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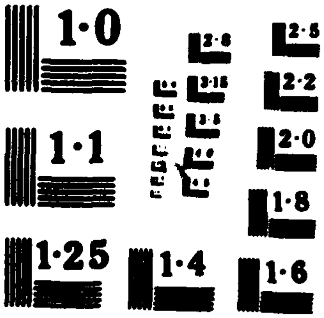
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RASOR ASSOCIATES, INC.

AFOSR-TR- 84-1070

NSR-22-2

CLOSE-SPACED HIGH TEMPERATURE KNUDSEN FLOW

ANNUAL REPORT

June 15, 1984

Prepared for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
CONTRACT NO. F49620-83-C-0068

Prepared by

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This work is a study of discharge processes in Knudsen mode (collisionless), thermionic energy converters. Areas of research involve mechanisms for reducing the effects of electron space charge in such devices. Such mechanisms are essential for thermionic converters to produce useful current and power densities. The mechanisms we have chosen to study are: reduction of space-charge through a very close inter-electrode gap (less than 10 microns); transport and retention of positive cesium ions generated by surface ionization; transport of positive cesium ions generated in an arc external to the electrodes; and the mechanism for enhanced current output due to a structured emitter in a mixed barium-cesium vapor. This last process may involve the production of barium-cesium dimer ions.

The experimental work used SAVTEC (Self-Adjusting, Versatile Thermionic Energy Converter) diode structures, which were tested in a chamber containing 0.1 - 1.0 torr

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of cesium vapor. Comparison of measured volt-ampere curves with theory gave excellent agreement and indicated an interelectrode gap of 6.5 microns at an emitter temperature of 1250 K. A theoretical model of the collisionless thermionic diode was developed which included surface ionization, auxiliary ions from an external source, and trapping of charged particles in potential wells due to infrequent collisions. Studies show that trapping of positive ions leads to a large, beneficial increase in current density. Using a diffusion analysis to couple this model to models of collision-dominated discharges gave predictions of the performance of SAVTEC devices in the presence of an auxiliary discharge, and led to design criteria for electrode size in order for auxiliary ionization to be effective. An experiment to test the model is in preparation.

TABLE OF CONTENTS

A. RESEARCH OBJECTIVES

The research program is aimed at studying various aspects of thermionic energy conversion in the Knudsen (collisionless, or nearly collisionless) mode of operation. The objectives fall into the following categories:

1. Investigate the Knudsen regime with thermal ion emission at close interelectrode spacing. Determine the effect due to production of auxiliary ions.

2. Investigate the quasi-vacuum regime at very close interelectrode spacing.

3. Confirm the existence of the structured emitter anomaly observed by Babinin et al[1]. Determine the mechanism for the anomaly.

4. Investigate interaction effects between adjacent SAVTEC-type diode structures.

The relevant physical processes in a Knudsen mode diode are illustrated in Fig. 1. Because the use of probes, electron beams, and other plasma diagnostics is impractical for the very close electrode spacings used, the output characteristics of the device itself, and their behavior with changing conditions, will be used as the diagnostic technique. Intercomparison of experimental results with results from the theoretical models we are developing will confirm our understanding of the dominant mechanisms in the discharge.

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[1] V. I. Babinin, A. S. Mustafayev, V. I. Sitnov, A. Ya. Ender "Increase in Specific Power of TEC in Regime with Surface Ionization by Use of Developed Cathode," Proc. 1975 Thermionic Conversion Specialists Meeting, Eindhoven, pp.271-273 (1975).

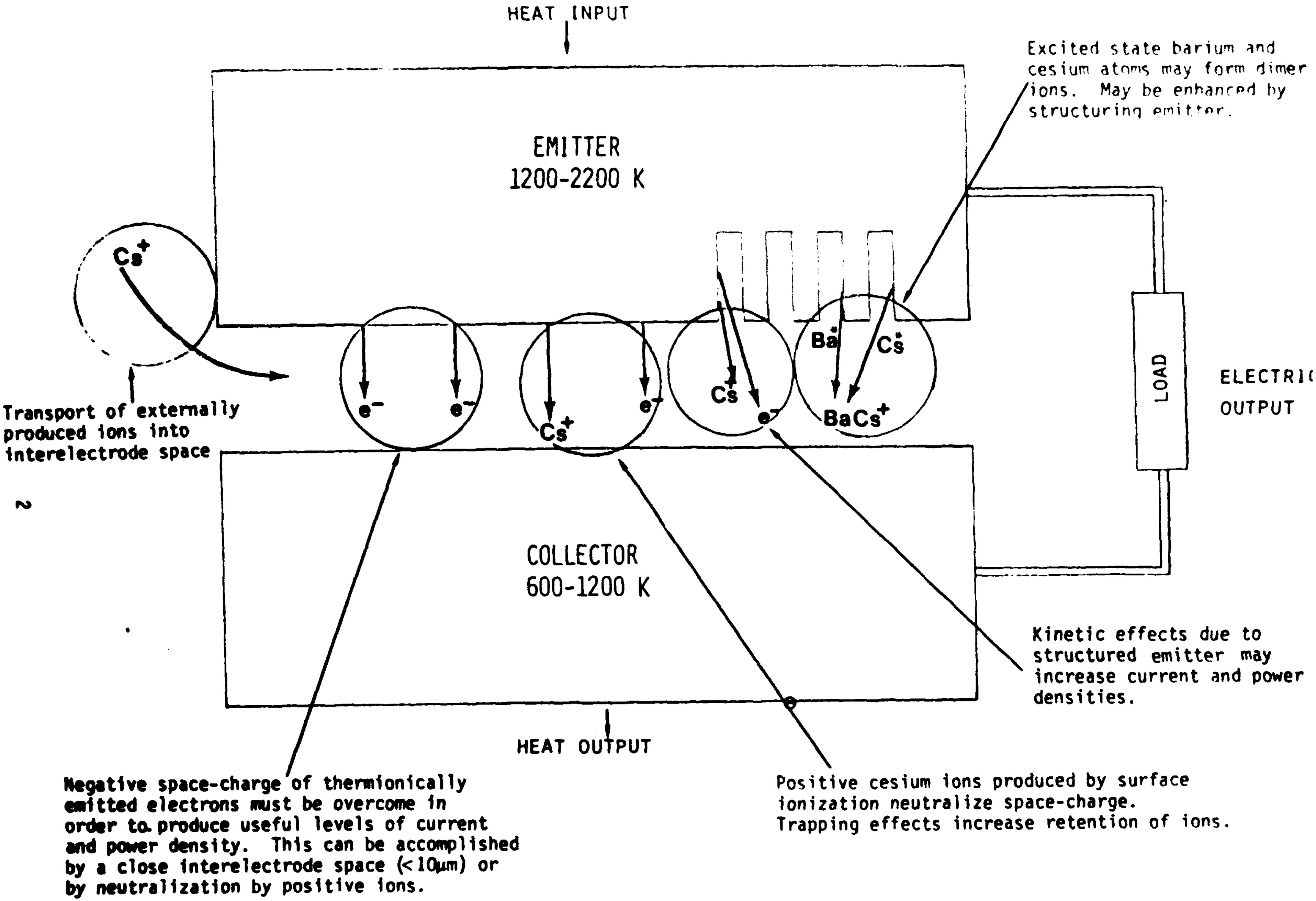


Fig. 1 Discharge processes in a knudsen-mode thermionic diode

WORK STATEMENT

1st Year:

Task 1 - Experimental Apparatus

Devise a demountable experimental apparatus for multiple investigations of different SAVTEC types of converter structures. Prepare SAVTEC converters.

Task 2 - Data Acquisition Experiments

Investigate Knudsen discharge operation regime with thermal ion emission from emitter electrodes.

Task 3 - Modeling

Formulate a composite analytical model which can deal with collisional and collisionless discharge regions in the same cesium space.

Task 4 - Analysis and Reporting

Submit report at end of first year.

2nd Year:

Task 1 - Data Acquisition Experiments

Continue thermal ion emission regime experiment. Investigate operation with very close electrode spacing. Determine effects of emitter structuring and mixed vapor operation.

Task 2 - Experimental Apparatus

Prepare barium-compatible SPC converters. Modify test stand for barium reservoir and additional converter envelope heating.

Task 3 - Modeling

Formulate a two-dimensional model of Knudsen mode plasma to investigate phenomena associated with emitter structure. Investigate associative ionization in a mixed barium-cesium vapor.

Task 4 - Analysis and Reporting

Compare results of experiment and modeling. Submit report at the end of the second year.

3rd Year:

Task 1 - Experimental Apparatus

Modify SPC converter if necessary. Prepare SAVTEC converters for interaction experiment.

Task 2 - Data Acquisition Experiments

Continue structured emitter/mixed vapor experiments. Investigate higher voltage breakdown between converters and envelope.

Task 3 - Modeling

Analysis in support of inter-converter breakdown experiment.

Task 4 - Analysis and Reporting

Submit comprehensive final report.

B. Status of the Research Effort

Task 1 - Experimental Apparatus

An instrumented test chamber for SAVTEC converters has been constructed. The chamber is equipped with radiant heating for the SAVTEC emitters, and a temperature-controlled, liquid-cesium reservoir to provide cesium vapor. The entire chamber can be heated to 400°C in order to prevent cesium condensation. Two SAVTEC converters are mounted side by side on a temperature controlled post. A diagram of an experimental SAVTEC is shown in Fig. 2. Current leads, voltage probes, and collector thermocouples are connected to the converters. Emitter temperature measurements are made through a sapphire window using optical pyrometry.

Four SAVTEC converter structures have been constructed. The first two had tungsten emitters, molybdenum collectors, and a tungsten-26% rhenium lead. These were designed to be clamped into the converter mounting post. Testing showed that collector cooling was inadequate with this design. The second two SAVTECs were designed to be brazed into the post. These had molybdenum emitters and molybdenum collectors. The lead material was changed to rhenium in order to get a greater interelectrode gap by thermal expansion. This was because only one only one of the previous set of converters unshorted upon heating.

The test facility has been demonstrated to be capable of testing SAVTEC converters in cesium vapor. In order to obtain data in the high-emitter temperature, inignited-mode regime, the test chamber was modified for better collector cooling, with brazed-in converters and shielding of the collector from the radiant heat source. Because the heater to emitter temperature drop was about 400°C, a welded tungsten radiant heat source assembly was substituted for the brazed molybdenum one in order to achieve higher radiant heater temperatures.

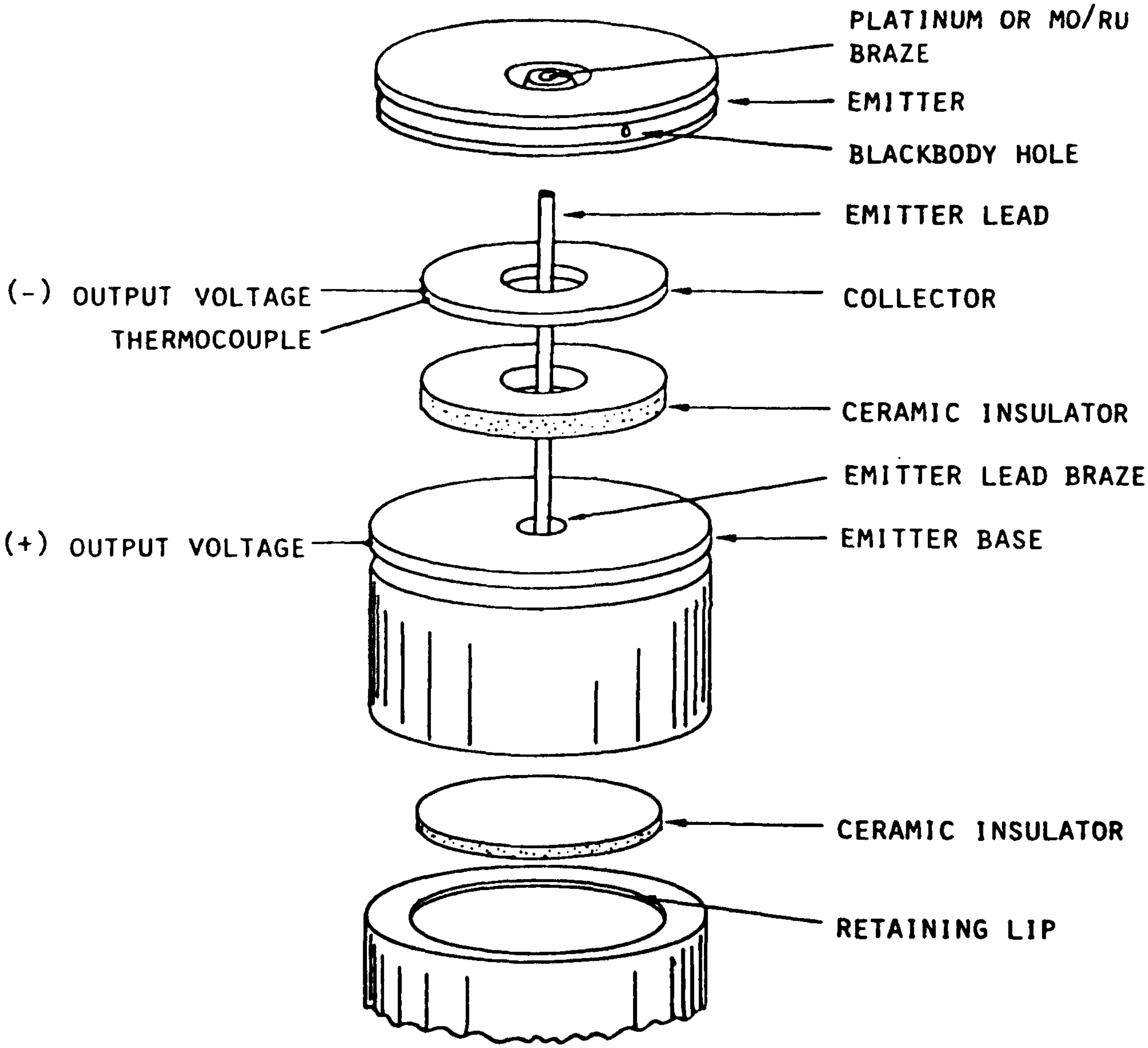


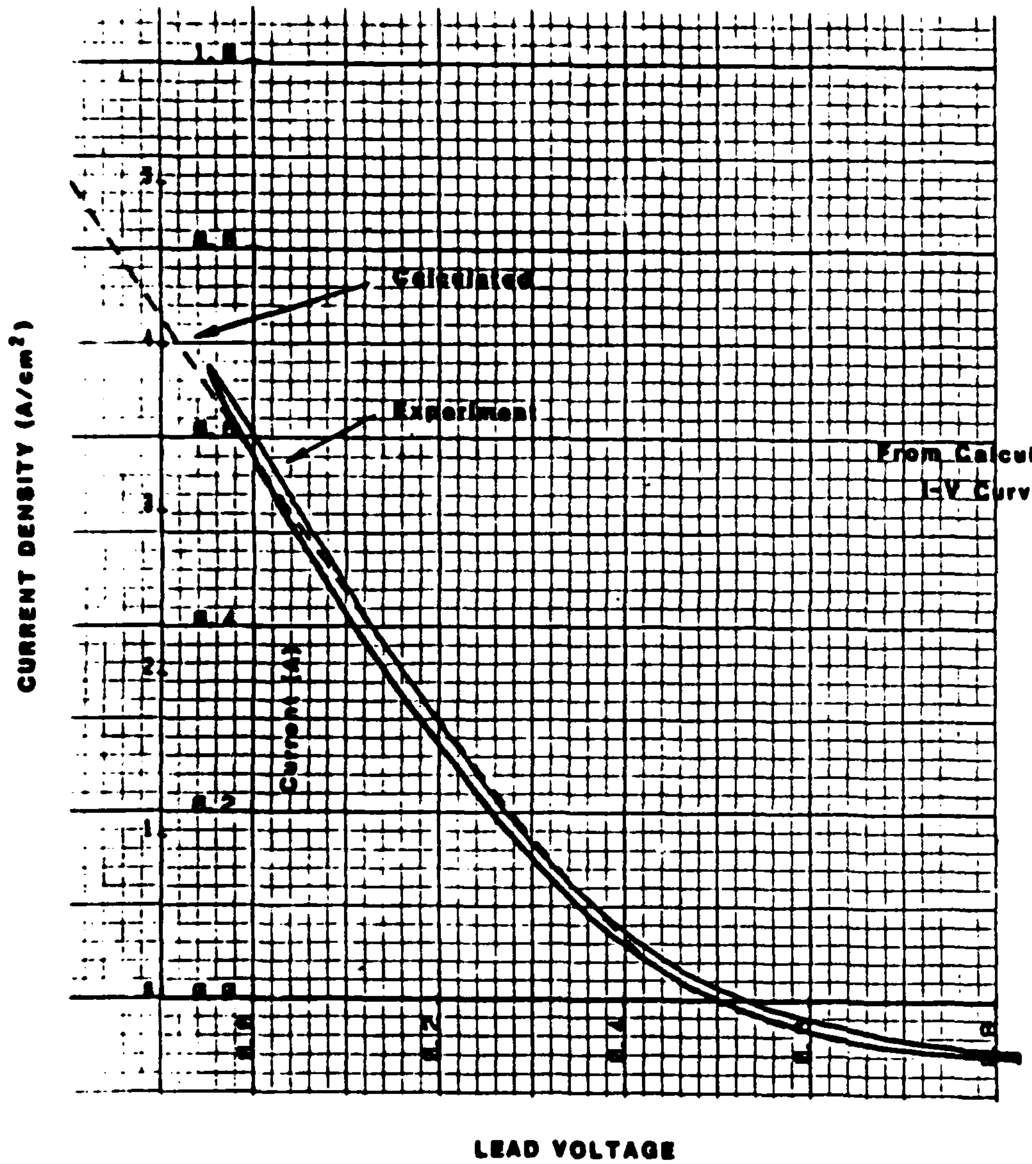
Fig. 2 SAVTEC Thermionic Converter

Task 2 - Data Acquisition Experiments

Two SAVTEC converters were tested in the chamber. Volt-ampere characteristics were obtained from one of these. Operation at emitter temperatures higher than 1250 K was prevented by an excessive rise in collector temperature. This caused thermal expansion of the collector which would short the converter.

The agreement between the experimental and theoretical results is shown in Fig. 3. For the case shown the interelectrode spacing which gave best agreement was 6.5 μm (0.25 mils).

A second set of converters were constructed and brazed into the tes' fixture. Both of these converters could be unshorted upon heating. / experiment was performed to measure the interelectrode gap by measuring .ne capacitance of the converter. This was done in order to cross-check the values of spacing determined from the theoretical model. However, during this test both converters cracked loose from the mounting post, due to a failure of the brazed joint. One converter was damaged at this time. The other converter was rebrazed by a different process into the post and is again ready for testing. An additional problem was loss of vacuum integrity of the radiant heater upon thermal cycling. A redesigned heater is now ready for assembly. This experiment will be concluded during the first part of the second year of the contract.



EMITTER : TUNGSTEN
COLLECTOR : MOLYBDENUM

EMITTER TEMPERATURE :	1170 K	
COLLECTOR TEMPERATURE :	800 K	
CESIUM RESERVOIR TEMPERATURE :	507 K	
EMITTER WORK FUNCTION :	1.66 eV	From Calculated I-V Curve
COLLECTOR WORK FUNCTION :	1.56 eV	From Calculated I-V Curve
ELECTRODE SPACING :	6.5 μm	From Calculated I-V Curve
COLLECTOR AREA :	0.174 cm^2	
LEAD RESISTANCE :	~30 mΩ	
BYPASS RESISTANCE :	~13.5 Ω	
MAXIMUM OUTPUT POWER DENSITY :	0.35 W/cm^2	

Fig. 3 Comparison of results from experiments theoretical model

Task 3 - Modeling

A comprehensive computer model of the Knudsen mode of discharge in one dimension has been developed. This model uses the Vlasov (collisionless Boltzmann) equation for charged particle distribution functions to derive expressions for charged particle density as a function of potential. These can be substituted into Poisson's equation which is solved for the spatial dependence of potential in the interelectrode gap. A finite difference method is used to numerically integrate Poisson's equation. Electron and ion currents can be calculated once the potential is known. Thermionically emitted electrons, positive cesium ions, back emitted electrons from the collector, and auxiliary ions are included in the formulation. Expressions for trapping of charged particles in potential wells due to infrequent collision have been included. These have been found to be important to the formulation. The effects of ion trapping under electron-rich (incomplete-neutralization of space charge) conditions are summarized in Fig. 4. For a close-spaced diode ($d<50$ μm) the effect is an increase in current density near the maximum power point of the volt-ampere characteristic. This gives a much larger maximum output power in the cases studied than for characteristics calculated without ion trapping. For conventionally spaced diode (0.05 mm < 0.5 mm) the effect is independence of the apparent saturation current density from emitter work function in the electron-rich regime. Without ion trapping the saturation current goes through a maximum as the work function is decreased and then falls off as the work function is decreased further.

The analysis of collisional discharges has been addressed using computer models of the unignited (ions generated by surface ionization) and ignited (ions generated by collisions) modes. These models have been developed by Rasor Associates prior to this contract, and have been extensively used to analyze thermionic phenomena in these modes. They have been used to calculate the ion and electron currents into the region surrounding the SAVTEC electrodes as a function of applied potential between the heat source and the emitter.

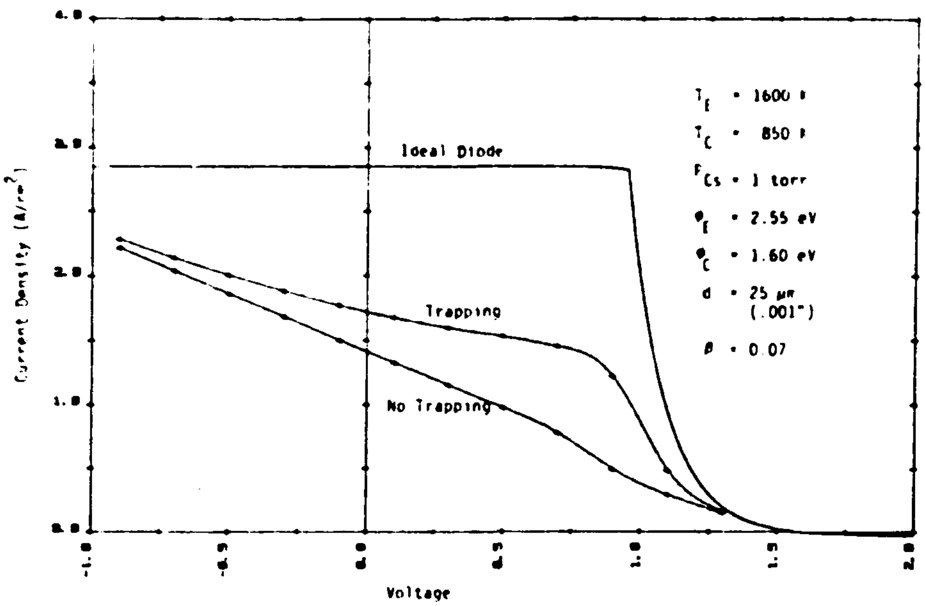


Fig. 4a Increase in current density near maximum power point due to positive ion trapping in a close-spaced diode

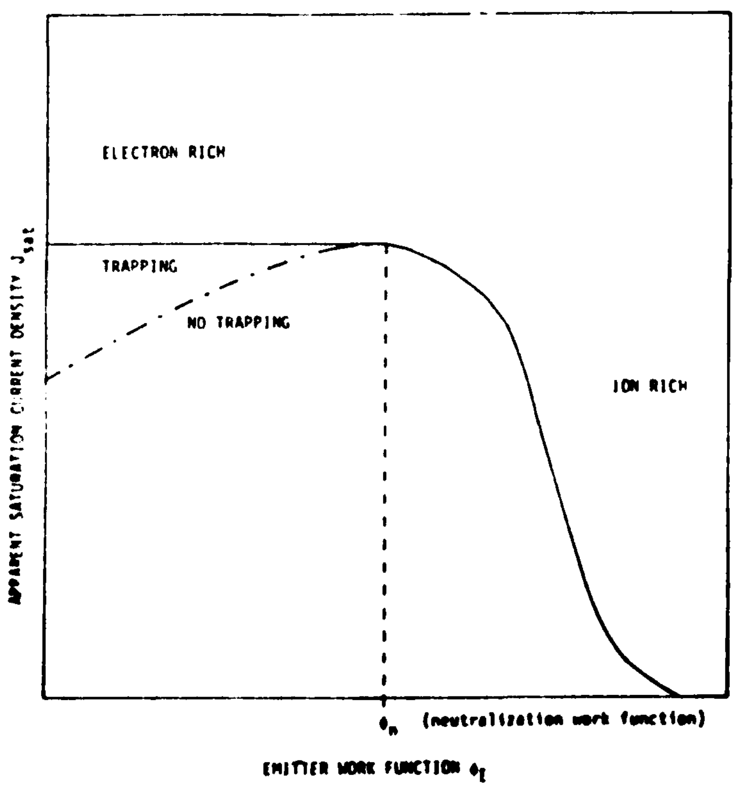


Fig. 4b Independence of apparent saturation current density from emitter work function due to trapping in a conventionally-spaced diode

An analytical expression was derived from diffusion theory which relates the ion density at the outer edge of two plane-parallel electrodes to the radially averaged ion density in the interelectrode space. This gives a value for the ion density term used in the Knudsen mode computer model, which can then predict the observable effect on output characteristics. A diffusion analysis has been used to compute the plasma density at the edge of a close-spaced electrode structure given the electron and ion current into this region.

Results from both the experimental and analytical tasks are summarized in Fig. 5.

RESULTS

- To Date

  -- Excellent agreement between theory and experiment in regime where positive ions do not contribute to space-charge neutralization.

  -- Close interelectrode spacing in experimental SAVTEC

  -- Understanding of the effects of positive ion trapping in both closed-spaced and conventionally spaced thermionic diodes

  -- Prediction of the effect of an externally generated arc on SAVTEC performance.

- Expected

  -- Experimental verification of predicted external arc effect and performance in surface ionization regime.

  -- Observation and understanding of the structured emitter effect in a barium-cesium mixed vapor diode

Fig. 5

C. Technical Journal Publications

No publications have been submitted to technical journals to date. An oral presentation was made at the 1984 IEEE International Conference on Plasma Science (see section I-3).

D. Interactions

(i) The paper Ion Trapping Effects in Electron-Rich, Unignited-Mode Thermionic Converters was presented in an oral session at the 1984 IEEE International Conference on Plasma Science. An abstract of the paper is included in the conference record, IEEE publication No. 84CH1958-8.

(ii) The principal investigator has also done work on contracts from Carnegie-Mellon University and the United States Department of Energy. The Carnegie-Mellon work involved the concept of a cesium heat-pipe recombination laser. The DOE work involved primarily engineering development of pre-prototype SAVTEC devices. A nineteen element SAVTEC array was tested using a combustion heat source.

E. New Discoveries and Specific Applications

The most immediate application of this research are to SAVTEC diode systems for thermionic energy conversion and similar devices. The multiregion formulation which has been developed yields design criteria for an auxiliary discharge in the array envelope to cause significantly improved performance in the SAVTEC diodes. The effect of geometry on diode performance due to radial loss of trapped positive ions has also been examined. This is an effect which was previously unknown.

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