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THERMIONIC PERFORMANCE OF A VARIABLE-GAP CESIUM DIMINIODE WITH A 110-SINGLE-CRYSTAL-TUNGSTEN EMITTER AND A POLYCRYSTALLINE-NIOBIUM COLLECTOR

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5.5	.47	1800	1000 to 1050
7.6	.63	2000	1000 to 1050

This characteristic supports the value of the diminiode as a well-controlled tool for thermionic-conversion research and development.

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SUMMARY

Results from tests of the first variable-gap diminiode at an initial interelectrode spacing of 0.23 millimeter indicate sharply defined, relatively low ultimate-power points:

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This characteristic supports the value of the diminiode as a well-controlled tool for thermionic-conversion research and development.

INTRODUCTION: PERFORMANCE EVALUATIONS FOR BETTER THERMIONIC DIODES

For most cesium-converter applications, greater outputs, higher efficiencies, and lower emitter temperatures are desirable. For land and sea requirements, as well as for space demands near or below 10 kilowatts, decreased collector temperatures are also attractive. And for all thermionic-diode uses, economical materials, fabrication ease, and long service lives are essential. But developing such improved cesium converters means intensive testing of promising electrode combinations (refs. 1 and 2). Furthermore, safe diode utilization depends on establishing statistically verified performance maps for on- and off-optimum conditions - with emphasis on instabilities. Finally, machine programs for thermionic-generator designs require simple, effective algebraic descriptions of output characteristics like the expressions of references 3 and 4.

Achievement of these goals became possible with the use of computers to control, collect, and correlate thermionic-diode data (refs. 5 to 13). Then a miniature guarded planar diode further facilitated cesium-converter testing and the screening of new emitters and collectors (the diminiode of refs. 14 to 17). This diminiode allows evaluations of rare thermionic materials because its electrode diameters can be 6 millimeters or less. In addition to smallness its advantages are simplicity, precision, cleanliness, full instrumentation, complete calibration, ruggedness, ease of fabrication, interchangeability and reuse of parts, and great economy. So computers and diminiodes make proper evaluation of cesium converters practical.

Initial diminiode experiments involved fixed-spacing versions with rather poorly performing emitter and collector materials (refs. 14 and 15). But this report summarizes data obtained from the first variable-gap diminiode (fig. 1). And the electrode combination represents some of the best contemporary thermionic-diode practices.

Figures 2 and 3 indicate maximum-power-output conditions for a 110-monocrystalline-tungsten emitter located 0.23 millimeter from a polycrystalline-niobium collector. The plots summarize the separate 90-point curves for current and for power as functions of voltage taken for each set of temperatures tested. These combinations include 1600, 1700, 1800, 1900, and 2000 K for the emitter; 700, 800, 900, 950, 1000, and 1100 K for the collector; and 10 K increments from 530 to 640 K for the cesium reservoir. Evaluation of the 0.23-millimeter gap first, rather than either of the spacing extremes, made the present variable-gap-diminiode results most applicable to currently practical thermionic-diode technology.

PROCEDURE: DIMINIODE PREPARATION AND TESTING

Electrode Processing, Assembly, and Bakeout

The variable-gap diminiode used in the present work has electrodes with high nominal purities (ref. 18): 99.999 percent for the monocrystalline-110-tungsten emitter and 99.99 percent for the polycrystalline-niobium collector. Brazes with special low-vapor-pressure fillers (ref. 19) hold these electrodes on their bases: (1) the zirconium, 22.8-percent-ruthenium eutectic melting at approximately 1510 K for the niobium collector and guard on their niobium, 1-percent-zirconium base and (2) the tantalum, 46-percent-iridium eutectic melting at approximately 2220 K for the tungsten emitter on its tantalum base. To eliminate all vapor-pressure problems the tantalum, 48.3-percent-osmium eutectic melting at approximately 2630 K (ref. 19) will serve as the brazing filler for any future diminiode emitters like tungsten, rhenium, or osmium.

After lapping and polishing, the guarded surfaces of the tungsten and the niobium electrodes were smooth to 10^{-5} millimeter and flat except for a 10^{-4} millimeter curvature at the collector edge. Subsequent cleaning, degassing, and assembly of the emitter, collector, and envelope sections (figs. 1(b) and (c)) preceded attachment by copper brazing of the heating and cooling coils (fig. 1(d)). Then mounting the diminiode on a vacuum-flange insert, connecting the electric leads and tubing, and adding calibrated cesium-reservoir and collector thermocouples prepared it for vacuum processing (figs. 1(e) and (f)).

In this procedure the bakeout, calibration, cesium insertion, and brazed closure of the diminiode all occur in one chamber after a single pumpdown (fig. 1(g) and ref. 16). The first step is a 10-hour vacuum degassing at temperatures above those for experimental operations - 2000 K for the emitter and 1100 K for the collector. If ion-gage readings so indicate, the bakeout continues until cleanliness is assured.

Emitter-Temperature Calibration

The next vacuum-processing stage is an emitter-temperature calibration duplicating the automatic pyrometry and optical path used in the actual performance tests. This procedure relates the temperatures of the external tungsten-lined hohlraum to those of the black-body hole in the emitter near its surface, exposed through the yet unblocked cesium reservoir (fig. 1(g)). Both cavities have length-to-diameter ratios greater than 5. The calibration includes combinations of emitter, collector, and cesium-reservoir temperatures encountered during diminiode testing experiments.

Interelectrode-Spacing Calibration

Further vacuum processing involves the cathetometric calibration of the emitter, collector gap - viewed through the still open cesium reservoir (fig. 1(g)). Diminiode design calculations indicated the interelectrode spacing would change little with the thermal variations encountered during performance evaluations. And the cathetometer revealed no significant gap alteration for permutations over the extremes of emitter and collector temperatures.

For the present work, electric zeroing and precision shimming checked by direct observations before vacuum processing fixed the cold interelectrode spacing at 0.23

millimeter. Then cathetometry yielded gap measurements having a 0.23-millimeter mean with a 0.015-millimeter standard deviation over all combinations of high- and low-temperature limits for the emitter (1600 to 2000 K) and the collector (600 to 1100 K).

The local averages of the hot-gap data show no meaningful trends with the separate emitter and collector temperatures or their differences. In fact, the characteristics of the complete set of spacing determinations closely approach those of a normal distribution: the "skewness" is 0.1, and the "kurtosis" is 2.7; the corresponding Gaussian values are zero and 3. Kurtosis has fallen from favor as a gage of "peakedness." But the similarities of the experimental skewness and kurtosis to corresponding properties of the normal distribution strongly suggest that random measuring errors caused the dispersion of the hot-gap data.

Cesium Insertion

The final vacuum-processing procedures are the cesium-capsule insertion and the brazed closure of the diminiode. For the present study, though, direct addition of unpackaged cesium seemed more practical. Although prior multiple encapsulation is advantageous and workable (refs. 14 and 15), running liquid cesium into the diminiode and then brazing the reservoir closed are less demanding than performing comparable operations with small molybdenum ampules (ref. 16). The lack of manpower and time to establish conditions for precision repetitive cesium packaging forced this change.

Testing

References 14 and 16 describe the stations, instrumentation, procedures, and data presentation for the thermionic performance mapping of diminiodes.

RESULTS: 0.23-MILLIMETER-GAP PERFORMANCE OF A 110-TUNGSTEN, NIOBIUM DIMINIODE

As previously stated, figures 2 and 3 present conditions of near-maximum power outputs for a directly calibrated, high-purity, variable-gap 110-tungsten, niobium diminiode operating with a 0.23-millimeter interelectrode spacing.

A cursory examination of figure 2 reveals at least two pertinent observations: first, the power maximums as functions of collector temperature at constant emitter temperatures vary rapidly near their indicated extremes or ultimate-power points.

These changes are more abrupt than those for the research diodes described in references 6 to 10. And second, the diminiode temperature combinations tested missed the ultimate-power points. The latter problem occurred because of early planning based on references 6 to 10. There ultimate power generally developed for collectors between 900 and 950 K rather than those between 1000 and 1050 K (fig. 2).

Initial evaluations stopped when the collector heater failed, probably because of the long, exceedingly high-temperature bakeout. Ordinarily this problem would be a minor one. But the termination of NASA thermionic-conversion work precluded further testing to define the unusually accentuated maximums resulting from variations of cesium-reservoir and collector temperatures in this diminiode. So determining the ultimate-power points required mild extrapolations.

Because diode outputs change rapidly with cesium-reservoir temperature T_{Cs} at constant emitter and collector temperatures T_E and T_C, approximations were also necessary to locate the optimum conditions represented by the following:

Emitter temperature, T_E, K	Collector temperature, T_C, K	Approximate cesium temperature, T_{Cs}, K	Maximum power output, P_{max}, W/cm^2 (a)	Output voltage, ΔV, volts (b)
1600	800	570	1.7	0.19
1600	1000	580	3.6	.25
2000	800	600	5.8	.56
2000	1000	610	7.5	.63

[a]From fig. 2.
[b]From fig. 3.

Fortunately, the estimated power maximums and ultimate outputs were close to measured values for most envelopes. But if the diminiode collector heater had been repaired, saturation testing around the apparent optimum conditions would have saved much time and labor and assured accuracy.

Perhaps the best performance measure of this 110-tungsten, niobium diminiode results from rating it relative to other similar diodes. To facilitate such a comparison figure 4 shows optimized outputs published previously for several thermionic converters with tungsten emitters. Reference 2 allowed the ready selection of the diodes for which curves are shown in figure 4 (taken from refs. 12 and 20 to 25). And because reference 2 abstracts performances of these selected diodes and many others, its citation numbers for references 12 and 20 to 25 appear in the reference list of this report for the convenience of the reader.

A comparison of ultimate outputs from figures 2 and 3 with those of figure 4(f) for another 110-tungsten, niobium diode indicates lower power and higher voltage for the diminiode version:

Emitter temperature, T_E, K	Power for present diode, P, W/cm^2 (a)	Voltage for present diode, V, volts (b)	Power for diode of ref. 23, P, W/cm^2 (c)	Voltage for diode of ref. 23, V, volts (c)
1600	3.7	0.25	3.4	0.25
1700	5.1	.36	5.5	.31
1800	5.5	.47	6.7	.44
1900	5.9	.55	7.8	.50
2000	7.6	.63	9.5	.54

[a]From fig. 2.
[b]From fig. 3.
[c]From fig. 4(f).

Estimated from the previous tabulation the 1840 K ultimate output for this diminiode is 5.7 watts per square centimeter at 0.51 volt. So ranked against the maximums of the curves shown in figure 4(j) the present 110-tungsten, niobium diode appears to fall quite low in the grouping.

DISCUSSION: IMPLICATIONS OF THE PRESENT DIMINIODE RESULTS

Certain aspects of the present study deserve emphasis: First, the electrodes are very pure and well defined, and the diminiode is exceedingly clean. Second, the gap dimension, electrode parallelism, and emitter temperatures are highly reliable owing to direct calibrations and checks in the assembled diminiode at operating conditions.

These points have a strong impact because small amounts of impurities and the electrode spacing and temperatures affect cesium-diode performance significantly. In particular, very low concentrations of oxygen increase thermionic-converter outputs considerably. Furthermore, impurities, electrode tilting, and emitter-temperature inhomogeneities smear out diode performance effects.

In contrast a clean, well-defined, directly calibrated thermionic converter should produce relatively low power with more discrete output characteristics. Most cesium-diode experts concurred with this generalization long ago. And as converter assembly techniques grew more sophisticated, performances of standard thermionic electrodes moved steadily downward. So in addition to the design, processing, and material improvements of this diminiode its sharply defined ultimate-power points at comparatively poor outputs support its effectiveness as a well-controlled tool for thermionic-conversion research and development.

Of course, these are interpretations based only on 0.23-millimeter-gap results. Effects of electrode-spacing variations are also of great interest and could provide a far more comprehensive view of the performance of this 110-tungsten, niobium diminiode. Furthermore, all parts for several other diminiodes were entering assembly to allow the statistical establishment of output characteristics for tungsten, niobium cesium diodes. And for low-temperature performances potentially much higher than those of tungsten, niobium converters, work was also under way on diminiodes with electrode materials such as iridium and lanthanum hexaboride. But this thermionic-conversion program ceased prior to complete evaluation of the initial interelectrode spacing for the first variable-gap diminiode.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 23, 1973,
503-25.

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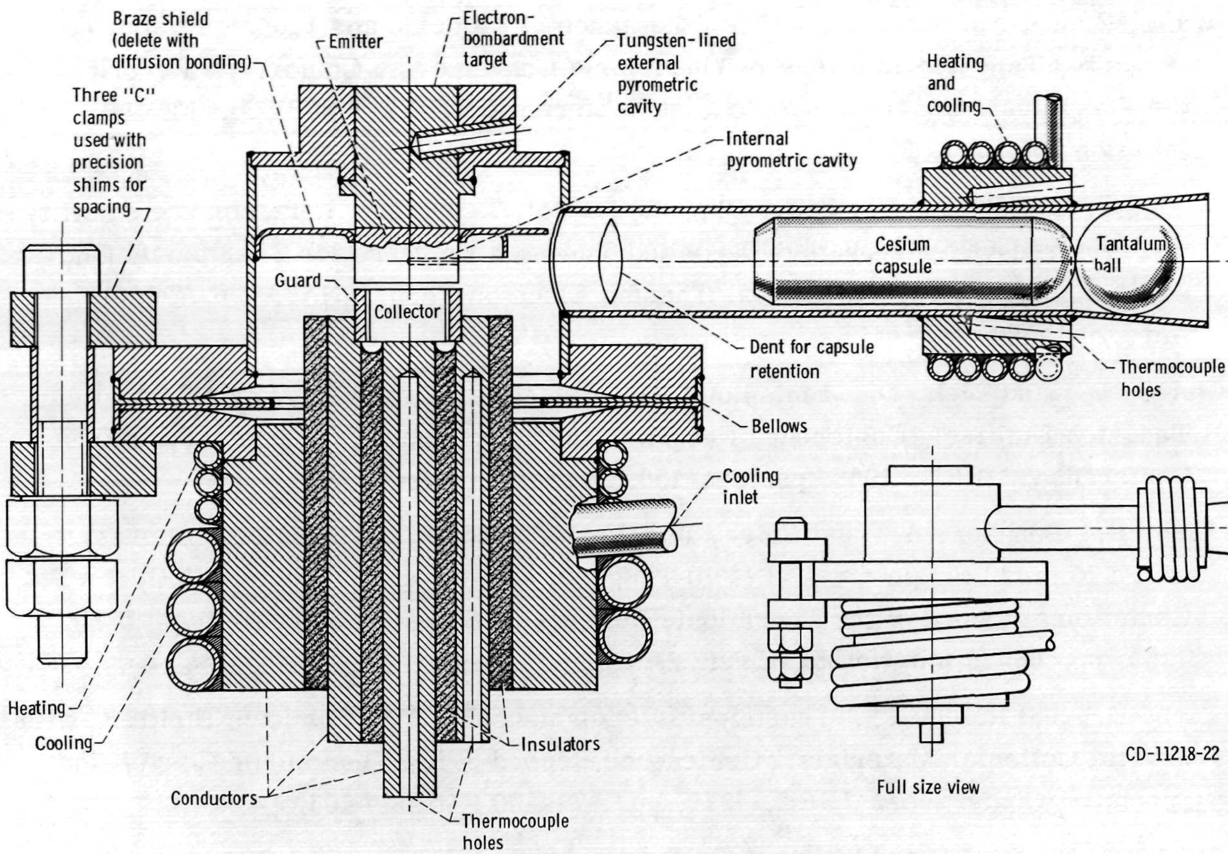
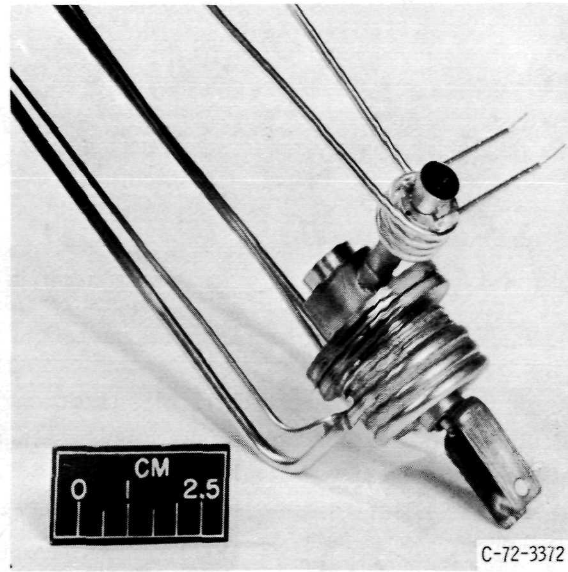


(a) Cross section.

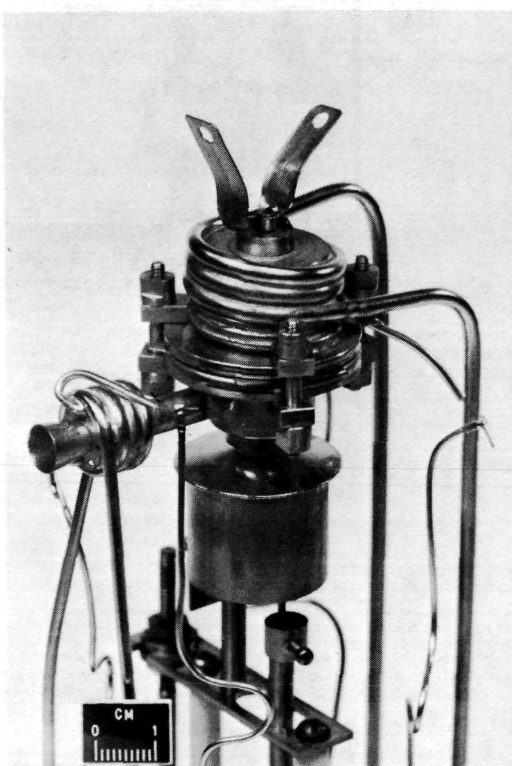
(b) Collector, envelope, and emitter sections of diminiode.

Figure 1. - Variable-gap diminiode.

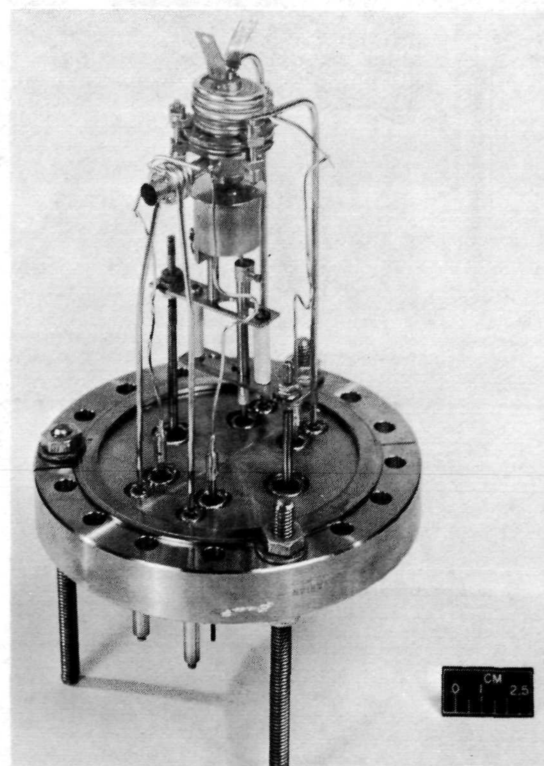
(c) Bare assembled diminiode.



(d) Diminiode with heating and cooling coils for cesium reservoir and collector.

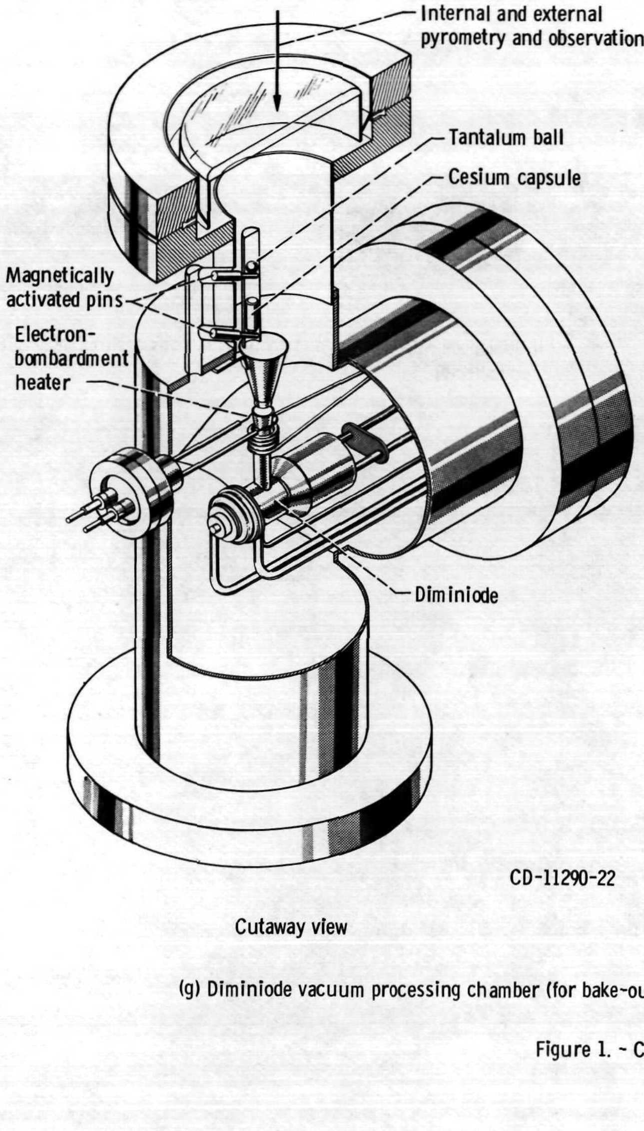


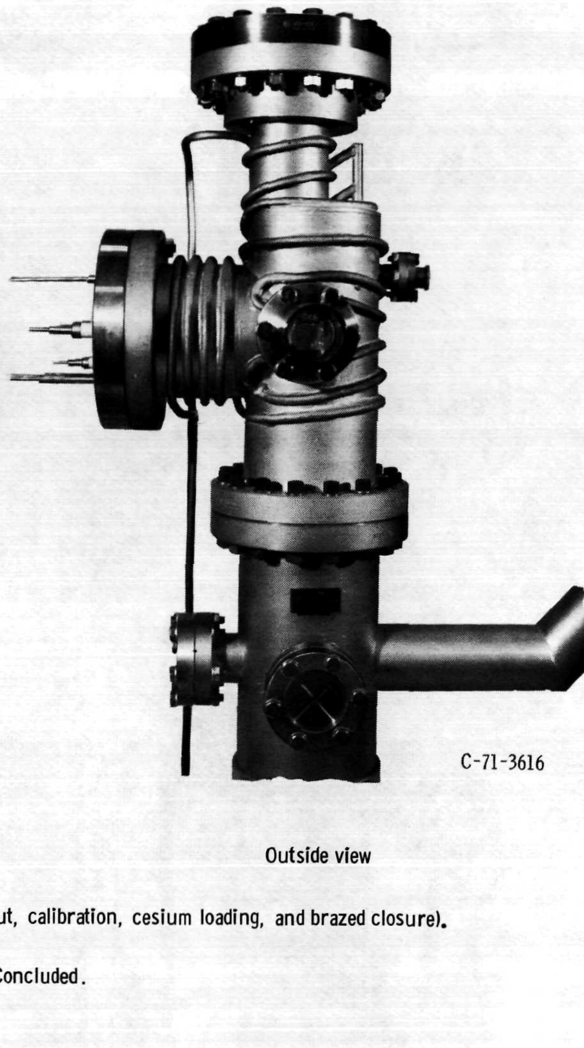
(e) Diminiode with heating and cooling coils for reservoir and collector and electron bombardment for emitter.



(f) Fully mounted diminiode.

Figure 1. - Continued.





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Cutaway view

Outside view

(g) Diminiode vacuum processing chamber (for bake-out, calibration, cesium loading, and brazed closure).

Figure 1. - Concluded.

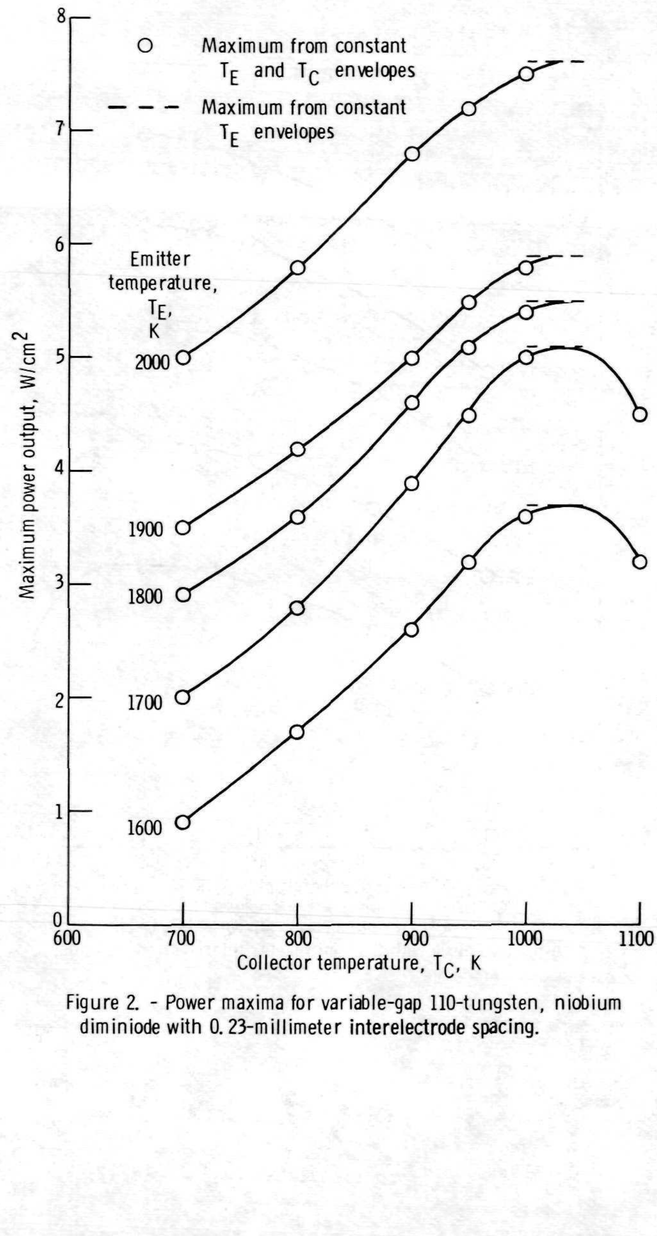


Figure 2. - Power maxima for variable-gap 110-tungsten, niobium diminiode with 0.23-millimeter interelectrode spacing.

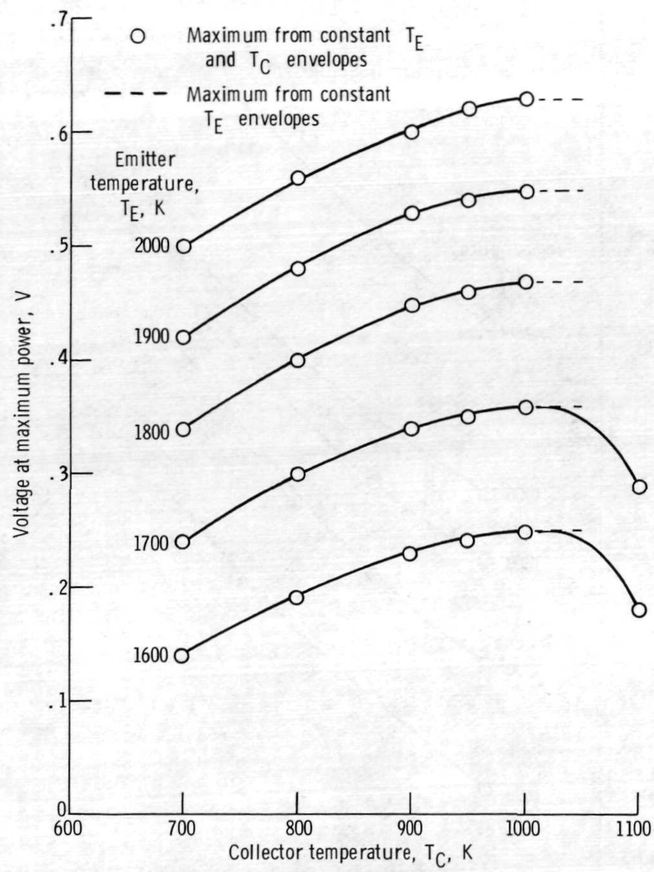
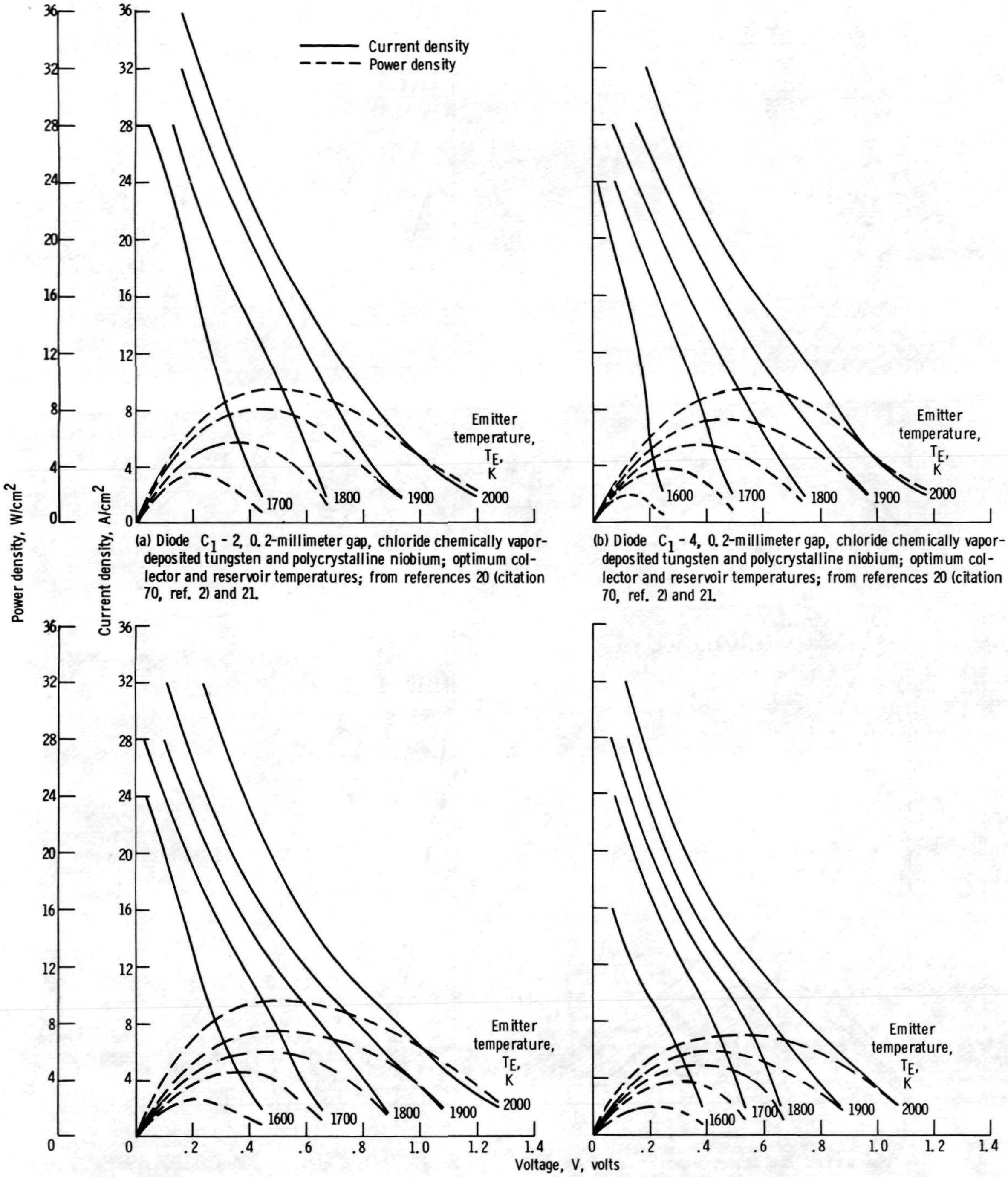


Figure 3. - Voltage at maximum power for variable-gap 110-tungsten, niobium diminiode with 0.23-millimeter interelectrode spacing.



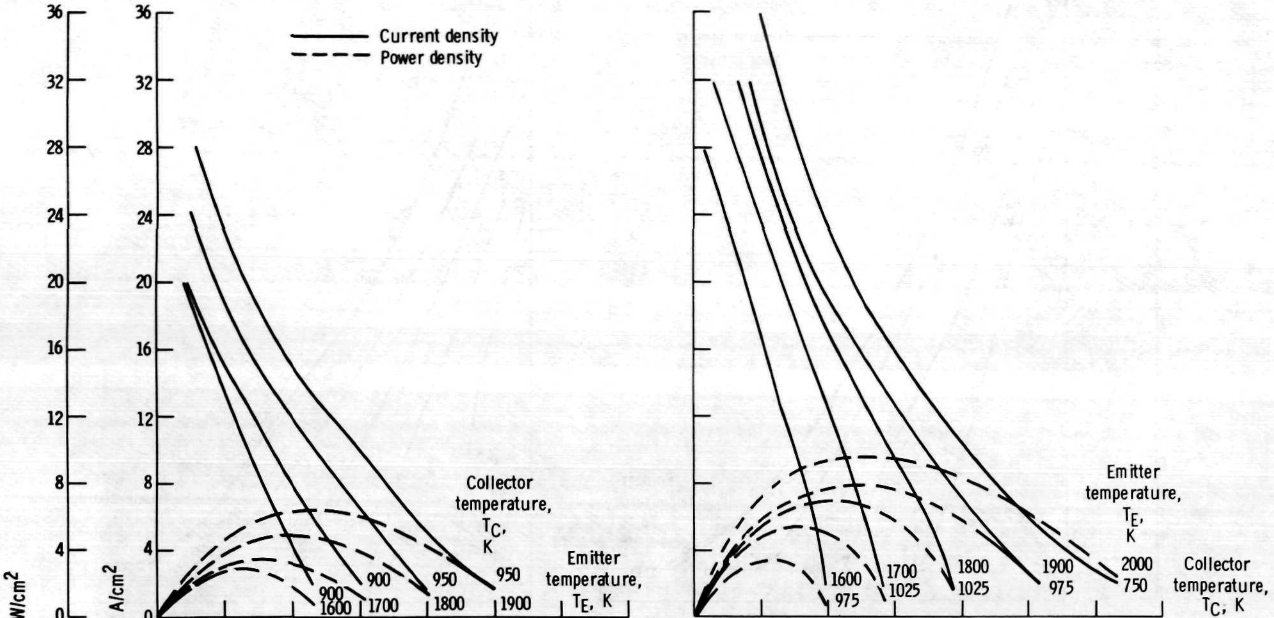
(a) Diode C_1 - 2, 0.2-millimeter gap, chloride chemically vapor-deposited tungsten and polycrystalline niobium; optimum collector and reservoir temperatures; from references 20 (citation 70, ref. 2) and 21.

(b) Diode C_1 - 4, 0.2-millimeter gap, chloride chemically vapor-deposited tungsten and polycrystalline niobium; optimum collector and reservoir temperatures; from references 20 (citation 70, ref. 2) and 21.

(c) Diode C_1 - 5, 0.2-millimeter gap, chloride chemically vapor-deposited tungsten and polycrystalline niobium; optimum collector and reservoir temperatures; from references 20 (citation 70, ref. 2) and 21.

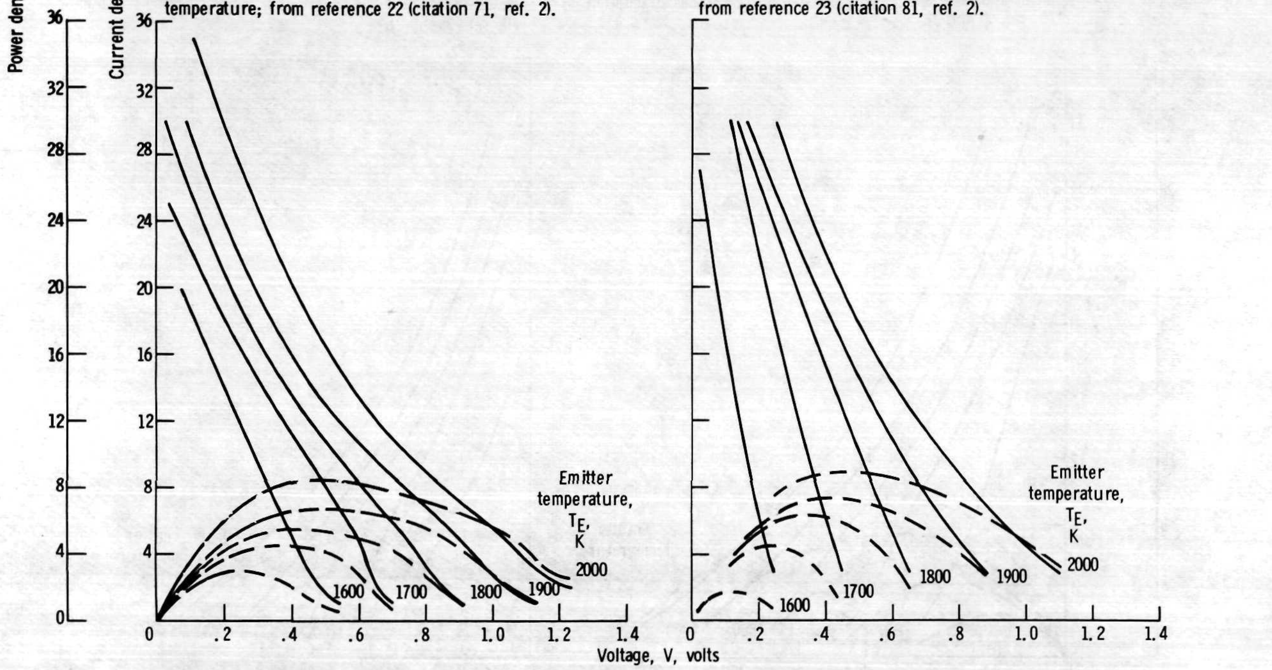
(d) Diode C_3 - 3, 0.2-millimeter gap, chloride chemically vapor-deposited duplex tungsten and polycrystalline niobium; optimum collector and reservoir temperatures; from reference 21.

Figure 4. - Cesium-diode output envelopes.



(e) Diode with 0. 25-millimeter gap, chloride chemically vapor-deposited duplex tungsten and molybdenum; optimum reservoir temperature; from reference 22 (citation 71, ref. 2).

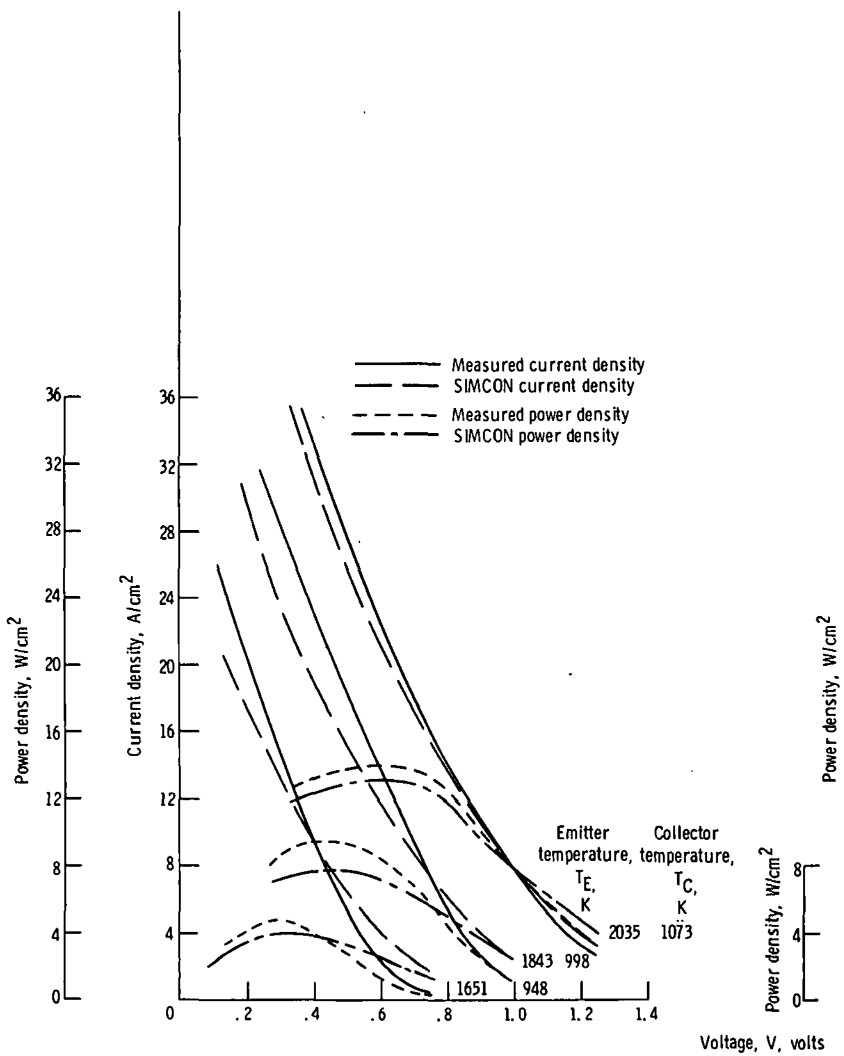
(f) Diode with 0. 25-millimeter gap, single-crystal 110-tungsten and polycrystalline niobium; optimum reservoir temperature; from reference 23 (citation 81, ref. 2).



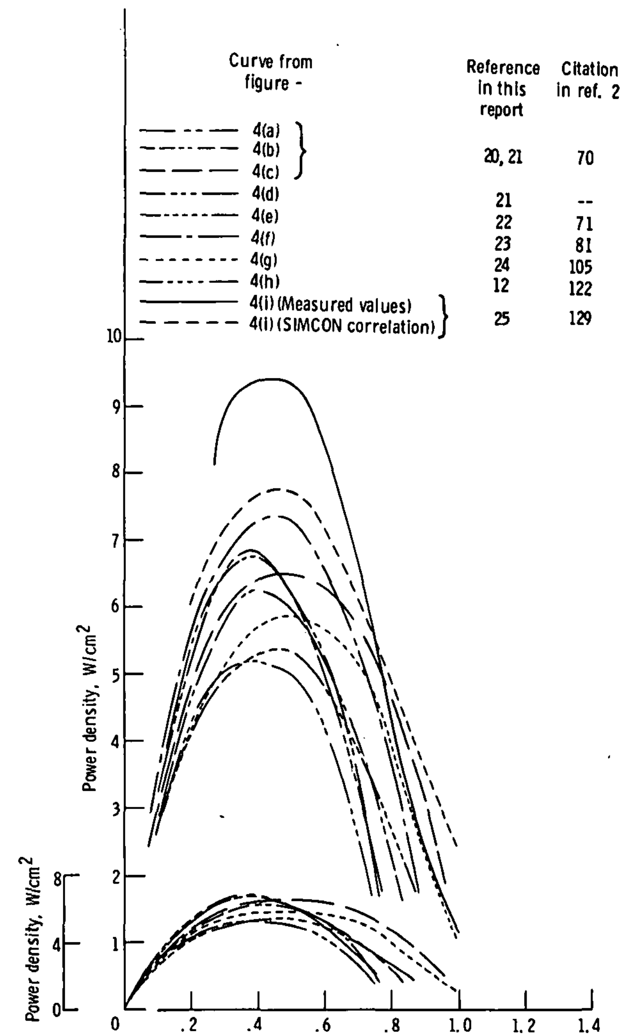
(g) Diode with 0. 25-millimeter gap, chloride chemically vapor-deposited tungsten and polycrystalline niobium; collector temperature, 1023 K for emitter temperature of 2000 and 973 K for all other emitter temperatures; optimum reservoir temperature; from reference 24 (citation 105, ref. 2).

(h) Diode with 0. 25-millimeter spacing, chloride chemically vapor-deposited tungsten and polycrystalline niobium; optimum collector and reservoir temperatures; from reference 12 (citation 122, ref. 2).

Figure 4. - Continued.



(i) Diode with 0.25-millimeter gap, chloride chemically vapor-deposited tungsten and polycrystalline niobium; from reference 25 (citation 129, ref. 2).



(j) Summary of envelopes; emitter temperature, 1840 K; nearly optimum collector temperature; optimum reservoir temperature.

Figure 4. - Concluded.

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