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TECHNOLOGY PROGRAM
PROGRESS REPORT NO. 29

November 1977

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PRINCETON PLASMA PHYSICS LABORATORY CONFERENCE

On November 17 and 18 a meeting arranged by Dr. Maria Stoenescu was held at Princeton with members of Dr. Robert Mills' Reactor Engineering Group. The Thermo Electron personnel were Dr. Fred Huffman, Mr. David Lieb, Dr. Peter Oettinger and Dr. Chi-Chung Wang. After the Thermo Electron group reviewed the status of thermionic energy conversion, Dr. Stoenescu's group described their analytical effort. A tour of the fusion reactor laboratory facilities was taken after lunch. For the balance of the afternoon, the potential efficiency improvements and problems of integrating thermionic energy converters into Tokamak fusion reactors were explored. The most practical means of topping the steam conversion system appeared to be to use helium as a means of cooling the blanket region and heating the converter emitters. The concensus of the meeting was that application of thermionic conversion to fusion reactors appeared promising and deserved further consideration. During the evening thermionic topics of mutual interest were reviewed with Dr. Harvey Lam. An extended discussion of the Princeton and Thermo Electron analytical models of the cesium diode took place the next morning. Parameters averaged from the Princeton results to be used in the Thermo Electron model were defined.

I. SURFACE STUDIES

A. SURFACE CHARACTERIZATION CHAMBER

No work was performed on this task during this reporting period.

B. ADJUSTABLE CESIUM PRESSURE ACTIVATION CHAMBER

The need for an apparatus which characterizes electrode materials in an equilibrium cesium pressure motivated the design of the Adjustable Cesium Pressure Activation Chamber (ACPAC). The design of the ACPAC is shown in Figure 1. An ultra-high vacuum stainless steel envelope is used to obtain low pressures and a glass window is provided for photo-emission studies. Samples are readily replaced by inserting the RCA vidicon structure. The small sample area is guarded by a ceramic brazed to a stainless steel sleeve. The current collecting electrode employs a metal shield with a large disc ceramic. The electrode is brazed to the center of the ceramic and connected to a feedthrough assembly in the top flange. Cesium is introduced by flashing a bank of cesium channels. The reservoir temperature is established by heating the entire system in an oven. Tubulation for a cesium capsule has been provided in the event that larger amounts of cesium are necessary. The ACPAC design is complete and fabrication is in progress.

Figure 1. Diagram of Adjustable Cesium Pressure Activation Chamber (ACPAC)

II. PLASMA STUDIES

A. CONVERTER THEORY

The performance characteristics of Thermo Electron Diode No. 36 has been mapped extensively. The data from this converter is being used to evaluate the accuracy of the present computer model of the thermionic diode. The measured emitter work function, ϕ_E , as a function of $kT_E \ln (P/3,000,000)$ is shown in Figure 2. In this relation, k is the Boltzmann constant, T_E is the emitter temperature and p is the cesium pressure. The collector work function, ϕ_C , is given as a function of the ratio of the collector temperature to the cesium reservoir temperature (T_C/T_R) in Figure 3. The experimental I-V data are shown in Figure 4 for the following operating conditions: $T_E = 1800$ K, $T_C = 948$ K, $d = 12.5$ μm and variable T_R . The I-V curves for $T_R = 564$ K and 577 K have been calculated with the plasma parameters for the former at a current density $J = 3.5$ A/cm^2 , plotted in Figure 5. Those for the latter at $J = 9$ A/cm^2 are plotted in Figure 6. The electron density, η_e , distribution of the low current case is symmetrical with respect to the central plane of the interelectrode spacing and is shifted toward the emitter in the high current case. The electron temperature, T_e , varies almost linearly in both cases. The total potential, ψ , changes in the plasma are relatively small.

The calculated I-V curves are compared with the experimental curves in Figure 7. For these cases, the theory provides reasonably accurate predictions for currents above those at the knee of the I-V curve. Loshkarev* gives the following relation to predict the formation of the double sheath:

*Loshkarev, A. I., "Nonmonotonic Potential Distribution in the Electrode Region," Sov. Phys. Tech. Phys. Vol. 19, No. 10, April 1977, p. 1308.

Figure 2. Emitter Work Function

Figure 3. Collector Work Function

Figure 4. Experimental I-V Curves

Figure 5. Calculated Plasma Parameters for the Case $T_E=1800\text{ K}$, $T_C=948\text{ K}$, $T_R=564\text{ K}$, $d=12.5\text{ }\mu\text{m}$, and $J=3.5\text{ A/cm}^2$

Figure 6. Calculated Plasma Parameters for the Case $T_E=1800\text{ K}$, $T_C=948\text{ K}$, $T_R=577\text{ K}$, $d=12.5\text{ }\mu\text{m}$, and $J=9\text{ A/cm}^2$

Figure 7. Comparison of Observed and Calculated I-V Curves

$$\left(\frac{J_S}{J} - 1 \right) \exp \left(\frac{V_e}{KT_e} \right) = \frac{\pi}{2\sqrt{2}} \frac{\sigma_{ia}}{\sigma_{ea}} \left[\frac{1 - \theta^{1/2}}{\theta^{1/2}} \left(\frac{J_S}{J} - 1 \right) \right]^2 \quad (1)$$

where J_S is the saturation current and θ is the ratio between electron and emitter temperatures. The location of the formation of the double sheath based on this theory is indicated on the calculated I-V curves.

The present program is able to calculate the plasma parameters when the diode is operated with a Pd product less than 15. For higher Pd values, the program has convergence problems. Improved convergence techniques are being studied.

B. EXPERIMENTAL PLASMA ANALYSES

Spectroscopic analyses in the 4000 to 8000 Å spectral region of a tungsten oxide converter in pulsed mode (5 μs pulse length, 2700 μs between pulses) operation revealed 14 cesium ion lines, none of which had been observed during the dc experiments. Furthermore, a number of discrete atomic lines previously recorded in dc tests did not appear in the pulsed experiments. The time to reach peak fluorescent emission, after initiation of the pulse, increased with higher cesium pressures. At 0.05 torr maxima were observed at 350 μs after ignition. This long time delay (after termination of the discharge) to reach maximum radiation suggests a recombinant population of the atomic excited levels. The noted distinctions between dc and pulsed operation indicate a significant difference in plasma properties for these two experimental modes.

C. ENHANCED MODE CONVERSION EXPERIMENTS

A 1.27 cm diameter molybdenum disc was ground, by means of standard machine-shop techniques, to a type-16 surface finish.

Dektak traces for this sample are shown in Figure 8. The asymmetrical nature of the surface texture is related to the unidirectionality of the grinding process. Flatness and smoothness of the worst-case ("with the grain") are well within the 2.5 μm limits necessary for the efficient operation of close-spaced thermionic diodes.

WITH
GRAIN

90° WITH
RESPECT TO
GRAIN

45° WITH
RESPECT TO
GRAIN

Figure 8. Roughness of Molybdenum Surface; Type-16 Surface Finish

III. CONVERTER DEVELOPMENT

A. LOW TEMPERATURE CONVERSION EXPERIMENTS

1. L605 Emitter, Nickel Collector (Converter No. 183)

L605 is an alloy composed of 10% nickel, 20% chromium, 15% tungsten and 55% cobalt and was obtained from International Nickel Company, Inc. This experiment is an attempt to repeat the excellent performance of Converter No. 143, which had a barrier index of 2.0 eV over a wide range of emitter temperatures. This performance, along with L605's high-strength at elevated temperatures, make it a candidate for low cost emitter material. This converter has been constructed and outgassing has begun.

B. HIGH EFFICIENCY CONVERSION EXPERIMENTS

1. Tungsten Emitter, Nickel Collector ("Heat Flux" Converter No. 175)

Several improvements have been made in the experimental arrangement for the heat flux converter in an attempt both to increase the accuracy of the determinations and to shorten the time required to make a measurement.

The heat flux converter experiments utilize a null balance technique. As the diode current is varied, the collector either heats or cools and the auxiliary collector heater must compensate exactly for this temperature change. The critical step is to vary the converter current without changing either the collector or emitter temperatures. Maintaining almost constant temperatures in the converter as the current is varied greatly reduces the time required to make a measurement. With the present test arrangement it is possible to maintain the emitter temperature at 1600 ± 1 K and the collector temperature at 850 ± 0.2 K.

A block diagram of the current experimental set up is shown in Figure 9. The cooling water for the collector is maintained at a constant temperature of 305 K in order to avoid day-to-day fluctuations in the baseline temperature of the collector. The power to the auxiliary heater is the most critical measurement in the experiment and is controlled by the computer. The voltage is measured by voltage taps located as close as possible to the heater element and the current is measured by a calibrated shunt. The computer samples the voltage and current at five-second intervals and then computes: the heater power, its running average, and its total average. The error in the computer power measurement is less than 0.02 watts. To obtain a data point, the converter is allowed approximately 5 minutes to reach equilibrium after the current has been varied and then the auxiliary heater power is averaged over a 10 minute period. Two representative curves of heater power versus converter current are shown in Figure 10. The data on the left-hand side was taken before the improvements to the equipment were made. Several experiments are currently underway with this converter.

2. Lanthanum Hexaboride Emitter, Guarded Nickel Collector (Converter No. 182).

Construction and outgassing of this converter was completed during the last reporting period.

Figure 10. Two Runs of Heat Flux Data

IV. COMPONENT HARDWARE PROGRAM

A. CVD COMPONENT DEVELOPMENT

Seven tungsten deposition runs were made during this reporting period. These structures will be coated with silicon carbide during the next reporting period.

The silicon carbide reactor was modified to provide greater variety of operating conditions. A graphite insert, schematically depicted in Figure 11, was added. The bulb-like end permits increased RF coupling at the sample's round end. The insert, which rotates with the sample, is hollow along the axis of rotation. A hydrogen purge, flowing out through the 1.2 mm vent hollows, can be operated independent of the reaction gas's flow. Presently, a study is being conducted on the distribution of the deposited SiC as a function of purging conditions and temperature distribution.

A technique was developed for removing tungsten deposited on the outside of a hollow graphite mandrel. The open end is plugged with a rubber stopper. The bottom edge of the mandrel and the exposed portion of the stopper are coated with Stop-Off[®] lacquer. The tungsten-coated end is then immersed in a solution of 10% HNO₃-90% HF until no visible trace of tungsten is left. The technique is not subject to mechanical shock and is considered superior to the previous technique of grinding away unwanted tungsten.

B. ALLOY HOT SHELL DEVELOPMENT

Simulated furnace testing continued at a furnace gas temperature of 1573 K. The inside of each shell is evacuated to 10^{-7} torr. Table 1

7712-3

Figure 11. Ventilated Graphite Insert for Fabrication
of Silicon Carbide Composite Hot Shells

TABLE 1

SIMULATED FURNACE TESTS
(December 1, 1977)

TEST PORT NO.	HOT SHELL	TEST HOURS	COMMENT	DATE OF TEST INITIATION
1	REACTION BONDED SILICON CARBIDE	14,213	LEAKTIGHT THIS HOT SHELL WAS BRAZED TO A MOLYB- DENUM SLEEVE WITH NICKEL-COPPER	9 April 75
2	KANTHAL A1	12,626	LEAKTIGHT	25 Aug. 75
3	446 CRES PLASMA ARC SPRAYED WITH NICHROME	521	LEAKTIGHT	31 Oct. 77
4	INCONEL 671	5,663	LEAKTIGHT	17 Nov. 76
5	446 CRES PLASMA ARC SPRAYED WITH Cr_2O_3	521	LEAKTIGHT	31 Oct. 77
6	KANTHAL A1	3027	LEAK OBSERVED REMOVED 14 NOV. 77	7 May 77

presents the status of these tests as of December 1, 1977. A leak was observed on the Kanthal A-1 sample on November 14, 1977 (Port #6). This shell has been removed from the furnace for failure analysis.

V. COMBUSTION-HEATED THERMIONIC DEVICE

The objective of this task is to design, construct, and test a flame-heated thermionic device for eventual use in combustion-heated panels. The first step in this development was the construction and flame-heated test of a "miniature device" employing the most promising materials in sizes that are readily available. The next step will be the fabrication of a larger "workhorse device," which will be evaluated in a test furnace that provides combustion parameters similar to those in fossil-fueled powerplants. The data and experience with the miniature and workhorse devices will then be factored into a larger "prototype device."

The design of the miniature device was described in last month's report. Fabrication has been completed and testing has begun. The test arrangement is shown in Figure 12. The test station is equipped with controllable collector and cesium reservoir heaters to facilitate diagnostic analyses. Connections to the computer system for dynamic I-V characteristics were also made. A photograph of the miniature device during flame heated testing is shown in Figure 13. Current-voltage characteristics for the miniature device are shown in Figure 14 for an emitter temperature of 1450 K. A power density of 1.0 watt/cm^2 has been obtained at an emitter temperature of 1500 K. This value is consistent with the data obtained from electron-beam-heated variable-spaced, research converters with the same electrode materials. Flame-heated testing of the miniature device is continuing.

Figure 12. Test Arrangement for Combustion Heated Miniature Diode

Figure 13. Photograph of Miniature Device During Flame Heated Test

Figure 14. I-V Characteristics of Miniature Flame Heated Device as a Function of Cesium Reservoir Temperature

The furnace for testing the larger diameter "workhorse device" has been assembled. A sketch of this unit is shown in Figure 15. The furnace is natural gas-fired by a North America 4832-4 flat-flame burner and typically operated at 15,000 Btu/hr. The burner fires horizontally into a 1-foot cubic cavity, with a rising flue. The workhorse device will be mounted flush with the chamber wall, facing the burner.

An emitter mock-up is presently mounted in the furnace. Testing is in progress to ascertain temperatures and heat fluxes available to the workhorse device. Temperatures of the simulated emitter and chamber walls are measured by thermocouples and by a pyrometer.

Figure 15. Combustion Facility for Testing Workhorse Device

VI. SYSTEM APPLICATION STUDIES

System application studies have been carried out in conjunction with Stone & Webster Engineering Corp. Emphasis has been directed at the study of thermionic topping of fossil-fired steam electric generating stations. Improved methods of coupling the thermionic converters to the steam cycle have been studied. Analyses have shown that direct-coupled and air-coupled thermionic converters can be combined advantageously in different portions of the boiler. A better match between the thermionic converters and the steam cycle was obtained by such an advanced boiler concept. These studies will be summarized in a topical report in the near future.