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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

REPLY TO ATTN OF: GP

TO: USI/Scientific & Technical Information Division
Attention: Miss Winnie M. Morgan

FROM: GP/Office of Assistant General Counsel for Patent Matters

SUBJECT: Announcement of NASA-Owned U. S. Patents in STAR

In accordance with the procedures agreed upon by Code GP and Code USI, the attached NASA-owned U. S. Patent is being forwarded for abstracting and announcement in NASA STAR.

The following information is provided:

U. S. Patent No. : 3,578,992

Government or Corporate Employee : Calif. Inst. of Techology Pasadena, Calif.

Supplementary Corporate Source (if applicable) : JPL

NASA Patent Case No. : NPO-10412

NOTE - If this patent covers an invention made by a corporate employee of a NASA Contractor, the following is applicable:
Yes ☑ No ☐

Pursuant to Section 305(a) of the National Aeronautics and Space Act, the name of the Administrator of NASA appears on the first page of the patent; however, the name of the actual inventor (author) appears at the heading of Column No. 1 of the Specification, following the words ". . . with respect to an invention of . . ."

Elizabeth A. Carter

Elizabeth A. Carter
Enclosure
Copy of Patent cited above

FACILITY FORM 602

N71-28421 (ACCESSION NUMBER) — 11 (PAGES) — (NASA CR OR TMX OR AD NUMBER) — (THRU) 00 (CODE) 09 (CATEGORY)

N71-28421

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6 Sheets-Sheet 1

FIG. 2

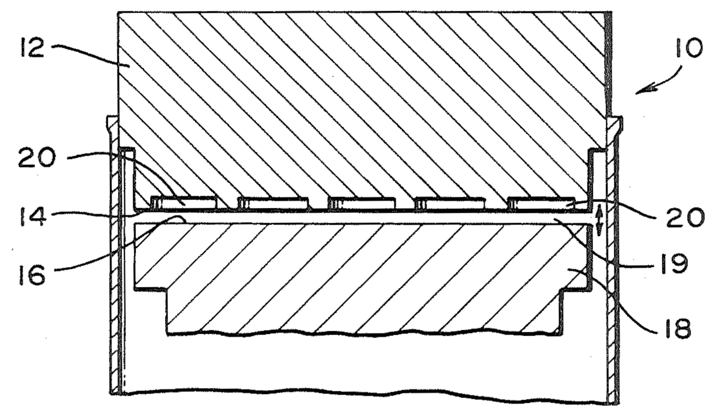



FIG. 3

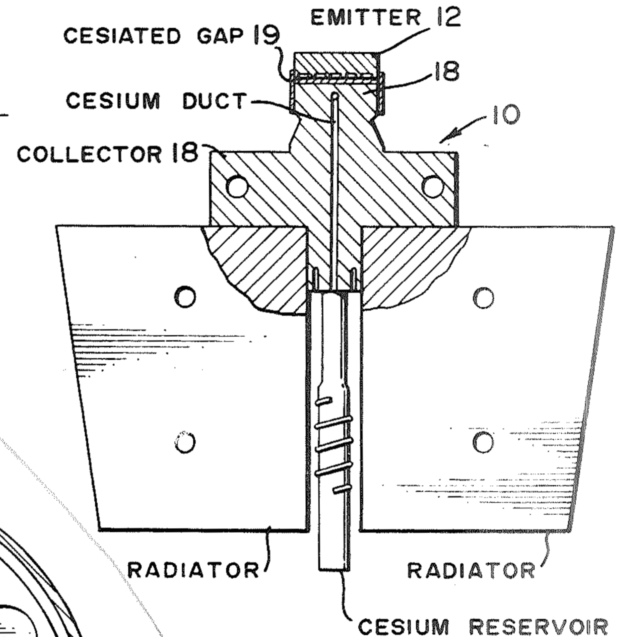
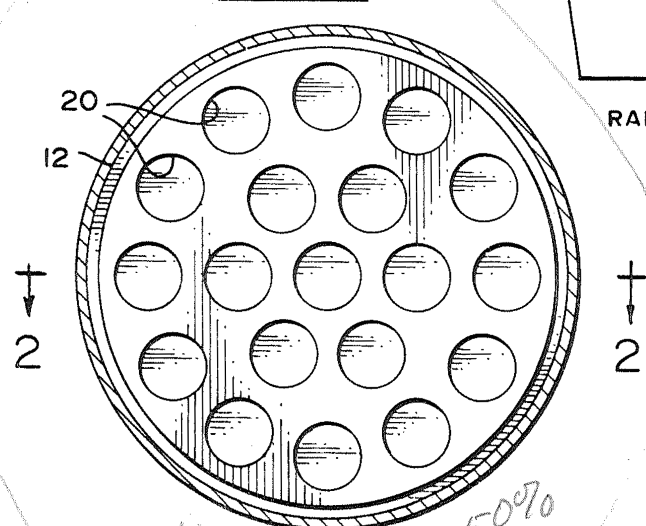



FIG. 1

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INVENTOR.
KATSUNORI SHIMADA

BY J. H. Warden
Edward ... Carey

ATTORNEYS

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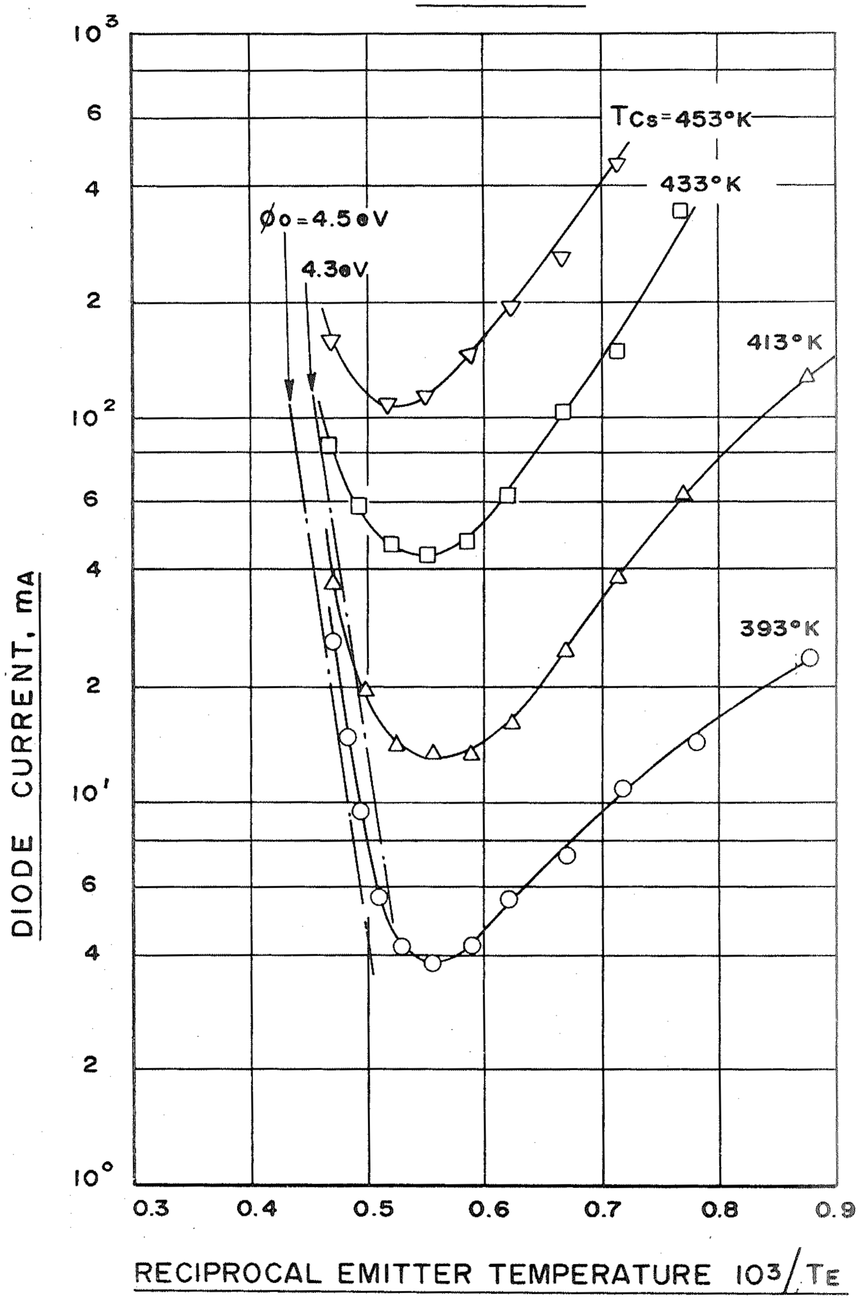
FIG. 4




INVENTOR.
KATSUNORI SHIMADA
BY J. H. Warden
Warden & Gary
ATTORNEYS

FIG. 5

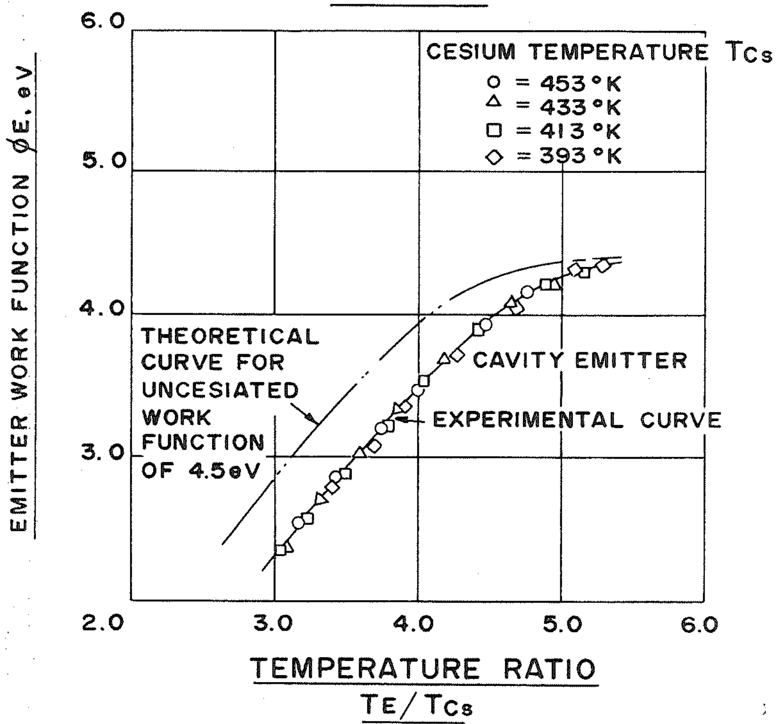
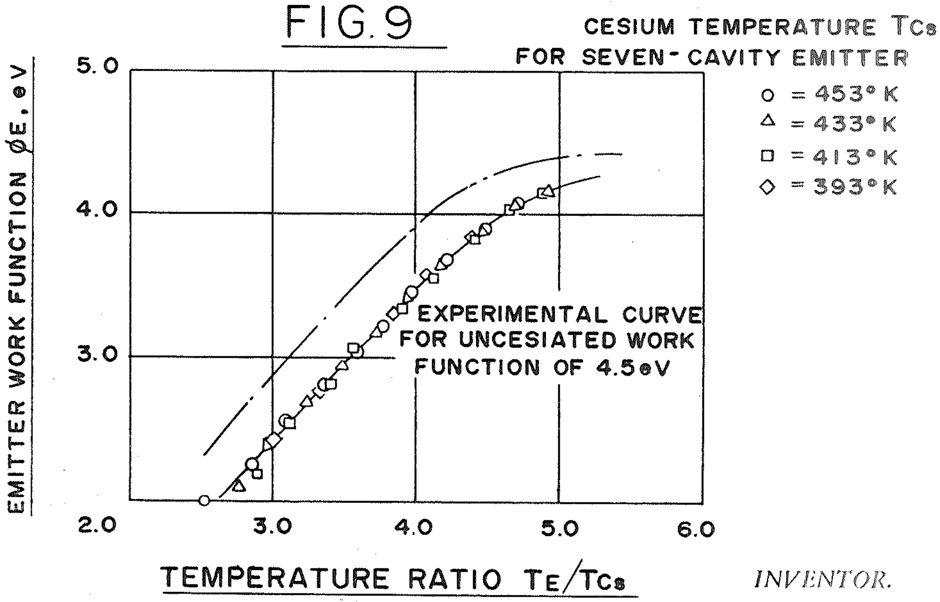
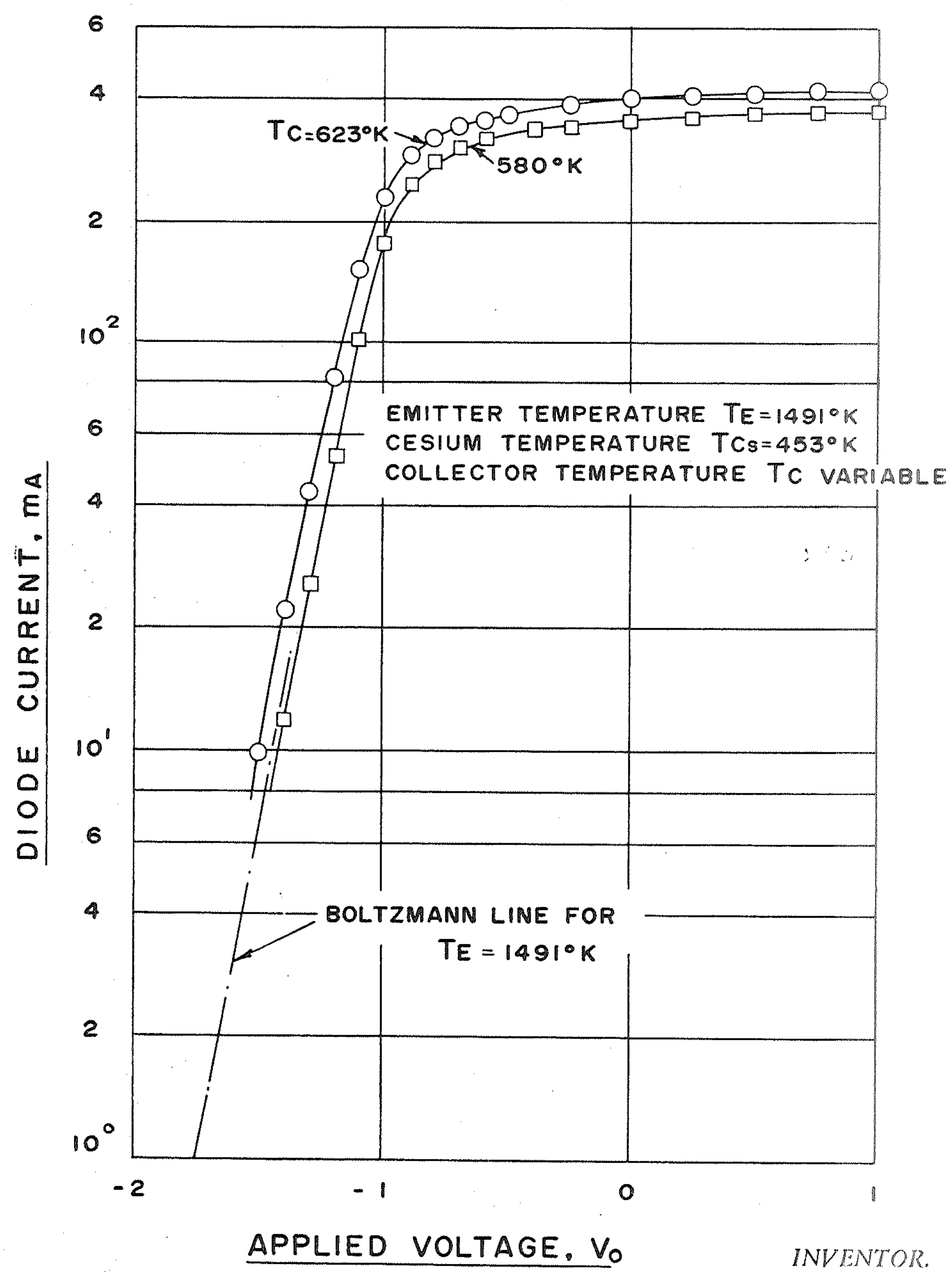



FIG. 9




INVENTOR.
KATSUNORI SHIMADA
BY
ATTORNEYS

FIG. 6




INVENTOR.
KATSUNORI SHIMADA

BY J. H. Warden

ATTORNEYS

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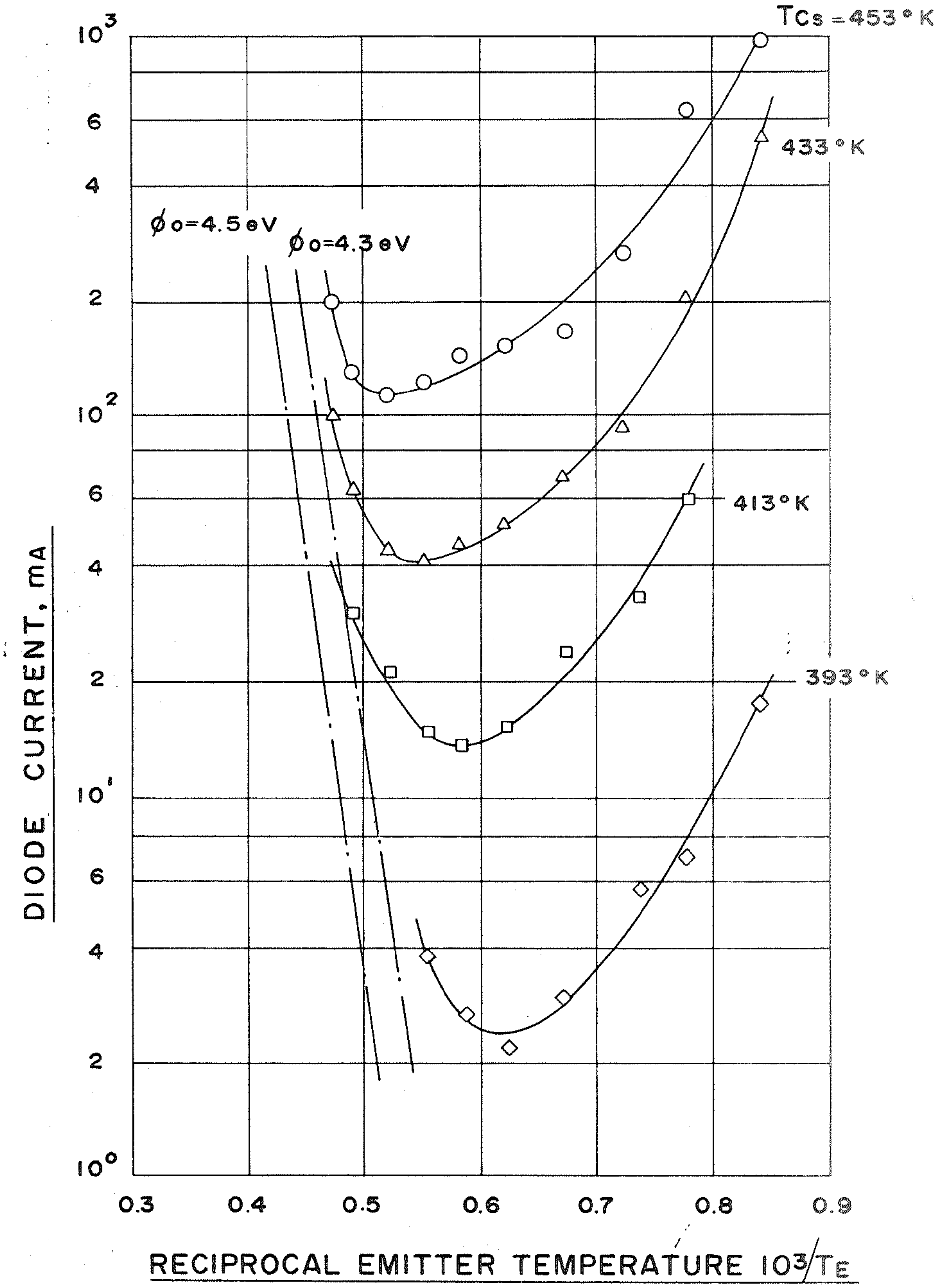
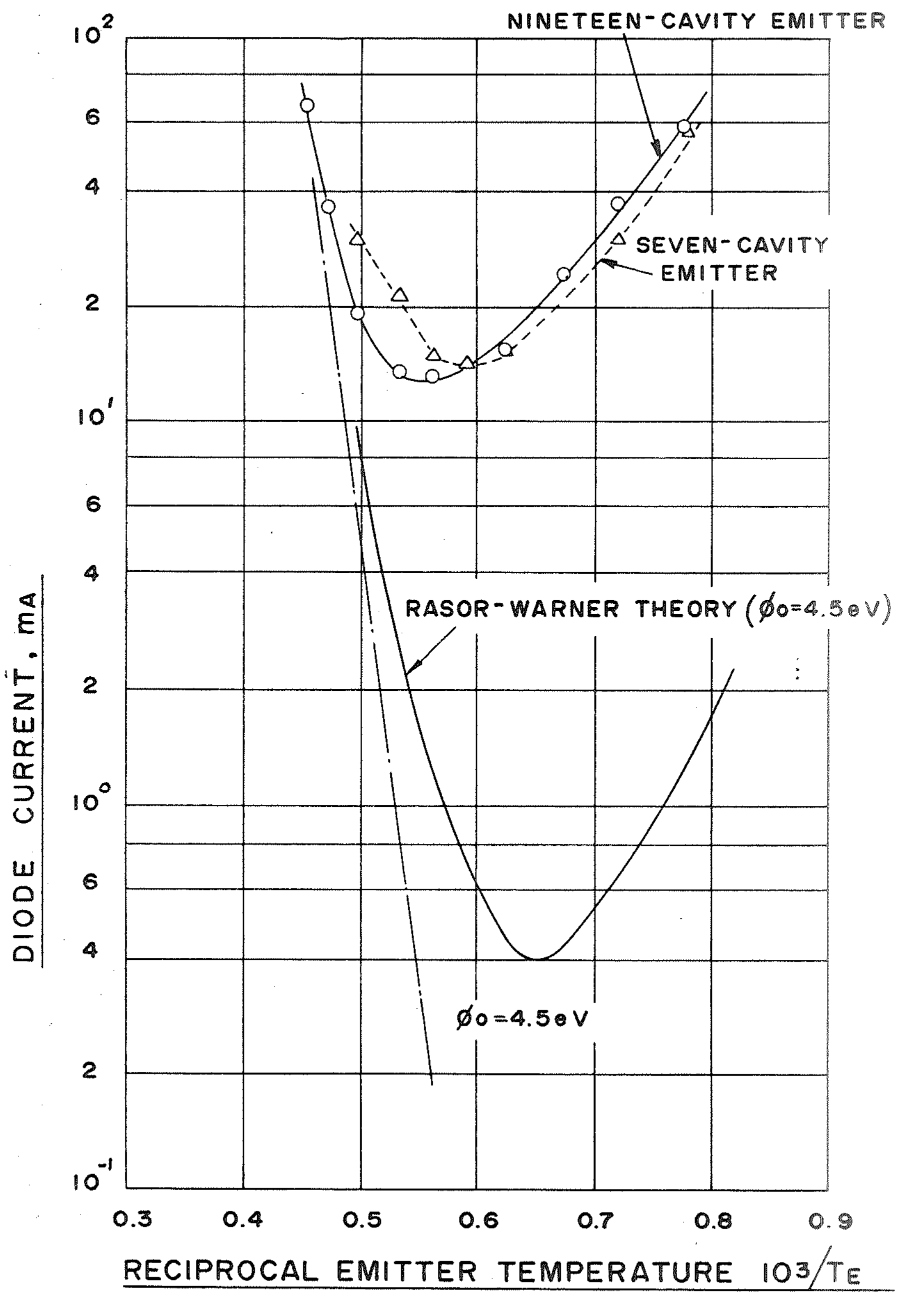
FIG. 7




INVENTOR.
KATSUNORI SHIMADA
BY J. H. Warden
[signature]
ATTORNEYS

FIG. 8




INVENTOR.
KATSUNORI SHIMADA
BY J. H. Warden
ATTORNEYS

# United States Patent

[11] 3,578,992

[72] Inventors T. O. Paine
Deputy Administrator of the National Aeronautics and Space Administration with respect to an invention of;
Katsunori Shimada, Pasadena, Calif.

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[22] Filed Oct. 17, 1968
[45] Patented May 18, 1971

[54] CAVITY EMITTER FOR THERMIONIC CONVERTER
7 Claims, 9 Drawing Figs.

[52] U.S. Cl. .......... 310/4
[51] Int. Cl. .......... H01j 45/00
[50] Field of Search .......... 310/4; 313/339, 346, (Consulted)

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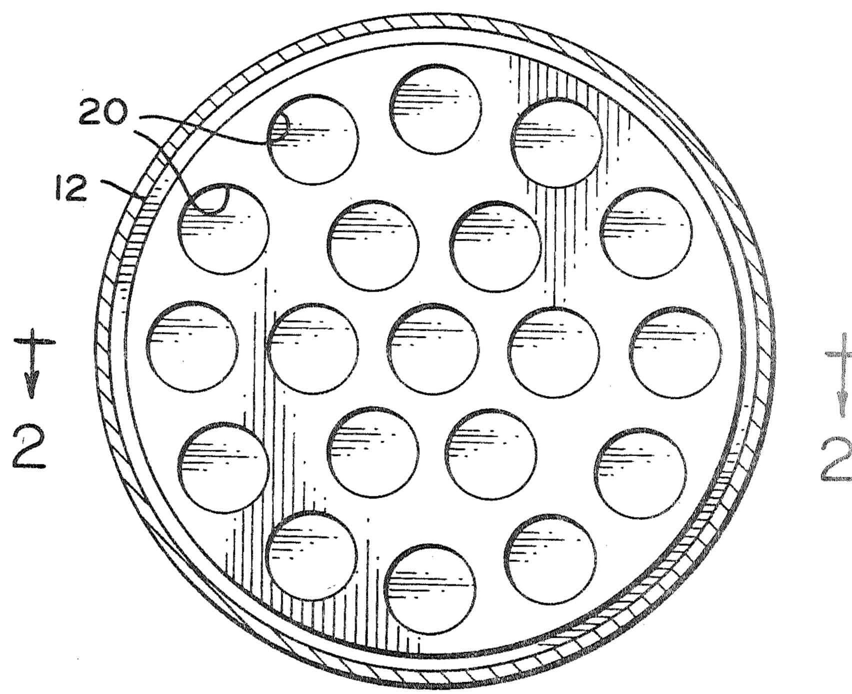
*Primary Examiner*—D. F. Duggan
*Attorneys*—J. H. Warden, M. F. Mott and G. T. McCoy

**ABSTRACT:** A thermionic cesium diode incorporating a cavity emitter is disclosed. The emitter defines a plurality of relatively shallow cavities extending inwardly from the surface thereof which faces the interelectrode gap. The depths of the cavities are comparable with the electron-neutral mean-free path and the ratios of the depths of the cavities to their diameters are large enough to neutralize electron space charge from occuring thereat.



# CAVITY EMITTER FOR THERMIONIC CONVERTER

## ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, Public Law, 85—568 (72 Stat. 435; 42 USC 2457).

## BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to thermionic converters and, more particularly, to a thermionic converter capable of converting thermal energy to electrical energy with increased efficiency.

2. Description of the Prior Art

The theory of operation of thermionic converters and the practical advantages realizable therewith are well known. Indeed, significant advancements have been made in recent years in developing usable thermionic converters. Although many of the mechanical problems, associated with the development of such devices have been solved and others approach solutions, one of the principal problems characterizing all known thermionic converters is the very low efficiency of energy conversion in converters having large interelectrode gaps. Large interelectrode gaps are more desirable for converters with large power output capabilities.

As the interelectrode gap is increased, the electrical power output and the conversion efficiency generally decrease, since the interelectrode losses increase. Therefore, the operating cesium reservoir temperatures at which the maximum power output occurs have to be lower in larger gap converters in order to minimize their interelectrode losses. The reduction of cesium temperature in turn results in a loss of power output since the converter current is lower due to the increased emitter work function, occurring at reduced cesium temperatures. Any significant increase in energy conversion efficiency and the power output at reduced cesium temperatures would be deemed a significant advance in the state of the art.

## OBJECTS AND SUMMARY OF THE INVENTION

It is a primary object of the present invention to provide a new improved thermionic converter.

It is another object of the invention to provide a thermionic converter characterized by increased energy conversion efficiency.

A further object is to provide a relatively simple thermionic converter which in most aspects is similar to prior art thermionic converters, except for a novel feature, which accounts for the thermionic converters increased energy-conversion efficiency.

Still a further object of the invention is the provision of an improved method of constructing a thermionic converter, by providing a novel step in the construction thereof.

These and other objects of the invention are achieved by providing a thermionic converter which includes an emitter and a collector as is the case in the prior art. Prior art emitter surfaces are typically flat or cylindrical. These surfaces have no indentations. The novel thermionic converter of the present invention incorporates emitter surfaces which define a plurality of inwardly directed cavities whose depths are comparable to the electronneutral mean-free path. The diameters of the cavities are chosen to prevent electron space charge from occuring at the open ends thereof. It has been found that such a cavity-defining emitter, hereafter referred to as the cavity emitter, has a cesiated work function which is lower by a significant value of electron volts (e.v.) than a flat or noncavity surface emitter for the same ratio between emitter temperatures and cesium-reservoir temperatures. Consequently, when the novel cavity emitter is used, the operating cesium-reservoir temperatures which are needed to produce a given amount of electrical energy at the same emitter temperatures are lower than those required when a conventional noncavity emitter is employed.



The novel features of the invention are set forth with particularity in the appended claims. The invention may best be understood from the following description when read in conjunction with the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a surface elevational view of a cavity emitter according to this invention;

FIG. 2 is a cross section through lines 2–2 of FIG. 1, showing the emitter region of a cavity emitter diode according to the invention including the adjacent collector thereof;

FIG. 3 is a schematic diagram of a typical cesiated converter in accordance with the present invention;

FIG. 4, 5 and 6 are diagrams useful in explaining the performance of one embodiment of the invention; and

FIGS. 7, 8 and 9 are diagrams useful in explaining the performance of another embodiment of the invention.

## DESCRIPTION OF THE PREFERRED EMBODIMENTS

Reference is now made to FIGS. **1** and **2** wherein numeral **10** designates a thermionic converter, often referred to as a diode, with an emitter **12** with its surface **14** in juxtaposition with a surface **16** of a collector **18**, across an interelectrode spacing or gap **19**. A cesiated converter according to the invention is shown in FIG. **3**. Therein, various elements are designated by descriptive legends.

Unlike the surfaces of emitters in prior art thermionic converters, in the present invention, emitter **12** defines a plurality of cavities **20** extending inwardly from surface **14**. A top view of surface **14** with the cavities is diagrammed in FIG. **1**. Since the teachings of the present invention are primarily directed to the formation of the cavities in the emitter surface to form a cavity emitter which accounts for the converter's increased efficiency, all the other elements including the sources of high temperatures, and other required devices for the converter's proper thermionic operation are purposely deleted, so that only the novel features are highlighted.

It has been found that by providing cavities **20**, at surface **14** to form a cavity emitter **12**, with depths of the cavities being comparable to the mean-free path of electron-neutrals which are present in the gap when the converter is operated, the converter's efficiency is greatly increased. In particular embodiments, actually reduced to practice, measured emission-current densities with the novel cavity emitter were nearly 10 times larger than those realizable with a flat surface emitter. The computed and measured work function of the cavity emitter has been found to be significantly less than the work function of a similar size but flat surface emitter. Consequently, lower cesium-reservoir temperature was required to provide the same electric current output. This represents an increased energy-conversion efficiency when the cavity emitter of the present invention is employed in a thermionic converter that operates at low cesium temperatures.

In one of the embodiments, actually reduced to practice, which was used to experimentally support the theoretical analysis, the cavity emitter had **19** shallow cylindrical cavities such as **20** in FIG. **1**. The emitter and collector materials were tantalum and molybdenum, respectively. The projected emitter area was 2 cm.$^2$, 0.83 cm.$^2$ of which represented the total projected area of the 19 cavities. The depth of each cavity was 0.407 mm., and the area of the cylindrical wall was 0.0302 cm.$^2$ per cavity. The 19 cavities had a total sidewall area of 0.573 cm$^2$. The net surface area for electron emission was 2.573 cm.$^2$, which is 29 percent larger than the projected area of the emitter.

The saturation current was determined from the intersection of two lines on a volt-ampere curve, one representing the saturation line and the other the Boltzmann line. Although the leakage current across the diode was negligible for the range of temperatures covered, it was subtracted from the measured values as required. The saturation currents thus obtained were plotted, as shown in FIG. **4**, as a function of reciprocal emitter temperatures ($10^3/T_E$). Therein $T_{cs}$ represents cesium-reservoir temperature. The result is a family of S-curves. Straight lines representing saturation currents obtained from emitters with work functions of 4.5 and 4.3 ev. are superimposed in FIG. 4 (the current values along these lines are calculated on the assumption of 2 cm.$^2$ for the emitter area). The uncesiated emitter work function (small $10^3/T_E$) appears, from this figure, to be 4.5 ev. which is slightly higher than expected. Although values as high as 4.9 ev. have been reported for the plane of tantalum, the handbook value is 4.19 ev.

The cesiated-surface work functions were calculated from the saturation currents in FIG. 4. The current density was determined from a projected emitter area of 2 cm.$^2$, not from the net area 2.573 cm.$^2$ of the cavity emitter. The Richardson constant (A-value) of 120 A/cm.$^2$°K.$^2$ was also used in these calculations. Because of the assumptions concerning surface areas and the uniqueness of the emitter construction, the work functions thus determined are the apparent work functions; however, these are satisfactory for comparing cavity emitters with ordinary flat emitters.

From the measured currents for various emitter and cesium-reservoir temperatures (FIG. 4), a Rasor-Warner plot for the emitter work function is obtained, in accordance with the teachings in an article by N. Rasor and C. Warner entitled "-Correlation of Emission Processes for Absorbed Alkali Films on Metal Surfaces," appearing in Journal of Applied Physics, Vol. 35, p. 2589 (1964). These results are shown in FIG. 4. The apparent work functions for various temperature ratios $T_E/T_{cs}$ fall on a well-defined curve; however, this curve deviates considerably from any one of the theoretical curves obtained from the Rasor-Warner theory. Since the uncesiated work function $\Phi_o$ must be 4.5 ev. to be consistent with the results shown in FIG. 4, the measured emitter work function is compared with the theoretical Rasor-Warner plot for $\Phi_o$=4.5 ev.

This comparison indicates that the same emitter work function can be achieved with the cavity emitter at a temperature ratio $T_E/T_{cs}$, which is significantly larger than for flat emitters. For example, the same emitter work function can be obtained at $T_E$=1,800°K., $T_{cs}$=400°K. in a diode with a flat emitter as at $T_E$=1,800K., $T_{cs}$=367°K. in a diode with the cavity emitter. The cavity emitter thus achieves the same emitter work function (apparent) as the conventional flat emitter at a 10 percent lower cesium-reservoir temperature.

The work function of the collector was determined from volt-ampere curves obtained in a deeply electron-retarding region, such as those shown in FIG. 6. The diode current varies logarithmically with voltage $V_o$ for voltages less than −1 v. In an electron-retarding region, the current density J can be expressed by:

$J = AT_E^2 \exp[-(\Phi_o - V_o)/KT_E]$

A=120 A/cm.$^2$—°K.$^2$

100$^c$=collector work function, ev.

$K$=1.38×10$^1$bh J/°K.

$e$1.6v. ×10$^{119}$C

Equation (1) may also be written as

$$\ln J = \ln (AT_E^2) - \frac{e\phi_c}{kT_E} + \frac{eV_0}{kT_E}$$

For $T_E$=1491 °K., one obtains

$$\ln J = 19.38 - 7.78\phi_c + 7.78V_0$$

Therefore, the log of the current density varies linearly with the voltage $V_o$. Such a dependence is clearly shown in FIG. 6, where a current density of 13ma./cm.$^2$ (projected area of the emitter=2.0cm.$^2$) at $V_o$=−13v. is observed. This current is obtained at a collector temperature of 580°K and a cesium-reservoir temperature of 453°K. Substitution of the above current and voltage values into Eq. (3) allows calculation of the collector work function $\Phi_c$. The result is $\Phi_c$=1.75 ev. at $T_c/T_{cs}$ =1.28.



Alternatively, the collector work function determined from the knee of the volt-ampere curve (FIG. 6) is found to be 1.77 ev. with $\Phi_E$=2.72 ev. and the voltage at the knee =−0.95. Similar calculations for $T_c$=623°K. yield comparable results.

The collector work functions were found to be well within the expected values. The work functions determined from the retarding plot agreed remarkably well with the values determined from the knee method. Since the knee method depends on the emitter work function, as well as on the voltage at the knee, the agreement implies the validity of the emitter work function measurement.

The temperature ratios $T_E/T_{cs}$ chosen for the experiments were such that the electron emission from the emitter occurred under ion-rich conditions. Thus, the measured saturation current was indeed the temperature-saturated current of the cavity emitter. Consequently, apparent work functions determined from the saturation current were not modified by the electron-space-charge sheath adjacent to the emitter, such as exists in a diode operating under electron-rich conditions. Also, the current must not be reduced by electron scattering, since the electron means-free path $\lambda_e$ is larger than the interelectrode gap $d$. (The mean-free-path $\lambda_g$ of cesium atoms is also larger than $d$.)

From the foregoing it should thus be appreciated that when employing the cavity emitter of the present invention, the apparent work function of the cavity emitter is nearly 0.4 ev. lower than expected for the same temperature ratio $T_E/T_{cs}$. Conversely, the same work function can be achieved at values of $T_{cs}$, which are nearly 10 percent smaller than expected. One should note that the projected area of the emitter (2 cm.$^2$) is used in determining the current density. If the net emitter area is used, the work functions will be only slightly larger (≈0.04 ev.) than those shown in FIG. 5. This small difference justifies the use of either the projected or net emitter area.

In another embodiment of the invention a seven cavity emitter was made of tantalum with seven cylindrical cavities of depths of 0.0407 cm. and diameters of 0.396 cm. The configuration is similar to that of the 19-cavity emitter, with approximately half of the projected emitter area of 2 cm.$^2$ occupied by the bottoms of the cavities. The interelectrode spacing at an emitter temperature $T_E$=1,400° C. and a collector temperature $T_c$=400° C. is 0.005 cm., and therefore the bottoms of the cavities are 0.0457 cm. from the molybdenum collector. Table 2 shows pertinent dimensions of the 7 and 19 cavity emitters. Both emitters were mechanically ground to remove excess burrs from the rims of the cylindrical cavities that resulted from the drilling operation, but the rectangular edges were intentionally preserved to maintain well-defined sidewall areas. The volt-ampere characteristics of the diode with the 7-cavity emitter were obtained with an X-Y recorder as the voltage across the diode was swept from −3 to +5 v. Those volt-ampere curves obtained from the unignited mode of the diode operation were used in the subsequent analysis. The results are shown in FIG. 7 as a family of S-curves. The emitter temperature ranged between 1,200 and 2,100°K. and the cesium-reservoir temperature was between 393 and 453°K. The cesium temperature was kept above 393°K. since the error of saturation-current measurements at lower temperatures became considerable (30 percent) because of the smallness of the current and the lack of clean saturation.

TABLE 2.—EMITTER DIMENSIONS

| Parameter | Seven-cavity emitter | Nineteen-cavity emitter |
|---|---|---|
| Cavity diameter, cm | 0.396 | 0.236 |
| Cavity depth, cm | 0.0407 | 0.0407 |
| Bottom area per cavity, cm$^2$ | 0.123 | 0.0437 |
| Total bottom area $A_B$, cm$^2$ | 0.862 | 0.831 |
| Side wall area per cavity, cm$^2$ | 0.0506 | 0.032 |
| Total side wall area $A_S$, cm$^2$ | 0.354 | 0.573 |
| Projected area $A_P$, cm$^2$ | 2.00 | 2.00 |
| Total emitter area $A_T = A_P + A_S$, cm$^2$ | 2.354 | 2.573 |
| $A_T/A_P$, percent | 117.7 | 128.6 |
| $A_B/A_P$, percent | 43.1 | 41.5 |
| $A_S/A_P$, percent | 17.7 | 28.6 |

At a cesium-reservoir temperature $T_{cs}$=453°K., the electron-neutral mean-free path is approximately twice the interelectrode distance at the location of a cavity. Therefore, the diode was operating in a collision-less regime for cesium temperatures below 453°K. In fact, for $T_{cs}$ larger than 453°K., the diode ignited at relatively small voltages, and the saturation region of the volt-ampere curves became obscured. The four S-curves shown in FIG. 7 appear to converge along a straight line representing the vacuum-emission current from an emitter with the work function $\Phi_o$=4.3ev. which can be taken as the uncesiated (vacuum) work function of the 7-cavity emitter. This value agreed with the work function for tantalum (4.2 ev.) within 0.1 ev. FIG. 8 shows the currents through diodes with the 7-cavity emitter, the 19-cavity emitter, and a flat emitter, all with the same uncesiated work function $\Phi_o$= 4.5 ev., as functions of reciprocal emitter temperatures when these diodes were operated at $T_{cs}$=413°K. There are only minor differences in electron emission between the 7-and 19-cavity emitters, but their currents are an order of magnitude larger than that from the flat emitter. The corresponding work function turns out to be 0.4 ev. lower for the cavity emitters than for the flat emitters.

The apparent work functions were determined from the saturation current by using Richardson's equation with an A-value of 120 A/cm.$^2$—°K$^2$. A projected emitter area of 2 cm$^2$ was used in calculating the current density, although the actual emitter area was 2.354 cm.$^2$ in the 7-cavity emitter. The apparent work functions thus determined could then be easily compared with those of a flat emitter with the same projected area. The values would be higher by approximately 0.03 ev. if the actual emitter area was used instead of the projected area.

The apparent work functions of the 7-cavity emitter are shown in FIGS. 9 together with the theoretical work function for a flat emitter with $\Phi_o$=4.5 ev. as a function of $T_E/T_{cs}$. Work functions of the 7-cavity emitter were nearly 0.4 ev. lower than those of the flat emitter for the same $T_E/T_{cs}$. The results are identical with those obtained from the 19-cavity emitter (FIG. 5) except that the work function of the 7-cavity emitter approached 4.3 ev. for large values of $T_E/T_{cs}$, at which the emitter is only slightly cesiated. If the uncesiated work function was 4.3 ev., the emission must have been ion rich for $T_E/T_{cs}$ larger than 2.8. It can be concluded, therefore, that the diode was operating in an ion rich, collisionless condition and that the apparent work functions are the true values which are not affected by the space-charge sheath.

The results shown in FIG. 9 can also be interpreted as follows. The same emitter work function of, say, 3.4 ev. is obtained at $T_E/T_{cs}$=3.9 and 3.5 for the 7-cavity and the flat emitter, respectively. Then, for the same emitter temperature $T_E$=1,500K., $T_{cs}$ will be 385°K. for the cavity emitter and 429°K. for the flat emitter, indicating a reduction of 44°K. in $T_{cs}$ to achieve the same work function with the cavity emitter. Since electron scattering will be less with lower cesium pressures and, therefore, with lower cesium reservoir temperatures, use of the cavity emitter will be advantageous in thermionic energy converters. It should be pointed out that these advantages are obtainable only in a diode operating in an unignited, collisionless regime achievable at relatively low operating temperatures.

From the foregoing it is thus seen that the apparent work functions of the 7-cavity emitter are 0.4 ev. lower than for the flat emitter with an uncesiated work function of 4.5 ev. Although the emitter configurations are different for the 7- and 19-cavity emitters in many respects, the electron emission properties are remarkably similar. Three independent methods utilizing (1) the Richardson equation, (2) the voltage at the knee of the volt-ampere curve, and (3) the ion-emission data, consistently yielded unusually low emitter work functions, thereby clearly demonstrating the increased energy conversion efficiency which is realizable with a thermionic converter in which the novel cavity emitter of the present invention is incorporated.

Although particular embodiments of the invention have been described and illustrated herein, it is recognized that modifications and variations may readily occur to those skilled in the art and, consequently, it is intended that the claims be interpreted to cover such modifications and equivalents.

We claim:

1. In a thermionic converter of the type including an emitter electrode operable at a first selected temperature range, a collector electrode operable at a second selected temperature range, said emitter and collector electrodes being separated to define an interelectrode gap, the improvement wherein said emitter electrode defines at least one cavity, inwardly extending from a side thereof opposite said collector electrode across said gap, the depth of said cavity being of the order of one electron-neutral mean-free path, and the open end of said cavity being of an area to minimize electron space charge thereat, the largest dimension across the area of the open end of said cavity being greater than the depth thereof.

2. In the thermionic converter as recited in claim 1 wherein said emitter electrode defines a plurality of cavities extending from said side thereof, whereby the work function of the emitter electrode is reduced when operated in said selected first temperature range.

3. In a thermionic converter of the type including an emitter electrode operable at a first selected temperature range, a collector electrode operable at a second selected temperature range, said emitter and collector electrodes being separated to define an interelectrode gap, the improvement wherein said emitter electrode defines a plurality of cavities, each inwardly extending from a side thereof opposite said collector electrode across said gap, the depth of said cavity being a function of the electron-neutral mean-free path, and the open end of said cavity being of an area to minimize electron space charge thereat, wherein the depth of each cavity definable as $d$ is related to the opening of said cavity, definable as D, where A=D/$d$ and A is in the range of 4 to 10.

4. In a thermionic converter of the type including an emitter electrode operable at a first selected temperature range, a collector electrode operable at a second selected temperature range, said emitter and collector electrodes being separated to define an interelectrode gap, the improvement wherein said emitter electrode defines at least one cavity, inwardly extending from a side thereof opposite said collector electrode across said gap, the depth of said cavity being a function of the electron-neutral mean-free path, and the open end of said cavity being of an area to minimize electron space charge thereat, and a source of cesium operable at a third selected temperature range, for providing cesium vapor in a selected pressure range in said gap, the depth of said cavity, definable as $d$, being in the order of 400 microns and being related to the opening of said cavity, definable as D, where A=D/$d$ and A is in the range of 4 to 10.

5. In a thermionic converter including an emitter electrode of a first material operable at a first temperature range, a collector electrode of a second material operable at a second temperature range, said collector being spaced apart from said emitter electrode to define an interelectrode gap therebetween, a source of cesium for providing cesium vapor in said gap at a selected pressure and within a third selected temperature range, the improvement wherein said emitter electrode defines a plurality of shallow circular cavities extending inwardly from a side of said emitter electrode forming said collector, with the openings of said cavities being greater than the depths thereof, wherein the depths of said cavities are related to the electron-neutral mean-free path at the operable temperatures and the openings of said cavities are large to minimize electron space charge from occurring thereat, the opening of said cavities being larger than the depths thereof by a factor which is not less than 4.

6. The thermionic converter as recited in claim 5 wherein the emitter and collector electrodes are tantalum and molyb-

denum, respectively and wherein said first temperature range includes 1,490°K., said second temperature range includes 617°K. and said third temperature range includes temperatures between 393°K. to 453°K. and the depths of said cavities are in the range of 0.04 cm.

7. The thermionic converter as recited in claim 6 wherein the projected area of said side of said emitter electrode is in a range including 2 square cm. and the number of said cavities is $n$ where $n$ includes 7 and 19, with the diameter of each cavity when $n$=7 being about 0.396 cm. and the diameter of each cavity when $n$=19 being about 0.236 cm.