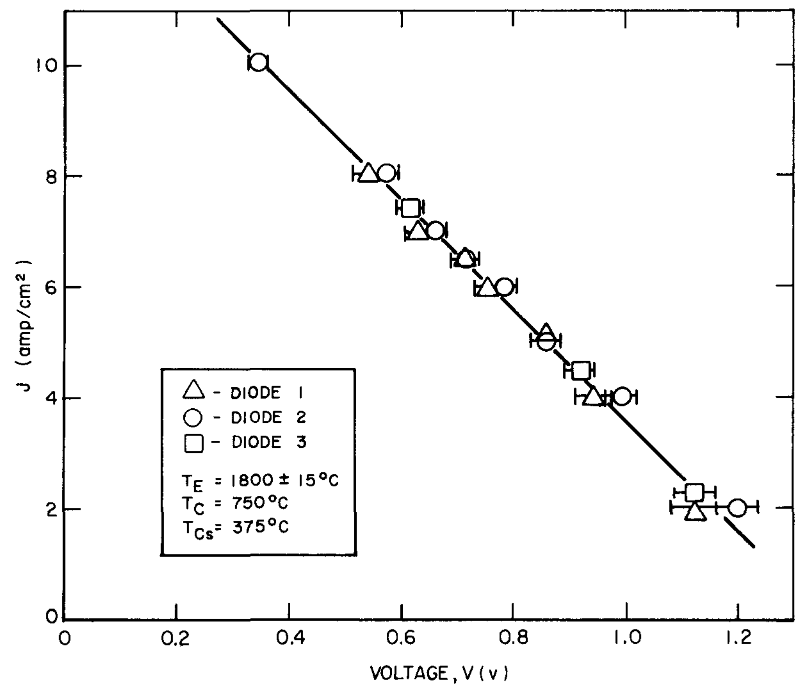

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Figure 11. Comparison of the Individual Performances of the Three Diodes at T_E = 1800 ± 15°C

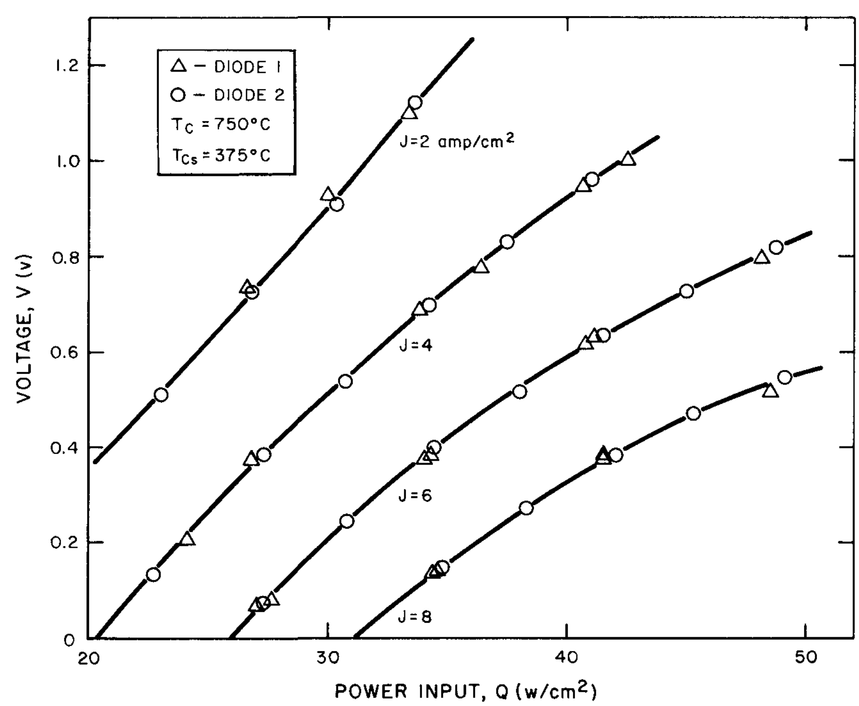

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Figure 12. Comparison of Diodes 1 and 2 at T_{Cs} = 375°C and T_C = 750°C (These two diodes are tested in series and parallel circuits)

IV. PERFORMANCE OF TWO DIODES IN SERIES AND PARALLEL CIRCUITS

A. CONDITIONS OF OPERATION

When two diodes are operated in-circuit 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 report, the applicable range of operation for Diode 2 is $0.5\, Q_1 \leq Q_2 \leq Q_1$.

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 also shown, 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 only slightly affected 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 Figures 13, 14, and 15. Given here is 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. The variation of T_{Cs} for the

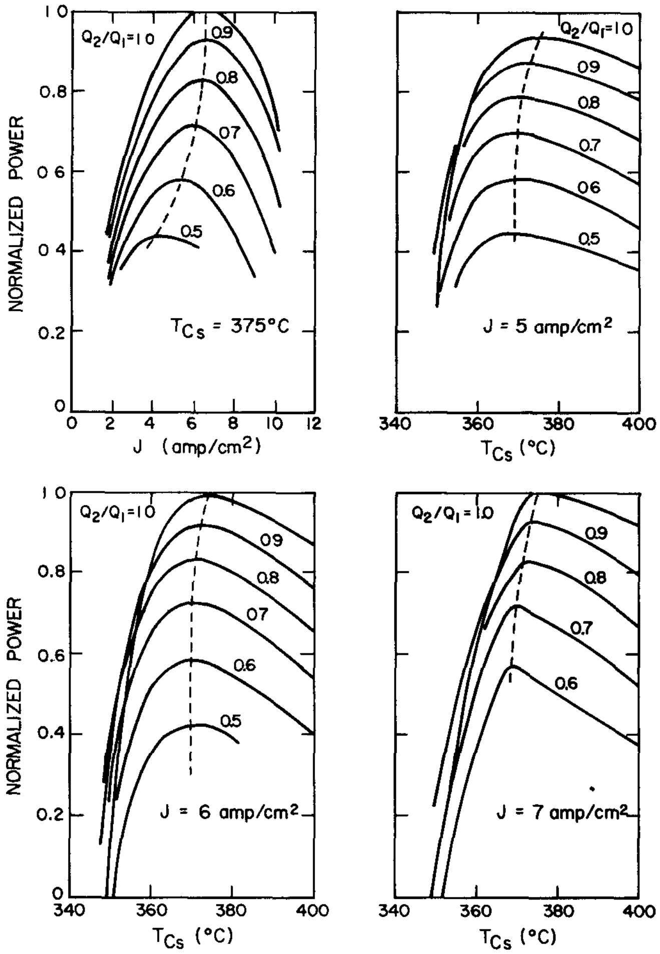

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Figure 13. Normalized Power Output of Two Diodes in a Series Circuit With Power Inputs Q_1 and Q_2 (Q_1 is the power at T_E = 1800°C)

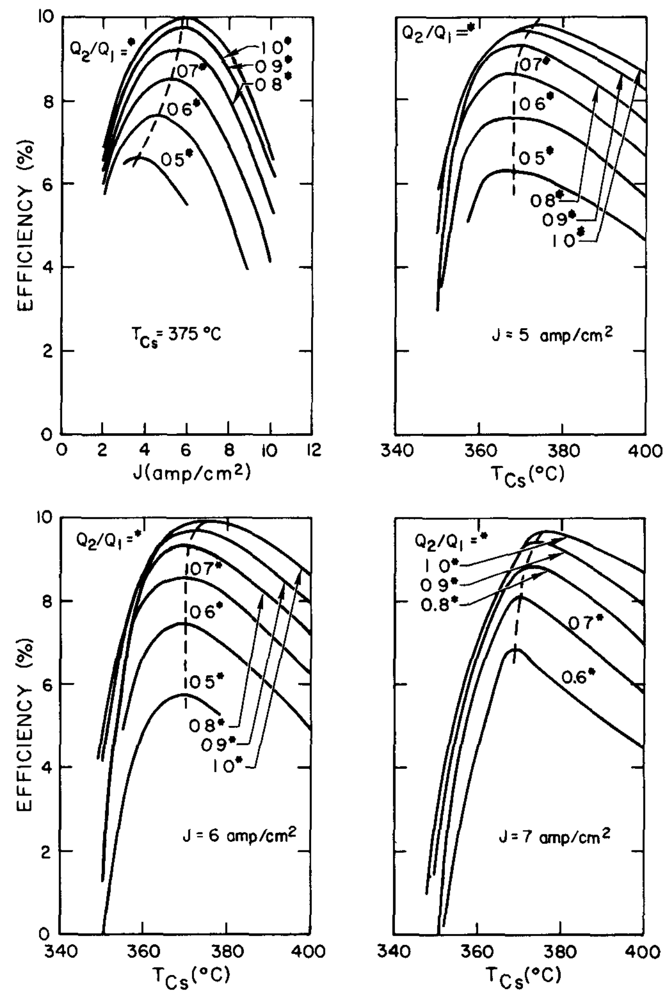

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Figure 14. Efficiency of Two Diodes in a Series Circuit With Power Inputs Q_1 and Q_2 (Q_1 is the power input at T_E = 1800°C)

parallel circuit is not given, because of less emphasis being placed on the parallel part of the experiment.

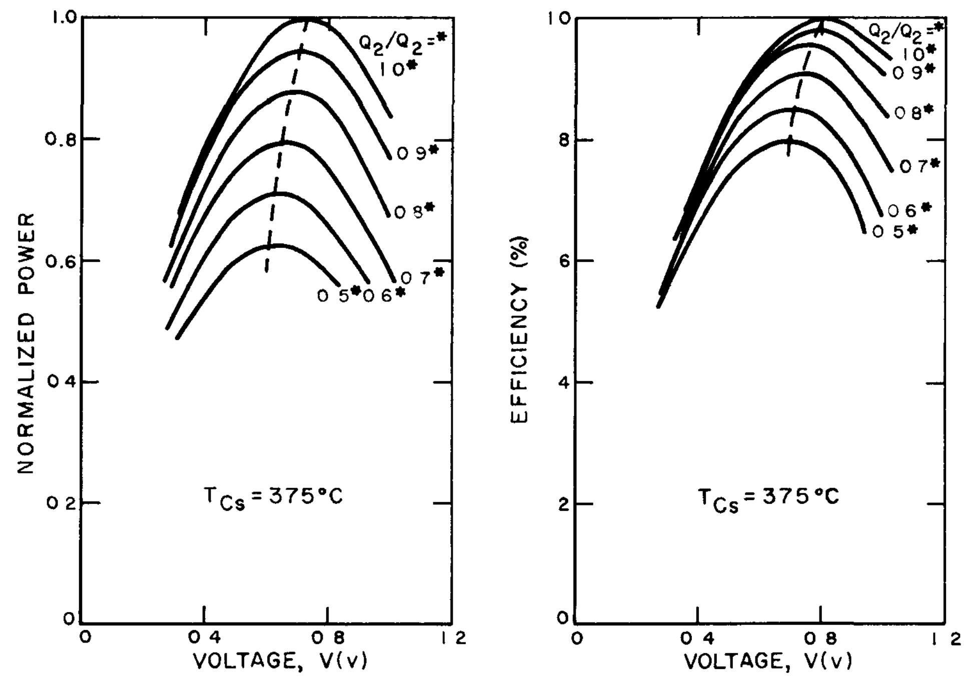

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Figure 15. Normalized Power Output and Efficiency of Two Diodes in a Parallel Circuit With Power Inputs Q_1 and Q_2 (Q_1 is the power input of T_E = 1800°C)

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 I. In order to establish more clearly the power or efficiency degradation trends indicated in this table, these results are plotted in Figure 16.

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.

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 made of the

TABLE I

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						PARALLEL OPERATION			
			POWER			EFFICIENCY			POWER		EFFICIENCY	
			$\frac{P_{max}}{2P_M}$	J_{opt} $\left(\frac{amp/cm^2}{diode}\right)$	$(T_{Cs})_{opt}$ (°C)	η_{max} (%)	J_{opt} $\left(\frac{amp/cm^2}{diode}\right)$	$(T_{Cs})_{opt}$ (°C)	$\frac{P_{max}}{2P_M}$	V_{opt} (v)	η_{max} (%)	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

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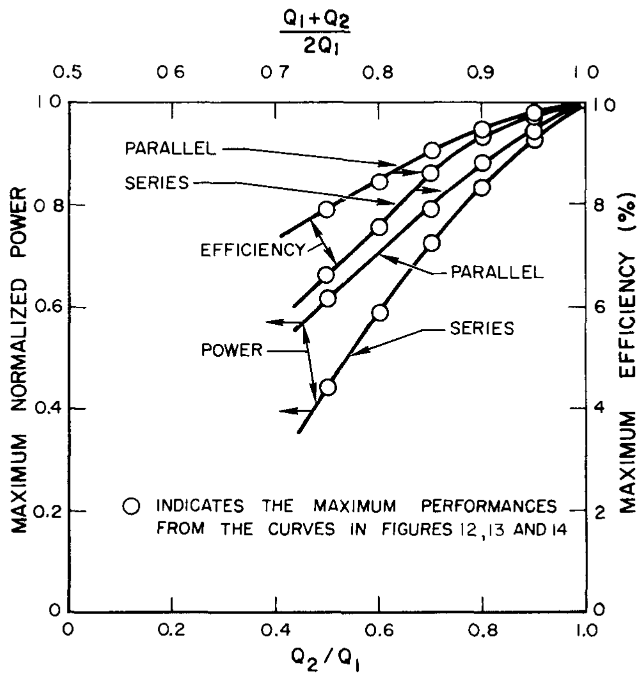

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Figure 16. Maximized Power and Efficiency of Two Diodes in Series and Parallel Circuits vs Q_2/Q_1

graphs of power output and efficiency vs T_{Cs}, Figures 13 and 14, is that the rates of change of the slopes of the curves are smaller 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 Figures 13 through 15. A sampling of the actual performance is compared with the calculated results, in Figures 17 and 18, 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 Figure 13, 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 band width of the control circuit result in 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.

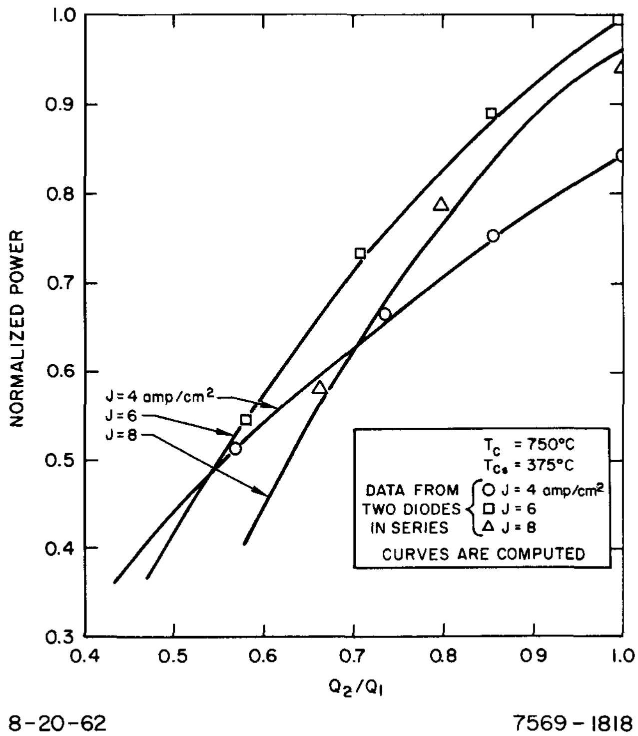

Figure 17. Operating Data for Series-Connected Diodes With Power Inputs Q_1 and Q_2 (Q_1 is the power input at T_E = 1800°C)

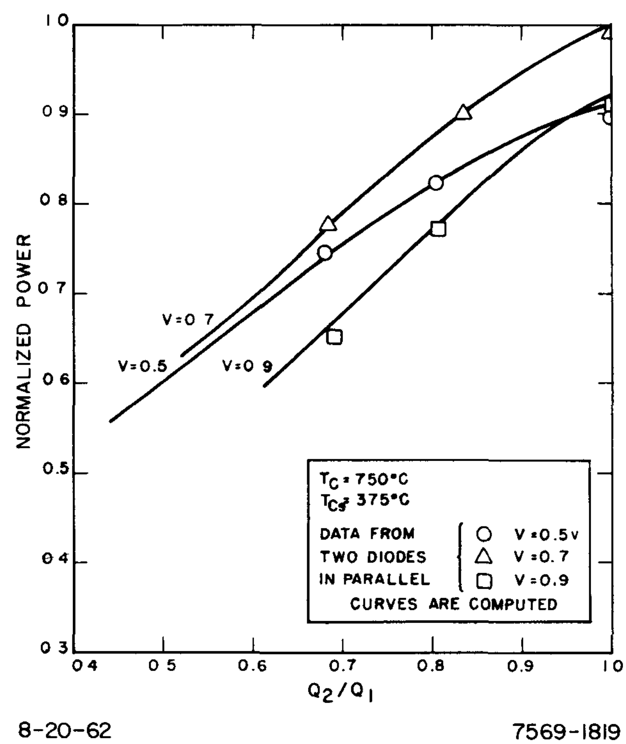

Figure 18. Operating Data for Parallel-Connected Diodes With Power Inputs Q_1 and Q_2 (Q_1 is the power input at T_E = 1800°C)

V. APPLICATION OF RESULTS TO A SPACE THERMIONIC REACTOR

The power and efficiency losses were computed next 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. 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 conclusions back up this decision. The first conclusion is that the extreme sensitivity of the performance to the cesium reservoir temperature makes a high degree of control essential. This control would probably require a sizable piece of equipment. If each diode has to have a separately controlled reservoir, the 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 would be essentially 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 Figures 19 and 20, 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 II.

The minimum power and efficiency degradation for the nonflattened output 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 was also found for the two-diode system.

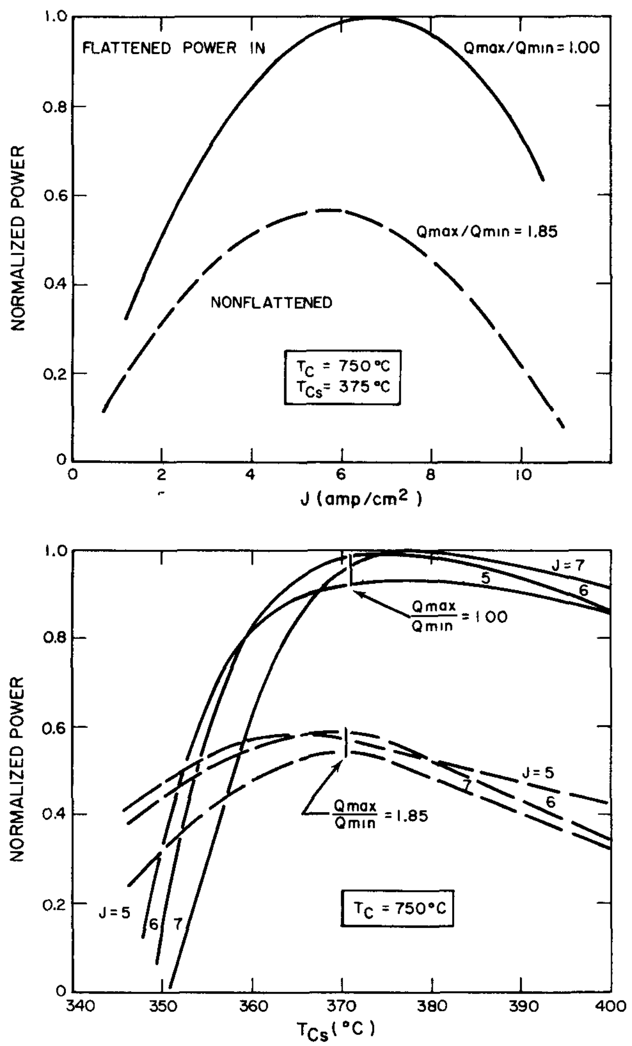

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Figure 19. Normalized Power Output of a Thermionic Reactor With 1000 Series-Connected Diodes

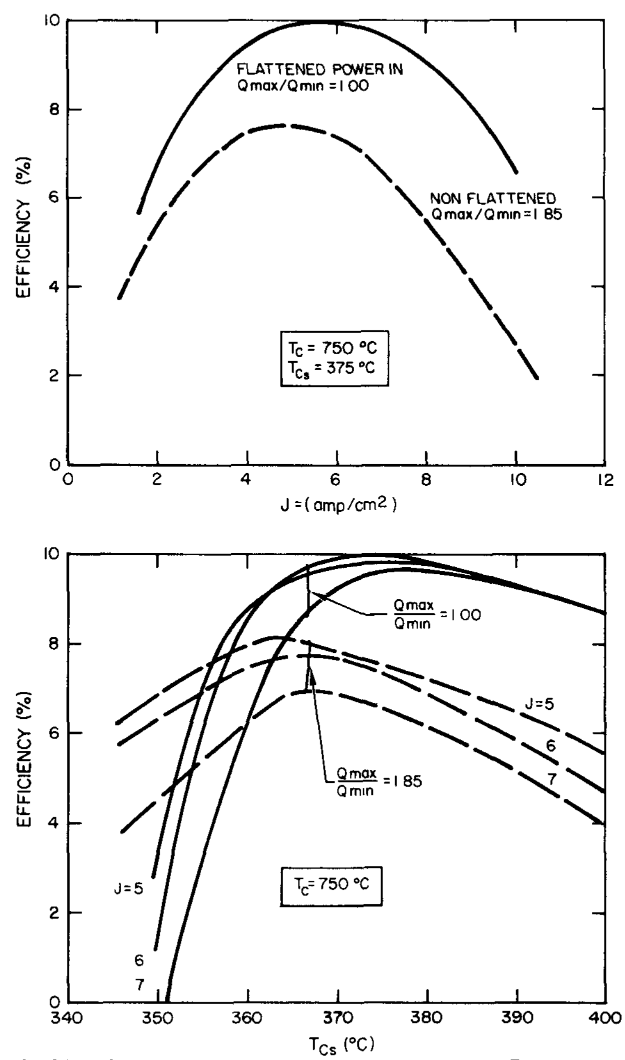

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Figure 20. Efficiency of a Thermionic Reactor With 1000 Series-Connected Diodes

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 proportion of diodes in the system which are operating at values of Q which are more optimum for the lower values of T_{Cs}.

TABLE II

SUMMARY OF THE MINIMUM DEGRADATION IN POWER AND EFFICIENCY OF A THERMIONIC REACTOR DESIGN[1]

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

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 for operating a multidiode plant where there are unequal power inputs has been established; 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 which 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:

a) Variation of emitter area, to optimize the current throughout the core, and

b) 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 exercised, 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.

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