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Contract AT(30-1)-4161

MASTER

Development of a High Voltage Heat Pipe Thermonic Module

Final Technical Report

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October 1, 1969 through June 30, 1971

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Prepared for

U.S. ATOMIC ENERGY COMMISSION

New York Operations Office
New York, New York

July 1971

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Contract AT(30-1)-4161

WASH-1199
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DEVELOPMENT OF A HIGH VOLTAGE
HEAT PIPE THERMIONIC MODULE

FINAL TECHNICAL REPORT

Author - R.W. Longsderff

Period of Performance

October 1, 1969 through June 30, 1971

Prepared for

U. S. ATOMIC ENERGY COMMISSION
New York Operations Office
New York, New York

Prepared by

RCA CORPORATION
Electronic Components
Industrial Tube Division
Lancaster, Pennsylvania

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FOREWORD

This report was prepared by RCA, Lancaster, Pennsylvania, under U. S. Atomic Energy Commission Contract AT(30-1)-4161 entitled "Development of a High Voltage Heat Pipe Thermionic Module." Mr. Lester Price served as Technical Director of the program for the U. S. Atomic Energy Commission, Space Nuclear Systems Division, Germantown, Maryland.

This Final Technical Report covers the work performed during the period from October 1, 1969 through June 30, 1971. The work described herein represents the efforts of the Special Power Devices Engineering Department. Mr. R. W. Longsderff provided technical direction for the program, directing a group of technical personnel in performance of the actual program of work.

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DEVELOPMENT OF A HIGH VOLTAGE
HEAT PIPE THERMIONIC MODULE

Contract AT(30-1)-4161

SECTION I

INTRODUCTION

This report describes RCA's efforts to design, fabricate and test a 5 volt, 10 diode, heat pipe thermionic module. The program was originally organized into three major tasks as follows: Task I - Heat Pipe Thermionic Module Development; Task II - Advanced High Voltage Module Technology; and Task III - Development of a 28 volt Thermionic Module. Due to a reduction in overall program effort, Task III was eliminated and efforts were concentrated on Task I.

The basic module design was centered about the design concept developed under Contract AT(30-1)-3979 (see Final Technical Report NYO-3979-3, dated September 1969). This concept consists of individual thermionic diode assemblies mounted on a Common heat pipe and internally series connected by a flexible high temperature lead. The primary objective of Task I was to design, fabricate and test a 5 volt, 10 diode, heat pipe thermionic module.

The primary objectives of Task II were to improve the tri-layer technology necessary for module use and to improve the insulation coatings required for arc-suppression in module applications.

SECTION II

PROGRAM ACCOMPLISHMENTS

I. Task I - Development of a Five Volt Module

The major emphasis of work for this task was directed to the design and fabrication of a five volt, 10 diode module employing the basic concept developed under Contract AT(30-1)-4161. This basic concept is shown in Figure 1. This effort included work in the areas of heat pipe design and fabrication, electrode fabrication, auxilliary sub-assembly fabrication and module assembly.

A. Heat Pipe Development

A heat pipe design was established based on the 5 volt, 10 converter module design discussed in later paragraphs of this report. Based on this design (see Appendix "A") a total power requirement of 2850 watts is required of the total system. This was assuming moderate evaporator surface shielding (approximately 5 wraps of 0.001 inch thick dimpled molybdenum foil) and the losses summarized in Appendix "A". The heat pipe dimensions were also dictated by the module design since emitter area and emitter/collector diameters are critical to the overall system efficiency.

A computer analysis was conducted based on these requirements. The results indicated that a heat pipe with dimensions 0.850 inch O.D. x 0.750 inch I.D. x 16.75 inches long (7 inch condenser, 9.75 inch evaporator) could transfer more than 7500 watts, using 3 wraps of 60 x 60 mesh molybdenum screen as the wick and operating in a 90° gravity

FIGURE 1 PHOTOGRAPH OF BASIC HIGH VOLTAGE MODULE
DESIGN CONCEPT

aiding orientation. The same design operating in a 0° gravity orientation was capable of transferring more than 3500 watts. The design was chosen for fabrication. A cross-sectional drawing of the design is shown in Figure 2.

The heat pipe was constructed in two pieces and electron beam welded in the condenser area just outside the power lead. This procedure was necessary from a machining point of view.

The heat pipe evaporator section length was calculated, using a computer program to determine the length/cross-sectional area ratio necessary to minimize the magnetic effects due to the high current (2200 amperes) resulting from directly heating the heat pipe. Different methods of heating could result in a shorter evaporator section.

The power leads employed were fabricated from vacuum-arc-cast molybdenum. These leads were designed to clamp onto the heat pipe O.D. surface using molybdenum threaded rod and nuts (1/4-20 thread). These leads also served as mounting clamps for support of the heat pipe during processing and testing.

Following fabrication, the heat pipe was loaded with 8.5 grams of lithium and processed to a temperature of 1600°C . The unit was then sealed and recycled to insure proper closure. The closure was completed using a molybdenum pin and orifice.

FIGURE 2 - High Voltage Module Heat Pipe

Following processing, the heat pipe was set-up for testing.

Temperature measurements were made, using an optical pyrometer, and thermal loading was accomplished by a clamp-on radiation lead. The measurements were taken with a maximum total heat transfer of 4000 watts. At this power level, the maximum temperature gradient measured between evaporator and condenser was 35°C at a heat pipe temperature of 1500°C . These measurements were made with the heat pipe in a horizontal position (0° gravity).

Following test, the heat pipe was set aside to await assembly of the module components.

B. Module Design and Fabrication

A module design incorporating the basic module concept was established. This design was co-ordinated with the heat pipe design to insure adequate power capability versus diameter dimensions chosen. The design is shown in Figure 3.

1. Design

A design based on heat pipe dimensions of 0.860 inch O.D. and an emitter length of 0.245 inch resulted in an emitter area of 5.5 cm^2 for each converter section. A thermal analysis of the system was conducted using the respective dimensions shown in Figure 4. The complete analysis is listed in Appendix A. This analysis was conducted assuming an emitter temperature of 1450°C , a power density of 3.6 watts/cm^2 , and a conversion efficiency of 10 percent. Using these parameters, it was calculated that the emitter tri-layer would have a temperature loss of 15.72°C . This

FIGURE 3 - Basic Module Design

Respective Radii

A = 0.430 in.,	1.092 cm
B = 0.490	, 1.245
C = 0.495	, 1.257
D = 0.570	, 1.448
E = 0.575	, 1.460
F = 0.670	, 1.702
G = 0.675	, 1.715
H = 0.780	, 1.981
J = 0.517	, 1.313
K = 0.320	, 0.813
L = 0.197	, 0.50

FIGURE 4 - Converter Cross-Sectional Dimensions

compares quite well with the values measured during tri-layer evaluation studies. This value plus the heat pipe losses (wick and wall) show a total temperature loss from inside the heat pipe to the emitter surface of 26.5°C . Thus the heat pipe must be operated at approximately 1475°C vapor temperature to achieve the 1450°C emitter temperature. These values are true only if a perfect thermal bond is achieved between the emitter tri-layer assembly and the heat pipe outer wall. Therefore, a more practical heat pipe temperature would be 1500°C . This value is within the design of the heat pipe.

This analysis was continued to determine the thermal loss for each converter device and the total gross power required for the overall module system. A summation of these losses showed that the total power required for each converter was 218 watts. Summarizing the remaining system losses, i.e., end caps, power leads, etc., the total system power required is 2833 watts. This power requirement was used for the heat pipe design analysis discussed previously.

2. Electrode Fabrication

Fabrication of the emitter/collector tri-layer assemblies was conducted by the technique established under Contract AT(30-1)-3979. Vacuum arc cast molybdenum (Climax-Climelt) was employed in all electrode fabrication. The casting technique employed was also the technique developed under Contract AT(30-1)-3979. A schematic diagram of this technique is shown in Figure 5 and a cross-sectional

FIGURE 5 SCHEMATIC DIAGRAM OF VACUUM CASTING TECHNIQUE

drawing of the casting is shown in Figure 6. The casting assembly was machined using facilities employed strictly for the machining of molybdenum, to reduce the change of metallic contaminants. A special recirculating coolant system using special non-sulfur coolant was employed with the machining facility. All parts were cleaned and vacuum fired prior to assembly for casting. All casting jointures were made by an electron beam welding technique. Following casting, sections were cut to proper length for machining. This cutting was accomplished using an Allison No. GCl20 abrasive wheel to prevent chipping and pull-out of the alumina tri-layer, and to reduce the amount of metal "smear-over" in the alumina end-area.

Following completion of machining the respective emitter and collector assemblies were electron beam welded to a non-slotted interconnection lead as shown in Figures 7 and 8. Two special assemblies (one each end) were required for connections of the external emitter lead at one end and the external collector lead at the other end. These assemblies are shown in Figures 9 and 10, respectively. A photograph of the completed emitter/collector assemblies is shown in Figure 11. Following electron beam welding, the assemblies were set up for slotting of the inter-connecting lead.

FIGURE 6 CROSS-SECTIONAL DRAWING OF VACUUM CASTING

FIGURE 7 CROSS-SECTIONAL DRAWING OF EMITTER/COLLECTOR TRI-LAYER ELECTRODE ASSEMBLY

FIGURE 8 CROSS-SECTIONAL DRAWING OF ELECTRON BEAM WELDING
FIXTURE FOR ELECTRODE SUB-ASSEMBLY FABRICATION

FIGURE 9 - Emitter Lead Sub-Assembly

FIGURE 10 - Collector Lead Sub-Assembly

Emitter/Collector Tri-Layer Sub-Assemblies

FIGURE 11

3. Interelectrode Lead Design and Fabrication

The lead connecting the emitter of one converter to the collector of the following converter assembly was designed to carry out several functions in addition to the inter-connection of successive electrodes. Through the use of spiralling radial slots, the lead can be utilized to relieve the axial differential expansion, due to temperature difference, between the emitter and collector columns. By varying the number of spiralled radial slots, the width between the slots and the length of the slots, the correct area-to-length relationship for optimum converter performance at a particular operating temperature can be achieved. A design was completed in which these functions were accomplished by the interelectrode lead. The details of this design are shown in Figure 12. The leads were drawn from 0.020 inch thick, deep drawing quality, Universal Cyclops molybdenum sheet. The slotting was performed with an abrasive cutting wheel and the fixture shown in Figure 13. This fixture held both electrodes in perfect concentric alignment during the slotting operations.

4. Auxiliary Sub-Assembly Design and Fabrication

The closure of the module units to the heat pipe at both ends, connection and support of the respective power leads, and electrical isolation of the power leads from the heat pipe was accomplished by the sub-assembly design shown in Figure 14. This assembly was welded directly to the heat pipe assembly to complete the module vacuum envelope. The end diaphragm served to accommodate differential

FIGURE 12 - Interelectrode Lead Slotting Details

FIGURE 13 - Interelectrode Slotting Fixture

FIGURE 14 - End Closure and Power Lead Sub-Assembly

expansion due to temperature difference between the heat pipe and converter columns. The power output leads were molybdenum, brazed to the sub-assembly with iron-palladium brazing alloy.

5. Exhaust Tubulation Sub-Assembly Design and Fabrication

The exhaust tubulation was positioned at the mid-point of the module. This sub-assembly is shown in Figure 15. The exhaust tubulation was 3/16 inch O.D. with a 0.020 inch wall thickness. This tubing was brazed to the adaptor ring with iron-palladium brazing alloy. The exhaust appendages were later attached to the tubulation using copper as the brazing alloy.

6. Arc Supression Coating

The internal module areas which are subject to voltage break-down were coated with the alumina/yttria coating developed under Contract AT(30-1)-3979. The average thickness of this coating was 0.004 inches. An evaluation of the coating following subsequent welding and/or brazing cycles proved the coating to be adequate for the application. A scanning electron microscope photograph of this coating is shown in Figure 16.

C. Module Assembly

A basic assembly procedure was developed which utilized the technology established under Contract AT(30-1)-3979, the two major concerns in establishing the necessary assembly techniques are the maintenance of accurate interelectrode spacing and the axial movement of the emitter/collector sub-assemblies along the heat pipe O.D. with minimum clearance.

FIGURE 15 - Exhaust Tubulation Sub-Assembly

Scanning Electron Microscope Photograph
of Aluminum/Yttria Arc-Suppression Coating
(Magnification-500X)

FIGURE 16

These requirements were met through proper fixturing and surface preparation.

1. Electrode Sub-Assembly Final Machining

Following the slotting and coating of the emitter/collector tri-layer sub-assemblies, the electrode surfaces were final machined. This procedure insured the maintenance of close tolerance and provided a clean surface free of any processing contaminants. Approximately 0.005 inch was removed from each electrode surface and all jiggling surfaces rechecked to insure concentricity and parallelism in the appropriate areas. The sub-assemblies were then stored in a "clean area" to await final assembly onto the heat pipe.

2. Assembly Procedure

Following the completion of the various sub-assemblies and module components, the final assembly was started. A flow chart showing the order of assembly is given in Table I. The order of assembly is shown starting at the heat pipe lead-end (bottom half) and progressing upward to the final weld of the top end-cap diaphragm and heat pipe extension. The principal sub-assemblies and components are shown in Figures 17 through 25, respectively. The sub-assemblies were "stacked" onto the heat pipe in the respective order shown in Figure 3 of this report. A molybdenum welding fixture was employed to set the spacing between the heat pipe surface and the collector surface of the assembly being welded to the respective collector

TABLE I

MODULE FLOW CHART

<u>C-260-125</u>	Fabrication Model (Ass'y.)	
<u>B-260-45</u>	Heat Pipe Sub-Ass'y.	1
A-260-46	Heat Pipe Extension	1
A-260-47	Orifice Cap	1
B-260-48	Condenser Section-Heat Pipe	1
B-260-49	Evaporator Section-Heat Pipe	1
A-260-50	Center Lead-Heat Pipe	1
A-260-51	End Lead-Heat Pipe	1
A-260-52	End Cap	1
<u>A-260-115</u>	Diaphragm Sub-Assembly	2
A-260-53	Diaphragm	2
A-260-13	Bottom Half-Diaphragm	2
A-260-14	Top Half-Diaphragm	2
A-260-34	Ceramic Insulator	2
A-260-38	Outer Lead Assembly	2
A-260-114	Lead Adapter Sub-Assembly	2
A-260-36	Lead Strain Isolation Flange (Made from A-260-2)	2
A-260-116	Lead Isolation Ring (Made from A-260-2)	2
A-260-124	Outer Lead Adapter	2
A-260-133	Solid Lead	4
<u>A-260-107</u>	Collector Lead Assembly	1
A-260-41	Ceramic Isolation Sub-Assembly	1
A-260-34	Ceramic Insulator	1
A-260-39	Strain Isolation Ring (Made from A-260-2)	1
A-260-40	Short Strain Isolation Flange (Made from A-260-2)	1
A-260-110	Collector Lead Cup	1
A-260-131	Collector Lead Sub-Assembly	1
A-260-109	Collector Lead Sleeve	1
A-260-120	Mach. End Collector Tri-Layer (Made from A260-99)	1

TABLE I (Cont'd)

<u>A-260-111</u>	Collector Connector	8
<u>A-260-91</u>	Emitter Ceramic Spacer	9
<u>A-260-132</u>	Coated Emitter-Collector Assembly	9
A-260-126	Slotted Em.-Col. Assembly	9
A-260-112	Emitter-Collector Assembly	9
A-260-7	Interelectrode Lead	9
A-260-16	Machined Emitter Tri-Layer	9
A-260-92	Cast Emitter Assembly	-
A-260-93	Outer Emitter Tbg.	-
A-260-94	Inner Emitter Tbg.	-
A-260-95	Emitter Bottom Plug	-
A-260-96	Emitter Bottom Cap	-
A-260-97	Emitter Top Plug	-
A-260-98	Casting Vac. Tbg.	-
A-260-108	Machined Collector Tri-Layer	9
A-260-99	Cast Collector Assly	-
A-260-100	Outer Collector Tbg.	-
A-260-101	Inner Collector Tbg.	-
A-260-102	Collector Bottom Plug	-
A-260-103	Collector Bottom Cap	-
A-260-104	Collector Top Plug	-
A-260-98	Casting Vac. Tbg.	-
<u>A-260-121</u>	Exhaust Tubing Sub-Assembly	1
A-260-122	Exhaust Tubing	1
A-260-123	Exhaust Tubing Ring	1
<u>A-260-41</u>	Ceramic Isolation Sub-Assembly	1
A-260-34	Ceramic Insulator	1
A-260-39	Strain Isolation Ring	1
	(Made from A-260-2)	
A-260-40	Short Strain Isolation Flange	1
	(Made from A-260-2)	
<u>A-260-42</u>	Emitter Lead Sub-Assembly	1
A-260-11	Emitter Lead	1
A-260-119	Mach. End Emitter Tri-Layer	1
	(Made from A260-92)

FIGURE 17 - Module Heat Pipe Sub-Assembly

NOTES:

1. **Copper** BRAZE AT 1080°C.
2. BRAZE USING TOOL NO.
260-115-T1

FIGURE 18 - Lower Diaphragm and Collector Power Lead Sub-Assembly

FIGURE 19 - Collector Lead Sub-Assembly

FIGURE 20 - Collector Interconnecting Ring

FIGURE 21 - Emitter Ceramic Spacer

NOTES:

1. COAT SURFACES INDICATED (---) WITH Al_2O_3

FIGURE 22 - Emitter-Collector Assembly

NOTES:

1. BRAZE IN VAC. AT 1350 °C.

FIGURE 23 - Exhaust Tubing Sub-Assembly

NOTES:

1. COPPER BRAZE AT 1080°C.
2. BRAZE USING TOOL NO. 260-41-TI-1

FIGURE 24 - Ceramic Isolation Sub-Assembly

FIGURE 25 - Emitter Lead Sub-Assembly

interconnecting ring. The next emitter/collector sub-assembly is then set in place, with the emitter sliding between the heat pipe and collector of the previous assembly with the proper emitter-collector spacing.

The original module assembly technique was altered in that the collector-to-collector interconnecting ring jointure was made by local induction heating for copper brazing (1080°C). This change was instituted to prevent any likely damage of the arc-suppression coating in the weld area adjacent to the collector-collector interconnecting ring joint. The same fixturing for determining electrode spacing was employed. The brazing operation employed utilized a carbon ring as a radiator source to reduce the likelihood of severe temperature non-uniformity. Thus the jointure was made by radiating heat from the carbon ring to the components being brazed. This technique also necessitated nickel plating the respective brazing areas to enhance wetting of the braze material to the molybdenum. Several test brazes were made prior to actual assembly in order to develop the proper furnace settings.

The module assembly was initiated using this brazing technique. The assembly was leak checked following each brazing operation. Successful joints were made on the first seven converter assemblies. However, on the eighth assembly, the brazing fixture froze to the collector assembly, necessitating the removal of this assembly. This required

the remachining of the brazing area for the previous assembly to insure concentricity and parallelism. The unit was set up and rebrazed. Upon leak checking it was determined that the exhaust tubing sub-assembly had developed a leak. Numerous attempts were made to rebraze this area with the same copper brazing alloy. However, new leaks developed due to the thermal cycling in these areas. It was decided that a rebrazing attempt should be made with a lower temperature alloy such as niaro (930°C) in order to salvage the assembly for minimum testing and concept evaluation. These rebrazing attempts proved to be successful and the final converter assemblies were added. During the final brazing of these units, additional leaks developed near the center of the module. Additional attempts to rebraze the assembly proved unsuccessful and no further work was conducted with the assembly.

3. Assembly Technique Analysis

The original collector-collector interconnecting ring joint was designed to be welded using the electron-beam welding technique. Therefore the collector joint had a small step for holding the interconnecting ring during this welding. When the decision was made to make this joint by a brazing technique, the parts and sub-assemblies were already completed, thus making redesign of the joint unfeasible. The design of this joint, from a brazing point of view, was not optimum. The small step made the use of flat brazing washers almost impossible. Ring brazing forms were also

difficult to handle since extremely small wire had to be employed. As a result, small brazing material fillets developed with only surface line contact jointure at best, in many cases. The nickel plating added also enhanced the chance of leak development through blisters and added impurities.

II. Task II - Advanced High Voltage Module Technology

The objective of this task was to continue efforts for the improvement and advancement of technology surrounding the high voltage module concept. The major areas of concern included tri-layer fabrication, and arc-suppression coatings.

A. Tri-Layer Technology

A program of continued tri-layer evaluation was conducted in the areas of welding, machining and interelectrode lead slotting. Additional welding tests were performed, using the accepted interelectrode lead. These leads were thicker (0.020 inch) and required greater electron-beam welding power, thus jeopardizing both the alumina layer and arc-suppression coating. These weld tests, however, showed a far superior weld with no lead buckling or local burn-through; cross-sections of the alumina layer also confirmed that no damage resulted due to the increased welding power.

Machining tests were conducted using actual end-use sub-assemblies to determine the accuracy and reproducibility of the technique developed. In all cases tried, accuracy of ± 0.0005 inch T.I.R. could be achieved repeatedly. The electrode surface finish was more than satisfactory.

Lead slotting techniques evaluated included electrical discharge machining and abrasive wheel machining. The tests conducted using the electrical-discharge machining technique showed non-uniformity in slot width. It is believed that this was due to the radius and taper of the lead to be slotted. Attempts were made to correct this by contouring the tool to match the part. The quality was improved, but was inferior to those parts fabricated using the abrasive wheel technique. The abrasive wheel technique was therefore used for actual parts fabrication.

B. Arc Suppression Coatings

While an adequate coating for arc-suppression was developed on Contract AT(30-1)-3979, efforts were continued to develop an improved application method for coating the complex emitter/collector assembly. This effort included the improvement of the previously developed alumina/yttria coating and the investigation of a "sputtering" technique for aluminum oxide.

1. Alumina/Yttria Coating

The application of the alumina/yttria coating involved the thermal cycling of the subject parts and sub-assemblies to temperatures as high as 1800°C. This spray/sinter technique required careful masking and surface preparation to insure a completely impervious coating. Through the use of improved spraying fixtures the required masking was substantially reduced. It was also determined that the sintering temperatures could also be somewhat reduced (approximately 1725°C) without sacrificing the quality of the coating. The most

critical area for coating was the tri-layer end-area. Small "chipped-out" areas of Al_2O_3 were difficult to completely cover. Repeated coatings created greater than optimum thickness, and cracking resulted when the assemblies were thermal cycled. Thus only those assemblies with void-free end-areas were utilized for module use.

2. Sputtering of Aluminum Oxide

The uniformity of coating thickness using the sputtering technique, as well as the controlled atmosphere of the coating (vacuum), make sputtering an attractive process for arc suppression coatings. Molybdenum samples were sent to Electrotec Corporation for evaluation of the process. The first samples were coated with approximately 4000 Å of aluminum oxide. These samples proved to be impervious in those areas where the surface finish was best. The coating appeared to be deposited in the exact pattern of the original surface finish. Thus rough surface finishes did not provide an impervious coating. As a result, four additional samples, 3/4" diameter disks, were prepared with varying surface preparations to determine the effects of surface finish and preparation on final coatings. The four samples were prepared as follows:

- a. Machine to 16 micro-inch finish, fire in hydrogen to 2000°C for 5 minutes.
- b. Machine same as "a", electropolish for 3 minutes before firing same as "a".

- c. Same as "a" except dental blast before firing.
- d. Same as "c" except electropolish for 3 minutes before firing.

These samples were photographed, using the scanning electron microscope before coating to record the surface finish and immediately following coating to compare the form of deposition. These photographs are shown in Figures 26 through 33. All samples were coated to a thickness of 25,000 $\text{\AA}$. From these photographs it can be seen that the deposition is completed according to the original surface finish. In general, the better the original surface finish (smoother) the better the chances of getting an impervious coating. Further evaluation was made to determine the effectiveness of sputter coating the tri-layer end-areas. Samples coated showed small void areas adjacent to the alumina layer. Since this is the most critical area, this method was not satisfactory as a coating process. Figure 34 is a photograph of the tri-layer end-area following coating with 25,000 $\text{\AA}$ of Al_2O_3 .

As a result of these studies, it was decided to continue with the alumina/yttria coating developed under contract AT(30-1)-3979, with minor modifications to the firing temperature and improved fixturing for the spray/sintering operation. All module sub-assemblies and components were coated using this application method.

Molybdenum Sample A
Prior to Coating with Al_2O_3 - Magnification - 500X

FIGURE 26

Molybdenum Sample A
After Coating with 25,000 Å of Al₂O₃ - Magnification 500X

FIGURE 27

Molybdenum Sample B
Prior to Coating with Al_2O_3 - Magnification 500X

FIGURE 28

Molybdenum Sample B
After Coating with 25,000 Å of Al_2O_3 - Magnification - 500X

FIGURE 29

Molybdenum Sample C
Prior to Coating with Al_2O_3 - Magnification - 500X

FIGURE 30

Molybdenum Sample C
After Coating with 25,000 Å Al_2O_3 - Magnification - 500X

FIGURE 31

Molybdenum Sample D
Prior to Coating with Al_2O_3 - Magnification - 500X

FIGURE 32

Molybdenum Sample D
After Coating with 25,000 Å Al_2O_3 - Magnification 500X

FIGURE 33

Photograph of Tri-Layer End-Area
Coated with 25,000 Å Al_2O_3 - Magnification 280X

FIGURE 34

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

The development of the internally series connected module concept appears to be a feasible concept for obtaining an output voltage of approximately 28 volts. While the concept was not proven through the actual operation of the working model, successful development of the key module components, such as the integral emitter/collector tri-layer assembly and arc suppression coating, has shown the feasibility of the concept. The successful development of a lithium heat pipe for distribution of the input thermal power has also been shown. The concept design should be modified to gain further thermal stress relief in the collector-to-collector interconnection ring joint to permit E-B welding without risking the integrity of the arc suppression coating. The design might also be modified to permit a stepped approach of emitter to heat pipe assembly in order to eliminate the risk of molybdenum-to-molybdenum seizure during assembly.

APPENDIX A
CONVERTER POWER LOSS ANALYSIS

Assuming

$$T_E = 1450^{\circ}\text{C}$$

$$T_C = 600^{\circ}\text{C}$$

$$\eta = 10\%$$

$$P_{O/\text{conv.}} = 20 \text{ watts}$$

$$A = 5.5 \text{ cm}^2$$

$$\text{H.P. O.D.} = .860$$

$$\text{H.P. I.D.} = .750$$

$$\text{Wick I.D.} = .720$$

$$\text{Power input} = \frac{20 \text{ w}}{\eta} = 200 \text{ watts/conv.}$$

or 47.79 Cal/sec

Emitter tri-layer loss

$$\Delta T_{\text{TRI-EM}} = \Delta T_2 + \Delta T_3 + \Delta T_4$$

$$\Delta T_4 = \frac{Q_c \ln (X_2/X_1)}{k \text{ moly } 2 \pi L}$$

$$\text{at } 1475^{\circ}\text{C}$$

$$k_{\text{moly}} = .21 \text{ cal/sec/cm/}^{\circ}\text{C}$$

$$\ln = \left(\frac{.570}{.495} \right) = .14105$$

$$\Delta T_4 = \frac{(47.79) (.14105)}{(.21) (6.28) (.813)}$$

$$\Delta T_4 = 6.24^{\circ}\text{C}$$

$$\Delta T_3 = \frac{(47.79) (.010147)}{(.028) (6.28) (.813)}$$

$$\text{at } 1475^{\circ}\text{C}$$

$$k_{\text{al203}} = .028 \text{ cal/sec/cm/}^{\circ}\text{C}$$

$$\ln = \left(\frac{.495}{.490} \right) = .010147$$

$$\Delta T_3 = 3.39^{\circ}\text{C}$$

$$\Delta T_2 = \frac{(47.79) (.13014)}{(.20) (6.28) (.813)}$$

$$\ln = \left(\frac{.490}{.430} \right) = .13014$$

$$k = .20 \text{ cal/sec/cm/}^{\circ}\text{C}$$

moly at $\approx 1480^{\circ}\text{C}$

$$\Delta T_2 = 6.09^{\circ}\text{C}$$

$$\Delta T_{\text{TRI-EM}} = 6.09 + 3.39 + 6.24$$

$$= 15.72^{\circ}\text{C}$$

$$\Delta T_5 \cong 1450^{\circ}\text{C} - 600^{\circ}\text{C} \cong 850^{\circ}\text{C}$$

COLLECTOR TRI LAYER LOSS

$$\Delta T_{\text{TRI-COL}} = \Delta T_6 + \Delta T_7 + \Delta T_8$$

$$\Delta T_6 = \frac{Q_c \ln(X_2/X_1)}{k_m 2 \pi L}$$

$$\Delta T_6 = \frac{(47.79) (.1527)}{(.285) (6.28) (.813)}$$

$$\ln\left(\frac{.670}{.575}\right) = .1527$$

$k_{\text{moly at } 600^\circ\text{C}}$
 $= .285 \text{ cal/sec/cm/}^\circ\text{C}$

$$\Delta T_6 = \underline{5.015^\circ\text{C}}$$

$$\Delta T_7 = \frac{(47.79) (.0074)}{(.024) (6.28) (.813)}$$

$$\ln\left(\frac{.675}{.670}\right) = .0074$$

$k_{\text{al}_2\text{O}_3 \text{ at } 600} = .024$

$$\Delta T_7 = \underline{2.89^\circ\text{C}}$$

$$\Delta T_8 = \frac{(47.79) (.1446)}{(.285) (6.28) (.813)}$$

$$\ln\left(\frac{.780}{.675}\right) = .1446$$

$k = .285$

$$\Delta T_8 = \underline{4.746^\circ\text{C}}$$

$$\Delta T_{\text{TRI-COL}} = 5.015 + 2.89 + 4.746 = 12.651^\circ\text{C}$$

HEAT PIPE LOSS

$$\Delta T_{\text{HP}} = \Delta T_{\text{wall}} + \Delta T_{\text{wick}}$$

$$\Delta T_{\text{HPwall}} = \frac{(47.79) (.1355)}{(.2073) (6.28) (.813)}$$

$$\ln\left(\frac{.430}{.375}\right) = .1355$$

$k_{\text{TZM at } 1500^\circ\text{C}}$
 $= .2073 \text{ cal/sec/cm/}^\circ\text{C}$

$$\Delta T_{\text{HPwall}} = \underline{6.12^\circ\text{C}}$$

$$\Delta T_{\text{HPwick}} = \frac{(47.79) (.0816)}{(.164) (6.28) (.813)}$$

$$\ln\left(\frac{.375}{.360}\right) = .0816$$

$k = .164 \text{ moly screen}$

$$\Delta T_{\text{HP}} = 6.12 + 4.66 = 10.78^\circ\text{C}$$

THUS

TOTAL ΔT FROM INSIDE H.P. TO EMITTER

$$\Delta T_T = \Delta T_{HP} + \Delta T_{TRI-EM}$$

$$\Delta T_T = 10.78 + 15.72$$

$$\Delta T_T = 26.50^\circ\text{C}$$

$$\text{LOSS/CONVERTER} = Q_{\text{CONV.}} + Q_{\text{CS}} + Q_{\text{RAD}}$$

$$Q_{\text{CONV.}} = 200 \text{ watts}$$

$$Q_{\text{CO}} = 10.52 \text{ watts}$$

$$Q_{\text{Rad/Connector Lead}} = 7.06 \text{ watts} \\ (\text{internal})$$

$$Q_{\text{TOTAL}} = \underline{217.58 \text{ watts/converter cell}}$$

RADIATION LOSS FROM END LEAD

(LEAD TO HEAT PIPE SECTION)

$$Q = \frac{A \sigma (T_1^4 - T_2^4)}{\left(\frac{1}{e_1} + \frac{1}{e_2} - 1 + \frac{1}{e_2} + \frac{1}{e_3} - 1 \right)}$$

$$\begin{aligned} e_1 &= .42 \\ e_2 &= .32 \\ e_3 &= .12 \\ A &= 8.7 \text{ cm}^2 \end{aligned}$$

$$Q_{\text{EL}} = \underline{27.1 \text{ watts}}$$

RADIATION LOSS, HEAT PIPE TO SHELL

$$\begin{aligned} e_1 &= .42 \\ e_2 &= .12 \\ A &= 13.05 \text{ cm}^2 \end{aligned}$$

$$Q_{\text{H-S}} = \underline{62.6 \text{ watts}}$$

RADIATION LOSS, END BELLOWS TO HEAT PIPE

$$\begin{aligned} e_1 &= .42 \\ e_2 &= .21 \\ A &= 34.5 \text{ cm}^2 \end{aligned}$$

$$Q_{\text{EB-HP}} = \underline{219.3 \text{ watts}}$$

END LEAD CONSTRUCTION

$$Q_{CL} = \frac{k A \Delta T}{L}$$

$$L \cong 2.54 \text{ cm}$$

$$A = .3119 \text{ cm}^2$$

$$k = .32 @ 310^\circ\text{C} \text{ mean}$$

$$Q_{CL} = \underline{22.39 \text{ watts}}$$

thus total Converter Power Loss for 10 Converter Module

$$A. \quad 10 \text{ conv.} \times Q_T = 10 \times 217.58 = 2175$$

$$B. \quad \text{END SLEEVES} = (Q_{EL} + Q_{HS}) 2 = 178$$

$$C. \quad \text{END BELLOWS} = 217 \times 2 = 434$$

$$D. \quad \text{POWER LEAD} = 2 \times 23 = \underline{46}$$

TOTAL LOSS 2833 WATTS

APPENDIX A

Respective Radii

A = 0.430 in.,	1.092 cm
B = 0.490	, 1.245
C = 0.495	, 1.257
D = 0.570	, 1.448
E = 0.575	, 1.460
F = 0.670	, 1.702
G = 0.675	, 1.715
H = 0.780	, 1.981
J = 0.517	, 1.313
K = 0.320	, 0.813
L = 0.197	, 0.50