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CONTRACT AT(30-1)-3979
ADVANCED HEAT PIPE
THERMIONIC TECHNOLOGY

FINAL TECHNICAL REPORT
FOR
TASK I
"DEVELOPMENT OF HIGH VOLTAGE MODULE"
AUTHOR - R. W. LONGSDERFF

PERIOD OF PERFORMANCE
MAY 1, 1968 THROUGH SEPTEMBER 30, 1969

PREPARED FOR:
U. S. ATOMIC ENERGY COMMISSION
NEW YORK OPERATIONS OFFICE
NEW YORK, NEW YORK

BY
RCA CORPORATION
ELECTRONIC COMPONENTS
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)-3979 entitled, "Advanced Heat Pipe Thermionic Technology". The program was monitored by Mr. Lester Price of the Space Nuclear Systems Division, Germantown, Maryland.

This Final Technical Report covers the work performed since program inception, 1 May 1968 through 30 September 1969. The studies and accomplishments presented herein represents the efforts of the Special Power Devices Engineering Department. Mr. W. E. Harbaugh, Project Engineering Leader, provided technical direction for the program. Mr. R. W. Longsdorff, Project Engineer for the program, directed a group of technical personnel in performance of the actual program of work.

ABSTRACT

The design of a heat pipe-thermionic module concept capable of output potentials as high as 28 volts has been investigated. Technologies required for this module design have been developed beyond the state-of-the-art. An advanced Al_2O_3 casting technique was developed for the fabrication of the key insulated tri-layer assembly. Arc suppression coatings have been developed for the prevention of voltage arcs in the module due to potentials above the ionization potential of cesium. Fabrication and assembly techniques necessary for the logical development of the high voltage module concept have also been investigated. Heat pipe designs capable of transferring the required thermal through-put for high voltage module concepts have also been investigated.

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TASK I - DEVELOPMENT OF HIGH VOLTAGE MODULE
(Responsible Person - R. W. Longsderff)

SECTION I

INTRODUCTION

This report describes RCA's efforts to develop technology pertinent for the development of a high voltage thermionic module. The basic design concept consists of individual thermionic diode assemblies mounted on a common heat pipe and internally series connected by a flexible high temperature lead. This concept is shown in Figure 1. The emitter section of each diode section is electrically insulated from but thermally bonded to the center heat pipe by a cast alumina layer. The collector section of each diode is similarly insulated from a common outer containment tubing.

The design technology includes (1) alumina casting techniques, (2) arc suppression coatings (cesium ionization potential is 3.89 volts), (3) interconnecting series leads and (4) techniques for maintaining adequate interelectrode spacing for a long string (up to 56 diodes) of series connected converter sections.

The design objective of the high voltage module is to provide a useful output voltage (28 volts) without the aid of power conditioning and/or external series connection of individual units.

FIGURE 1 PHOTOGRAPH OF BASIC HIGH VOLTAGE MODULE
DESIGN CONCEPT

SECTION II

PROGRAM ACCOMPLISHMENTS

A. Electrode Technology (Responsible Person - R. W. Longsderff)

Considerable effort was expended to develop technology which permits insulated electrode assemblies to be fabricated on a repetitive basis. This effort included work in the areas of alumina casting, weld tests of cast alumina layers, interelectrode lead development and finish machining techniques.

1. Casting Techniques

The major effort was devoted to the refinement of the previously developed vacuum casting technique. This technique is described in the block diagram shown in Figure 2. The casting assembly was first heated to the melting temperature of alumina in an atmosphere of six parts helium to one part hydrogen. The exhaust port on the lower side of the casting was sufficiently pressurized to hold the alumina in the reservoir until complete melting occurred. The line was then evacuated, drawing the liquid alumina into the capillary area. This process is completed when the alumina solidifies at the heat sink on the exhaust port thereby prohibiting further flow of liquid alumina. A cross-sectional drawing of the casting assembly is shown in Figure 3. Although this technique produced good quality alumina layers, additional tests were performed to gain control of casting parameters such as optimum temperature, helium back pressure, optimum casting orifice geometry.

Tests, designed to evaluate the effect of temperature on the casting quality, showed that higher temperature (2080° C or greater) produced

FIGURE 2 SCHEMATIC DIAGRAM OF VACUUM CASTING TECHNIQUE

FIGURE 3 CROSS-SECTIONAL DRAWING OF VACUUM CASTING

void areas and small bubble formations in the alumina layer. It is believed that these void areas develop when sporadic, uneven flow (due to lower alumina viscosity) encapsulates gas pockets in the capillary area. The small bubble formations are formed by reduction of Al_2O_3 and outgassing of the molybdenum casting assembly. A more thorough cleaning and pre-firing of parts plus the use of pure sapphire chips has reduced the formation of bubbles. An example of these small bubbles can be seen in the microphotograph of Figure 4. An optimum temperature of $2050^{\circ}C (\pm 10^{\circ}C)$ has been established. At this temperature, adequate support of the liquid can be maintained with little or no reduction of the Al_2O_3 . Figure 5 is a photomicrograph showing a sound vacuum cast tri-layer.

When helium back pressure is increased to the point where bubbling takes place in the liquid alumina, small bubble like voids are introduced into the alumina layer. Back pressure must, therefore, be controlled to provide adequate support of the fluid but not great enough to introduce bubbles in the liquid alumina. This optimum back pressure is somewhat dependent upon the orifice geometry at the entrance to the capillary. Large area openings make it difficult to support the liquid alumina until melting is complete. An orifice, which consists of the slip-fit of the two concentric cylinders, aids in the support of the fluid but limits the flow of the liquid into the capillary. An orifice design of eight flats, equally spaced on the inner molybdenum cylinder, has provided an adequate orifice geometry.

Castings were fabricated using these established parameters. Electrode samples were cut from the castings and used for further electrode developmental testing.

FIGURE 4 PHOTOMICROGRAPH OF VACUUM CAST
ALUMINA TRI-LAYER SHOWING SMALL
BUBBLES RANDOMLY DISPERSED IN
ALUMINA LAYER (Indirect Light, 260 X)

FIGURE 5 PHOTOMICROGRAPH OF VACUUM CAST ALUMINA TRI-LAYER (INNER SLEEVE REMOVED) FREE OF VOIDS AND BUBBLES. END BROKEN AWAY TO REVEAL ALUMINA THICKNESS

2. Electrode Fabrication

Following the development of a satisfactory casting technique, electrode assemblies were fabricated using cast assemblies produced by this technique. Electrode assemblies were fabricated by cutting sections, approximately one-quarter inch in length, from the cast assembly. These sections are cut using an abrasive cutting wheel, preferably Allison No. GC120 or Beuhler No. 4110, to prevent chipping or pull-out of the alumina in the tri-layer. Most sections exhibited an impedance of 1000 ohms or greater following initial cutting. Voids in the casting promotes deposition of metal across the capillary area. Hydro-blasting of these areas removes this metal. However, end void areas create additional problem areas for voltage stand-off. Therefore, only cast sections completely free of voids can be considered for use in the fabrication of electrode assemblies.

Machining of the tri-layer assembly is complicated by the presence of the 0.005 inch thick alumina layer. Techniques have been developed which permit machining to be completed with little or no pull-out or chipping of the alumina. The importance of a void free, solid alumina layer in the end areas has been demonstrated by voltage hold-off tests conducted for the U.S. Air Force.⁴ Voltages, up to 50 volts DC, were applied across the tri-layer while subjected to 1500° C temperature. In most samples, voltage breakdown occurred in the end areas. The quality of the machining of the tri-layer is largely dependent upon the quality of the alumina layer. Spongy porous alumina chips-out in ragged edges when machined. However, solid nonporous alumina layers can be machined to dimension with little or no chip-out. A cross-sectional drawing of the electrode assembly, as machined, is shown in Figure 6. A photograph of a complete electrode assembly is shown in Figure 7.

FIGURE 6 CROSS-SECTIONAL DRAWING OF EMITTER/COLLECTOR TRI-LAYER ELECTRODE ASSEMBLY

FIGURE 7 PHOTOGRAPH OF EMITTER/COLLECTOR
TRI-LAYER ELECTRODE ASSEMBLY

The electron beam welding of the emitter and collector tri-layer assemblies to the interconnecting lead must produce sound mechanical joints without destroying the alumina layer in the weld area. Alignment of the lead to the electrodes is very critical.

The electrode assembly technique involves the welding of the emitter-lead-collector assembly prior to the slotting of the lead. The weld fixture, shown in Figures 8 and 9, has proven to be completely satisfactory for this operation. Electrode assemblies were successfully fabricated using this technique. Tolerances of ± 0.0002 inch were maintained on electrode concentricity. No thermal damage was experienced at the alumina layer due to welding of the interelectrode lead. Figure 10 is a microphotograph showing the weld area including the alumina layer.

Weld tests were conducted primarily to determine if damage to the alumina tri-layer occurs during normal electron beam welding. Assemblies were welded using an electron beam welding schedule of 65 kilovolts at 6 milliamperes and at a part rotation of 20 rpm. This schedule produced more local heating than the normal schedule of 70 kilovolts at 6 milliamperes and at a part rotation of 30 rpm. However, no damage to the cast alumina layer was observed.

Weld tests were also conducted to determine whether leads could be slotted before welding thereby simplifying the slotting process described in later paragraphs. Tests, using slotted leads, produced some buckling

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

FIGURE 9 WELDING FIXTURE FOR EMITTER/COLLECTOR
SUB-ASSEMBLY

FIGURE 10 PHOTOMICROGRAPH SHOWING WELD OF INTER-
CONNECTING LEAD TO ALUMINA TRI-LAYER (40X)

and fold-back of the leads at the point of welding. The fold-back occurs due to the difference in mass between the electrode member and the lead. The addition of a weld detail on the electrode member will reduce this distortion during welding.

The interelectrode lead previously mentioned forms the series connection between the collector and the higher temperature emitter. Therefore, it is necessary that this lead be designed with an area to length ratio which prohibits excessive electrical losses and excessive thermal losses from emitter to collector. An optimization of the lead area to length ratio can be established by slotting the lead as shown in Figure 11. By varying the number of slots, slot length and slot thickness, an optimized area/length relationship can be established.

The interelectrode lead used for operation of a 1450° C emitter, (used in the initial module design) was optimized by employing 0.005 inch thick molybdenum having six 0.85 inch long slots, 0.015 inch wide. These slots are spiraled and over-lap each other by approximately 50% as shown in Figure 11. The width of the slot is approximately 0.100 inch. Slotting tests, using the electrical discharge cutting technique, were performed. This method has proven successful in that accuracy can be maintained without experiencing severe mechanical stress. However, this technique becomes quite complex when slotting is done after welding of the lead to the electrode assemblies. A welding technique, which permits welding of the lead to the electrodes after slotting, is desirable.

B. Cast Alumina Technology

The cast alumina tri-layer technology is the key to the high voltage module concept. Cast alumina has been used to insulate the emitters of multi-converter modules from the central heat source. Although the tri-layer was exposed to

Before Slotting

After Slotting For
Lead Correction

FIGURE 11 CROSS-SECTIONAL DRAWING OF INTER-ELECTRODE LEAD

cesium, there was no voltage impressed across the tri-layer during these tests. In other tests, tri-layer elements held off 30 volts in vacuum at 1600° C while conducting thermionic input heat fluxes greater than 30 watts per square centimeter.⁵ Further evaluation of the tri-layer was necessary to determine the voltage hold-off capabilities in a cesiated atmosphere over the range of temperatures employed in the high voltage module concept.

A test vehicle was designed and fabricated for tri-layer assembly testing. A cross-section of the test vehicle is shown in Figure 12. A photograph of the test vehicle is shown in Figure 13. This test vehicle, which utilizes a heat pipe to supply the heat input to the tri-layer assembly, is designed to permit calorimetric measurements of heat flux through the tri-layer assembly. Cesium pressure can be varied over the entire range of thermionic pressure by use of an external liquid cesium reservoir. Voltage can also be applied across the alumina layer since the heat pipe and calorimeter are separated by a ceramic insulator.

As a result of a crack which developed in the molybdenum window flange during welding, the window was removed and a metal closure made to complete the cesium envelope.

The test sample was coated at both ends with an arc suppression coating to prevent cesium from entering the alumina layer and to extend the insulating path beyond the 0.005 inch thickness of the alumina layer. This coating is described in later paragraphs.

The design goals for this test were: (1) voltage hold-off of 30 VDC, (2) heat transfer of 30 watts per square centimeter through the alumina layer. These conditions were achieved at an emitter temperature of 1450° C and 4 mm Hg cesium pressure. The 30 watts/cm² is based upon a converter performance

FIGURE 12 CROSS-SECTIONAL DRAWING OF CAST ALUMINA TEST VEHICLE

FIGURE 13 CAST ALUMINA TEST VEHICLE
(Photograph Taken During Test)

of 4 watts/cm² at an efficiency of 12%. The ΔT through the alumina tri-layer was assumed to be less than 25° (actual measurements were taken previously).

The results of this test are presented in Table I. Voltage-current characteristics were measured at temperatures ranging from 1200 to 1500° C and at cesium pressures ranging from 0.1 to 20 mm Hg. These volt-ampere measurements were taken using a Tektronix Model 122C curve tracer with a 50 ohm current limiting resistor in series with the applied voltage. Volt-ampere curves at emitter temperatures, ranging from 1200° - 1500° C and a cesium temperature of 300° C are shown in Figure 14. Figure 15 shows the effect of cesium pressure on the volt-ampere curve for 1450° C emitter temperature. Data was also taken with the cesium reservoir held at a temperature below the solidification temperature of cesium. Under these conditions, voltage and current measurements were recorded in order to calculate the electrical resistivity of the alumina layer as a function of temperature. The results are presented in Figure 16. The data is in good agreement with data published in the WADC Technical Report 58-476, Volume III, Thermophysical Properties of Solid Materials-Ceramics".² It must be noted however, that current instability does occur at a particular temperature and applied voltage. For example, at 1600° C, current instability occurs at voltages as low as 20 volts, at 1500° C, 30 volts can be held-off with no current instability. It is believed that a current avalanche, similar to that noted in semiconductors, is produced largely due to the impurities impounded in the alumina layer.

The results of this test show that a 0.005 inch thick alumina layer can be used as an insulating method to temperatures of 1500° C when the applied voltage does not exceed 30 volts. Higher voltages can be held-off at lower temperature. The results also indicate that adequate arc suppression at typical cesium pressures can be achieved by sealing the end areas of the tri-layer assembly with a high temperature arc suppression coating.

TABLE I TRI-LAYER VOLTAGE HOLD-OFF TEST RESULTS

<u>Sample Temperature</u>	<u>Cesium Temperature</u>	<u>Sample Positive</u>		<u>Sample Negative</u>	
		<u>Voltage</u> VDC	<u>Current</u> Ma	<u>Voltage</u> VDC	<u>Current</u> Ma
1200° C	200° C	30	18.5	30	34
	300	30	19.5	30	37
	400	30	19.5	30	39
1300° C	200	30	39		56
	300	30	42		59
	400	30	45		65
1400° C	200	30	110		275
	300	30	121		270
	400	30	129		290
1450° C	200	30	300		490
	300	30	315		480
	400	30	350		485
1500° C	200	30	520		685
	300	30	522		682
	400	30	530		688
1550° C	200	30	750*		1500*
	300	30			
	400	30			

* Not stable, current runaway experienced.

FIGURE 14 VOLT AMPERE CURVES FOR ALUMINA LAYER AT 1200° -1500° C AND A CESIUM RESERVOIR TEMPERATURE OF 300° C

FIGURE 15 VOLT AMPERE CURVES FOR ALUMINA LAYER AT 1450°C

FIGURE 16 ELECTRICAL RESISTIVITY OF ALUMINA

The fact that higher current flow is observed, (depending upon polarity) is an indication that the electrical resistivity of the alumina layer is not stable over longer life operating schedules. The voltage/temperature dependency for current stability is also an indication that alumina purity is an important factor in long term current stability.

C. Ceramic Spacer Technology

The design criteria of the high voltage module concept necessitates use of high strength alumina rings for spacing of electrode assemblies. These rings also aid in the shielding of adjacent areas having a difference in potential.

A study of materials, which qualify for the established design criteria shows that high purity alumina and yttria ceramics can be considered as good candidates for this application.³

The use of single crystal Al_2O_3 or Y_2O_3 has been eliminated because of the difficulty and cost of fabrication with respect to the advantages over alumina or yttria. The ability to fabricate high purity alumina ceramics in varying geometries has been demonstrated in previous ceramic work for fossil-fuel fired thermionic systems. Alumina, therefore, was selected as the material for evaluation.

The ceramic spacer design and application is shown in Figure 17. The ceramic spacer is located between two adjacent emitter assemblies during assembly of the module components on the common heat pipe. Ceramic spacer tolerances must be adequate to accommodate the inherent difference in thermal expansion between the molybdenum heat pipe and emitter section versus the alumina spacer.

FIGURE 17 CROSS-SECTIONAL DRAWING OF
MODULE CERAMIC SPACER/
COLLECTOR CLOSURE

A ceramic spacer, fabricated from high purity alumina powder by a hydrostatic pressing/sintering technique, was evaluated in the same test vehicle used for the tri-layer evaluation. The spacer was fabricated with a clearance tolerance of 0.002 inches at 1500° C heat pipe temperature. The spacer was then placed between the test tri-layer sample and a molybdenum ring to simulate the actual application. No detrimental effects were observed during testing.

The results of this test have provided adequate evidence that sintered alumina spacers can be used for this application.

D. High Voltage Coating Technology

The high voltage module concept provides that certain internal portions of the module be at maximum output potential difference while exposed to cesium vapor at elevated temperatures. Therefore, it is necessary to prevent arcs from occurring between these sections by coating them with a layer of insulation.

The predominant use of molybdenum as a base metal in the module system adds complexity to the coating development because of the inherent low thermal expansion of molybdenum.⁸ Proven materials, such as aluminum oxide, have a much higher rate of thermal expansion.³ The complexity is increased by the fact that material compatibility with cesium vapor at elevated temperature (1350-1450° C) is required thus ruling out many of the known low thermal expansion coating materials such as zircon, fused quartz, silicides, etc.

A program, having an objective to develop an "enamel" type coating suitable for application on molybdenum and capable of operating to

temperatures as high as 1500° C in a cesiated atmosphere was pursued. This coating must be capable of withstanding thermal cycling from ambient to maximum temperature and present an electrical resistivity of not less than 1×10^3 ohm-cm at maximum temperature.

Because of the probability of having a thermal expansion gradient between the coating and the molybdenum, a thin (0.001-0.003 inch) coating is necessary to prevent cracking or crazing. The quality of a thin coating is extremely critical since common defects such as bare spots, cracks, craze lines, pinholes, bubbles, etc. provide unprotected areas on the base metal. Heavier coatings (0.008 inch-0.010 inch) are more tolerant of these defects since successive layers can bridge most of these common defects.⁶ Thus, the thickness and quality of the coating are dependent upon the degree of thermal expansion match which can be achieved.

Efforts were then directed to develop a coating which matched the thermal expansion of molybdenum or be tolerable of thermal mismatch at reasonable thicknesses. Test samples of various coatings were melted or sintered to one side of thin molybdenum strips to determine the relative thermal mismatch by the degree of bending exhibited by the thin molybdenum strip. Tests were conducted using alumina/yttria, alumina/yttria/zirconia and pure alumina. In all cases, definite bending was observed after firing. The bending was in a concave direction on the coated side, indicating a state-of-tensile stress in the coating.

In another series of tests, discs of various ceramic composition¹ were melted in drawn molybdenum cups. Flow characteristics as well as adherence and wetting to the molybdenum cup were observed. The results of these tests are presented in Table II. While these tests are somewhat elementary, a

TABLE II ARC SUPPRESSION COATING TEST RESULTS

<u>Sample Number</u>	<u>Composition Weight %</u>	<u>Firing Temperature° C and Time (H₂)</u>	<u>Comments/Results</u>
2	100 % Al ₂ O ₃	1900, 5 min.	Wets moly with fair adherence, clear and glossy, severely crazed at edges.
3*	60 % Al ₂ O ₃ 40 % Y ₂ O ₃	1900, 5 min.	Wet moly with good adherence, white glossy, crazed at edges.
4	61.25 % Y ₂ O ₃ 30.00 % Al ₂ O ₃ 8.75 % Zr ₂ O ₃	1900, 5 min.	More fluid than #3, good wetting and adherence, white crystalline, no crazing.
5	90 % Al ₂ O ₃ 9.9 % Y ₂ O ₃ 0.1 % Cr ₂ O ₃	1825, 5 min.	Wets moly very well, dark but glossy, good adherence, no crazing.

* Eutectic Composition

a broad knowledge of composition fit to molybdenum was provided by visual observation of the properties of interest.⁷

A series of tests were conducted using one-quarter inch diameter molybdenum tubing as the test sample. Pieces, 1-2 inches in length, were coated with sample compositions of interest. Following preliminary elimination of several compositions, six sample compositions were tested more extensively to refine compositions in order to conform more closely to the established design goals. The results of these tests are presented in Table III. Photographs of two samples, made by use of a scanning electron microscope, are shown in Figures 18 thru 21. The melt patterns observed were due to shrinkage following firing. These lines can be reduced by additional high temperature firing to the melting point of the coating. Samples 1, 2, 4 and 7 were chosen for test in the cesiated test vehicle shown in Figure 22. The lower ends of the samples were sealed by welding the support lead. The upper ends were sealed using a high alumina ceramic plug. The spacing from the coated samples to the test vehicle electrodes was set at 0.200 inch. The results of this test were nonconclusive due to a leakage problem at the lead support of the samples. However, the fact that the samples remained free of cracks following extensive thermal cycling and exhibited no evidence of cesium incompatibility provided support to warrant the use of the best sample (No. 2) for the coating of the tri-layer ends for further test.

The tri-layer test, previously described, was coated on both ends with Coating No. 2. The results of this test were also previously described herein.

Analysis of this test shows that the coating remained intact and resisted thermal cracking and peeling. The mode of failure is believed to have been

TABLE III ARC SUPPRESSION SAMPLE COMPOSITION TEST RESULTS

Sample Number	Coating Sequence/ Accumulative Thickness - in.	Method of Application	Firing Temp °C	Time at Temp.-min.	Atmosphere	Results/Comments
1.	a. Al_2O_3 (0.0005)	Spr/Sin	1820	5	H ₂	Wetting to molybdenum good, adherence good, gray glossy, no crazing after vacuum firing. Electrolosis Check (35 ma at 30 volts)
	b. Al_2O_3 (0.001)	Spr/Sin	1800	5	H ₂	
	c. C47 (0.002)	Spr/Sin	1800	5	H ₂	
	d. C374C (0.003)	Spr/Sin	1800	5	H ₂	
	e. Al_2O_3/Y_2O_3 (0.0035)	Spr/Sin	1800	5	H ₂	
	f. Al_2O_3/Y_2O_3 (0.004)	Spr/Sin	1800	5	H ₂	
	Fired		1775	5	Vac	
2.	a. Al_2O_3 (0.0005)	Spr/Sin	1820	5	H ₂	Wetting to molybdenum good, adherence good, light gray glossy, definite surface melt, no crazing. Electrolosis Check (3.5 ma at 30 volts)
	b. Al_2O_3 (0.001)	Spr/Sin	1800	5	H ₂	
	c. C374C (0.0025)	Cataphoretic	1800	5	H ₂	
	d. Al_2O_3/Y_2O_3 (0.0035)	Spr/Sin	1800	5	H ₂	
	e. C374C (0.0045)	Cataphoretic	1800	3	H ₂	
	f. Al_2O_3/Y_2O_3 (0.005)	Spr/Sin	1800	3	H ₂	
	Fired		1775	5	Vac	
3.	a. Al_2O_3 (0.0005)	Spr/Sin	1820	5	H ₂	Wetting to molybdenum good, adherence good, gray glossy, some surface melt, some crazing evident. Electrolosis Check (65 ma at 30 volts)
	b. Al_2O_3 (0.001)	Spr/Sin	1800	5	H ₂	
	c. C47 (0.002)	Spr/Sin	1800	5	H ₂	
	d. Al_2O_3/Y_2O_3 (0.003)	Spr/Sin	1800	5	H ₂	
	e. C47 (0.004)	Spr/Sin	1800	3	H ₂	
	f. Al_2O_3/Y_2O_3 (0.0045)	Spr/Sin	1800	3	H ₂	
	Fired		1775	5	Vac	

TABLE III (Continued)

Sample Number	Coating Sequence/ Accumulative Thickness - in.	Method of Application	Firing Temp °C	Time at Temp -min.	Atmosphere	Results/Comments
4.	a. Al_2O_3 (0.0005)	Spr/Sin	1820	5	H_2	Wetting to molybdenum good, adherence good, dark gray glossy, good surface melt, some crazing evident. Electrolosis Check (45 ma at 30 volts)
	b. Al_2O_3 (0.001)	Spr/Sin	1800	5	H_2	
	c. C374(0.002)	Spr/Sin	1800	5	H_2	
	d. C374(0.003)	Spr/Sin	1800	5	H_2	
	e. Al_2O_3 (0.0035)	Spr/Sin	1800	5	Vac	
	f. Al_2O_3/Y_2O_3 (0.0045)	Spr/Sin	1750	5	Vac	
5.	a. Al_2O_3 (0.0005)	Spr/Sin	1820	5	H_2	Wetting to molybdenum good, adherence good, light gray, very glossy, complete surface melt, moderate crazing. Electrolosis Check (85 ma at 30 volts)
	b. Al_2O_3 (0.001)	Spr/Sin	1800	5	H_2	
	c. C47 (0.0025)	Cataphoretic	1800	5	H_2	
	d. C47 (0.0035)	Cataphoretic	1800	5	H_2	
	e. Al_2O_3/Y_2O_3 (0.0045)	Spr/Sin	1800	5	H_2	
	f. Al_2O_3/Y_2O_3 (0.0055)	Spr/Sin	1800	5	Vac	
6.	a. Cr(0.0002)	Vapor Depos.	1200	5	H_2	Wetting to molybdenum good, adherence good, light pink and glossy, some surface roughness sporadically over coated area. Electrolosis Check (82 ma at 30 volts)
	b. Al_2O_3 (0.00075)	Spr/Sin	1750	5	H_2	
	c. Al_2O_3 (0.0015)	Spr/Sin	1750	5	H_2	
	d. Al_2O_3 (0.003)	Spr/Sin	1750	5	H_2	
	Fire		1700	5	Vac	

TABLE III (Continued)

<u>Sample Number</u>	<u>Coating Sequence/ Accumulative Thickness - in.</u>	<u>Method of Application</u>	<u>Firing Temp °C</u>	<u>Time at Temp-min.</u>	<u>Atmosphere</u>	<u>Results/Comments</u>
7.	a. Al_2O_3 (0.0003)	Spr/Sin	1820	5	H_2	Wetting to molybdenum good, adherence good, light gray glossy, surface melt, no crazing. Electrolosis Check (0 ma at 30 volts)
	b. Al_2O_3 (0.001)	Spr/Sin	1800	5	H_2	
	c. C374C(0.002)	Spr/Sin	1800	5	H_2	
	d. Al_2O_3/Y_2O_3 (0.003)	Spr/Sin	1800	5	H_2	
	e. C374C(0.004)	Spr/Sin	1800	5	H_2	
	f. Al_2O_3/Y_2O_3 (0.0045)	Spr/Sin	1800	5	H_2	
	Fire		1775	5	Vac

FIGURE 18 SCANNING ELECTRON MICROSCOPE PHOTOGRAPH
OF COATING SAMPLE NO. 1 (100X)

FIGURE 19 SCANNING ELECTRON MICROSCOPE PHOTOGRAPH
OF COATING SAMPLE NO. 1 (500X)

FIGURE 20 SCANNING ELECTRON MICROSCOPE PHOTOGRAPH
OF COATING SAMPLE NO. 2 (100X)

FIGURE 21 SCANNING ELECTRON MICROSCOPE PHOTOGRAPH
OF COATING SAMPLE NO. 2 (500X)

FIGURE 22 CROSS-SECTIONAL DRAWING OF ARC SUPPRESSION TEST VEHICLE

destruction of the coating in the alumina layer area due to an electrical arc. A voltage of 70 volts was placed across the tri-layer immediately prior to the complete breakdown on the coating. The pitted coating area is shown in Figure 23.

In summary, while a coating which met the design objectives was developed, it must be noted that the process is somewhat lengthy and critical since routine cracks, bare spots or craze lines can not be tolerated. Also, the fact that the coating does not match the molybdenum from a thermal expansion point of view. Thickness becomes an important factor. In view of this, an effort to refine and improve this coating should be continued.

E. High Voltage Module Assembly Techniques

The basic module assembly technique developed employs complete sub-assemblies which can be machined to close tolerance after electron beam welding or brazing and assembled onto the heat pipe. All closures are made by electron beam welding except the ceramic-to-metal seal subassembly.

The major sub-assemblies and their order of assembly is shown in Figure 24. These sub-assemblies include the upper and lower end cap sub-assemblies, shown in Figures 25 and 26, and the integral emitter-collector tri-layer assembly.

The most critical module assembly technique requirement is the establishment of accurate interelectrode spacing (0.008 inch). The fact that sub-assemblies can be post weld machined provides uniformity of sub-assemblies plus repeatable stack height dimensions. The interelectrode spacing is fixed on individual emitter/collector units as they are stacked in place for electron-beam welding. This fixture is shown in Figure 27.

FIGURE 23 PHOTOGRAPH OF TRI-LAYER/ARC SUPPRESSION
COATING TEST SAMPLE AFTER TEST

FIGURE 24 CROSS-SECTIONAL DRAWING OF MODULE ASSEMBLY DESIGN

FIGURE 25 CROSS-SECTIONAL DRAWING OF UPPER
END-CAP SUB-ASSEMBLY

FIGURE 26 CROSS-SECTIONAL DRAWING OF LOWER END-CAP SUB-ASSEMBLY

FIGURE 27 CROSS-SECTIONAL DRAWING OF
INTERELECTRODE SPACING FIXTURE

A second criteria required for an acceptable assembly technique is an adequate bond between the emitter tri-layer assembly and the heat pipe. Results of bond tests conducted showed that adequate bonding can be achieved with reasonable parts tolerance (0.002 - 0.003 inches/diameter). The fact that the heat originates from the inside diameter of the module is an advantage which permits this tolerance.

Deletion of the outer collector closure sleeve eliminates the bond requirement between the collector and the heat sink thus, the heat sink can be directly attached to the collector outer sleeve. This design is shown in Figure 28.

F. Heat Pipe Development

A preliminary heat pipe design was established and used as the basis for sizing other module elements. This design is based on a 14 volt, 600 watt (30 converters, 4 watts/cm², 5 cm²/converter) module system. While a 28 volt module system is the ultimate design goal, an interim design is desirable in order to develop technology necessary for a 28 volt system. Components, sized for the 14 volt system design, do not necessitate use of abnormally sized materials. Material and fabrication costs can thus be held to more reasonable levels while achieving a more thorough technology development.

The heat pipe design for a 14 volt module system has a geometry of 0.860 inch diameter x 26 inches overall length. The required gross heat throughput is approximately 8.5 kilowatts based on the preliminary module design previously described. This is based on a converter efficiency of 10% and miscellaneous losses of 2.5 kilowatts. The theoretical maximum power throughput capability of the heat pipe is approximately 12 kilowatts.

FIGURE 28 CROSS-SECTIONAL DRAWING OF MODULE DESIGN WITH COLLECTOR CONTAINMENT TUBING ELIMINATED

The heat pipe used for initial system feasibility evaluation will be of the same diameter as that required for the 14 volt module system but, shorter in length to accomodate a 5 volt module system. A cross-sectional drawing of this heat pipe is shown in Figure 29. All components have been sized around this diameter for adequate system versatility. The heat pipe envelope is made of TZM molybdenum alloy and a molybdenum mesh will be employed for the capillary structure. Lithium working fluid will be used.

Other heat pipe designs have been investigated, using computer analysis, to determine heat pipe diameters and length required for transfer of adequate power for a 28 volt module system. The minimum diameter required for transfer of an adequate heat flux in a 28 volt, 2 kilowatt module, is approximately 1.400 inches. The length of the heat pipe will be approximately 48 inches. This 28 volt design will be reviewed and modified as technology becomes more defined through testing of the smaller system.

G. Module Design

A preliminary module design has been established based on the previously described heat pipe design. The initial module includes 10 converter sections each having an emitter area of 5 cm^2 . The predicted module performance is expected to be 200 watts at an output potential of 5 volts. By varying the load impedance, voltages as high as 8 volts can be attained. This voltage level, which is considerably above the 3.89 volts ionization potential of cesium, will suffice as a practical demonstration to prove the feasibility of the high voltage approach. Ten converter sections are also adequate for the evaluation of the electrode alignment and inter-cell connection techniques. All component elements to be used for the various technology developments will be based on this preliminary design. A cross-sectional drawing of this module concept is shown in Figure 28.

FIGURE 29 CROSS-SECTIONAL DRAWING OF HEAT PIPE DESIGN

SECTION III

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