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CONVERTER PERFORMANCE FINAL TEST REPORT TFE VERIFICATION PROGRAM

**Prepared by
RASOR ASSOCIATES, INC.
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MASTER

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CONVERTER PERFORMANCE TEST PROGRAM

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1.0 INTRODUCTION

1.1 Objective of TFE Verification Program

The program objective is to demonstrate the technology readiness of a TFE suitable for use as the basic element in a thermionic reactor with electric power output in the 0.5 to 5.0 MW(e) range, and a full-power life of 7 years. A TFE for a megawatt class system is shown on Fig. 1-1. Only 6 cells are shown for simplicity; a megawatt class TFE would have many more cells, the exact number dependent on optimization trade studies.

1.2 Technical Approach

The TFE Verification Program built directly on the technology and data base developed in the 1960s and early 1970s in an AEC/NASA program, and in the SP-100 program conducted in 1983, 1984 and 1985. In the SP-100 program, the attractive features of thermionic power conversion technology were recognized but concern was expressed over the lack of fast reactor irradiation data. The TFE Verification Program addressed that concern.

The technical approach followed to achieve the program objective is shown on Fig. 1-2. Five prior programs form the basis for the TFE Verification Program:

- 1) AEC/NASA program of the 1960s and early 1970s.
- 2) SP-100 concept development program [Ref. 1-1].
- 3) SP-100 thermionic technology program [Ref. 1-2].
- 4) Thermionic irradiations program in TRIGA in FY-86 [Ref. 1-3].
- 5) Thermionic Technology Program in 1986 and 1987 [Refs. 1-4, 1-5].
- 6) SPRIME (40 kWe) Thermionic Design and Technology Demonstration Program [Ref. 1-6].

These programs provided both the systems and technology expertise necessary to design and demonstrate a megawatt class TFE.

A TFE was designed that met the reliability and lifetime requirements for the 2 MW(e) conceptual reactor design. This was used as the basis for designing components for test

Figure 1-1. TFE for Megawatt Class System

Figure 1-2. Logic to Demonstrate Technology Readiness of Megawatt Class TFE

and evaluation. The demonstration of a 7-year component lifetime capability was through the combined use of analytical models and accelerated, confirmatory tests in a fast test reactor. Iterative testing was performed where the results of one test series led to evolutionary improvements in the next test specimens.

The TFE components underwent screening and initial development testing in ex-reactor tests. Several design and materials options were considered for each component. As screening tests permitted, down selection occurred.

In parallel with ex-reactor testing and fast reactor component testing, components were integrated into a TFE and tested in the TRIGA test reactor at General Atomics (GA). Realtime testing of partial length TFEs was used to test support, alignment and interconnective TFE components, and to verify TFE performance in-reactor with integral cesium reservoirs. Realtime testing was also used to verify the relation between TFE performance and fueled emitter swelling, to test the durability of intercell insulation, to check temperature distributions, and to verify the adequacy over time of the fission gas venting channels.

Predictions of TFE lifetime rested primarily on the accelerated component testing results, as correlated and extended to realtime by the use of analytical models.

1.3 Organization of the Program

Contracting Agency:	Department of Energy, San Francisco Operations Office
Prime Contractor:	General Atomics (GA)
Subcontractors:	ThermoTrex Corporation (TTC), a subsidiary of Thermo Electron Corporation Rasor Associates, Incorporated (RAI) Space Power Incorporated (SPI)
Fast reactor testing manager:	Westinghouse Hanford Corp. (WHC)
Fast reactor facilities:	Fast Flux Test Reactor (FFTF), with testing managed by WHC EBR-II, with testing managed by Argonne National Laboratory-West (ANL-W)
Technical oversight for DOE:	Los Alamos National Laboratory (LANL)

1.4 Structure of Test Program

The TFE-VP was broken down into 7 tasks, generally corresponding to the components of a TFE. Fig. 1-3 shows a thermionic cell with the various components identified. Fig. 1-4 shows a one cell TFE fabricated for test in the program. A multi-cell TFE has 2 or more cells in series. When compared to Fig. 1-1, it is clear that this test article is not quite prototypical. The test conditions dictate the design to some extent. Also, the test approach is to first test simple TFEs and then gradually test TFEs more prototypic.

For each component, the work involved:

- a) Component design and analyses
- b) Materials evaluation and selection
- c) Performance testing
- d) Life testing, both accelerated and real time

In addition, performance models were developed for converter performance, fueled emitters and cesium reservoirs.

A brief description of each task is given below. For each of the component tasks, fabrication process specifications were developed and materials were chosen.

1.4.1 Conceptual Design

A TFE optimized for a 2 MW(e) system was designed. Its scalability over the range of 500 kW to 5 MW was demonstrated.

1.4.2 Converter Performance

The performance of converters of interest for megawatt class systems was measured and existing models on converter performance were refined.

Figure 1-3. Thermionic Cell

Figure 1-4. One Cell TFE Test in TFE Verification Program

1.4.3 Insulator Seals

The insulator seal isolates the space filled with gaseous fission products from the cesium filled interelectrode gap. It also routes the electron flow from the collector of one cell to the emitter of an axially adjacent cell.

1.4.4 Sheath Insulators

The sheath insulator is a structure composed of 3 layers:

- The inner layer is the collector.
- The middle layer is an insulator isolating the collector from the reactor coolant and structure.
- The outer layer is a metallic sheath that assures the structural integrity of the sheath.

1.4.5 Fueled Emitters

The fueled emitter is the emitter component inside of which are the following components:

- UO_2 fuel.
- Fuel holddown device to prevent damage to the cell during launch and ascent.
- Fission product trapping components to trap solid and condensible fission products and prevent them from exiting the cell.
- Heat shields to protect the upper and lower parts of the emitter from the high temperatures of the UO_2 .

1.4.6 Cesium Reservoir and Interconnected Components

The cesium reservoir provides cesium vapor to the interelectrode gap. A graphite cesium reservoir was demonstrated in the program. Interconnective components are those metal parts and insulator which are necessary to attach one cell in series with another.

1.4.7 TFEs

The TFE is an axial series of one or more cells. It also contains a cesium reservoir. TFEs with one, three and six cells were fabricated and tested. The TFEs fabricated under the TFE Verification Program are designated the "H" series TFEs, the next series following the "E", "F" and "G" series which were studied in the 1960s and 1970s. The E series TFEs had an emitter diameter of 0.625 inch; the F series, 1.1 inches; and the H series, 0.5 inches. A specific TFE has a designation xHy, the "x" being the number of cells in the TFE and the "y" being the specific TFE in question. For example, the TFEs fabricated and tested in the program were:

TFE-1H1 the first of the 1-cell TFEs.

TFE-1H2 the second of the 1-cell TFEs.

TFE-1H3 the third of the 1-cell TFEs.

TFE-3H1 the first of the 3-cell TFEs.

TFE-3H5 the fifth of the 3-cell TFEs.

(Numbers 2, 3, and 4 were eliminated early in the program.)

TFE-6H1 the first of the 6-cell TFEs.

1.5 Semiannual Progress Reports

Semiannual progress reports provide a running account of technical progress which reflects the work done at GA, TTC, RAI and SPI. These reports also summarize the status and results of the irradiation program at WHC and ANL-W. The technical work performed at LANL is also summarized there. Table 1-1 shows a complete list of all semiannual progress reports.

1.6 Final Reports

Final test reports give details on each of the major components outlined in Section 1.4. A list of these final reports is given in Table 1-2. It is assumed in these reports that the reader is familiar with thermionic technology and the structure and operation of thermionic fuel elements and their components.

Table 1-1
Semiannual Progress Reports

Period Ending:	Date Issued:	Report Number:
March 31, 1987	April 1987	GA-A18780
September 30, 1987	March 1988	GA-A19115
April 30, 1988	June 1988	GA-A19269
October 31, 1988	January 1989	GA-A19412
April 30, 1989	September 1989	GA-A19666
September 30, 1989	March 1990	GA-A19876
March 31, 1990	July 1990	GA-A20119
September 30, 1990	January 1991	GA-A20335
March 31, 1991	April 1991	GA-A20493
September 30, 1991	December 1991	GA-A20804
March 31, 1992	April 1992	GA-A20911
September 30, 1992	January 1993	GA-A21210
March 31, 1993	May 1993	GA-A21326
September 30, 1993	January 1994	GA-A21511

Table 1-2
Final Test Reports of TFE Verification Program

Report Title:	Document No.
Conceptual Design	GA-A21590
Converter Performance Final Test Report	GA-A21591
Insulator Seal Final Test Report	GA-A21592
Sheath Insulator Final Test Report	GA-A21593
Fueled Emitter Final Test Report	GA-A21594
Cesium Reservoir Final Test Report	GA-A21595
TFE Performance Final Test Report	GA-A21596
TFE Design Package	GA-A21597

1.7 References

- 1-1 General Atomics Report GA-C18052, GES Baseline System Definition and Characterization Study, Final Report for the period December 1984 through July 1985; prepared under JPL Contract #956472, August 9, 1985.
- 1-2 General Atomics Report GA-A18182 (1985), SP-100 Thermionic Technology Program Annual Integrated Technical Progress Report for the period ending

September 30, 1985, by GA Technologies, Rasor Associates, Inc., Space Power, Inc. and Thermo Electron Corporation, General Atomics, San Diego, CA, November 1985.

- 1-3 General Atomics Report GA-A18915 (1987), Thermionic Irradiations Program Final Report, General Atomics, San Diego, CA.
- 1-4 V.P. Cone and J. Dunlay (1987), Thermionic Technology Program Fiscal Year 1986 and Final Technical Report, Thermo Electron Report No. TE4400-227-87.
- 1-5 G.L. Hatch (1988), Thermionic Technology Program: Thermionic Converter Performance Final Report, NSR-25-25, E-533-003-B053188 (DOE Contract No. DE-AC03-86SF15954).
- 1-6 Interim Design Review, 40 kWe SPRIME Thermionic Design and Technology Demonstration Program (DE-AC03-92SF19138), San Diego, CA June 24-25, 1993.

2.0 CONVERTER PERFORMANCE TESTING OBJECTIVES

2.1 Converter Performance Test Program

The objective of the Converter Performance Task was to establish accurate converter performance models which correlate with observed test data. The data base was developed from near prototypic converters using emitter and collector materials of interest over the full range of anticipated operating parameters. A thermionic reactor is composed of a large array of thermionic cells, each of which has a unique input power, emitter temperature, and operating current density. In addition, individual cells will vary in performance over the system lifetime due to changing operating conditions caused by fuel burnup and variations in operating power requirement or losses of some of the cells. Therefore, the design and performance prediction of a thermionic reactor require an extensive data base on prototypical cell performance over a wide range of operating conditions. Also of importance are the data and models for the startup of TFEs in TRIGA and FFTF and also in the startup of thermionic reactors. The observed current-voltage data during startup can be related to system temperature with the help of ex-reactor correlations.

2.2 Test Matrix

The Test Matrix shown in Tables 1 and 2 were originally set-up to assist with the description of the various aspects of this program task. The rationale for the converter performance testing plan was fourfold:

- a. To document any fundamental changes in converter performance due to the use of graphite-cesium reservoirs instead of a conventional liquid cesium pool. This would involve the evaluation of both the planar converter configuration and the cylindrical configuration.
- b. To provide verification for a model used to relate converter output to emitter distortion for application in TFE designs.

Table 2-1

Ex-Reactor Planar Converter Test Program

	EMITTER	COLLECTOR	Cs RESERVOIR	RATIONALE for TEST
PC-1	Duplex W*	Nb	Graphite	Performance map with graphite-cesium reservoir.
PC-2	Duplex W	Nb tilted	Pool	A verification of the model which relates converter output to emitter distortion.
PC-3	High Strength Emitter	Nb	Pool	Establish data base on performance with high strength emitter.
PC-1 (MOD)	Duplex W*	Nb	Graphite	UO ₂ in contact with the emitter. Differential data on the UO ₂ effect will be obtained during a life test.

* To be combined into one experiment to be designated PC-1 (MOD).

Table 2-2

Ex-Reactor Cylindrical Converter Test Program

	EMITTER	COLLECTOR	RESERVOIR	LIFE TEST	RATIONALE for TEST
CC-1 X	Duplex W	Nb	Graphite	No	Performance map with reference electrodes and reservoir.

- c. To establish a database on performance of converters equipped with a high strength emitter.
- d. To examine the effect of UO₂ in contact with the emitter through lifetime testing of a standard converter. This work would serve to complement earlier work of a similar nature. For instance, in an earlier study [Ref. 2-1] it was reported that the performance of a cylindrical converter consisting of a

rhenum emitter containing uranium oxide fuel decreased by 15% after 2400 hours of testing at an emitter temperature of 2000 K. It was concluded that oxygen and uranium continuously diffused through the rhenum emitter, with oxygen enhancing the uncesiated emitter work function and uranium depositing on the collector. Shimada [Ref. 2-2] also studied a planar converter consisting of a tungsten emitter containing uranium nitrude fuel. Here the performance increased up to 4300 hours at an emitter temperature of 1900 K, followed by degradation at 4700 hours. Von Bradke and Henne [Ref. 2-3] tested a converter consisting of a molybdenum emitter containing uranium oxide and found an overall beneficial effect of oxygen. Since performance evaluation does not exist for converters with tungsten emitters containing uranium oxide fuel, the purpose of the present study is to generate this information so as to supplement the finding of the earlier studies in this area.

During program restructuring the subtask described in c. above was eliminated. Furthermore initial testing carried out after UO_2 loading but prior to extended lifetime testing of the planar converter was taken to be representative of the performance of the converter without UO_2 , hence eliminating the original subtask for separate performance mapping of the converter prior to UO_2 loading. The restructured testing schedule was as follows:

- a. Performance testing of cylindrical converter (CC-1X) fitted with an integral cesium-graphite reservoir.
- b. Performance testing of a variable spacing planar converter (PC-2) with a tilted collector to simulate emitter distortion.
- c. Initial performance testing of a variable-spacing planar converter with UO_2 embedded in emitter and fitted with a cesium-graphite reservoir (PC-1).
- d. Lifetime testing of PC-1 (PC-1 MOD).

2-3. References

- 2-1 K. Shimada, "Out-of-Core Evaluations of a Nonfueled and a UO_2 Fueled Cylindrical Thermionic Converter", in *Proc. Thermionic Spec. Conf.*, San Diego, CA, 1971, p. 248.
- 2-2 K. Shimada, "Out-of-Core Evaluations of Uranium Nitride-Fueled Converters", in *Proc. 3rd Int. Conf. on Thermionic Power Generation*, Juelich, Germany, 1972, p. 1269.
- 2-3 M. VonBradke and R. Henne, "Electrodes for Low Temperature Thermionic Energy Converter: Recent Results and Compatability Considerations", in *Proc. 12th IECEC*, Washington, DC, 1977, p. 1582.

3.0 CONVERTER PERFORMANCE MODELS

3.1 Ignited Mode Performance (TECMDL)

TECMDL Computer Code

A survey of computer models performed at the beginning of the Thermionic Fuel Element Verification Program resulted in the choice of TECMDL as the basis for the Standard Planar Converter model to be used for reactor system studies and in-core experiment diagnostics. The purposes of the TECMDL computer program are [Ref. 3-1]:

- a. To enable an approximate calculation of converter performance and J-V characteristics in the ignited mode.
- b. To semi-quantitatively reproduce trends due to changes in electrode temperatures, electrode materials, cesium pressure, and interelectrode spacing.
- c. To provide insight into the most important physical mechanism which determine converter performance.

TECMDL is based on a simplified physical model described by McVey and Rasor [Ref. 3-2]. In the model all quantities are described by easily solved algebraic equations. The equations in the model contain a set of "effective plasma parameters" which are related to fundamental properties and cross-sections. Their values of these parameters were adjusted slightly within their ranges of uncertainty in order to optimize the agreement between calculated results and experimental data. It must be pointed out, however, that these parameters are not simply fitting parameters since all can be calculated from known properties to within 20% of their true values.

The development of the code began in 1982 as the computer implementation of the "phenomenological model" described by Rasor [Ref. 3-3]. It has been continuously upgraded for improved accuracy and more comprehensive physics since that time. TECMDL simulates the

ignited-mode thermionic converter performance. The ignited-mode volt ampere characteristics consist of the obstructed region and the saturation region. The obstructed region is characterized by a "double-valued sheath barrier", or a virtual cathode at the emitter. The formulation by Rasor [Ref. 3-3] was primarily relevant to the obstructed region and consisted of a combination of simplified boundary conditions with the fluid transport equations for electrons in the plasma. This resulted in an expression for the current attenuation in terms of "effective plasma parameters", which are in turn related to fundamental properties and cross-section. In order to improve the accuracy of the plasma model, several improvements were effected on the original formulation and incorporated into TECMDL. These changes have been detailed by McVey and Rasor [Ref. 3-2]. In addition to the plasma model improvements, the simplified expressions for cesiated emitter and collector work function used in Rasor [Ref. 3-3] have been replaced by somewhat more rigorous models and have resulted in better agreement with experimental data [Ref. 3-2].

TECMDL is implemented through a series of subroutines. TECMDL input parameters consist of the following:

- The emitter temperature in Kelvin.
- The collector temperature in Kelvin.
- The liquid cesium reservoir temperature in Kelvin.
- An integer value which selects from a menu of emitter surface base work functions. The menu of integer values are:
 - 0 = The value for the emitter bare work function will be supplied by user.
 - 1 = Use of a value characteristic of chloride CVD tungsten with (110) preferred orientation.
 - 2 = Use of a value characteristic of (110) single crystal tungsten (5.14 eV).
 - 3 = Use of a value characteristic of chloride-deposited CVD rhenium with (0001) preferred orientation.
 - 4 = Use of a value characteristic of (0001) single-crystal rhenium (5.5 eV).

- The value of the cesiated collector work function. If unavailable, the value supplied to the program is "0", following which the program obtains a value from a curve which relates work function to the ratio of the collector temperature to the cesium reservoir temperature. (Note: This curve is obtained by an empirical fit of available experimental data for converters containing niobium and molybdenum converters.) The collector work function so obtained will appear in the output.
- The interelectrode gap spacing in millimeters.
- The operating current density in amperes/cm².

The output parameters from TECMDL are:

- The output voltage in volts.
- The emitter electron cooling in watts/cm.
- A logical parameter called JCNFDN related to the shape of the calculated volt-ampere characteristics.

Note: JCNFDN is set "FALSE" if the point of evaluation is far from the region of confidence, namely, the knee of the curve.

Mathematically, this is accomplished as follows:

In the low current regime (i.e., a points much below the knee of the J-V curve) the program performs the following:

$$\text{JCNFDN} = \text{FALSE}$$

If:

$$\frac{e\Delta V}{kT_E} > 0.85$$

where ΔV is the "negative space-charge barrier height" at the emitter, and T_E is the emitter temperature.

In the high current regime (i.e., at points much higher than the knee of the J-V curve) the following is carried out by the program:

JCNFDN = FALSE

If:

$$\frac{eV_E}{kT_{eE}} > 3$$

where V_E is the voltage of the emitter sheath, and T_{eE} is the temperature of the plasma electrons at the emitter.

Comparison with Experimental Data

The standard of performance chosen for the Thermionic Fuel Element Verification Program was the performance characteristic of the TTC Converter #46. This was a variable-spacing planar converter with an active guard ring. The emitter was chloride-deposited tungsten and the collector was niobium. It should be pointed out, however, that data pertinent to Converter #46 did not possess variations in collector temperatures. As a result, data from two other converters, namely PD-6 and TTC #42, were also utilized to investigate TECMDL accuracy as a function of collector temperature variations. These two converters were essentially similar to #46 except that they used single-crystal tungsten emitters.

Comparisons of TECMDL predictions with experimental data has been reported by McVey and Rasor [Ref. 3-2]. They compared J-V characteristics using the cesium pressure family, emitter temperature family, spacing family, and voltage-collector temperature plots. The effective plasma parameters contained in the TECMDL formulation were adjusted within their ranges of uncertainty to give the best possible fit to experimental data from the converters mentioned above. These data corresponded to the following range of experimental parameters:

Emitter Temperature	1600 - 1200 K
Collector Temperature	800 - 1100 K
Cesium Pressure	1 - 12 torr
Interelectrode gap	0.064 - 1.0 mm

They reported the overall trends as follows:

- Accuracy begins to diminish for spacings below 0.127 mm probably because the model is based on a fluid approximation which breaks down at small values of the pressure-spacing product.
- TECMDL has a tendency to predict lower optimum collector temperature than shown by experimental data. However, the discrepancy falls within the uncertainty in performance exhibited by similar experimental converters.
- Comparison of the simulated J-V curve and the experimental curves show that the accuracy of the TECMDL degrades sharply for portions of the J-V curve which are far from the transition point. The inaccuracy of the saturation region of the curve (above the transition point) has been attributed to:
 - a. neglect of the plasma electric field in the derivation of the electron temperature; and
 - b. neglect of the voltage drop within the plasma as a contribution to the emitter sheath height.

The inaccuracy in the lower obstructed region has been observed in all existing models and is not clearly understood. The speculation is that it may be due to the thickening of the emitter sheath which invalidates the physical representation of distinct sheath and plasma regions. However, the code returns a warning if the calculated points are too far away from the transition point for acceptable accuracy.

One approach to improve this drawback of TECMDL is to combine TECMDL with the UNIG unignited mode model. This combination would produce a reasonable approximation to the overall volt-ampere curve, rather than just the ignited mode portion. This modification would avoid a non-physical effect where the voltage calculated by TECMDL

approaches large negative values at small current. The UNIG unignited mode model is described in the next section.

3.2 Unignited Mode Performance (UNIG, MASTERPC)

The UNIG computer model is a set of subroutines for calculating unignited mode J-V curves for thermionic converters. The primary assumptions made in UNIG are the spatial invariance of the electron temperature, ion temperature, and transport coefficients. Volume ionization is also ignored. MASTERPC, on the other hand, includes this effect and therefore can reproduce the ignition behavior of the experimental data at emitter temperatures above 1750 K. These computer models are based on a physical model for the unignited mode which was developed for the purpose of accurately inferring the emitter temperature of in-core thermionic converters. This was accomplished by fitting the unignited mode portion of the J-V curve with the calculated results from the model. Details of the model have been presented as a preliminary technical report (UNIG) [Ref. 3-4] and as a paper in the Thermionic Specialist Conference at Eindhoven (MASTERPC) [Ref. 3-5].

Basic Physical Model: In the case where charged particles make several collisions in crossing the interelectrode space, the plasma can be described by a set of transport equations [Ref. 3-6]. These equations assume that there are enough collisions in the interelectrode space and the electric field is so small that the inertia of the charged particles can be ignored. Boundary conditions for the transport equation come from an analysis of the electrostatic sheaths adjacent to the electrodes [Ref. 3-7], wherein the sheaths are assumed to be of negligible thickness. The ions near the electrodes are assumed to be in thermal equilibrium with the electrodes. The presence of non-monotonic sheaths and the Schottky effect, both of which are important in the ignited mode, have been neglected.

The unignited mode has several advantages for emitter temperature diagnostics. Under typical conditions for the TFE tests, the unignited mode is in the "electron-rich" regime, where the J-V curve is insensitive to parameters other than the emitter temperature, interelectrode spacing, cesium pressure, and collector work function. The unignited mode saturation current, in particular, is insensitive to collector work function but is very sensitive to emitter temperature.

The cesiated emitter work function is calculated from the emitter temperature, cesium pressure and bare work function using the Rasor-Warner formulation [Ref. 3-8]. The cesiated collector work function is calculated from an analytical fit to measurements on planar thermionic converters with the same electrode materials.

Comparison of Model Predictions with Available Data: A comparison between experimental data at lower emitter temperatures and corresponding UNIG predictions indicated that, while the saturation current is underestimated by the model, the agreement is reasonably good over the rest of the curve. This worsens at temperatures greater than 1750 K. This is attributable to the fact that UNIG ignores volume ionization and, hence, cannot simulate the ignition behavior that is exhibited by the experimental data at temperatures greater than 1750 K. Therefore, determination of emitter temperatures using UNIG tended to be high by about 10 K for temperatures around 1600 K and by about 40-50 K for temperatures around 1800 K. MASTERPC, on the other hand, included volume ionization and hence reproduced ignition behavior.

A comparison between experimental data from the PD-6 planar converter, a calculation using MASTERPC, and a calculation using UNIG is shown in Fig. 3-1. The UNIG curve is somewhat less steep than both the PD-6 data and the MASTERPC calculation. It has a saturated region at about 0.86 A/cm^2 , whereas the actual data reaches ignition before saturating. The ignition current is at about 1.1 A/cm^2 , about 20% higher than the calculated saturation current density. As pointed out earlier, the reason for this is the neglect of volume ionization in the UNIG formulation. This effect becomes important for emitter temperatures above about 1750 K and leads to an increase in current as the ignition point is approached. By including this effect in the MASTERPC formulation, it was possible to reproduce the ignition behavior of the experimental data.

As shown in Fig. 3-2, the agreement between experimental data and UNIG predictions improves at lower emitter temperatures. However, the predicted saturation current density was still somewhat lower than the data. Determinations of emitter temperature using UNIG will tend to be high by about 10 K for lower temperatures (1600 K) and by about 40-50 K for temperatures of about 1800 K.

Fig. 3-1 Comparison between PD-6, MASTER-PC, and UNIG

Fig. 3-2 UNIG predictions showing improvement at lower temperatures

3.3 References

- 3-1 John B. McVey, TECMDL Ignited Mode Planar Thermionic Converter Computer Model, Report 1, Doc. No. 909692.
- 3-2 J.B. McVey and N.S. Rasor, Proc. 27th IECEC, San Diego, CA, August 1992.
- 3-3 N.S. Rasor, "Thermionic Energy Conversion", Chap. 5 in Applied Atomic Collision Physics, Vol. 5, Massey, McDaniela and Bederson eds., Academic Press, 1982.
- 3-4 Rasor Associates, Inc., Preliminary Technical Report, "UNIG Unignited Mode Thermionic Converter Model", Report #NSR-53, January, 1991.
- 3-5 J.B. McVey, "Computer Modeling and Diagnostics of Unignited and Pulsed-Ionization Thermionic Converters in Thermionic Energy Conversion," Proceedings of the Specialist Conference, Eindhoven, Netherlands, 1989.
- 3-6 G.N. Hatsopoulos and E.P. Gyftopoulos, "Thermionic Energy Conversion Volume II: Theory, Technology, and Application", MIT Press, Cambridge, MA, 1979, pp. 405-416.
- 3-7 Ibid, pp. 428-430.
- 3-8 N.S. Rasor and C. Warner, "Correlation of Emission Processes for Adsorbed Alkali Films on Metal Surface", Journal of Applied Physics, 35 (9), pp. 2589-22600, 1964.

4.0 PERFORMANCE TESTING OF CYLINDRICAL CONVERTER CC-1X

4.1 Introduction

The testing of CC-1X converter was aimed at providing a database for prototypic cylindrical converters for multi-megawatt space nuclear power systems using techniques established in the Thermionic Technology Program. It was part of the Thermionic Fuel Element Verification Program which addressed the design of a 2 MWe thermionic reactor with a full power life of seven years. The specific test objective was to map the performance of the CC-1X cylindrical converter which is equipped with a cesium-graphite integral reservoir. This included: a) recording the current density vs. voltage characteristics; b) optimization of converter parameters; c) determination of emitter input power requirements; and d) determination of converter lead efficiency in a flashlight configuration. (Note: The flashlight configuration refers to the location of the emitter and collector leads with respect to each other in the converter and has been described in Section 4.3.)

The specific design parameters for the 2 MW TFE applications are:

- * emitter temperature, T_E 1800 K
- * collector temperature, T_C 1070 K
- * interelectrode gap 0.25 mm (10 mils)
- * current density 7 A/cm²

The objectives of the experiments were to map the performance of a prototypic cylindrical converter for TFE applications. This includes recording current density vs voltage characteristics, optimization of the converter parameters, determination of the emitter input power requirements and of the converter lead efficiency in a flashlight configuration.

4.2 Fabrication of CC-1X Converter

The objectives of CC-1X were to provide an electrically-heated test vehicle to simulate a nuclear-fuelled converter similar to the "H" series converters, and to provide a means for estimating the temperature of the emitter and collector from converter performance characteristics. The converter design was as prototypic as possible while including the provisions

for the temperature measurements. The emitter wall thickness was increased to allow holes to be drilled in the emitter wall for thermocouples. Collector cooling was accomplished by a water-cooled jacket coupled to the collector body through an inert gas gap. An external graphite-cesium reservoir was used.

The main converter features detailed in this section can be summarized as follows:

- * a tungsten layer 0.25 mm thick chemically vapor deposited (CVD) from WCl_6 at TTC onto a tungsten mandrel CVD from WF_6 . After grinding, the finished surface is the emitting surface, with an effective area of 20 cm^2 .
- * a niobium collector, part of a GA Nb- Al_2O_3 -Nb trilayer.
- * a Litton insulator seal, Nb- Al_2O_3 -Nb.
- * centering of the emitter is achieved by a W-25% Re ring in a close fit with an Al_2O_3 washer, allowing for axial expansion.
- * an intercalation-type cesium reservoir containing pyrolytic graphite exposed to cesium vapor during the converter processing at TTC.
- * four holes drilled at various depth along the emitter can be used as black body holes for optical pyrometry or as thermocouple wells.

Converter Description: The converter is shown in Fig. 4-1. The major components are: a) emitter assembly, including emitter heater and seal; b) collector and collector cooler; and c) cesium supply. These components are further described below.

Emitter: The emitter substrate of the converter was tungsten made by chemical vapor deposition (CVD) from tungsten fluoride, the emitter surface was deposited from tungsten chloride under conditions favorable for the deposition of (110) crystal orientation. The thick inner core of the emitter was made of powder metallurgy tungsten. The thick part of the emitter had three thermocouple holes: one shallow, one deep, and one extending to the midplane of the emitter. There was one blackbody hole also extending to midplane. The emitter diameter was 12.7 mm (0.5 inch) with a length of 51 mm (2 inches) and an effective area of 20 cm^2 . A double helical tungsten filament of 0.5 mm (0.02 inch) diameter heated the emitter by radiation and

Fig. 4-1 CC-1X converter description

electron bombardment. The tungsten filament was pressed into 2 mm (0.08 inch) diameter tantalum leads which were connected to molybdenum filament holders. These were mounted on top of the converter, electrically isolated from the converter by threaded ceramic standoffs. The emitter and collector were isolated electrically by a Litton-type taper seal with niobium cuffs and an alumina insulator.

Collector: The collector was niobium. It was insulated from the collector sheath by a graded niobium-alumina cermet. The thickness of the cermet was 0.5 mm (0.16 inch). The outer surface of the collector sheath had four grooves to accept the collector thermocouples. The collector sheath was inserted into a cooling assembly with an inert gas gap and a water cooled jacket. The inert gas connection was brought off the belljar for gas mixture adjustments. The amount of cooling was varied by changing the inert gas mixture from pure helium, for maximum cooling, to pure argon or a mixture of the two or simply evacuating the gap for minimum cooling. Two collector current leads were provided, one on top of the converter and another on the bottom, thus the converter could be used with either the conventional lead configuration or in the flashlight cell mode.

Cesium Supply: The cesium supply for this converter was provided by a cesium-graphite intercalated reservoir. The graphite was a Poco-grade CZR2 [Ref. 4-1]. The cesium loading of the graphite was accomplished in a separate operation, shown in Fig. 4-2. The graphite is enclosed in a tantalum pillbox which is then enclosed in the niobium reservoir. The tantalum reduces the chance of graphite reacting with the niobium. The volume of the pillbox was twice that of the uncesiated graphite to allow for swelling. The lower tube of the reservoir was sealed with a pinch open device which was used to isolate the graphite reservoir from the converter. The cesium was charged to the graphite by double distillation. Initially, the entire assembly was outgased. Next, the cesium capsules were cracked and the cesium distilled into the cesium drum. The tube containing the capsules was then pinched off. Finally, the cesium was distilled from the drum into the graphite reservoir at the specified temperature. The system pumping was continued during this step to thoroughly outgas the graphite. During this period cesium vapors, which condensed in the upper part of the cesium still, returned to the reservoir. The cesium was equilibrated with the graphite for approximately 15 hours, after which the

Fig. 4-2 Set-up for cesium loading of graphite

reservoir was pinched off. Next, the reservoir was turned upside down and welded to the converter, as was shown in Fig. 4-1. Next, the converter was outgased through the pumpout port which was then pinched off. At an appropriate instant the pinch-open device was activated by connecting the precharged cesium graphite reservoir to the converter and, hence, readied for testing.

4.3 Experimental Setup and Methodology

The CC-1X emitter was heated by electron bombardment and the collector was coupled through a gas gap to a water cooling block. The gas gap could be filled with helium at low pressure to vary the heat conduction. Collector temperatures above 970 K could only be reached, however, by pumping away all the helium and carrying DC current through the converter; even then, at 7 A/cm² DC, the maximum achievable T_C was about 1025 K, slightly lower than the design set point.

Emitter temperatures at the four locations indicated in Fig. 4-3 were measured by four Ta-sheathed W-5% Re/W-26% Re thermocouples. These were calibrated against a black body hole where temperature was determined by optical pyrometry. The four thermocouple readings were used to get an average emitter temperature, hereafter referred to as the emitter temperature. Aside from a possible general drift of the thermocouples due to aging, averaging minimizes the impact of one thermocouple degradation or poor thermal equilibrium. The subjects of thermocouple reliability and of temperature profiles along the emitter will be discussed later.

The J-V characteristics were obtained by a single 60 Hz Ac voltage sweep with the converter set at a given DC point. This DC point could be adjusted by varying the output voltage of a DC power supply, with a constant lead resistance around 20 m Ω . Fig.4-4a shows a schematic of the electrical circuitry.

In the "flashlight configuration" the emitter current lead and the collector current lead are located at opposite ends of the cylindrical converter length. Figs. 4-4a and 4-4b show the emitter current lead at the top of the CC-1X, and the collector lead connected to the bottom end. As a result, the current flows in the same direction in both the emitter and the collector, as shown

Fig. 4-3 Detailed cross-sectional view of CC-1X converter showing thermocouple locations

Fig. 4-4a Schematic electrical circuit for CC-1X testing

Fig. 4-4b Current configuration and voltage probes for CC-1X flashlight. Converter lead voltage $V = V_{EL} - V_{CB}$

by the current arrow in Fig. 4-4b. The flashlight configuration is appropriate to reactor core designs involving multiple TFEs connected in series. An alternative configuration is the "unit cell mode" wherein the emitter lead and the collector lead are located at the same end of the cylindrical assembly. Here the current flows in the opposite directions in the emitter and the collector.

CC-1X was tested in the flashlight current configuration which is appropriate for series connections of several converters. In Fig. 4-4b the configuration of the voltage probes and current leads is shown. For TFE applications the current is taken off the emitter lead at V_{EL} and enters the converter at the bottom at V_{CB} . The converter lead voltage (or net output voltage) is $V = V_{EL} - V_{CB}$. Two additional probes were attached to the collector top near the insulator at V_{CT} and on the Ta sheath of the second emitter thermocouple, giving the emitter electrode voltage V_{EE} . Using the I-V characteristics from the various voltage probes, the resistance of the emitter sleeve (the thin tungsten tube acting as a heat dam) was measured at $0.25 \text{ m}\Omega$, the resistance of the thick emitter itself being negligible. The collector resistance was $1.0 \text{ m}\Omega$.

Emitter heat input power P_{in} was determined for various emitter temperatures T_E and current densities. An upper limit for P_{in} can simply be obtained from the sum of filament heating and emitter bombardment. However, a correction should be applied to reflect the heat lost by radiation through the top opening of the emitter well. An accurate calculation of this heat loss would be quite difficult and instead an estimate was obtained, as in [Ref. 4-1], by assuming that the emitter opening radiates like a black body to a receptor at the emitter sleeve average temperature. Due to the small opening area, the heat loss calculated in this fashion amounts to only 13 W at 1800 K and 9 W at 1700 K. This correction was applied to P_{in} and the result converted into input heat fluxes $Q_{in} \text{ (W/cm}^2\text{)}$. The converter output power density Q_{out} then obtained from the DC voltage and current density and the lead efficiency is expressed as $\eta \text{ (\%)} = 100 Q_{out}/Q_{in}$.

The data acquisition system used to store and process all measurements pertinent to J-V characteristics and converter parameters was the same as the one used in the DOE Thermionics Technology Program (TTP) at RAI to map additive converter performance [Ref. 4-2].

The software includes the capability of obtaining the envelope of a cesium reservoir family, i.e. the optimized J-V curve at a given set of emitter and collector temperatures.

4.4 Results and Evaluation of Performance Tests

Evaluation of Emitter Temperature Profiles: This step was aimed at verifying the validity of the four thermocouple measurements used to characterize emitter temperature. For this purpose, an alternative temperature measurement was carried out using the four thermocouple wells as black-body holes for optical pyrometry. Comparisons between thermocouple and pyrometer measurement were made under identical conditions of input power, collector and reservoir temperature and output current density. Fig. 4-5 shows the results of this comparison performed at $J = 7 \text{ A/cm}^2$. (Note: The emitter temperature regulation system required a thermocouple input. The deepest thermocouple reading was therefore used and served as a common reference point for the comparison of the thermocouple profile and pyrometry profile.)

It can be seen that the pyrometer and thermocouple readings are in good agreement. This agreement was true even at lower current densities (i.e. $J = 3 \text{ A/cm}^2$). In mapping the performance of CC-1X the average of the four thermocouple readings is used in defining the emitter temperature. Temperature gradients appeared between individual thermocouples have been attributed to non-uniform heating possibly due to off-axis filament bombardment. However, an 80° error in two individual thermocouples translated into a 20°K error in the averaged T_E . The level of confidence in the T_E measurement was further enhanced by the similarity observed between the CC-1X performance studied here and the PD-6 performance evaluated in prior work. Another noteworthy fact in Fig. 4-5 is that the CC-1X temperature is less uniform than that calculated for the in-core TFE-1H1 capsule. This is surprising since the CC-1X emitter is three times as thick as that in the TFE-1H1 design.

Evaluation of Cesium-Graphite Reservoir Families: A cesium family of J-V curves is typically generated at a fixed emitter and collector temperature by changing the reservoir temperature. The envelope of a T_R family like the one shown in Fig. 4-6 determines the optimum output voltage and reservoir temperature at a particular current density.

Fig 4-5 Comparison of emitter temperature profiles observed for CC-1X and calculated for 1H1

CC-1X IGNITED J-V CURVES

Fig. 4-6 Cesium-graphite reservoir temperature family for an average emitter temperature of 1800 K and a collector temperature of 1000 K.

The optimized characteristics for the CC-1X were then compared with that of other converter containing similar electrodes, like the PD-6 planar converter and the CD-2 cylindrical converters which were tested at similar electrode temperatures and spacing in prior work. For the purpose of this comparison the envelopes for CC-1X were generated in the cell current configuration (i.e., $V = V_{EL} - V_{CT}$ in Fig. 4-4b) because the data for the PD-6 and CD-2 were generated only in the cell current configuration. This was justified because both PD-6 and CD-2 had very thick collectors, hence enabling the assumption $V_{CB} \approx V_{CT}$.

Envelopes at $T_E = 1800$ K and $T_C = 1000$ K for the CC-1X and CD-2 are shown in Fig. 4-7. Figs. 4-8 and 4-9 show the envelopes for CC-1X and PD-6 at $T_E = 1800$ K; $T_C = 1000$ K (Fig. 4-8) and $T_E = 1600$; $T_C = 900$ K (Fig. 4-9). The agreement between the optimized characteristics of the three converters is very good. As pointed out in the previous section, the agreement between CC-1X and PD-6 at two different emitter temperatures (Figs. 4-8 and 4-9) further validates the use of average emitter temperature measurement in CC-1X in lieu of the black-body pyrometry. This conclusion was based on the fact that in the PD-6 T_E was measured by optical pyrometry using a radial black-body hole. Unignited characteristics were also recorded for diagnostic purposes. These unignited characteristics were used to calibrate the emitter temperature correlation of the in-core converter TFE-1H1. Fig. 4-10 shows a typical evolution of unignited characteristics at a constant T_R when T_E is varied.

Cesium Vapor Pressure above the Graphite Reservoir: The converter performance characteristics described above are based on the cesiated graphite reservoir temperature T_R . However, for completeness it is necessary to evaluate the cesium vapor pressure P_{Cs} in equilibrium with the graphite reservoir. This can be accomplished using the pressures measured during the loading procedure employed for reservoir fabrication. Two methods were used to estimate P_{Cs} vs T_R , both based on a comparison of J-V characteristics.

Method 1: Using Ignited Characteristics

Following fabrication, CC-1X was tested at TTC in conjunction with liquid cesium reservoir before the graphite reservoir was cesiated. The ignited J-V characteristics for fixed emitter and collector temperatures, obtained with the

CC-1X & CD-2 ENVELOPE

Fig. 4-7 Comparison of cesium family envelopes for CC-1X and CD-1 for the temperatures indicated

Fig. 4-8 Comparison of cesium family envelopes for CC-1X and PD-6 for the temperatures indicated

Fig. 4-9 Comparison of cesium family envelopes for CC-1X and PD-6 for the temperatures indicated

Fig. 4-10 Emitter temperature family at constant collector and cesium-graphite temperatures

liquid cesium reservoir (at TTC) can be correlated with those obtained with the cesium-graphite reservoir (at RAI). In this manner a desired correlation $P_{Cs}(T_R)$ can be obtained using the $P_{Cs}(T_{Cs})$ relationship. An example of such a comparison using the J-V knee is shown in Figs. 4-11 and 4-12.

Method 2: Using Unignited Characteristics

Ignition current densities (i.e. the discontinuity in the characteristics) are compared to calculations of the unignited saturation current densities corresponding to the emitter calibration of TFE-1H1. This method is illustrated in Fig. 4-13 for two values of T_R covering the range of interest.

The correlations for $P_{Cs}(T_R)$ obtained by both methods are shown in Fig. 4-14 together with earlier correlations obtained at GA on POCO graphite. Assuming the absence of cesium consumption, these correlations were deemed adequate.

Emitter Input Power Requirements and Converter Efficiency: The input power P_{in} was measured as a function of converter current at two emitter temperatures, 1700 K and 1800 K, with collector temperature at 1000 K. In order to reduce the scatter in P_{in} measurements caused by the regulation of the emitter temperature (which resulted due to feedback on the bombardment current), four or five instantaneous P_{in} readings were averaged.

Variation of the heat flux Q_{in} , at a given T_E , vs the current density J for CC-1X is shown in Fig. 4-15. Electron cooling theory predicts a linear correlation, which is indeed observed. The corresponding variation for CD-2 [Ref. 4-2] is also shown in Fig. 4-15. Though the slopes of the variation for the two converters are similar to each other, the heat flux at '0' current is about 20% less for CC-1X. The heat flux at '0' current is the sum of radiation and conduction losses from the emitter and should have been the same for both converters. The difference was attributed to the shorter emitter sleeve of CD-2, which was not optimized.

Fig. 4-15 also shows the measured lead efficiencies for the CC-1X plotted as a function of J . These efficiency measurements were the first ones dealing with a prototypic TFE

Fig. 4-11 Cesium family at given parameters: ThermoElectron measurements with liquid reservoir

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Fig. 4-12 Cesium family at given parameters: RAI measurements with graphite reservoir

Fig. 4-13 Comparison of unignited current densities calculated for TFE-1H1 as a function of T_{Cs} with experimental values obtained with CC-1X graphite reservoir at T_R .

Fig. 4-14 Cesium pressure above the cesium-graphite reservoir of CC-1X, evaluated from various methods (POCO data from Ref. 4).

Fig. 4-15

Emitter input heat flux and lead efficiency of CC-1X as a function of the current density at two emitter temperatures. Emitter heat flux data for CD-1 are also displayed for comparison.

converter at 1800 K and operated in the flashlight current configuration. This data is directly relevant to series operation of several TFEs at operation temperatures.

Output Power Density: Comparison with CD-2: The T_R family envelopes yield the optimum output power density Q_{out} as a function of T_E and T_C as a given current density J . A comparison of Q_{out} of CC-1X with that of CD-2 is warranted because both converters have the same electrode materials and interelectrode gas. Q_{out} is plotted vs T_E at constant collector temperatures. Plots for $J = 7 \text{ A/cm}^2$ and $J = 10 \text{ A/cm}^2$ are presented in Figs. 4-16 and 4-17, respectively. The overall performances of the two converters are similar, particularly at the emitter design setpoint of 1800 K. Some differences were evident at the lower T_E of 1600 K and were attributed to different emitter temperature profiles caused by a higher conduction heat loss along the emitter sleeve of CD-2. It should be pointed out that although the maximum efficiency for CC-1X was obtained around 6 A/cm^2 , more output power was available at 10 A/cm^2 . The effect of collector temperature on the output power density was also compared for the CC-1X and CD-2 at 7 A/cm^2 ; the results are shown in Fig. 4-18.

4.5 Conclusions of Performance Testing

Average temperature along emitter length was concluded to be a valid measurement of effective emitter temperature for comparison with other converters. CC-1X was operated in flashlight configuration (i.e. series operation of several converters with the cesium-graphite reservoir using an emitter temperature $T_E = 1800 \text{ K}$ and provided output lead power density of 4 W/cm^2 for a current density of 7 A/cm^2 with a lead efficiency of 9.5%.

4.6 Simulated Startup and Shutdown of CC-1X

Introduction

The objectives of the simulated startup and shutdown of CC-1X were as follows:

- a) To simulate prototypic reservoir thermal coupling via programmed control of the heat input to the external cesium-graphite reservoirs; and
- b) To evaluate the trends in converter performance during periods of increasing power and periods of decreasing power, and hence evaluate the

Fig. 4-16

Dependence of output power density on emitter temperature at given collector temperatures for CC-1X and CD-2 at $7 A/cm^2$.

Fig. 4-17 Dependence of output power density on emitter temperature at given collector temperatures for CC-1X and CD-2 at 10 A/cm^2 .

Fig. 4-18

Dependence of output power density on collector temperature at given emitter temperatures for CC-1X and CD-1 at 7 A/cm^2 .

stability of converter operation that can be expected during power surges that could occur in service.

Test Set-up:

An investigation of the startup behavior and stability of a prototype cylindrical converter having an integral cesium reservoir was performed. Experiments were therefore conducted on the CC-1X converter under conditions that are typical of a generic TFE generator core design. The study was particularly relevant to the SPRIME (see Ref. 1-6) Program.

Fig. 4-19 summarizes the pressure vs. temperature relationship for the cesium graphite reservoir and was experimentally obtained by comparing volt-ampere characteristics to the corresponding measurements made on this device using a liquid cesium reservoir, together with a comparison of the saturation current in the unignited mode.

As described earlier, the reservoir in the CC-1X is heated by an auxiliary electric-heater. However, the prototypic arrangement appropriate to the TFE generator core involves a reservoir which is thermally coupled to the emitter and the liquid metal coolant. For the purpose of the experiments performed here, a feedback control on the reservoir heater was modified in order to force the reservoir temperature to be a function of the emitter and collector temperatures. In CC-1X the collector temperature was controlled by varying the composition of a He-Ar gas mixture in the collector cooling gap. A constant-resistance electrical load ($0.5 \text{ m}\Omega$) was connected across the emitter and collector current leads (outside the vacuum system) in order to simulate the prototypic case. The effective load resistance, together with leads and internal connections, was 4.67-4.69 milli Ω across the converter. Output voltage of the converter was monitored from the emitter and collector voltage probes while output current was monitored by leading the voltage across the 0.5 milli Ω resistor.

Simulated Startup/Shutdown Tests: In these tests the variation in critical converter parameters, namely current density, emitter temperature, collector temperature, and estimated cesium pressure, were plotted as a function of thermal input power. The results of these tests have been presented here. Details of the experimentation were previously published by McVey, et al [Ref. 4-5]. The full power baseline condition was defined as that in which the average emitter

Fig. 4-19 Comparison of CC-1X Cs pressure vs. temperature curve with TFEVP data

average emitter temperature was 1800 K. Cesium pressure families of J-V curves taken at this temperature showed that the optimum cesium pressure was about 2.8 torr, which is close to the design value for the S-PRIME system.

The study consisted of two experiments. The first was intended to obtain preliminary information and consisted only of a startup procedure wherein the cesium reservoir was manually controlled and the collector gap self-evacuated. The second startup simulation examined both startup and shutdown and used an automatic control circuit to model the transient reservoir temperature. A proportionality constant which takes into account the difference in cesium loading between the CC-1X and the S-PRIME TFE generator core design was fed into the controller, resulting in a reservoir temperature which is proportional to that predicted by thermal models for the S-PRIME thermionic fuel elements (i.e. roughly $0.2 T_E + 0.8 T_C$).

Results of Tests: Figs. 4-20 thru 4-23 show the current density, emitter temperature and estimated cesium pressure as functions of the thermal input power. The three curves in each of these plots corresponds to: a) data for a preliminary test which was performed for increasing thermal power only; b) data for a second test obtained during increasing thermal power; and c) data for the second test obtained during decreasing thermal power. The overall significance of these trends are summarized below.

Ignition occurred at nearly the same power for both startup tests (Fig. 4-20), even though collector temperature and cesium pressure at ignition were different (Figs. 4-22 and 4-23). A current spike seen during the first startup was not observed in the second and has been attributed to the lower cesium pressure at ignition during the second startup, which was 0.4 torr compared to the 1.0 torr cesium pressure during the first startup. Another observation during the second simulation, which has also been attributed to the lower cesium pressure, is the appearance of small damped oscillations in current, emitter temperature and cesium reservoir temperature as the thermal input power is changed between ignition and 420 watts. The explanation presented for this observation is centered around the appearance of Schock instability immediately following ignition. At this point the cell tends to operate in the quasi-saturation region of the J-V curve due to the low cesium pressure, making it susceptible to cesium burnout which, in turn, causes a 10-20 K increase in emitter temperature and a concurrent decrease in output current. The increase in emitter

Fig. 4-20 Variation of current and voltage with input thermal power.

Fig. 4-21 Variation of average emitter temperature with input thermal power.

Fig. 4-22 Collector temperature during simulated startup and shutdown.

Fig. 4-23 Calculated cesium pressure for startup and shutdown.

temperature induces a higher graphite reservoir temperature which sets up the higher cesium pressure required to increase the output current and hence decrease the emitter temperature.

The oscillations arise, therefore, from the irreducible time lag in the experiment between a change in emitter temperature and a change in cesium pressure (~1 min). In all but one test the oscillations continued for a duration of 8 to 9 minutes. It appears that since a prototypic converter would have a better thermal coupling to its reservoir than this test, such oscillation would not appear during prototypic operation.

The power increase and power decrease curves display hysteresis. Such an hysteresis was particularly noticeable in the oscillation regime described above. In this regime, the ignited mode prevailed during both the increasing power test and the decreasing power test. The curve for decreasing power de-ignited at 195 watts.

Thermal models for the S-PRIME thermionic fuel elements predict that the reservoir temperature is proportional to $(0.2 T_E + 0.8 T_C)$. For the test data, therefore, the ratio of reservoir temperature to $0.2 T_E + 0.8 T_C$ was plotted as a function of input thermal power (see Fig. 4-24) and was found to be fairly constant. The various operating points along the load line is shown relative to a measured volt-ampere in Fig. 4-25. The load resistance was determined by a least-squares fit to be $4.69 \text{ m}\Omega$.

Maintaining stability, in spite of perturbations in thermal input power, is a requirement of the design and operation of the cesium-graphite reservoir. The tests performed indicated that the CC-1X converter always exhibited stability while input power was decreased. The effect of increasing power on stability was characterized relative to a baseline operating condition of 700 watts input. Input power was then increased to 800 watts in 5 minutes, resulting in an increase in cesium pressure from 2.9 torr to 4.4 torr. The average emitter temperature change was 1802 K to 1866 K with an associated increase in current density from 5.7 A/cm^2 to 6.0 A/cm^2 . These trends imply that startup/shutdown of the converter is unconditionally stable in that any power surges that may occur would not result in a thermally induced instability in converter performance. This basically resulted from the thermal coupling between the emitter and

Fig. 4-24 Ratio of reservoir temperature to prototypic relationship.

Fig. 4-25 Current-voltage points along the resistive load line compared to a reference J-V characteristic.

the cesium-graphite reservoir which allowed the reservoir temperature to increase (or decrease) with increases (or decreases) in the emitter temperature.

Conclusions: The CC-1X experiments demonstrated the basic feasibility of the integral cesium reservoir planned for S-PRIME. Through means of control of its external cesium reservoir based on emitter and collector temperatures, CC-1X was made to simulate a converter whose reservoir is in thermal contact to the emitter and liquid metal coolant. Operation of the converter was stable either when its power level was held steady or ramped slowly from 0 to 114%. In addition, current and voltage transients at the onset on ignition were within the tolerance limits of the proposed S-PRIME power conditioning system.

4.7 **References**

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5.0 PERFORMANCE TESTING OF PLANAR CONVERTER WITH TILTED COLLECTOR (PC-2)

In-core thermionic conversion designs (TFE) are based on designs in which the emitter is loaded with fuel which undergoes swelling under neutron irradiation. In turn, the emitter becomes gradually distorted during operation and the interelectrode distance locally decreases. It is important to evaluate the effect of such distortion on the electrical characteristics of the converter. This would ultimately result in correlations which could help predict the effect on converter performance from non-uniform emitter distortions. In this investigation, distortion was simulated by tilting the usually parallel electrode of a planar converter and examining the resulting characteristics.

5.1 Fabrication

The variable-spacing planar converter PC-2 used for the present work was performance mapped earlier during the TTP study while maintaining the parallel electrode configuration [Ref. 5-1]. It was then labelled PD-6. It features a plain niobium collector and a "duplex tungsten" emitter, which is an electropolished tungsten surface obtained by vapor deposition from WCl₆ onto a substrate deposited from WF₆. The subassemblies for this converter are shown in Fig. 5-1. The photograph of the completed converter is shown in Fig. 5-2. The assembly sequence for such a converter is shown in Fig. 5-3. A cross-section view of the assembled converter is shown in Fig. 5-4. The converter is tested in vacuum bell jar which, in addition to the emitter electron bombardment heater, the collector and the cesium reservoir heater-coolers, contains the variable spacing assembly. This assembly consists of three micrometers which are usually geared together and adjusted so that the emitter and collector remain parallel as the spacing is adjusted. The minimum spacing achievable in the parallel electrode configuration is actually determined by a shoulder built in the emitter flange structure: when a short-circuit is realized by bringing the collector in contact with this shoulder, a gap of 1.5 ± 0.5 mils is left between the electrodes when in their normal temperature range [Ref. 5-1]. The converter design, as described by Lieb, et al [Ref. 5-2], is composed of: a.) an emitter subassembly consisting of the flexile bellows, a ceramic seal and the emitter; b.) the collector subassembly consisting of the nickel collector, a substrate cap (if required) and the collector coating; and c.) the cesium reservoir. The completed converter is mounted in a test stand which contains the heater-cooler assemblies for temperature control and the spacing mechanism that allows continuous adjustment

Fig. 5-1 Photograph of converter subassemblies

Fig. 5-2 Photograph of the assembled converter with cesium reservoir.

CONVERTER ASSEMBLY

Fig. 5-3 Complete assembly sequence used for converter fabrication.

Fig. 5-4 Cross-sectional view of converter PC-2.

of the interelectrode gap from about one mil (0.02 mm) to 80 or more mils (2.5 mm). Projections on the collector body are machined before converter assembly to prevent emitter-collector contact and to establish parallelism of the electrodes. This converter forms an inexpensive test vehicle for thermionic research and development.

5.2 Experimental Setup and Methodology

The translation mechanism used to vary the spacing in the parallel configuration is the same as the one schematically described in [Ref. 5-2]. Tilting the collector is achieved by adjusting, with respect to the emitter flange, the height of the sapphire balls on which the three micrometers rest. Defining α as the angle between the two planar electrodes, R_1 and R_2 as the respective radii of the collector and outer edge of the emitter shoulder (see Fig. 5-5), the minimum, average, and maximum spacings are, respectively,

$$d_{\min} = 1.5 + (R_2 - R_1) \sin \alpha$$

$$d_{\text{avg}} = 1.5 + R_2 \sin \alpha$$

$$d_{\max} = 1.5 + (R_2 + R_1) \sin \alpha$$

Analytical Approach: To evaluate the J-V characteristic of a converter with a varying spacing, one can decompose the whole converter into an ensemble of n elementary converters with a set of fixed spacings and assume that each component contributes a current $I_i = A_i J_i$, where A_i is the area and J_i is the current density at the particular spacing d_i . In this process it is implicitly assumed that there is no interaction between the various adjacent converters and, therefore, no localization of the ignited plasma. This approach was tested on the tilted converter as follows:

- Spacing families were recorded at $T_e = 1800$ K, $T_C = 1000$ K, and various cesium reservoir temperatures T_R on the parallel converter. Fig. 5-6 is an example of such a spacing family.
- The tilted converter was divided in five sections of equal width, $0.4R_1$, as indicated in Fig. 5-7. The spacing of each section is $d_i = d_{\text{avg}} + 0.4(i-3)R_1 \sin \alpha$, $i = 1$ to 5.

Fig. 5-5 Geometry of parallel (top) and tilted (bottom) planar converter.

PC-2 PARALLEL CONVERTER DATA

Fig. 5-6 Spacing family for PC-2 in a parallel electrode configuration.

PC-2 TILTED CONVERTER TEST

Fig. 5-7 Comparison of measured and calculated characteristics for PC-2 in a tilted electrode configuration at the conditions indicated.

- The average current density was calculated as $J_{avg} = \Sigma A_i J_i / \Sigma A_i$.
- The computed J_{avg} was compared to the current density at the average distance, $J(d_{avg})$ and to the experimental J_l obtained with a tilt $d_{max} - d_{min} = 10$ mils and $d_{avg} = 11.5$ mils.

5.3 Results and Evaluation of PC-2 Performance Tests

Spacing families such as shown in Fig. 5-6 were originally obtained for integer values of d in mils, e.g. 7, 9, 11, etc. The re-evaluation of d_{avg} , as explained in Section 2.2, resulted in values of d_i like 7.5, 9.5, etc., which are within the uncertainty on the determination of the absolute minimum spacing of 1.5 mils in the parallel converter. The comparison of J_l , J_{avg} and $J(d_{avg})$ is shown in Figs. 5-7 and 5-8 as J-V curves labelled 1, 2, and 3, respectively, at two cesium temperatures, 577 and 608 K: the agreement is excellent, which validates the assumptions used to calculate J_{avg} .

5.4 Conclusion

The conclusion is, therefore, that a tilted planar converter, which simulates the varying spacing induced by emitter distortion, behaves as a parallel planar converter with the average spacing. Furthermore, it has been shown that it is justified to compute the J-V characteristics of a converter with a distorted emitter by decomposing this converter into an array of smaller converters with fixed spacings in parallel.

Since it has been shown elsewhere [Ref. 5-1] that cylindrical and planar converters at the same spacing and average emitter temperatures have similar performances, it seems logical to extend the previous conclusions to in-core cylindrical converters subject to emitter swelling.

5.5 References

- 5-1 G.L. Hatch, RAI Final Report for DOE Contract No. DE-AC03-86SF15954, April 1988, Document No. E-553-003-B-053188.
- 5-2 D. Lieb, D. Goodale, T. Briere and C. Balestra, Proc. of the 12th IECEC, Washington DC, Vol. 2, p. 1555, 1977.

PC-2 TILTED CONVERTER TEST

Fig. 5-8 Comparison of measured and calculated characteristics for PC-2 in a tilted electrode configuration at the conditions indicated.

6.0 INITIAL PERFORMANCE TESTING OF PLANAR CONVERTER PC-1 (MOD) WITH UO_2 IN EMITTER

A variable spaced research converter, designated PC-1 (MOD), was fabricated with UO_2 embedded in the emitter and operated in conjunction with a cesium-graphite reservoir in order to: a) study its initial performance relative to the equivalent cylindrical converter performance (CC-1X), and b) subsequently carry out a lifetime test to evaluate the possible effect of oxygen diffusion from the embedded UO_2 fuel through the emitter sheath. Also obtained during the life test is information on the thermo chemical stability of the converter with a graphite-cesium reservoir.

6.1 Fabrication of PC-1 (MOD)

The planar variable-spaced research converter used for the test is shown in Fig. 6-1 and has been described in detail by Hatch [Ref. 6-1] and Goodale, et al, [Ref. 6-2]. It has an overall emitter diameter of 2.0 cm and an effective collector diameter of 1.13 cm, resulting in a collector area of 1 cm^2 . The emitter is a duplex tungsten with the emissive surface having a preferred $\langle 110 \rangle$ orientation derived through chemical vapor deposition from tungsten chloride on $\langle 100 \rangle$ W substrate. The collector is made of niobium which is ground flat. The emitter is supported on a thin sleeve made of molybdenum rhenium alloy and is electrically isolated from the collector by a high-purity aluminum oxide insulator. Niobium bellows between the emitter and collector allow the spacing to be changed from 0.05 mm to 2.0 mm. Details of the generic experimental converter structure and the fabrication procedures utilized have been described in Section 5.1 ahead. The cesium vapor for the converter is supplied from an external cesium-graphite reservoir which is loaded to be prototypic for in-core converters. To make the experimental converter prototypic the graphite reservoir was charged with cesium through an isolation valve to attain the loading level to be utilized in the TFE tests. The arrangement of the liquid cesium and cesium graphite reservoirs is shown schematically in Fig. 6-3. The entire test fixture and vacuum bell jar is shown in Fig. 6-4.

The emitter, shown in Fig. 6-2, was designed with four 4 mm diameter cavities to contain the fuel. This configuration was found to minimize emitter distortion relative to designs with one large central cavity for the fuel [Ref. 6-3]. The emitter assembly was fabricated as

Fig. 6-1 Planar variable spaced research converter FC-1 (MOD).

Fig. 6-2 Emitter design for PC-1 (MOD).

Fig. 6-3 Reservoir arrangement during initial testing of PC-1 (MOD).

Fig. 6-4 Overall test arrangement during initial testing of PC-1 (MOD).

follows. First, the four cavities for the depleted uranium oxide fuel were machined in a tungsten disc made by chemical vapor deposition of tungsten fluoride. Next, the fuel pellets were inserted and two wafer lids, one of tungsten -25% rhenium alloy and one of tungsten, were assembled. The fuel pellets were separated from the tungsten -25% rhenium lid by the tungsten wafers so as to minimize the interaction between the fuel and the rhenium in the alloy. The entire assembly was uniaxially pressure-bonded in vacuum. The emitting surface was then chemically vapor deposited from tungsten chloride, yielding a preferred <110> crystal orientation then electropolished. The distance separating the UO_2 pellets from the emitting surface is around 1 mm, which is the same as the fuel cladding thickness in the present design for the TFE Verification Program.

6.2 Experimental Methodology: Cesium Loading and Initial Testing

The converter was equipped with two reservoirs, one liquid cesium, the other cesium-graphite. After outgassing the converter, cesium was first distilled from the glass ampules into a temporary receiver where residual gases were pumped out through a reflux column and then distilled into the cesium reservoir. After this, the cesium distillation apparatus was pinched off and removed, leaving a cesium and cesium graphite reservoir [Ref. 6-3]. A bakeable valve isolated the cesium reservoir from the rest of the converter.

For the initial tests the converter was first tested with only the liquid cesium reservoir active. This was accomplished by heating the cesium-graphite reservoir to a high enough temperature to exclude cesium condensation. The converter was subsequently tested with the saturated cesium-graphite reservoir by isolating the liquid cesium reservoir with the valve. Subsequent lifetime testing was carried out with only the cesium-graphite reservoir after finally pinching off the liquid cesium reservoir.

6.3 Results and Evaluation

Using the above isolation procedure, PC-1 (MOD) performance corresponding to liquid cesium reservoir was obtained and is shown in Fig. 6-5. The data corresponding to the cesium-graphite reservoir obtained by isolating the liquid cesium reservoir using a valve is presented in Fig. 6-6. These performance data are used as the baseline for the evaluation of the lifetime tests.

Fig. 6-5 Initial performance data for PC-1 (MOD) corresponding to liquid cesium reservoir.

Fig. 6-6 Initial performance data for PC-1 (MOD) corresponding to cesium-graphite reservoir.

temperature of the cesium-graphite reservoir and the temperature of the liquid cesium reservoir was therefore generated by matching different J-V curves in the cesium families corresponding to the two reservoirs.

Fig. 6-7 shows the correlation obtained using the cesium families shown in Figs. 6-5 and 6-6. This information yielded a cesium pressure vs. graphite temperature variation which was close to that reported by Salzano and Aronson [Ref. 6-4] for a cesium loading of the graphite between 1108-1384 mgCs/gC.

6.4 Conclusions

The variation of cesium pressure vs. graphite reservoir that resulted from the cesium families during initial testing of PC-1 (MOD) was compatible with a cesium loading level of the graphite between 1108-1384 mgCs/gC, which was reported by Salzano and Aronson [Ref. 6-4]. This information is utilizable during lifetime testing to monitor the cesium pressure in the converter, assuming that no physical changes take place in the cesium-graphite structure in the reservoir.

6.5 References

- 6-1 G.L. Hatch, RAI Final Report for DOE Contract No. DE-AC03-86SF15954, April 1988, Document No. E-553-003-B-053188.
- 6-2 D.B. Goodale, C. Lee, D. Lieb and P.E. Oettinger, Proc. of the 14th IECEC, Boston, MA, Vol. 2, p. 1862, (1979).
- 6-3 G. Miskolczy, D. Lieb and G.L. Hatch, Proc. 27th IECEC, San Diego, CA, Vol. 2, 253 (1992)
- 6-4 F.J. Salzano and S. Aronson, "Thermodynamic Properties of the Cesium-Graphite Lamellar Compounds", J. Chemical Physics, V. 43, N1, pp. 149-154, July 1, 1965.

Fig. 6-7 Correlation between liquid cesium reservoir and cesium-graphite reservoir temperature obtained from PC-1 (MOD) initial performance data.

7.0 LIFETIME TESTING OF PLANAR CONVERTER PC-1 (MOD) WITH UO₂ IN EMITTER

7.1 Experimental Protocol

The standard test conditions used by Hatch [Ref. 7] were employed. The electrode temperatures were fixed and at each cesium pressure the J-V curve (current density vs. voltage curve) was recorded while driving the converter with a 60 Hz alternating current sweep. An automatic data acquisition system was used to perform measurements, display and store functions pertaining to the J-V curves and the diode parameters. This system utilized a Hewlett-Packard 200 series computer together with software modules which allowed for convenient viewing of temperatures and other parameters relevant to diode performance. The system was also capable of functioning as a low-speed digital oscilloscope by displaying the J-V curves on the CRT and saving them on the mass storage media. The data acquisition system was calibrated using a bipolar DC power supply and a standard laboratory shunt prior to data collection. The emitter temperature was also calibrated using an optical pyrometer prior to the generation of J-V curves.

7.2 Results and Discussion

Preliminary results of the lifetime tests up to 3200 hours were presented by L. D'Cruz, et al [Ref. 7-2]. Testing was continued up to 8000 hours. Fig. 7-1 shows the output power vs. time for the PC-1 (MOD) with a graphite reservoir obtained after 7115 hours. Also shown for the purpose of comparison is the equivalent data obtained during the initial tests (TTC data). Fig. 7-2 shows the time dependence of the knee current density at two different cesium pressures (i.e. reservoir temperatures).

It was expected that uranium deposition on the collector surface would lead to a perceptible increase in the barrier index and hence lowering of the output power with time. On the other hand, a significant increase in the knee current density would have been indicative of increased emission caused by the enhanced emitter work function resulting from oxygen adsorption on the emitter surface. Fig. 7-1 does not, however, show a perceptible change in the output power vs time, while Fig. 7-1 indicates fluctuations in the knee current about a slightly increasing mean

Fig. 7-1 Output power vs time for the PC-1 (MOD) using the cesium graphite reservoir obtained after 7115 hours of testing.

Fig. 7-2 Time dependence of the knee current density at two different cesium pressures (i.e., reservoir temperatures).

level. The J-V curves corresponding to 1200 hours, 3144 hours, and 7115 hours are shown in Figs. 7-3, 7-4 and 7-5, respectively.

7.3 Conclusions

Lifetime tests were carried out on a planar converter, PC-1 (MOD), which has a tungsten emitter containing UO_2 fuel. The time dependence of the output power (i.e. barrier index) observed in the tests was not significant, which suggests that the diffusion of uranium oxide to the emitter surface was minimal up to 7115 hours. The reason for the fluctuations in the knee current vs time are yet unclear. After a detailed evaluation of the spacing control mechanism, as well as the reservoir thermocouple contact, it was concluded that these were not the source of the fluctuation. More detailed studies of the chemical and stability of the cesium-graphite compound as a function of time may give some insight into the origins of this behavior.

7.4 References

- 7-1 G.L. Hatch, RAI Final Report for DOE Contract No. DE-AC03-86SF15954, April 1988, Document No. E-553-003-B-053188.
- 7-2 L. D'Cruz, J-L Desplat, G.L. Hatch, G. Miskolczy and D. Lieb, Proc. 28th IECEC, Atlanta GA, Vol. 2, 531 (1993).

Fig. 7-3 Cesium family of J-V curves for PC-1 (MOD) obtained after 1200 hours of testing.

Fig. 7-4 Cesium family of J-V curves for PC-1 (MOD) obtained after 3144 hours of testing.

Fig. 7-5 Cesium family of J-V curves for PC-1 (MOD) obtained after 7115 hours of testing.

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