2-

MASTER

There is no objection from the patent
point of view to the publication or
dissemination of the document(s)
dated in this letter.

8/27 19 88 By WLL
BROOKHAVEN PATENT GROUP

**Thermo
Electron**

CORPORATION

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Report No. TE4258/4247-226-80

DOE/JPL
ADVANCED THERMIONIC
TECHNOLOGY PROGRAM
PROGRESS REPORT NO. 42

January, February, March
1980

DOE Contract DE-AC02-76ET11291
JPL Contract 955009

Prepared by
Thermo Electron Corporation
101 First Avenue
Waltham, Massachusetts 02154

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof nor any of their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

BLANK

CONTENTS

INTRODUCTION AND SUMMARY.....	vii
<u>1.0 PART ONE: DOE TASKS.....</u>	1
1.1 THERMIONIC AND MATERIAL RESEARCH AND TECHNOLOGY	1
1.1.1 TASK I. SURFACE AND PLASMA INVESTIGATIONS	1
A. Surface Characterization Chamber Experiments	1
B. Converter Theory	8
1.1.2 TASK II. LOW-TEMPERATURE CONVERTER DEVELOPMENT	10
A. Heat Flux Diode	10
B. Converter No. 226: CVD Electropolished Tungsten Emitter, Nickel Collector	12
1.1.3 TASK III. ENHANCED MODE CONVERTER EXPERIMENTS	14
1.1.4 TASK IV. COMPONENT HARDWARE DEVELOPMENT	16
A. Alloy Hot Shell Development	16
B. CVD Hot Shell-Emitter Development	18
C. Integral Cesium Reservoir Converter No. 229: Tungsten Emitter, Nickel Collector, Cesium- Graphite Reservoir	26
1.2 THERMIONIC POWER MODULE EVALUATION	30
1.2.1 TASK V. SYSTEM STUDIES	30
1.2.2 TASK VI. TAM MODULE DEVELOPMENT	32
A. Converter No. 218 (CVD Silicon Carbide Converter No. 1): CVD Fluoride Tungsten (As Deposited) Emitter, Nickel Collector	32
B. Converter No. 228 (CVD Silicon Carbide Converter No. 3): CVD Tungsten (As Deposited) Emitter, Nickel Collector	33
C. Converter No. 230: Two-Inch Diameter CVD Silicon Carbide Converter	35
D. High-Temperature Gas and Oil-Fired Furnace	35
1.2.3 TASK VII. COAL-FIRED TAM TEST UNIT	38
<u>2.0 PART TWO: NASA-OAST/JPL TASKS</u>	39
2.1 THERMIONIC CONVERTER EVALUATION.....	39
2.1.1 TASK VIII. HIGH-TEMPERATURE CONVERTER EVALUATION	39
A. Converter No. 227: (JPL Converter No. 1) Molybdenum Emitter, Niobium Collector.....	39

CONTENTS (continued)

B. Converter No. 231: (JPL No. 3): Molybdenum Emitter, Sublimed Molybdenum Oxide Collector.....	40
C. Converter No. 232 (JPL No. 4) Molybdenum Emitter, Molybdenum Oxide Collector	50
2.1.2 TASK IX. ADVANCED CONVERTER STUDIES	58
A. Particle Thermionic Converter - Converter No. 235: Magnesium Oxide Sprayed Tungsten Emitter-Guarded Molybdenum Collector	58
2.1.3 TASK X. POSTOPERATIONAL DIAGNOSTICS.....	59
2.2 CYLINDRICAL CONVERTER DEVELOPMENT	65
2.2.1 TASK XI. CYLINDRICAL CONVERTER COMPONENT DEVELOPMENT	65
2.2.2 TASK XII. CORRELATION OF DESIGN INTERFACES	67
REFERENCES	81

DOE Contract No. DE-AC02-76ET11292
WORK BREAKDOWN STRUCTURE

7911-11

JPL CONTRACT NO. 955009
WORK BREAKDOWN STRUCTURE

Note. Roman Numerals Designate Level at which Tasks are to be Reported.

1.0 PART ONE: DOE TASKS

1.1 THERMIONIC AND MATERIAL RESEARCH AND TECHNOLOGY

1.1.1 TASK I. SURFACE AND PLASMA INVESTIGATIONS

The objective of this task is to support the development of thermionic energy converters by providing experimental data and analyses relating to plasma characteristics and electrode properties.

A. Surface Characterization Chamber Experiments

Previously, a minimum work function of 3.0 eV had been obtained by the "bulk diffusion" method for depositing zirconium and oxygen on W(100). This work function value is higher than the value of 2.67 ± 0.05 eV reported by Danielson and Swanson.⁽¹⁾ In the last report, it was suggested that this discrepancy might be due to a slight misorientation of the (100) single crystal. This crystal was examined by Laue x-ray diffraction and found to be four degrees off from the (100) plane. This was considered a significant deviation in orientation.

Four well-oriented W(100) crystals of emitter dimensions (0.440 inches diameter by 0.060 inches thick) were procured from Metron, Inc. These crystals were mechanically polished, electropolished and determined to be within 1 degree of the (100) plane by Laue x-ray diffraction. One of these crystals was mounted in the Surface Characterization Chamber (SCC) and studied by two different bulk diffusion techniques, the alternating dose (AD) technique and a new simultaneous dose (SD) technique.

The AD technique consists of depositing zirconium onto the W(100) crystal, then terminating the zirconium dose and heating the crystal in oxygen to drive the Zr-O complex into the bulk, and finally heating in vacuum. After three of these cycles, the work function at the center of the well-oriented crystal was 2.78 eV.

This value is 0.22 eV lower than the minimum work function obtained on the poorly oriented W(100) crystal, indicating that accurate crystal orientation is critical in obtaining the minimum work function for this emitter.

The work functions at four other areas near the edge of the crystal were within 0.05 eV of the value at the center, even though the original zirconium distribution over the crystal varied by a factor of two. Apparently during the AD cycles the Zr-O complex diffuses in both perpendicular and parallel directions to the surface, so the vacuum heating can provide a constant zirconium coverage and work function over the entire surface.

A SD technique was developed in which zirconium and oxygen are simultaneously supplied to the tungsten crystal at 1500 K. A 15-minute simultaneous dose followed by vacuum heating yielded a work function of 2.80 eV. The work function variation for different areas of the crystal was 0.05 eV. The SD technique thus yields the same work function as the AD technique and is easier and faster to apply.

Two life tests were made for the Zr-O-W(100) emitter. In the first test, an emitter ($\phi = 3.0 - 3.5$ eV) was heated at 1800 K for 10 hours in a vacuum of 10^{-7} torr. A collector was positioned 0.3 cm from the emitter to collect any vaporization products. After the test, the collector was inserted into the SCC, and

Auger analysis showed no zirconium. However, the possibility exists that the zirconium may have been masked by copper deposited on the collector from the heater legs. Under the same conditions a pure molybdenum emitter would have evaporated 20 monolayers onto the collector, so that this result implies that the vapor pressure of this Zr-O-W(100) sample is approximately 2000 times less than molybdenum.

The results of the second life test are shown in Figure 1. A Zr-O-W(100) emitter prepared by the SD technique was heated to 1800 K for 23 hours. Only small changes in coverage and work function were seen after 3 1/2 hours. However, after 23 hours all the oxygen has disappeared and a very large carbon coverage is evident. Presumably, carbon has diffused from the bulk to the surface during this time and removed the oxygen via CO desorption. Although it has been shown previously that carbon can reduce the work function, this experiment demonstrates that too much carbon can destroy the low work function surface.

Figure 1. Auger Percent Coverages and FERP Work Function Versus Time of a Zr-O-W(100) Emitter

The deposition of controlled amounts of carbon was attempted by heating the Zr-O-W(100) emitter in methane. Eleven separate runs were made but no carbon could be deposited even when the CH_4 exposure was 1.5×10^{-3} torr-sec and the crystal temperature was 1800 K. These dosing conditions applied to clean tungsten produced a 28% carbon surface (see Progress Report No. 41). A mass spectrometer confirmed that the dosing gas was CH_4 with only small amounts of inert gases as impurities. The surprising inertness of the Zr-O-W(100) emitter to carbon deposition from CH_4 is evidently due to the lack of available "dangling bonds" which are found on clean metal surfaces. Carbon monoxide will be used in future experiments as a carbon source for this emitter.

The adsorption of cesium on MgO was studied and compared to similar adsorption on tungsten (see Figure 2). The graph shows the initial sticking factor for Cs on MgO is approximately one-tenth that of Cs on tungsten. The final saturated coverage on MgO is only one-sixth that of tungsten. Heating the surfaces to 200 C reduced the Cs on tungsten by a factor of two and the Cs on MgO by a factor of four. Thus cesium is much less

Figure 2 Cesium Peak Height versus Cesium Dose Time

strongly bound to MgO than to tungsten and indicates MgO might be a good insulator in a cesium environment. The FERP work function of MgO with and without cesium could not be measured due to the high electrical resistivity of MgO.

B. Converter Theory

After the formation of a double sheath, the typical calculated J-V curve behaves very closely as the Boltzmann line (i.e., an exponential function). However, most of the experimental data indicate that the slope of the J-V curve in this region is steeper than the Boltzmann line. This discrepancy between experimental data and theoretical calculation was studied during this reporting period.

The thickness of the double sheath is larger than that of the monotonic sheath. After the formation of the double sheath, the thickness of the plasma will be reduced. The computer program for plasma analysis was modified so that the thickness of the plasma can be changed as the output current decreases. This modification shows that the change of the plasma thickness

does have a small effect on J-V curves but the effect is too small to account for the discrepancy between the theoretical calculation and experimental data. The second possible cause is the contraction of the plasma. Since the present analytical model is for one-dimensional problem, it is not able to evaluate the two dimensional contraction effect. Spectroscopic observation of the plasma was made. The result does not provide enough evidence that the plasma makes significant contraction in its obstructed regions.

1.1.2 TASK II. LOW-TEMPERATURE CONVERTER DEVELOPMENT

The objective of this task is to develop thermionic diodes with improved performance at low collector temperatures (i.e., 500-900 K). Converter characteristics will be measured as a function of emitter temperature, collector temperature, cesium pressure, interelectrode spacing and, if applicable, additive gas pressure.

A. Heat Flux Diode

During operation of the previous heat flux diode, several problems associated with the auxiliary collector heater were identified. The heater was fabricated from a 0.062 x 0.002-inch ribbon of nichrome wrapped inside a nickel tube which had an inside diameter of 0.156 inches. A thin coating of MgO prevented successive turns from shorting. A heat flux diode with an auxiliary heater of this design is shown in Figure 3. This type of heater had a resistance of approximately 1.0 ohm. The power which could be dissipated by this design was approximately 13 watts. The heater was also fragile and burnouts occurred frequently.

773-33

Figure 3. Heat Flux Diode - Old Design

These shortcomings prompted the design of an improved flux collector. The auxiliary heater is fabricated from a length of commercially available sheathed heater wire with an outside diameter of 0.020 inches. This design is shown in Figure 4. The sheathed heater wire is wound in a tight coil and brazed to the collector.

A collector-heater of this design has been built. The resistance of the heater is 5.0 ohms at 850 K, and 25 watts have been dissipated without any apparent degradation. This high resistance will provide adequate power dissipation at low converter currents which will ensure a longer lived heater. The positioning of the thermocouples directly behind the auxiliary heater and the good thermal contact (between the collector body, auxiliary heater and collector core) will minimize the perturbations on the heat flux measurement.

B. Converter No. 226: CVD Electropolished Tungsten Emitter, Nickel Collector

The performance characteristics of this converter were presented in Progress Report No. 41 (October, November, December 1979). During the present reporting period the converter was disassembled and leak checked. A leak at the emitter sleeve was found.

Figure 4. Heat Flux Diode - New Design

1.1.3 TASK III. ENHANCED MODE CONVERTER EXPERIMENTS

The objective of this task is to formulate and evaluate thermionic converter configurations which have the potential of operating more efficiently than the conventional ignited mode diode. In the ignited mode, the mechanism for supplying the ions for space charge neutralization is not efficient. Other techniques which allow the converter to operate in the unignited mode (e.g., those utilizing auxiliary discharge regions and surface contact ionization electrodes) should be more efficient in producing ions and, hence, more efficient in converting heat into electricity. Close-spaced devices that do not require ions should also be more efficient than ignited mode diodes. In the ignited mode, structured electrodes offer the possibility of significantly reducing the plasma losses. Several types of enhanced mode converters will be investigated experimentally.

A boron nitride sample provided by Dr. Ivor Brodie of SRI International was tested for possible use as an electrical insulator on the emitter for a low bare work function ionizer electrode. The sample was tested on tungsten at converter operating conditions. Unfortunately, this test indicates that boron nitride is not suitable for this application. After testing at a temperature of 1700 K in a cesium pressure of 3 torr for a period of 150 hours, the boron nitride showed no attack by the cesium but considerable evaporation at the higher temperature. The boron nitride vapor pressure at 1700 K is much too high to be practical.

1.1.4 TASK IV. COMPONENT HARDWARE DEVELOPMENT

The objective of this task is to develop converter hardware suitable for operation in a combustion atmosphere such as would be encountered in a thermionic-topped fossil fuel powerplant. Although the effort includes considerable materials evaluation, the focus is on the fabrication and testing of hot shell - emitter subassemblies utilizing chemical vapor deposition (CVD) of composite silicon carbide-graphite-tungsten structures.

A. Alloy Hot Shell Development

The testing of alloy hot shells in the Simulated Furnace continued during this reporting period. In this furnace, the domes of the hot shells are exposed to products of combustion of a liquid hydrocarbon at 1475 K. The interiors of the shells are evacuated by an ion pump. The furnace temperature and the interior vacuum of each shell are recorded on a strip chart recorder. The accumulated test hours on the specimens are shown in Table I.

TABLE I
SIMULATED FURNACE TESTS
(16 April 1980)

Test Port No.	Hot Shell	Test Hours	Comments	Date of Initiation
1	446 CRES Cr-Ni Slurry Sinter	4453	Leaktight	20 Nov 1978
3	446 CRES Plasma Arc Sprayed with Cr O	9927	Leaktight	31 Oct 1977
4	RA333	2821	Leaktight	31 Aug 1979
5	446 CRES Plasma Arc Sprayed with Nichrome	9927	Leaktight	31 Oct 1977
6	INCONEL 671	4148	Leaktight	8 Mar 1979

Clock Reference 26931

B. CVD Hot Shell-Emitter Development

1) Hot Shell Fabrication

During this reporting period, six two-inch diameter and five one-inch diameter CVD hot shell - emitter structures were fabricated. All units were leaktight. Two improvements were made to the tungsten deposition that resulted in better control of the thickness profile on the dome area.

- Graphite shells are machined on a tracer lathe with a precision of ± 0.001 inches.
- Improved injector design uses a slit two inches long and 0.008 inches wide for WF_6 gas dispersion.

These changes allow the tungsten to be uniformly deposited on the inside of the graphite dome to within ± 0.002 inch thick. This improvement in uniformity will give a better defined collector-to-emitter spacing in the converter.

2) Composite Hot-Shell Emitter-Flange Test Program

Both one- and two-inch hot shell - emitters and flange structures were tested at operating temperatures. The one-inch shell was heated in air by R.F. induction, while the two-inch shell was flame fired in a natural gas furnace. Results of these tests are summarized in Table II.

TABLE II

HOT SHELL-EMITTER-FLANGE STRUCTURE TESTS

804-29

DESCRIPTION	NUMBER OF HOURS	TEMPERATURE OF DOME OF SHELL	AVERAGE TEMPERATURE OF FLANGE	MAXIMUM TEMPERATURE OF FLANGE	NUMBER OF TEMPERATURE CYCLES	COMMENTS
ONE-INCH DIAMETER HOT SHELL	110	1925 K	675 K	875 K for 20 hours	9	No cracking of shell. Tungsten leak tight. MoO and CuO on flange.
TWO-INCH DIAMETER HOT SHELL	70	1655 K	675 K	925 K for 8 hours	1	SiC cracked, not leak tight. Braze swelled (to be analyzed).
MOLYBDENUM FLANGE COATED WITH CERMETEL 487	110	-	925 K	925 K	2	No change in appearance of flange.

Both hot shell-emitter structures were copper brazed to molybdenum flanges. A second flange made of nickel was brazed to the molybdenum flange. A pumpout port was brazed to the nickel flange to maintain a pressure of 10^{-6} torr on the inside of the composite shell. This vacuum was maintained during the testing of all the shells.

Observations of the shell and flange were made periodically. Both shells could be cooled to room temperature in less than five minutes. The one-inch shell was temperature cycled from room temperature to 1925 K in four minutes. This was repeated four times and produced no change to the one-inch shell. However, increasing the temperature of the molybdenum flange from 675 K to 875 K caused the braze area to expand in volume and change to a dark gray color. After 110 hours of testing, the one-inch shell was cross-sectioned to observe the braze area (see Figure 5). X-ray analysis of the gray braze area showed both copper oxide and molybdenum oxide. No tungsten oxide or nickel oxide was found. The tungsten remained leaktight during the entire exposure, but helium soak tests indicated a possible leak to the graphite through the braze area.

Figure 5. One-Inch Hot Shell-Emitter-Flange Structure After Test

The two-inch shell had similar results when the flange temperature was raised to 925 K (see Figure 6). The swelling of the braze area was accelerated due to the higher temperature of the flange. Also, the swelling penetrated more deeply into the braze and probably caused the shell to crack at this end. The two-inch shell had many cracks at the SiC and tungsten interface. This shell is being analyzed to determine the composition of the compounds in the braze area. It was concluded that the life of the braze joint is a function of temperature. A molybdenum flange coated with Cermetel 407 (SiC powder) has been heated to 925 K for 110 hours with no apparent degradation (see Table II). Four attempts were made to CVD SiC directly onto graphite and the molybdenum flange in a single operation. In all cases the SiC had no adhesion to the molybdenum and broke away during temperature cycling.

3) CVD Tungsten Emitter on a Reuseable Mandrel

A smooth and even coating of tungsten was deposited on the outside diameter of a graphite mandrel (see Figure 7). A different grade of pure, very dense graphite of higher expansion coefficient was used. This mandrel was highly polished and coated with a carbon release agent.

TUNGSTEN (CVD)

Figure 6. Two-Inch Hot Shell-Emitter-Flange Structure After Test

Figure 7. Tungsten Deposition on Outside of Graphite Mandrel

The injector design for the WF_6 gas was modified with a 0.008-inch wide slot, 1.5 inches long. Three runs were made with this arrangement and in all cases the tungsten deposit was separated intact from the graphite mandrel. The same graphite mandrel was used for all runs. One-inch tungsten shells with reusable graphite mandrels can now be made. In the future, efforts will be made to coat the outside diameter of the tungsten with a carbon layer followed by a SiC deposit. This will reduce dramatically the cost of manufacturing such structures in production quantities.

4) CVD Molybdenum Emitter

Five runs were made using MoF_6 gas to deposit molybdenum on the inside of a two-inch diameter graphite shell. Temperature of the substrate, injector water and MoF_6/H_2 ratio were varied. Two runs resulted in thin molybdenum coatings (0.003 inch thick) inside these shells. The molybdenum deposits were not leaktight.

Leaktight SiC coatings were deposited on the two-inch shell with no cracking in the molybdenum coating. These shells remained intact after they were temperature cycled from 1475 K to room temperature.

5) TRW Analyses

Flyash erosion tests showed no apparent reaction between the CVD SiC shell and slag. Specimens were exposed for 100 hours at 1675 K.

Results of microstructural analysis of four CVD SiC shells (Nos. 202, 206, 218 and 226) are summarized in Table III. Although more refined analysis is required to conclusively characterize the SiC structure, the following observations may be summarized:

- A wide variety of SiC microstructures is possible (i.e., crystal form, grain size, and crystal orientation).
- β -SiC is the most predominant phase.
- The structure of the CVD SiC may be laminar, columnar, or random.
- The microhardness is greater at the open end than at the center section or the dome.

C. Integral Cesium Reservoir Converter No. 229: Tungsten Emitter, Nickel Collector, Cesium-Graphite Reservoir

This was the third in a series of tests designed to study the characteristics of a converter utilizing a cesium-graphite reservoir.

TABLE III

Summary of Microstructural Analysis Results
of Four CVD Shells

Shell Number	Microstructure of SiC	X-ray Diffraction Analysis of SiC	Microhardness of SiC, Avg. (KHN)
206	Columnar coarse grains	Random orientation β -SiC (tentatively identified) with probably traces of α -SiC.	Lip - 2880 Center - 2530 Dome - 2550
202	Columnar fine grains	Preferred orientation with (111) plane parallel to deposition surface. β -SiC tentatively identified.	Lip - 2790 Center - 2580 Dome - 2550
226	80% of thickness laminar structure starting from graphite substrate; random on surface.	β -SiC tentatively identified; random orientation.	Lip - 2500 Center - 2460 Dome - 1640
218	Columnar 80% of thickness at lip area. All other sections random structure.	β -SiC tentatively identified; random orientation.	Lip - 2950 Center - 2540 Dome - 2560

Converter Nos. 208 and 220 both had an external graphite reservoir in addition to an external cesium reservoir. These converters are described in detail in Progress Report Nos. 36 and 40, respectively. In Converter Nos. 229 the graphite reservoir is inside the collector. The graphite slug is in contact with the converter atmosphere via a small hole drilled into the collector body. The collector assembly is shown in Figure 8.

The converter was tested at $T_E = 1650$ K and $T_C = 800$ K. Originally, the converter had a barrier index of 2.15 eV at a cesium reservoir temperature of 577 K (corresponding to a cesium vapor pressure of 2 torr). The graphite was "soaked" at this condition overnight. The external cesium reservoir was then pinched off. The converter was tested again at the conditions $T_E = 1650$ K and $T_C = 800$ K, with the expectation of duplicating the converter characteristics. However, the performance dropped radically to a barrier index of 2.95 eV. Further tests suggested that the converter had leaked. The converter was disassembled and a leak was found at the emitter sleeve.

29

Figure 8. Collector with Internal Graphite-Cesium Reservoir

1.2 THERMIONIC POWER MODULE EVALUATION

1.2.1 TASK V. SYSTEM STUDIES

The objective of the system studies task is to identify the design approaches to integrate thermionic energy converters into fossil fuel applications in the most cost effective manner. The results of these studies will help orient the design of the thermionic array module (TAM) being developed in Task VI.

Stone and Webster Engineering Corporation has devoted the last reporting period to the investigation of a thermionic combustor. This component is illustrated in Figure 9. It is essentially a gas turbine combustor modified by adding thermionic converters to the walls. The thermionic combustor is capable of supplying hot gases to a gas turbine, an industrial process or a heat recovery boiler. The detailed calculations and results of this study will be summarized in a topical report to be issued at the conclusion of this study.

Figure 9. Thermionic Topped Combustor

1.2.2 TASK VI. TAM MODULE DEVELOPMENT

The objective of this task is to develop combustion heated TAM thermionic converters, individually and in small arrays, which are prototypic for topping a central station powerplant. Devices with both alloy and silicon carbide hot shells will be made and tested. In order to define the transient thermal and electrical characteristics of a TAM, a four-converter array will be constructed and tested.

A. Converter No. 218 (CVD Silicon Carbide Converter No. 1: CVD Fluoride Tungsten (As Deposited) Emitter, Nickel Collector)

The life test of this converter continued at an emitter temperature between 1600 and 1650 K. The performance remained stable throughout the test. On March 24 (after 5120 hours of operation), the converter developed a leak in the cold end of the converter and the test was terminated. After removing the converter from the furnace mounting fixture, a second leak was discovered. These leaks were located at the cesium tubulation and at the interface of the silicon carbide and tungsten. The latter leak may have been caused by handling during the removal from the furnace. Iron slag that flowed onto the mounting fixture during the early

part of the test made the removal of the converter difficult. This converter will be carefully analyzed in order to understand the failure and to improve the design of future converters.

B. Converter No. 228 (CVD Silicon Carbide Converter No. 3). CVD Tungsten (As Deposited Emitter, Nickel Collector)

This converter continued on life test during the last reporting period. The performance has remained stable at a barrier index of 2.1 eV. The measured power density is 2.3 W/cm^2 at an emitter temperature of 1650 K. As of March 31, the converter had operated for 2980 hours at this emitter temperature.

A plot of output power density versus emitter temperature for the three flame-heated converters and a planar, variable-spaced research converter is given in Figure 10. The planar converter had a CVD tungsten emitter similar to that used by the flame-fired converters. The performances of the four converters are almost identical. The greater power density of the variable-spaced converter at the higher emitter temperatures is caused by the fact that this converter was fully optimized for the measurement, whereas the fixed spacings of the flame-fired converters were greater than optimum at the higher temperatures.

Figure 10 Electrode Power Density versus Emitter Temperature for Flame Heated and Electron Bombardment Heated Converters with Identical Electrodes

A summary of the flame-fired converter life tests is given in Table IV. Three significant points are that: 1) the characteristics have been both reproducible from converter-to-converter, 2) the outputs have been stable during the test periods and, 3) the performance of the flame-heated diodes are almost identical to those of the electron bombardment heated research converters.

C. Converter No. 230: Two-Inch Diameter CVD Silicon Carbide Converter

The first two-inch diameter converter was outgassed and tested during March. The converter operated for only one day after cesium was distilled into the reservoir. This early failure was probably due to severe stress to the silicon carbide dome during installation into the furnace. The construction of a second such converter is in progress at this time.

D. High Temperature Gas and Oil-Fired Furnace

During this reporting period, construction of the high-temperature furnace was completed. A photograph of two halves of the furnace is shown in Figure 11. The furnace has been fired to cure the brick and to check

TABLE IV
CVD SILICON CARBIDE DIODE TEST SUMMARY
Average Test Temperature 1630 K

Converter No.	Test Period (hr)	Performance	Thermal Cycles	Comment
218	5120	2.3 W/cm at 1630 K 4.5 W/cm at 1850 K Barrier Index 2.1 eV	11	Operated as high as 1850 K. Operated at 1700 K for 375 hours. Output stable. Test terminated due to leak at cold end of converter.
221	630	2.1 W/cm at 1600 K Barrier Index 2.1 eV	3	Output stable. Terminated due to leak in hot shell.
228	2980	2.1 W/cm at 1600 K Barrier Index 2.1 eV	6	Output stable. Test continuing.

Figure 11 High-Temperature Furnace.

the operation of the automatic control system. After a horizontal mounting fixture is fabricated a one-inch converter will be installed in the furnace. The furnace should be capable of heating converters to emitter temperatures up to 1800 K.

1.2.3 TASK VII. COAL-FIRED TAM TEST UNIT

The objective of this task is to prepare plans for a TAM coal-fired test unit. The preliminary design will be formulated by taking into consideration the results of the system studies and TAM module development. The TAM test unit design will be the smallest size consistent with a realistic simulation of the temperatures, heat fluxes, and slag conditions of a coal-fired steam powerplant.

A manufacturer of a laboratory size, test facility has been identified. The unit under consideration would be capable of firing 100 lb/hr of coal. A cost estimate of such a unit has been requested.

2.0 PART TWO: NASA-OAST/JPL TASKS

2.1 THERMIONIC CONVERTER EVALUATION

2.1.1 TASK VIII. HIGH-TEMPERATURE CONVERTER EVALUATION

The objective of this task is to characterize the performance of candidate emitters, collectors and converter configurations at the high collector temperatures (900-1100 K) required for nuclear electric propulsion. Variable-spaced, planar converters will be used for this task. Evaluation of each converter will include measurements of the output current density versus load voltage as a function of emitter temperature, collector temperature, interelectrode spacing and cesium pressure.

A. Converter No. 227: (JPL Converter No. 1) Molybdenum Emitter, Niobium Collector

The performance characteristics of this converter were presented in Progress Report No. 41 (October, November December 1979). At the completion of testing, a leak was found at the emitter sleeve.

B. Converter No. 231. (JPL No. 3) Molybdenum Emitter,
Sublimed Molybdenum Oxide Collector

The molybdenum oxide collector of this converter contained 1130 ppm of oxygen by weight. Oxygen content was determined by wet chemical analysis of a surface prepared under identical conditions. Performance data have been obtained at emitter temperatures of 1400 and 1650 K over a range of collector temperatures.

Initial experiments with this diode were aimed at identifying an oxygen additive effect from the sublimed molybdenum oxide collector. The increase in emitter saturation current with increasing collector temperature was less pronounced than that of Converter No. 210, the previous sublimed molybdenum oxide diode. A collector temperature family at $T_E = 1650$ K, $T_R = 528$ K, and $d = 0.50$ mm is shown in Figure 12. Apparently, less oxygen is available in Converter No. 231 than in Converter No. 210. Two possible explanations for this observation are:

1. There is less oxygen in the collector (1130 ppm in Converter No. 231 versus 3200 ppm for Converter No. 210).
2. The temperature of the collector during sublimation was higher for Converter No. 231 than for Converter No. 210 - 1265 K versus 1025K. Perhaps the higher temperature inhibited the formation of the more volatile oxides on the collector surface.

Figure 12 Collector Temperature Family of Converter No. 231
at $T_E = 1650 K$, $T_R = 528 K$ and $d = 0.50 mm$

The converter has been fully optimized at emitter temperatures of 1400 and 1650 K. Figures 13 and 14 show the optimized converter performance at various spacings for $T_E = 1400$ and 1650 K, respectively. At a current density of 5 A/cm^2 , the barrier index was 2.28 eV at both emitter temperatures. The collector work function was measured by the retarding plot method. The relatively high minimum work function of 1.94 eV, occurring at $T_C/T_R = 1.45$, reflects the high barrier index. Collector work function versus T_C/T_R data is given in Figure 15.

Studies performed at Thermo Electron and JPL indicate that system weight is sensitive to collector temperature. Thus, extensive performance measurements were made at the design point emitter temperature of 1650 K and collector temperatures up to 1100 K. The converter was optimized for cesium pressure and spacing over a range of collector temperatures from 800 to 1100 inK increments of 50 degrees. The optimized current-voltage characteristics at $T_E = 1650 \text{ K}$ and various collector temperatures are shown in Figure 16. The barrier index at $T_C = 800 \text{ K}$ was 2.28 eV. This value increased to 2.37 eV at a collector temperature of 950 K. At $T_C = 1000 \text{ K}$ the barrier index decreased to 2.34 eV, and again increased to 2.45 eV at 1100 K.

Figure 13 Optimized Performance (Collector Temperature and Cesium Pressure) of Converter No. 231 at $T_E = 1400 \text{ K}$ at Various Spacings

Figure 14 Optimized Performance (Collector Temperature and Cesium Pressure) of Converter No. 231 at $T_E = 1650$ K

Figure 15 Collector Work Function versus the Ratio of Collector and Cesium Reservoir Temperatures for Converter No. 231

Figure 16 Optimized Performance (Spacing and Cesium Pressure) of Converter No. 231 at Emitter Temperature of 1650 K and Various Collector Temperatures

The decrease in the barrier index at $T_C = 1000$ K suggested a heretofore unobserved "activation procedure" for the sublimed molybdenum-oxide collector, similar to that for a tungsten oxide collector. At this point the converter was again optimized at collector temperatures from 900 to 1050 K in 50 degree steps. The barrier index was appreciably lower at the lower collector temperatures ($V_B = 2.20$ eV at $T_C = 900$ K) and unchanged at the higher temperatures. A third run resulted in a barrier index lower than the first, but higher than the second run ($V_B = 2.30$ eV at 900 K). These results are shown graphically in Figure 17 where barrier index is plotted against collector temperature for the three runs. The sequential runs were made from the lower to the higher temperatures. Figure 18 shows the maximum power density versus collector temperature for $T_E = 1650$ K, with optimum cesium pressure and interelectrode spacing. After approximately 430 hours of operation the diode developed a leak at the window braze which prevented further measurements.

Figure 17 Barrier Index versus Collector Temperature for Converter No. 231

Figure 18 Maximum Power Density versus Collector Temperature for Converter No. 231

C. Converter No. 232 (JPL No. 4) Molybdenum Emitter,
Molybdenum Oxide Collector

Converter No. 232 is identical to Converter No. 231 in construction. The collector contains 11,600 ppm of oxygen by weight. The temperature of the collector during sublimation was 1193 K. Converter Nos. 231 and 232 will give a direct comparison of low- and high-oxygen concentration collectors.

Difficulties have been encountered in making a long-lived window for the variable-spaced research diode. Such a window must remain leaktight for a minimum of 1000 hours at temperatures of 500 to 650 K. Furthermore, the window must be compatible with hot cesium vapor and be clear enough for optical measurements. A system used extensively in industry consists of a sapphire window with tungsten-titanium metallizing which is copper-brazed to kovar. This design has been only partially successful, with approximately 50% of the window diodes failing at the metallized sapphire-to-kovar braze.

Activities undertaken to improve the window design were.

- Several metallizing compositions were tested. Tungsten-titanium was selected over molybdenum-titanium and molybdenum-manganese.
- Various metallizing temperatures were tried. For W-Ti 1920 K appeared to be optimum.
- Nickel was tried as a replacement for kovar with little success.
- Closer inspection of the sapphire windows (windows with minute flaws were rejected).

Tests indicated that the W-Ti to kovar braze would remain leaktight if the braze did not exceed a temperature of 773 K.

A thermocouple was attached to the metallized sapphire-to-kovar braze of Converter No. 232. During outgassing, it was noticed that the window braze was at 790 K when the emitter temperature was 1700 K. A copper sleeve with copper cooling straps (which were to be heat-sunk to the test stand) was built to slip over the nickel window sleeve. As outgassing continued, the window braze temperature remained sufficiently cool (at $T_E = 1800$ K the window temperature was 660 K). Subsequently, the diode has remained leaktight after cycling many times over a period of 700 hours.

Initial performance measurements of Converter No. 232 gave a relatively high barrier index. At an emitter temperature of 1650 K, the barrier index at 5 A/cm² was 2.32 eV. No dramatic increase in emitter saturation current with increasing collector temperature was observed and the initial current-voltage characteristics of the diode appeared to be somewhat resistive.

A cesium reservoir temperature family (at $T_E = 1650$ K, $T_C = 750$ K, and $d = 0.50$ mm) is given in Figure 19. After approximately 30 hours of operation, the diode output improved dramatically (the barrier index decreasing to 1.98 eV at $T_E = 1650$ K). Output characteristics at $T_E = 1650$ K, $T_C = 750$ K, $d = 0.50$ mm and several cesium reservoir temperatures are given in Figure 20. The conditions for Figures 19 and 20 are identical. The data in Figure 19 were taken before the performance improvement, while the data in Figure 20 were taken afterwards. A comparison of cesium pressures in these two figures demonstrated that the latter performance requires much less cesium. At $PC_S = 0.50$ torr ($T_R = 528$ K), the short-circuit current density was 3.7 A/cm² for Figure 19 and 15.0 A/cm² for Figure 20. This behavior is attributed to an oxygen additive effect.

Figure 19 Cesium Reservoir Temperature Family at $T_E = 1650 \text{ K}$,
 $T_C = 750 \text{ K}$ and $d = 0.50 \text{ mm}$ for Converter No. 232

Figure 20 Cesium Reservoir Temperature Family at $T_E = 1650$ K,
 $T_C = 750$ K and $d = 0.50$ mm for Converter No. 232

At an emitter temperature of 1650 K, the converter optimized to a barrier index of 1.98 eV. Performance characteristics at $T_E = 1650$ K, optimum collector temperature and cesium pressure at various spacings are given in Figure 21. Measurements were also made at high collector temperatures. The diode was optimized for cesium pressure and spacing at $T_E = 1650$ K and collector temperatures of 750, 800, 850 and 900 K. These results are given in Figure 22.

Testing will continue on this converter.

Figure 21 Optimized Converter Performance at $T_E = 1650 \text{ K}$ and Various Spacings for Converter No. 232

Figure 22 Optimized Converter Performance (Cesium Pressure and Interelectrode Spacing) at $T_E = 1650$ K at Various Collector Temperatures for Converter No. 232

2.1.2 TASK IX. ADVANCED CONVERTER STUDIES

In the conventional ignited mode diode, transport losses due to ionization, and coulombic and neutral atom scattering greatly reduce conversion efficiency. The objective of this task is to demonstrate improved thermionic converter performance by means of reduced potential loss in the interelectrode space. Based on previous studies, the particle thermionic converter (PTC) has been chosen for further investigations. Specifically, the electrical and thermal properties of PTC configurations will be tested as a function of particle composition and electrode spacing.

A. Particle Thermionic Converter - Converter No. 235:
Magnesium Oxide Sprayed Tungsten Emitter-Guarded
Molybdenum Collector.

This converter, designed to measure the cesiated work function of magnesium oxide, has been constructed and is outgassing. Testing will be initiated during the next reporting period.

2.1.3 TASK X. POSTOPERATIONAL DIAGNOSTICS

The variable spaced planar converters built for JPL are deliverable items. However, if it appears advisable on mutual agreement between JPL and Thermo Electron, selected converters shall be opened for postoperational diagnostics after performance testing. The objective will be to identify the degradation mode, if any, and identify the probable mechanisms of formation.

Extensive postoperational diagnostics were performed on the emitters of Converter Nos. 225 and 226 to attempt to explain the superior performance of Converter No. 226. Converter No. 225 had a CVD tungsten as deposited emitter and nickel collector, and Converter No. 226 had a CVD tungsten electropolished emitter and nickel collector. A summary of the results based on SEM, AES, FERP work functions and x-ray diffraction is given in Table V. The x-ray and SEM results showed that the emitter from Converter No. 226 was (100) oriented and composed of grains 0.05 - 0.1 mm in diameter and that the emitter from Converter No. 225 was primarily an unoriented structured surface (see Figure 23).

TABLE V

POST OPERATIONAL DIAGNOSTICS OF CONVERTER 225 AND 226

● SEM PHOTOGRAPHS

- CONVERTER 225 EMITTER - STRUCTURED SURFACE WITH OCCASIONAL W(100) AREAS
- CONVERTER 226 EMITTER - W(100) GRAINS APPROXIMATELY 0.5 -1.0 mm IN DIAMETER

● AES STUDIES

- CONVERTER 225 EMITTER - AUGER SPECTRUM SHOWS OXYGEN, TUNGSTEN, CARBON AND CESIUM. HEATING TO 1400 K LEAVES ONLY TUNGSTEN AND OXYGEN.
- CONVERTER 226 EMITTER - AUGER SPECTRUM SHOWS CARBON, OXYGEN, SILICON, TUNGSTEN, AND SODIUM. HEATING TO 1400 K LEAVES ONLY TUNGSTEN AND CARBON.

● FERP MEASUREMENTS

- CONVERTER 225 EMITTER - AFTER HEATING 1800 K, = 5.37 eV
- CONVERTER 226 EMITTER - AFTER HEATING 1800 K, = 4.85 eV

● X-RAY PATTERNS

- CONVERTER 226 EMITTER SHOWED ONLY W(100) ORIENTATION, AS EXPECTED (DIFFRACTOMETER DETERMINATION)

Figure 23a. SEM Micrograph of Electropolished Emitter No. 226 Showing (100) Grains

Figure 23b. SEM Micrograph of as Deposited Emitter No. 225 Showing Unoriented Structured Surface

A detailed presentation of the Auger and FERP measurements is shown in Figures 24 and 25. Relative elemental coverages and FERP work functions were measured for both emitters after heating to 300, 1400, 1600, and 1800 K. The bare work function for the emitter from Converter No. 225 is higher than the bare work function for the emitter from Converter No. 226 (implying that the former diode would give better performance than the latter). However, the performance of Converter No. 225 was inferior to that of No. 226!

The carbon and oxygen coverages for the two emitters after heating to 1400 - 1800 K were quite different. The emitter from Converter No. 225 showed 20% oxygen and no carbon at 1600 K, whereas the emitter from Converter No. 226 showed 37% carbon and no oxygen at 1600 K. The large amount of carbon seen in the emitter from Converter No. 226 may be the result of the leak which was found after testing of this converter. In summary, the diagnostic tests were interesting but did not reveal the reason for the superior performance of Converter No. 226 compared to Converter No. 225.

Figure 24 Surface Coverages and FERP Work Function versus Heating Temperature for Emitter, Converter No. 225

Figure 25 Surface Coverages and FERP Work Function versus Heating Temperature for Emitter, Converter No. 226

2.2 CYLINDRICAL CONVERTER DEVELOPMENT

2.2.1 TASK XI. CYLINDRICAL CONVERTER COMPONENT DEVELOPMENT

The objective of this task is to develop the technology required to construct cylindrical converters, excluding the electrode surfaces. This task includes electrode insulation, seal-bellows subassembly and thermoelectric lead components.

The third cast sapphire test has been performed to evaluate this material for electrical insulation at an emitter temperature of 1650 K. The casting technique involves melting high purity crushed sapphire and flowing it between two molybdenum cylinders (simulating a heat pipe from the reactor and the emitter of a thermionic converter) with diameters projected for the NEP mission. For the third test, the casting fixture was modified by drilling a hole in the bottom of the outer cylinder to provide better observation of the liquid sapphire. In addition, both molybdenum surfaces were roughened with 80 threads per inch. During the casting, the bottom of the fixture was held at a slightly higher temperature than in previous efforts to improve the flow of the sapphire. This flow was terminated as soon as it reached the bottom vent hole. Inspection showed that the sapphire flow filled the entire fixture.

The initial cold resistance was greater than 10^8 ohms and the initial resistance at 1650 K was greater than 20 ohms. However, a vacuum pump failure resulted in severe oxidation of the molybdenum and shorted the test fixture. After cleaning the apparatus and repairing the vacuum system, the unit was returned to test. However, the sapphire casting shorted at operating temperature. Efforts to clear the shorts with capacitor discharges were not successful.

2.2.2 TASK XII. CORRELATION OF DESIGN INTERFACES

The objective of this task is to provide technical coordination between Thermo Electron and other contractors as well as with government agencies in order to assure overall compatibility of design, materials and interfaces between the thermionic conversion and other subsystems. This effort will be continuously updated. In this task, technical coordination between Thermo Electron government agencies and other contractors is provided. Thus the overall compatibility of the various subsystems is ensured.

The parametric system calculations presented in the last report have been extended. A computer program written to model the effect on the system masses has been refined by including the voltage drop in the emitter wall as well as in the emitter sleeve. The model is based on the layout of the spacecraft shown in Figure 26.

Figure 26 Schematic Arrangement of Spacecraft Power System

The model corresponds to the guidelines given at the Nuclear Electric Propulsion Interface Working Group meeting at Rasor Associates on 16 January 1980. The computer program flow diagram is given in Figure 27. The required subroutines are shown in Figure 28. For all calculations, the system output was assumed to be 120 kW, and the power conditioner efficiency was constant at 77%. For each thermionic converter operating condition (i.e., emitter and collector temperatures, arc drop, barrier index and current density) several emitter geometries were selected. The emitter diameter, emitter length and emitter wall thickness were varied. For each set of parameters, the voltage drop in the emitter wall was calculated and the emitter sleeve was optimized.

Figure 27. System Mass Calculations

803-12

Figure 28. Subroutines for System Mass Calculations

The number of converters was then determined from the output of each converter (the calculations were performed for 2 and 3 converters per reactor heat pipe). The reactor mass was determined from the required heat input and an equation fitted to data from Los Alamos. The masses of the reactor heat pipes, the converters, radiator and radiator heat pipes were calculated by the program. The masses of the structure, shield and miscellaneous components were assumed constant. The results are summarized in Figure 29 for an emitter temperature of 1650 K and for barrier indices of 1.65 and 1.85 eV. This graph shows the envelope of the calculations for all the emitter geometries that were studied. From this figure, the optimum collector temperature is around 900 K.

The effects of variable emitter geometry are shown in Figures 30, 31 and 32. The system mass is not very sensitive to the emitter size and shape for the dimensions studied. The results of the calculations are also shown in Tables VI to IX.

Figure 29. Reactor Mass Versus Collector Temperature

Figure 30. Reactor Mass Versus Emitter Geometry

Figure 31. Reactor Mass Versus Emitter Geometry

Figure 32. Reactor Mass Versus Emitter Geometry

TABLE VI
SYSTEM MASS CALCULATIONS, 120 kW OUTPUT

$T_E = 1650 \text{ K}$ $T_C = 900 \text{ K}$ $V_D = 0.3 \text{ eV}$ $V_B = 1.85 \text{ eV}$ $J = 10 \text{ A/cm}^2$	CONVERTERS/ HEAT PIPE = 3 $D = 1.25 \text{ cm}$ $L = 11.5 \text{ cm}$ $T = 0.50 \text{ cm}$	CONVERTERS/ HEAT PIPE = 2 $D = 1.25 \text{ cm}$ $L = 13.2 \text{ cm}$ $T = 0.75 \text{ cm}$	CONVERTERS/ HEAT PIPE = 2 $D = 4.25 \text{ cm}$ $L = 21.25 \text{ cm}$ $T = 0.75 \text{ cm}$
NUMBER OF CONVERTERS	289	203	72
LEAD EFFICIENCY (%)	14.5	14.7	12.1
ELECTRODE EFFICIENCY (%)	18.2	18.5	15.5
POWER COND. EFFICIENCY (%)	77.0	77.0	77.0
<u>MASSES (KG)</u>			
REACTOR	188	185	225
REACTOR HEAT PIPES	147	155	228
CONVERTERS	576	633	603
RADIATORS & RADIATOR HEAT PIPES	372	326	256
STRUCTURE	95	95	95
SHIELD	541	541	541
MISC.	80	80	80
<hr/>			
TOTAL MASS (KG)	1999	2015	2028
SPECIFIC MASS (KG/KW)	16.7	16.8	16.9

TABLE VII
SYSTEM MASS CALCULATIONS, 120 kW OUTPUT

$T_E = 1650 \text{ K}$ $T_C = 800 \text{ K}$ $V_D = 0.3 \text{ eV}$ $V_B = 1.85 \text{ eV}$ $J = 10 \text{ A/cm}^2$	CONVERTERS/ HEAT PIPE = 3 $D = 1.25 \text{ cm}$ $L = 11.5 \text{ cm}$ $T = 0.50 \text{ cm}$	CONVERTERS/ HEAT PIPE = 2 $D = 1.25 \text{ cm}$ $L = 13.2 \text{ cm}$ $T = 0.75 \text{ cm}$	CONVERTERS/ HEAT PIPE = 2 $D = 4.25 \text{ cm}$ $L = 21.25 \text{ cm}$ $T = 0.75 \text{ cm}$
NUMBER OF CONVERTERS	290	204	73
LEAD EFFICIENCY (%)	14.3	14.5	11.9
ELECTRODE EFFICIENCY (%)	18.2	18.4	15.4
POWER COND. EFFICIENCY (%)	77.0	77.0	77.0
<u>MASSSES (KG)</u>			
REACTOR	190	187	228
REACTOR HEAT PIPES	147	156	231
CONVERTERS	578	636	612
RADIATORS & RADIATOR HEAT PIPES	508	462	391
STRUCTURE	95	95	95
SHIELD	541	541	541
MISC.	80	80	80
	<hr/>	<hr/>	<hr/>
TOTAL MASS (KG)	2139	2157	2178
SPECIFIC MASS (KG/KW)	17.8	18.0	18.2

TABLE VIII
SYSTEM MASS CALCULATIONS, 120 kW OUTPUT

$T_E = 1650 \text{ K}$ $T_C = 900 \text{ K}$ $V_D = 0.5 \text{ eV}$ $V_B = 1.85 \text{ eV}$ $J = 10 \text{ A/cm}^2$	CONVERTERS/ HEAT PIPE = 3 $D = 1.25 \text{ cm}$ $L = 11.5 \text{ cm}$ $T = 0.5 \text{ cm}$	CONVERTERS/ HEAT PIPE = 2 $D = 1.25 \text{ cm}$ $L = 13.2 \text{ cm}$ $T = 0.75 \text{ cm}$	CONVERTERS/ HEAT PIPE = 2 $D = 4.25 \text{ cm}$ $L = 21.25 \text{ cm}$ $T = .75 \text{ cm}$
NUMBER OF CONVERTERS	296	205	73
LEAD EFFICIENCY (%)	14.3	14.4	11.8
ELECTRODE EFFICIENCY (%)	18.2	18.3	15.3
POWER COND. EFFICIENCY (%)	77.0	77.0	77.0
<u>MASSES (KG)</u>			
REACTOR	190	188	229
REACTOR HEAT PIPES	150	156	231
CONVERTERS	583	640	612
RADIATORS & RADIATOR HEAT PIPES	512	463	391
STRUCTURE	95	95	95
SHIELD	541	541	541
MISC.	80	80	80
	<hr/>	<hr/>	<hr/>
TOTAL MASS (KG)	2151	2163	2179
SPECIFIC MASS (KG/KW)	17.9	18.0	18.2

TABLE IX
SYSTEM MASS CALCULATIONS, 120 kW OUTPUT

$T_E = 1650 \text{ K}$ $T_C = 900 \text{ K}$ $V_D = 0.5 \text{ eV}$ $V_B = 1.85 \text{ eV}$ $J = 10 \text{ A/cm}^2$	CONVERTERS/ HEAT PIPE = 3 $D = 1.25 \text{ cm}$ $L = 11.5 \text{ cm}$ $T = .75 \text{ cm}$	CONVERTERS/ HEAT PIPE = 2 $D = 1.25 \text{ cm}$ $L = 13.2 \text{ cm}$ $T = 0.75 \text{ cm}$	CONVERTERS/ HEAT PIPE = 2 $D = 2.25 \text{ cm}$ $L = 11.25 \text{ cm}$ $T = .5 \text{ cm}$
NUMBER OF CONVERTERS	280	247	248
LEAD EFFICIENCY (%)	12.4	12.0	11.8
ELECTRODE EFFICIENCY (%)	15.9	15.4	15.2
POWER COND. EFFICIENCY (%)	77.0	77.0	77.0
<u>MASSES (KG)</u>			
REACTOR	219	227	230
REACTOR HEAT PIPES	142	188	388
CONVERTERS	789	771	645
RADIATORS & RADIATOR HEAT PIPES	368	350	350
STRUCTURE	95	95	95
SHIELD	541	541	541
MISC.	80	80	80
<hr/>			
TOTAL MASS (KG)	2234	2252	2329
SPECIFIC MASS (KG/KW)	18.6	18.8	19.4

REFERENCES

1. L.R. Danielson and L.W. Swanson, "High Temperature Coadsorption Study of Zirconium and Oxygen on the W(100) Crystal Face," Surface Sci. 88 (1979) 14-30.