DEVELOPMENT OF A BARIUM-FREE HIGH TEMPERATURE CESIUM TACITRON*

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Abstract

A barium free, high temperature, cesium Tacitron has been developed using a platinum, hollow cathode, emitter. The hollow cathode emitter used in our investigation is designed to enhance the current emission of a Tacitron without the use of barium in the switch. In a barium-cesium Tacitron, the barium is known to cover the surface of a molybdenum emitter lowing it's work function. The barium however limits the lifetime of the Tacitron, unless sophisticated seal technology is used in the manufacture of the Tacitron.

The hollow cathode emitter was operated at current densities from 2.5 A/cm^2 up to 7.0 A/cm^2. Continuous operation of the Tacitron was demonstrated at 100-150 V, and repetition rates up to 5.8 kHz with measured voltage drops of 3.5 V to 9.0 V. The results of the experimental characterization are compared to the computer model, and the applicability of this unique Tacitron design is discussed.

Introduction and Description of Cathode Model

The hollow cathode (emitter) used in the investigation is designed to enhance the emission current of a Tacitron without the use of barium in the switch (Figure 1). In a barium-cesium Tacitron, the barium is known to cover the surface of a molybdenum emitter, lowering its work function (1). The emission current from the cathode is thermionic in nature and can be calculated using the Richardson-Dushman equation (2). The barium itself presents a problem, for at high temperature, barium is rather corrosive, and present day seal technology cannot be used for long lifetime barium-cesium Tacitrons.

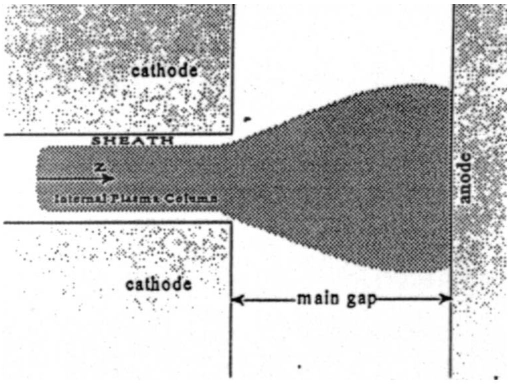

Figure 1. Simple model of the cesium plasma penetrating the hollow cathode emitter.

0-7803-4214-3/97/$10.00 © 1997 IEEE

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **JUN 1997**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Development Of A Barium-Free High Temperature Cesium Tacitron**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Missouri-Columbia Dept. of Electrical Engineering, 205 Engineering Bldg. West, Columbia, MO 65211**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT

A barium free, high temperature, cesium Tacitron has been developed using a platinum, hollow cathode, emitter. The hollow cathode emitter used in our investigation is designed to enhance the current emission of a Tacitron without the use of barium in the switch. In a barium-cesium Tacitron, the barium is known to cover the surface of a molybdenum emitter lowing its work function. The barium however limits the lifetime of the Tacitron, unless sophisticated seal technology is used in the manufacture of the Tacitron. The hollow cathode emitter was operated at current densities from 2.5 A/cm2 up to 7.0 A/cm2. Continuous operation of the Tacitron was demonstrated at 100-150 V, and repetition rates up to 5.8 kHz with measured voltage drops of 3.5 V to 9.0 V. The results of the experimental characterization are compared to the computer model, and the applicability of this unique Tacitron design is discussed.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**7**	

A somewhat different approach to the design of an emitter for a high temperature Tacitron was taken in our investigation. In order to enhance the emission current of the emitter, a hollow cathode emitter structure was used to increase the surface area of the cathode, and thus increase the current emission characteristics of the emitter without the use of barium. Moreover, we specifically selected the cathode material to lower the work function of the cathode. As part of the investigation, three materials were surveyed; Pt, Mo, W. Of the three materials investigated, platinum had the lowest work function, and thus the highest emission characteristics in cesium of the three materials. The cathode was designed using platinum after a design analysis was performed which indicated that the high emission current characteristics of platinum were required to meet our cathode design goal specification of 15 A/cm^2 with a minimum goal of 5 A/cm^2. The minimum operational voltage of the Tacitron was set at 100 V with a goal of 250 V.

In order to design a hollow cathode emitter, the work function of the emitter as a function of cesium pressure (reservoir temperature), and the plasma penetration depth into the hollow cathode was calculated. In order to calculate these parameters, and thus the emitter emission current. A simple computational model of a hollow cathode was developed. The model is based on the theory of Ferreira and Delcroix (3). The model predicts trends in the hollow cathode emission current during the steady state conduction phase of the plasma. The model utilizes NEDSPHI to calculate the work function of the cathode given the emitter temperature and the cesium reservoir temperature (pressure). The α ionization coefficient for the model is calculated using a Monte Carlo code developed by Joshi at Old Dominion University. It should be mentioned that the model does not include the voltage drop due to the grid structure in the Tacitron, the voltage drop from the work function or the collector of the voltage drop of the collector-emitter plasma. Since the purpose of the model is to understand the conduction phase of the discharge, it is limited to the steady state conduction phase of the cesium plasma. Moreover, it is assumed that the internal plasma column (IPC) in the hollow of the emitter is sustained by excitation and ionization of the gas by primary electrons emitted by the wall and accelerated by the cathode fall of sheath. In our region of interest, the debye length which determines the scale size of the sheath is on the order of 10^{-4} cm. The primary electron mean free path is typically on the order of 10^{-1} cm at 1 eV - 2 eV, for a cesium pressure in the 10 mTorr range.

The theory of Ferreira and Delcroix is based on the following phenomenological description: The internal plasma column (IPC) fills the hollow, except for a thin sheath at the wall, and enters to a depth determined by the voltage drop (Figure 1)(3). As voltage is increased, the IPC penetrates deeper, and extracts more current. The plasma in the main gap is highly conductive, and hence the cathode fall is close to the full anode-cathode voltage drop neglecting the voltage drop due to the grid and collector-emitter plasma. Ferreira and Delcroix include a gas flow cathode model, but for purposes of our model, gas flow can be ignored (3). In a cold cathode, ion bombardment produces electron emission and also heats the wall surface producing thermionic emission. Since the focus of our model is on a thermionic cathode, the model considers only thermionic emission and ignores ion heating to first order. The radial electric field in the sheath accelerates the primary electrons into the IPC, but does not affect axial transport toward the opening of the hollow. The IPC current is dominated by diffusion, aided by the axial electric field. Thus, the total current is the cumulative thermionic current amplified by ionization in the IPC. The cesium also provides space charge neutralization.

The hollow cathode emitter (HCE) model is based on the following assumptions: The IPC can be considered locally homogeneous. That is, the energies and densities of all particles (primary and thermalized electrons, ions, and neutrals) are considered uniform within the plasma at any circular slice through the hollow, except for the cathode fall, whose area is negligible. This allowed us to ignore variations in all directions except Z, the distance along the hollow axis (3). Ferreira and Delcroix developed a cascade theory to calculate the multistep ionization process along the plasma column. The net result of Ferreira and Delcroix's multistep ionization model is to produce a specific number of secondary electrons for every primary thermionic electron. The ratio of secondary electrons to primary electrons is the α parameter. Fortunately, energy conservation makes α the ionization coefficient insensitive to details of the process.

The hollow cathode model thus reduces to a self-consistent set of ordinary differential equations (ODE) in Z, which can be integrated numerically using a set of realistic boundary conditions. For our immediate purpose, we initialize the electron temperature, T, to the emitter temperature, and everything else to zero at an arbitrary point corresponding to the bottom of the IPC inside the hollow cathode, and then integrate toward the opening of the hollow cathode. This reduces the model to an initial-value ODE problem. Based on these simplifications a computer model was written to calculate the current density of hollow cathodes in cesium, the penetration depth of the plasma and the internal voltage drop in the hollow cathode.

Using the computer code, a design analysis was done to verify the current emission from each hollow cathode. The results of the calculation are shown in Figure 2. The current emission for a voltage drop of 2 or 3 volts along the length of the hollow cathode is shown in Figure 2. Platinum had the highest emission current density in cesium, at emitter temperatures ranging from 1000 K to 1200 K. The calculations showed that platinum had 2-10 times the emission current of the other materials. For purposes of the cathode design, the peak current density of each emitter as shown in Figure 1 can be calculated based on a cathode utilization factor η as shown in equation 1.

$$j_{avg} = j_{peak} \bullet \eta \tag{1}$$

where j_{avg} is the average current density and j_{peak} is the peak current emitted at the exit of each hollow cathode. The utilization factor η is the ratio of the total cathode area to the hollow cathode area. The peak current density j_{peak} is calculated by the HCE model as shown in Figure 2.

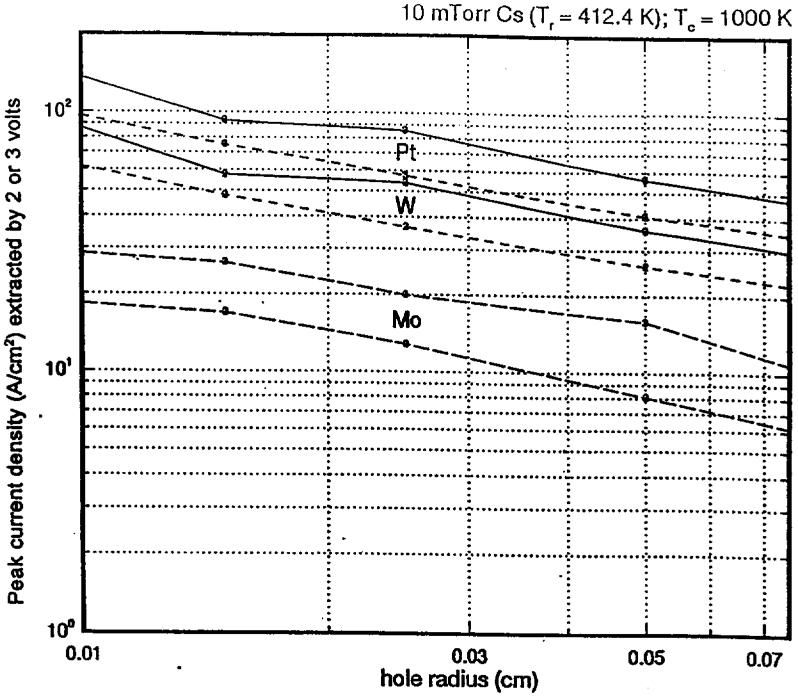

Figure 2. Hollow cathode radius versus single hollow cathode current emission for 1000 K operation of Pt, W, Mo at 2 V and 3 V and 10 mTorr. The cesium reservoir temperature T_r = 412.4 K, and the emitter temperature T_e = 1000 K.

Design of the Hollow Cathode Emitter

The hollow cathode emitter shown in Figure 3 was designed using the HCE computer model. The platinum hollow cathode emitter shown in Figure 3 was constructed from a 2.1 cm diameter, 2 cm long platinum rod. Using EDM machining techniques, 297 holes with an average radius of 0.033 cm were drilled in the platinum rod. The preliminary design for the hollow cathode emitter utilized platinum tubing in the place of a drilled piece of solid platinum. The cost of brazing 297 tubes together for a cathode was found to be cost prohibitive for a prototype device, but would be cost effective for a commercial production device.

The cathode design targeted the 15 A/cm^2 goal at an operational temperature of 1200 K. The cathode was designed to operate at between 1000 K and 1200 K. Nominally at 1000 K the current density of the cathode was somewhat reduced from the 15 A/cm^2, e.g., 10 A/cm^2. Although not included in the statement-of-work specification, a collector-emitter voltage drop of 3 to 3.5 V across the Tacitron at 1200 K was also desired. The cathode was designed to operate at an upper cesium pressure of 10 mTorr and a nominal pressure of 5 mTorr. This pressure regime was selected based on the operational range of cesium-barium Tacitrons (4,5).

To determine the final number of holes to be drilled in the emitter, an analysis was done using the HCE computer model. The current per emitter hole was calculated versus the voltage drop of the plasma in the hollow cathode plasma. Based on the peak current density, j_{peak}, which could be extracted from the emitter holes, a fractional utilization factor, η, of 0.3 was selected. Given the hole radius of 0.033 cm, (the minimum practical hole size) 297 holes were required. It should be mentioned that the HCE model did not include the voltage drop due to the Tacitron grid structure, or additional voltage drops across the emitter to collector spacing. These had been previously measured by Murray and Wernsmann, and are on the order of 1.0 - 2.0 V (4,5). Thus for a cathode plasma voltage drop of 2 V, we expected a total voltage drop of about 4 V across the Tacitron (T_e = 1200 K) which is consistent with the voltage drop observed in cesium-barium Tacitrons.

Tacitron Test Stand

A photograph of the cesium only Tacitron is shown in Figure 4. The emitter (cathode), grid and collector are insulated using boron nitride insulators. The emitter grid and collector are pressure clamped between the boron nitride insulators. The Tacitron assembly is vacuum immersed and cesium is flowed into the Tacitron through a stainless steel tube. Insulated thermocouples were incorporated into the grid, emitter and collector for real time temperature measurements.

A schematic of the Tacitron test circuit is shown in Figure 5. The assembled test stand is comprised of a diffusion pumped vacuum station, a 5 kW, 0-150 V power supply, a filament power supply, a grid pulser a power supply, and a computer for data acquisition. A DSA602 waveform digitizer was also used for acquisition of waveforms. The current (current density) switched by the Tacitron is adjusted by varying the power supply voltage and the value of a series current limiting resistor which is rated at 5 kW average power. The test stand developed allows Tacitrons to be DC tested at up to 5 kW average power.

A grid pulser was designed to turn-on and turn-off the Tacitron. The grid pulser is comprised of two separate field effect transistor switched channels, which allow independent adjustment of the turn-on and turn-off voltage. Power is supplied by two separate EMI adjustable voltage power supplies, for the positive turn-on pulse and the negative turn-off pulse.

As part of the control system, a PID controller was used to control the temperature to the cesium reservoir. The cesium reservoir, which consisted of a stainless steel tube, could operate between 373 K and 463 K, and was regulated to a temperature of ± 0.2 K.

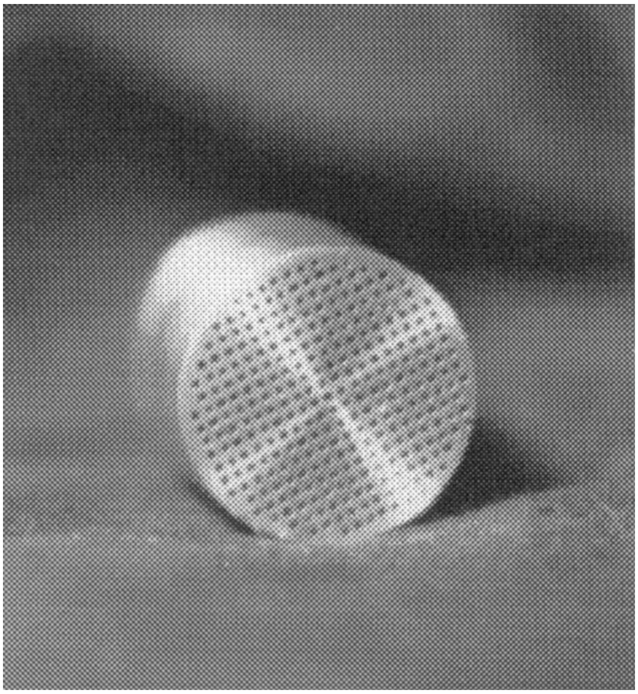

Figure 3. Platinum hollow cathode emitter used for the Tacitron test.

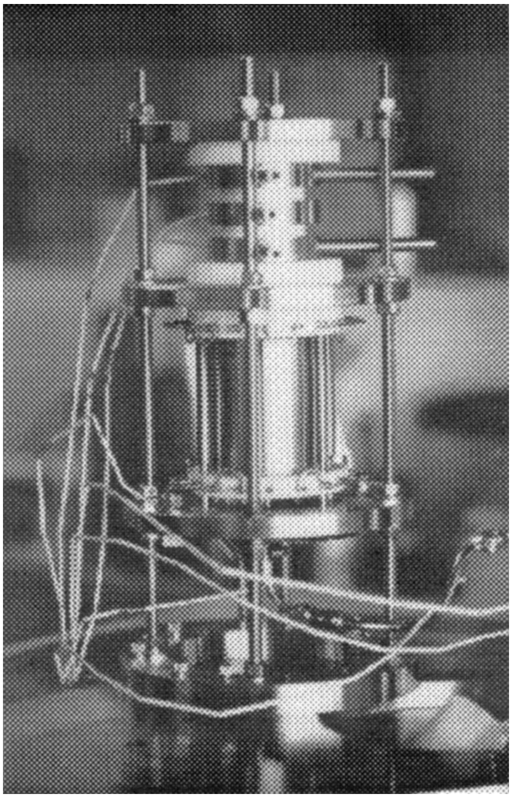

Figure 4. Photograph of assembled cesium only Tacitron

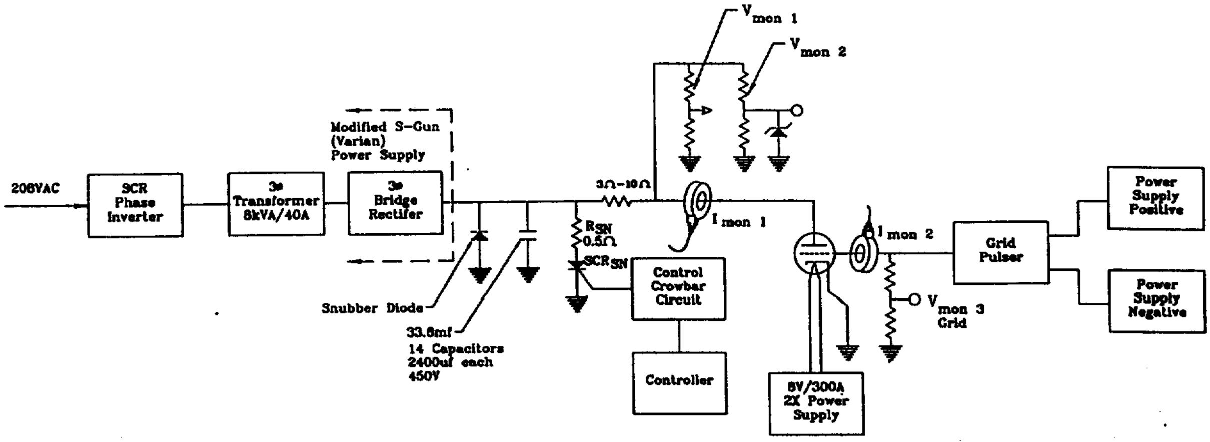

Figure 5. Schematic of the Tacitron test stand.

Tacitron Tests

The operating range of the Tacitron illustrated above was investigated at operating temperatures up to 942 K. The initial thermal cycling tests revealed that the upper emitter temperature was limited to less than 1000 K. Even at this low temperature, we were able to demonstrate 500 Hz - 5.8 kHz, 40-150 V DC, operation of the Tacitron using a platinum hollow cathode emitter. Average current densities of 2.5 to 7 A/cm^2 were demonstrated using both aligned and unaligned grids. The Tacitron emitter was tested at up to 10^8 pulses without signs of erosion. During the experimental investigation, a new mode for Tacitrons was found. At low frequency operation, the voltage drop across the Tacitron was high. Above about 1 kHz, the impedance of the Tacitron would drop a factor of 2-3 and the current carrying capability would increase by a comparable amount. Respectively, the voltage drop across the Tacitron would decrease a factor of 2-3 times.

Grids aligned and unaligned with the holes of the hollow cathode, 0.5 mm thick, 24% transparent were tested. The spacing between the emitter and collector was kept constant during the tests. The grid to emitter spacing was 1.5 mm. The grid to collector spacing was kept constant at 2 mm. A peak current of 24 A (7A/cm^2) was switched using the aligned grid. A peak current of 23.2 A (6.8 A/cm^2) was switched using the unaligned grid. Within the scatter of the data, no trend was observed, indicating that the gas pressure in the Tacitron was independent of frequency. During the tests, the emitter, grid, and collector temperatures were approximately equal.

Although the Tacitron operated reliably with both aligned and unaligned grids, much higher duty factors were achieved with the unaligned grid. For 130 V operation, a duty factor of 77.5% was demonstrated. During the 130 V, 77.5% duty cycle tests, 2095 watts was switched continuously at 3 kHz with a voltage drop of 7 V. A duty factor of 69% was achieved at 140 V, 4 kHz operation (Figure 6). At 140 V operation, the Tacitron current was 23.2 A (6.82 CA/cm^2) with a corresponding 5.5 V, V_{CE} voltage drop. The peak grid turn-on voltage was 20 V decreasing to 6 V during the pulse. The grid emitter turn-off voltage was -128 V. The peak grid-emitter turn-on current was 1.52 A decreasing to 1.28 A during the pulse. The peak grid turn-off current was 5.84 A decreasing to 3.6 A. During the 140 V tests, an average power of 2240 watts was switched. Approximately 106 watts of the 2240 watts switched was dissipated in the Tacitron which corresponds to a 4.7% switching loss. Approximately 240 watts was required by the grid pulser to turn the Tacitron on and off. Thus the switching efficiency of the Tacitron is 95.3% (2134 watts transferred vs. 2240 watts switched).

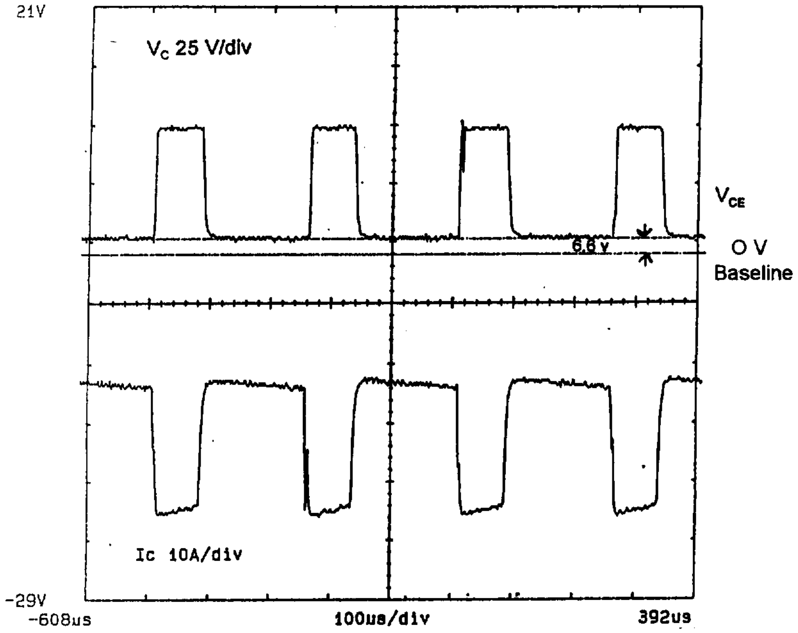

Figure 6. Waveforms of a 140 V, 4 kHz unaligned grid test showing the collector current (Bottom; 10 A/div) and the voltage drop across the collector-emitter (Top; 25 V/div) at a duty cycle of 69%.
T_e = 872 K T_r = 441 K.

The measured voltage drop versus the average current per hollow cathode hole is plotted in Figure 7, the data was curve fit to the equation:

$$V_{CE} = 2.13\ \text{V} + 0.932 * j_{avg} \tag{2}$$

where V_{CE} is the voltage drop across the collector-emitter of the Tacitron, and j_{avg} is the average current density of the hollow cathode emitter. From equation 1, $j_{avg} = \eta \, j_{peak}$, where η is the fractional utilization of the cathode. In our experiments $\eta = 0.3$. If a low temperature, low voltage drop Tacitron was to be optimized, we would need to increase the number of hollow cathodes in the emitter, e.g., $\eta = 0.6$. If η was increased to 0.6 at an average current density of 6.5 A/cm^2 the Tacitron voltage drop would be 5.1 V conservatively at 900 K based on the data of Figure 7. This would, of course, drop the peak current density by a factor of two for each hollow cathode hole which would further lower the voltage drop due to penetration of the plasma into the hollow cathode.

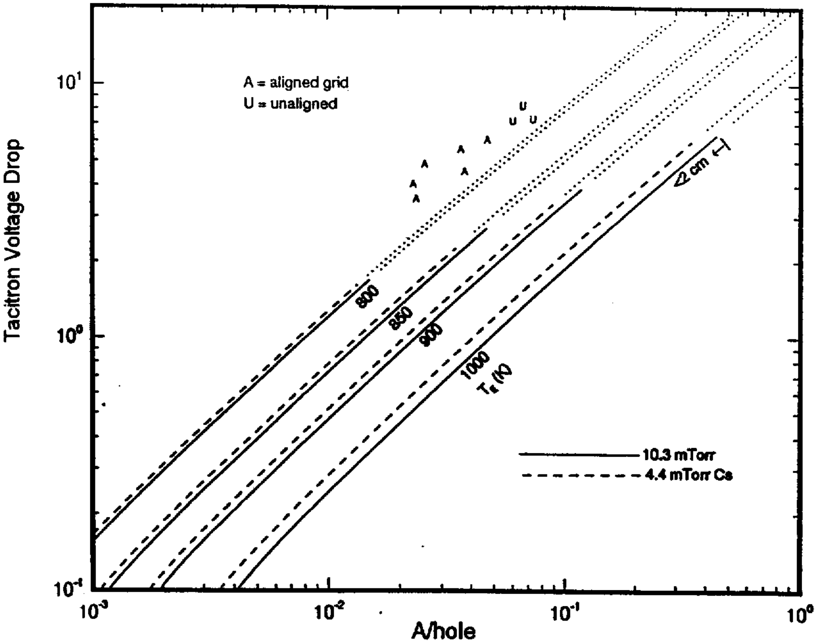

Figure 7. Plot of V_{CE} versus the calculated voltage drop of the hollow cathode plasma and current per emitter.

Although further research is required to optimize the hollow cathode emitter for operation at temperatures less than 1000 K, calculations and our HCE model indicate that cesium only Tacitrons which operate at 1000 K to 1200 K can be designed which are equivalent in switching efficiency and voltage drop to cesium-barium Tacitrons.

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*This contract was funded by the Phillips Laboratory under Contract No. F29601-93-C-0015.