Quarterly Progress Report

1 April to 31 May 1966

HIGH-TEMPERATURE, ZERO-DROP THYRATRON TUBE PROGRAM

Prepared for
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California
Attention: Mr. D. C. Maginski

Contract 951352

EOS Report 7016-Q-2 15 June 1966

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This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

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1. INTRODUCTION

1.1 General

This second quarterly report covers the period from 1 April to 31 May 1966, and describes work on JPL Contract 951352. It should be noted that in the interest of bringing the reporting schedule more in line with the original plan, the period covered in this quarterly is two months and not three months.

The 12-month contract is concerned with the development of a high-temperature power conditioning system for a 150-watt thermionic converter generator consisting of thyratrons, a high-temperature transformer, and associated circuitry. Two schemes are to be investigated: (1) high-temperature ceramic thyratrons and a high-temperature-inverter-transformer to be mounted directly behind the thermionic converter generator to eliminate the need for high-current bus bars from the generator to the load (a low-current, low-temperature grid-drive circuit will be located a safe distance from the heat source); and (2) high-temperature, ceramic thyratrons to be mounted directly behind the thermionic-converter generator but connected to a low-temperature transformer and grid circuit by high current bus bars. In both approaches, the thyratron cathode will be heated by thermal energy from the generator cavity, the thermal energy will be absorbed by the thyratron being used to provide electron emission and work function adjustment to effect zero-drop operation. This thermal energy would normally be considered rejected heat from the solar concentrator.

The program was divided into two phases. The first phase, originally of three months' duration, was an analytical study of both schemes. The study compared the relative merits of the integrated tube and transformer approach with the more conventional low-temperature transformer approach. It will also include the design, fabrication, and testing of a low-current cesium device to determine deionization times and other discharge parameters to be expected in the thyratron. Quantitative knowledge of such parameters is not available in the literature. Due to some difficulties in the fabrication of the deionization time test device, Phase I actually extended for five months; and Phase II has been reduced to seven months' duration. This change in scheduling was negotiated in the last period. Phase II has been started after JPL approval of the results of Phase I. During Phase II, a high-temperature ceramic thyratron, a high-temperature transformer, and dc-to-dc converter circuits will be designed according to the criteria established in Phase I. At least four high-temperature thyratrons, two high-temperature transformers, and one complete dc-to-dc converter of each type described above will be fabricated and tested.

1.2 Summary

During the last period, additional data were obtained from the deionization time device including measuring the starting characteristics.

The circuit work in this period was devoted primarily to improving the circuits used for taking data.

Core material for the high-temperature transformer has been defined, samples of high-temperature insulation have been obtained for testing and resistance measurements on two types of insulation were made in vacuum at 600°C. The transformer design is essentially complete, lacking only the verification that glass insulation is acceptable for long life at high temperature in vacuum.

A thyratron of cylindrical geometry has been designed on the basis of the earlier measurements on this program and the results of other thermionic converter programs.

2. THYRATRON DESIGN CONSIDERATIONS

In order to design devices like thermionic converters or cesium vapor thyratrons, it is essential to investigate potential energy distribution of the interelectrode space. The voltage output of a thermionic energy converter is given by:

$$V_o = \phi_e - \phi_c + V_m - (V_s + V_c + V_p)$$

where

V_o = output voltage

ϕ_e = cathode work function

ϕ_c = collector work function

V_m = potential minimum in front of the emitter

V_s = height of the double sheath between the potential minimum and the beginning of the plasma

V_p = plasma drop

V_c = collector sheath

This diagram is shown in Fig. 1 for conditions expected to be encountered in the operation of the thyratron. The collector sheath, V_c, can be positive, negative, or zero depending on whether or not the plasma is matched to the collector. For the present analysis, V_c will be considered equal to zero. Since the quantities V_m, ϕ_c, V_p, and V_c are internal potentials, there is no way of measuring them directly; however, estimates on these quantities can be obtained from variable spacing thermionic converters which yield values for V_s, the sheath drop in front of the emitter between 0.5 and 0.8V. Similarly, the plasma drop has been estimated to be between 0.5 and 5.0V per inch. A voltage spacing curve for a variable spacing converter working under conditions expected to be encountered in the thyratron operation is

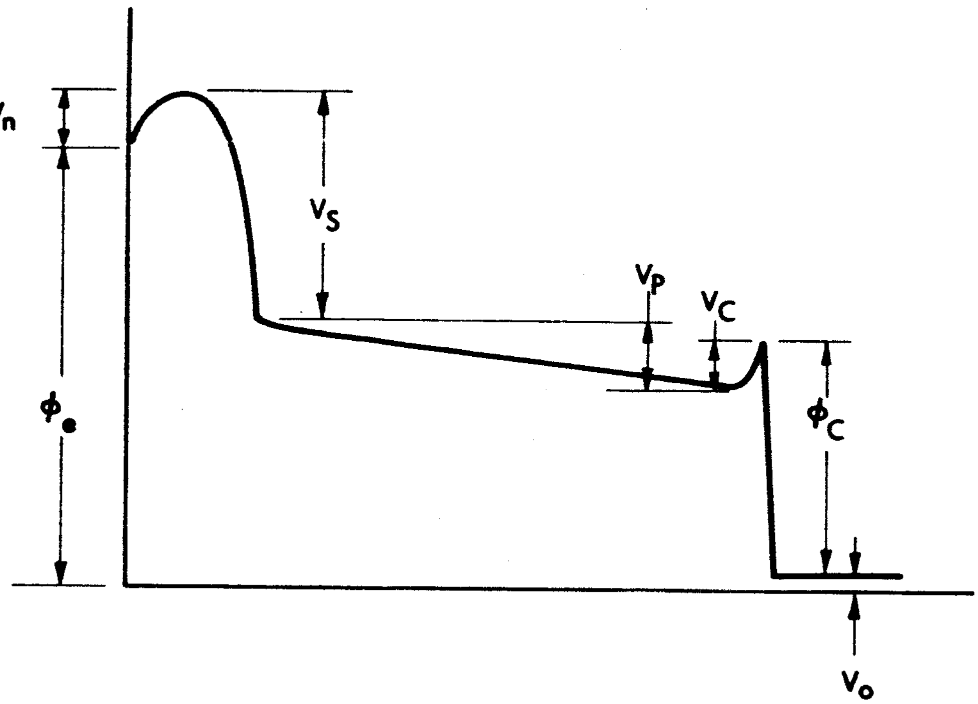


FIG. 1 POTENTIAL DISTRIBUTION IN CONDUCTION REGION BETWEEN EMITTER AND COLLECTOR

shown in Fig. 2. The voltage as shown here is the device terminal voltage while operating at a current of 20 amperes. This is different from the curve of Fig. 1 in that it is not an internal potential distribution, but rather a curve showing a change in the output voltage of the device by the formation of a positive column between the collector and the emitter as the spacing is varied. This positive column has started to form at a spacing corresponding to the maximum voltage shown. The slope is initially rather steep as the spacing is increased, but tapers off to about 0.5V per inch at the widest spacing. The spacing is 16 mils as shown here and is much too close for practical operation since the grid must be interposed between the collector and emitter for successful controlled action.

It can be seen by referring to the equation that the work functions of the emitter and collector are extremely important in determining the actual operating voltage of the device. The collector work function should be the minimum value obtainable with a cesium film on a substrate. With a minimum obtainable anode temperature, a work function for the collector of about 1.5V is achievable. As will be shown below, a cathode work function of 2.5V, at least, would be desirable and can be achieved in the device now under consideration. Using these values in the equation and solving for plasma drop, it can be seen that even for extreme ranges of sheath voltage a plasma drop of 0.2 to 0.5V could be tolerated and still achieve an output voltage close to zero. Comparing this value with a value of plasma drop calculated in a different manner by multiplying the emitter-collector spacing by the slope of the curve in Fig. 2, the plasma drop is found to be between 0.03 and 0.3V. Both cases are within the values calculated above.

2.1 Optimum Pressure Conditions

A further consequence of the work on the variable spacing test vehicle has been the determination of the optimum pressure-spacing product for thermionic converters. That is, the highest

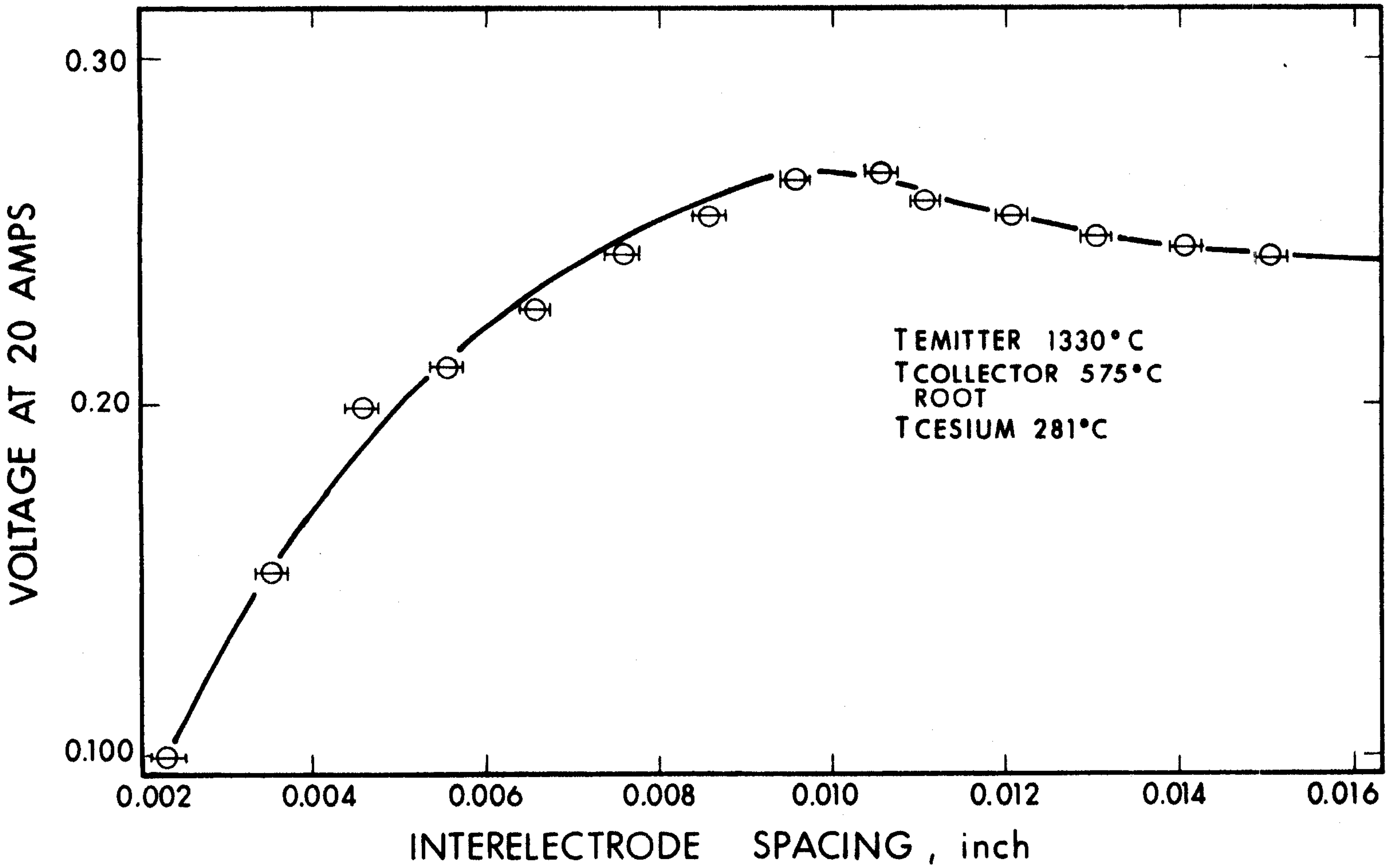


FIG. 2 INTERELECTRODE SPACING IN INCHES VERSUS VOLTAGE. EMITTER, COLLECTOR, AND CESIUM RESERVOIR TEMPERATURES ARE CONSTANT (all dc data points)

output powers have been obtained in converters where the product of the cesium pressure times the collector emitter spacing is between 16 and 18 mil-torr. This relation is plotted in Fig. 3 to permit visual inspection of the curve and, thus, to ascertain the most optimum range for operating the proposed thyratron. Several considerations of an operating range enter in here. For example, the pressure must be high enough to insure adequate emission at a reasonable temperature on the cathode, but low enough that it does not produce excessively long deionization times. On the other hand, the spacing between the emitter and collector must be wide enough to permit the insertion of the grid for the thyratron but close enough that the deionization time is not excessive. The rectangle on Fig. 3 shows the region of practical operation for a thyratron for the frequency and current ranges expected.

2.2 Emitter

It is the emitter which actually determines the size and current capability of any thermionic device. As mentioned above, it is desirable to keep the cathode work function as high as possible for a given emission level. The work function of the emitter is determined by the cathode temperature and the cesium arrival rate, which in turn determines the emission level. These parameters are conveniently displayed in Fig. 4 which is a plot of the emission current versus the reciprocal temperature of the emitter. These currents are portions of the familiar Langmuir "S" curves which are used extensively to determine the emitting properties of cesium films on various metallic substrates. By applying the criteria of maximum work function and maximum emission as selecting the pressure and distance, from Fig. 2, the best operating point for the thyratron can be determined. These operating conditions are tabulated below:

Cesium pressure = 0.3 torr
Cathode work function = 2.45 volts
Cathode temperature = $1500^{\circ}K$ ($1227^{\circ}C$)

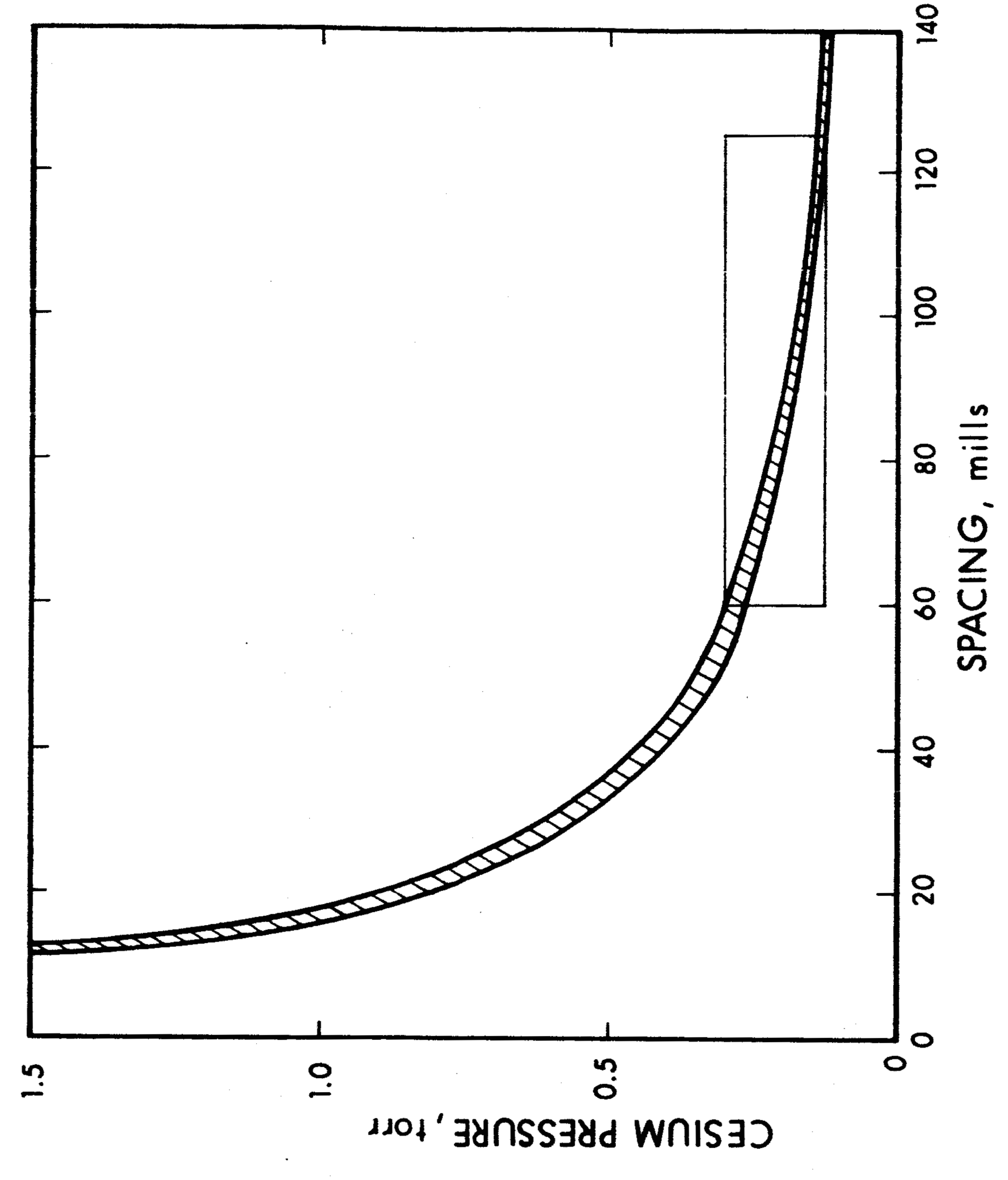


FIG. 3 PRESSURE SPACING RELATIONSHIP FOR OPTIMUM PD OF 16-18 MIL-TORR

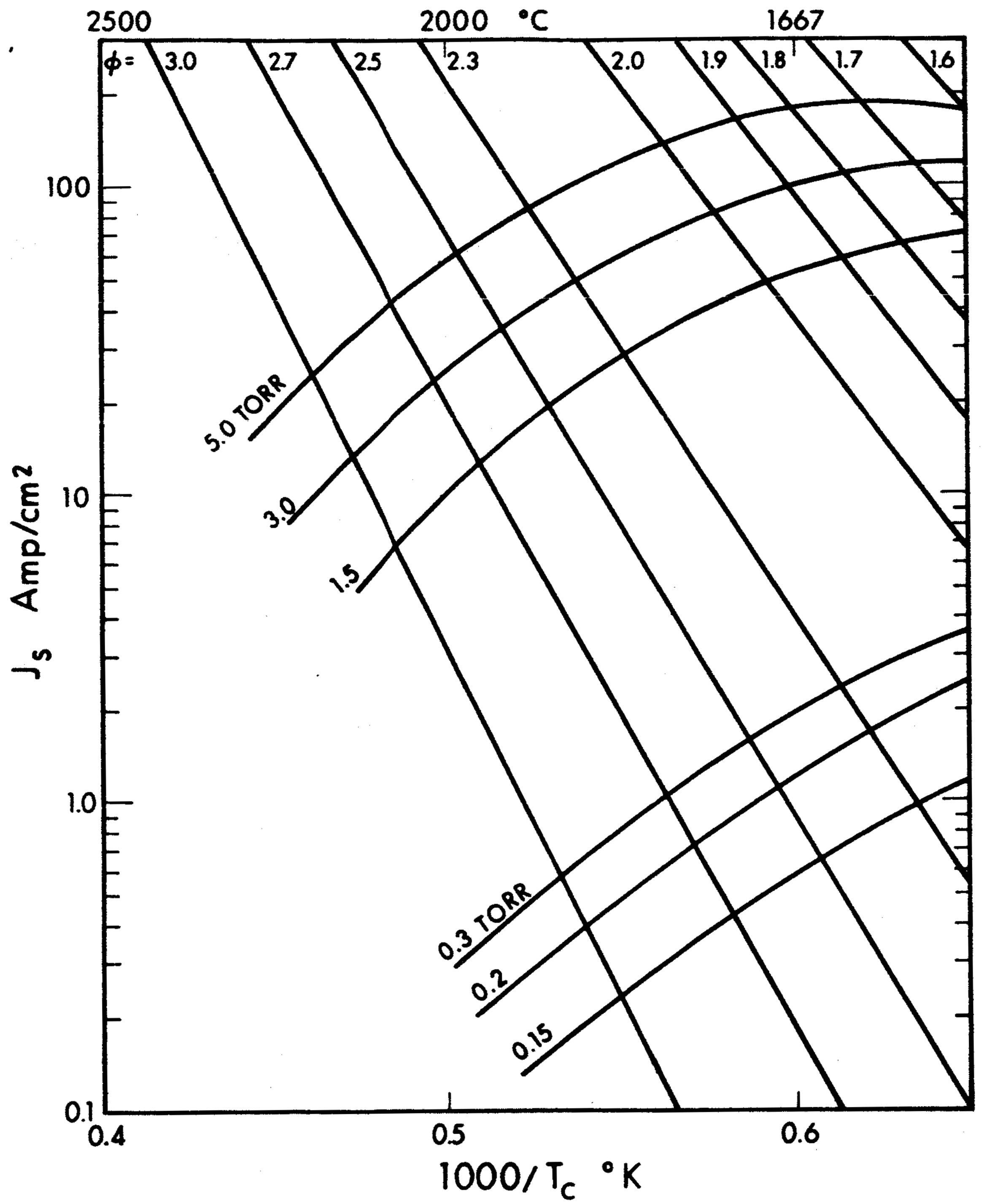


FIG. 4 SATURATED ELECTRON EMISSION FROM POLYCRYSTALLINE RHENIUM

2.3 Grid

In thyratron design, common practice is to keep the grid as cool as possible to avoid grid emission which would trigger the tube at some undesirable point in the operating cycle. For an application such as the cesium vapor thyratron, however, the voltages are so low and the operating conditions so unique that a considerable amount of grid emission can be tolerated without either causing malfunction of the circuit or without loading down the grid drive circuit excessively. In a device such as this, however, it is almost impossible to keep the grid running cool and still maintain the criteria that fit the optimum pd values discussed above. Therefore, it is better to use a refractory material for the grid which can operate at a high temperature, maintain its dimensional stability and have surface properties which prevent, or at least minimize, cesium adsorption so that its work function at that temperature in the presence of cesium vapor is too low to produce excessive grid current. Coatings such as zirconium carbide, tantalum carbide, or tantalum silicide applied on top of a tantalum substrate can produce such results. Niobium itself is a good material to use for grids since the emission from niobium in cesium is several orders of magnitude below that of rhenium and tantalum which are used for the other elements in the thyratron. The effect of the grid is to introduce an electrostatic shield between the emitter and collector such that (with a suitably applied voltage) electrons will be reflected back to the cathode and prevented from getting into the grid-cathode region where they will cause voltage breakdown and subsequent conduction through the device. Normally, a grid for a thyratron is fairly thick with a maximum of 50 percent transparency. For this design the grid will be very thin, on the order of 20 mils, and will have a transparency of at least 50 percent, so that the grid will introduce a minimum impedance in the flow of current between emitter and collector. It is felt that an open grid of 50 to 60 percent transparency is feasible in a low-voltage device such as this because of the effects noticed in guard ring diodes. Variable potentials applied to the guard ring of a cesium diode have a marked influence on the behavior of the diode even though the potentials applied were only 0.1V and the region affected was fairly far away. Therefore, the grid design in this device is in many ways different from that in standard thyratrons where much higher voltages and high energy electrons are encountered.

2.4 Collector

The collector, or external cylinder, of the thyratron will be cooled so that its temperature is no greater than 500-600°C. At this temperature, the collector will have an adsorbed film of cesium with a work function on the order of 1.5V, a minimum practical achievable value. From this point of view the collector is the simplest electrode to consider in the whole tube since it is only necessary to maintain a low temperature on this electrode and not an optimum value as is necessary for adequate emission from the cathode or for preventing emission from the grid.

3. THYRATRON DESIGN AND CONSTRUCTION

It is felt that the most efficient way to achieve the desired results of ease of construction and, at the same time, meet the internal optimum criteria discussed above is to make the tube with the cylindrical geometry. This is a departure from the usual thermionic converter techniques wherein the planar geometry is employed with very close spacing and very close control of temperatures. Even though this is a different approach in geometry, many of the same features of planar construction will be employed for reasons to be outlined below.

3.1 Emitter Design

The emitter will be a heavy-wall tantalum cylinder on which will be brazed a piece of rhenium strip about 10 mils thick. The data in Fig. 4 are for the use of rhenium in the emitter, since this gives by far the highest emission of any available substrate for use with cesium. The problems with rhenium, however, are that it is not only difficult and expensive to obtain, but it is very hard to work. It must be handled under special rolling conditions, by machines that operate in a protective atmosphere at the high working temperature required. The cathode cylinder could be made completely out of rhenium. However, because of the working difficulty of the metal, it was felt that if it could be successfully anchored to a tantalum substrate, the entire device would be much easier to build. Therefore, it is anticipated that a rhenium cylinder will be obtained which will be slipped over the tantalum cylinder forming the wall of the tube and a base for the rhenium. The rhenium will be brazed into place for good thermal contact so that it has a uniform temperature surface for emission. The tantalum cylinder which is relatively easy to machine will have a heat choke in each end to protect the seals. It is supported at either end and connected to the insulator flanges. A thermocouple will be utilized for monitoring the emitter temperature during operation. A schematic of the tube design, not to scale, is shown in Fig. 5.

Other methods of applying rhenium to tantalum substrates have been tried, for example, chemical vapor deposition of the material. This vapor deposition is a possible process, but according to those with experience in the field it is not a very feasible one, and is subject to many difficulties. For this reason it is felt that brazing of a rhenium plate onto the tantalum substrate is a far superior method.

3.2 Grid Design

The grid will be made of niobium sheet if it is determined that the niobium will have low enough grid emission in the 1000°C region. Also, tantalum silicide and/or tantalum carbide are to be investigated. These coatings, or coatings like them, have a low adsorption for a cesium vapor so that such a surface can be in a cesium atmosphere without becoming a very efficient electron emitter. The thin material in the grid will serve as its own heat choke and the grid cylinder can be brought directly out to a niobium flange which will be sealed to the alumina insulators. The thermal calculations made on a typical grid bar which is inserted between two hot surfaces, in this case, the emitter at 1500°K and the collector at 600-700°K, indicate that the grid temperature will be between 800-1000°C.

3.3 Collector Design

The collector will be simply a tantalum cylinder which is machined to the proper configuration and arranged so that each end will be brazed to the ceramic seal flanges. Of the three electrodes involved in the tube as mentioned above, this is probably the most simple electrode to design and build. The main mechanical support for the thyratron will be a strap around the collector which will serve both as an electrical lead, mechanical support, and a thermal

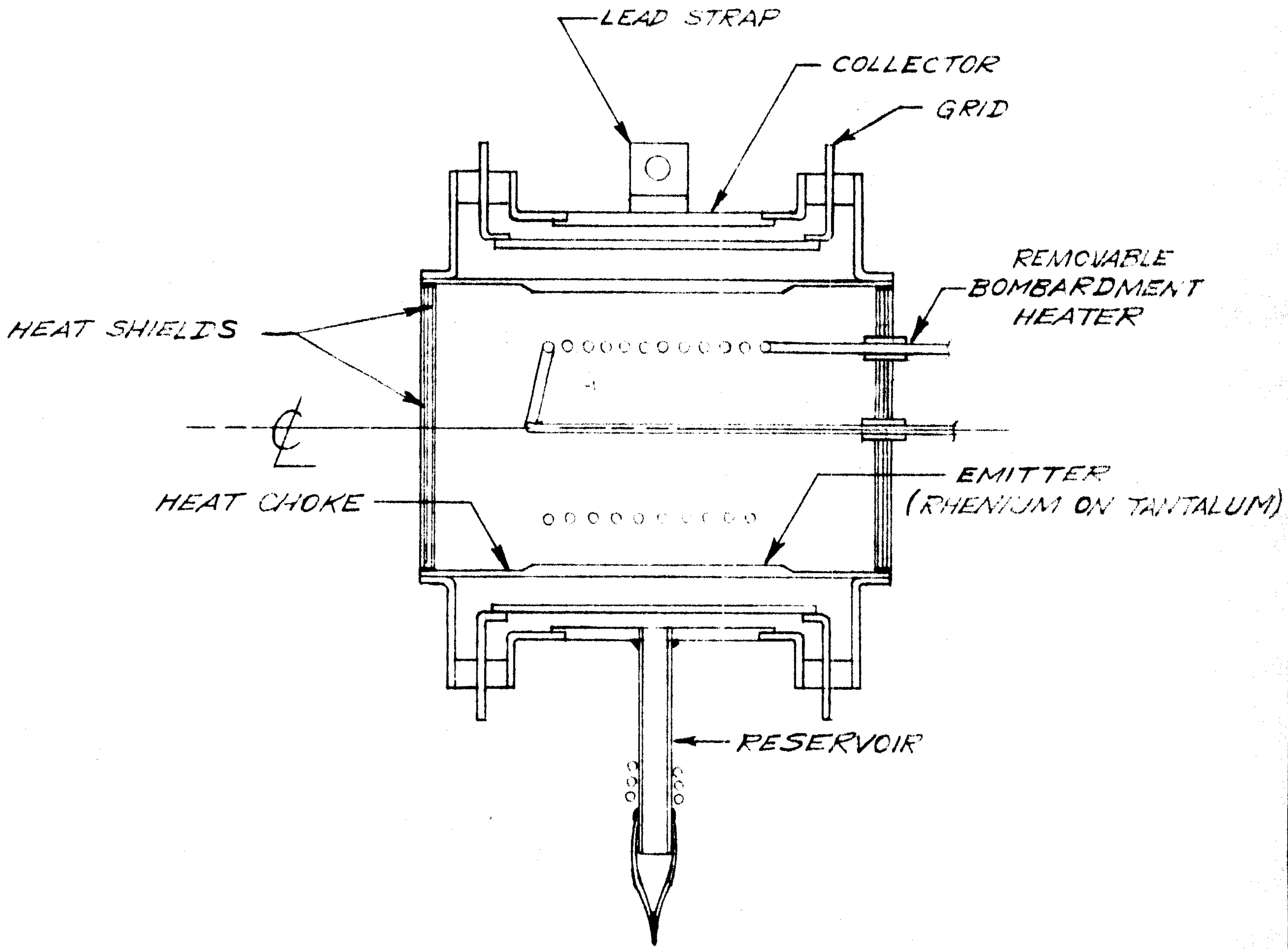


FIG. 5 THYRATRON CONFIGURATION

insulator. The temperature of the collector will also be monitored by a thermocouple which can be spot welded directly to the outside surface of the cylinder.

3.4 Seal Design

The seals will be made of alumina planar design of the type used on thermionic converters. Two flanges will be brazed to each side of an insulator as subassemblies. These, in turn, will be welded into the final tube during the final stages of assembly. In this way parts of the tube can be built and leak-tested ahead of time. If any difficulties should occur, only one part of the tube is affected and other parts are not lost. The reservoir for the thyratron will be attached to the collector and will be very similar to that used on the converters except for a possible modification of the heat choke.

3.5 Emitter Heater

The emitter heater for operating the thyratron will consist of a tungsten filament concentric with the axis of the tube which can be inserted inside the emitter cavity and heated to emitting temperature. The emitter will be heated both by radiation from this tungsten heater and by electron bombardment from the heater to the emitter cylinder. Radiation shields at either end of the bombardment heater structure will conserve heat and provide the proper temperature distribution within the thyratron.

3.6 Transformer Design

As a result of the deionization time measurements, the transformer design is proceeding on the basis that a frequency range of 1000-1600 Hz is possible with the thyratron. A schematic of the transformer showing the turns ratio is given in Fig. 6a. Materials to be used in the construction of the transformer are Hiperco 50 for the core laminations, OFHC copper for the windings and glass or alumina insulation. The critical items in the construction of the transformer are the core material and the insulation material because of the high temperatures involved.

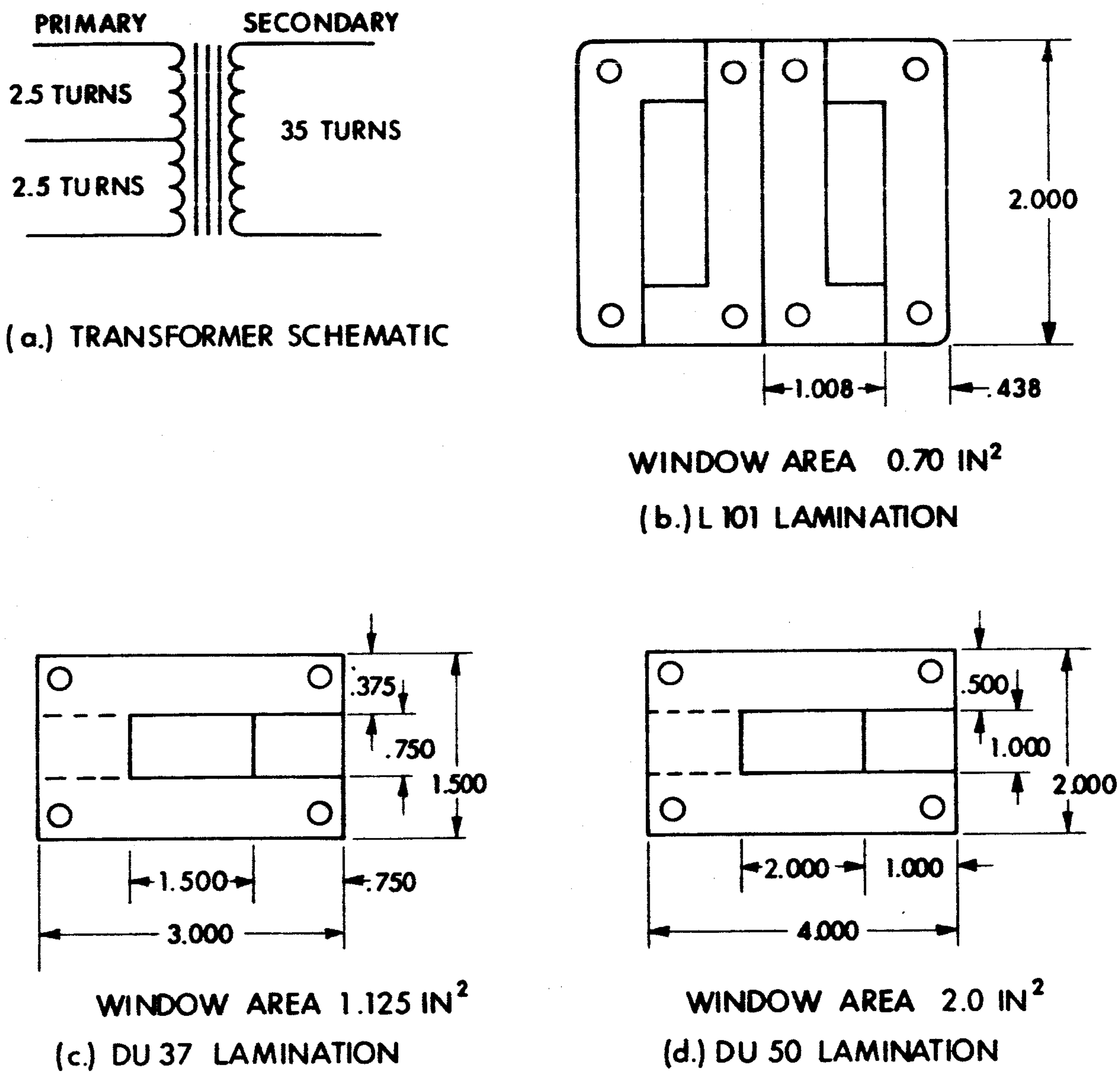


FIG. 6 TRANSFORMER SCHEMATIC AND LAMINATION CONFIGURATIONS

3.6.1 Core Materials

The high-temperature alloy, Supermendur, was chosen as the core material. As pointed out in the Phase I final report, the two most likely materials are Supermendur and Hiperco 50. Hiperco 50 and Supermendur are identical chemically. The main difference is that Supermendur is heat-treated in the magnetic field so that domain alignment occurs in the laminations, thus, giving it superior magnetic properties. Because of the critical nature of this application, Supermendur was ordered. However, it was learned from the vendor that the Supermendur presently available is of variable quality and the order was, therefore, changed to Hiperco 50. The following information was obtained from the vendor regarding the relative qualities of these two materials.

1. Supermendur is best for square loop or saturation operation. At this time the quality of Supermendur as supplied by the manufacturer is not under control. Since our application is for a nonsaturating operation, and, in fact, a large margin of safety has been provided to avoid saturation of the core, this transformer can be made equally well with Hiperco 50.
2. Magnesium methylate is the usual transformer insulation material because it has both insulating and lubricating properties for ease of assembly. For very high temperature applications, it is recommended that straight magnesium oxide be used instead of the magnesium methylate. However, magnesium oxide is relatively fragile and may have a tendency to come off during handling. It may be necessary to touch up the laminations if any of the insulation is damaged either in handling or in shipment.
3. Hiperco 50 is as good as Supermendur for nonsaturating applications such as for this transformer. Although a slight increase in core loss may occur under the same conditions,

it is more readily available than Supermendur and much cheaper. Specifically, Hiperco 50 costs $10 per pound compared with $100 per pound for Supermendur.

4. Both Supermendur and Hiperco 50 should never be operated hot in air because oxidation causes a permanent change in magnetic properties. Since this transformer will be operated in vacuum, there will be no expected deterioration in magnetic properties even at temperatures in excess of 600°C. The Curie temperature for these materials is about 950°C.

To reduce delay, standard core shapes were selected from the vendor's catalog. The shapes are shown in Fig. 6b, 6c, and 6d. Figure 6b shows the first choice in core shape. Four L-shaped laminations were to be put together to form a symmetrical, double-window core with the windings being around the central leg of the core frame. After consultation with the vendor, it was decided that the window area of this core shape might be too small for our windings and more margin should be provided for insulation and variations in thickness due to winding irregularities. Therefore, the shape shown in Figs. 6c and 6d was selected. The first choice of these two sizes is Fig. 6c which will have a window size of 0.750 x 1.5 inches and should be adequate for the total winding required. If this window should prove to be too narrow because of insulation size, the larger core frame shown in 6d, which has a window size of 2 x 1 inches will certainly be more than adequate. Since this material is relatively inexpensive, both DU-37 and DU-50 core shapes were ordered.

The amount of material required for each transformer core was based on the operating frequency and the saturation flux and the volts per turn ratio. At a volts per turn ratio of 1.5, an operating frequency of 1600 Hz, and a flux intensity of 5 kilogauss, about 1.5 pounds of core material are needed per transformer (Fig. 7). At a 1000 Hz operating frequency, B_m increases to about 5300 gauss and at 500 Hz B_m equals 8000 gauss. The amount of core material required for

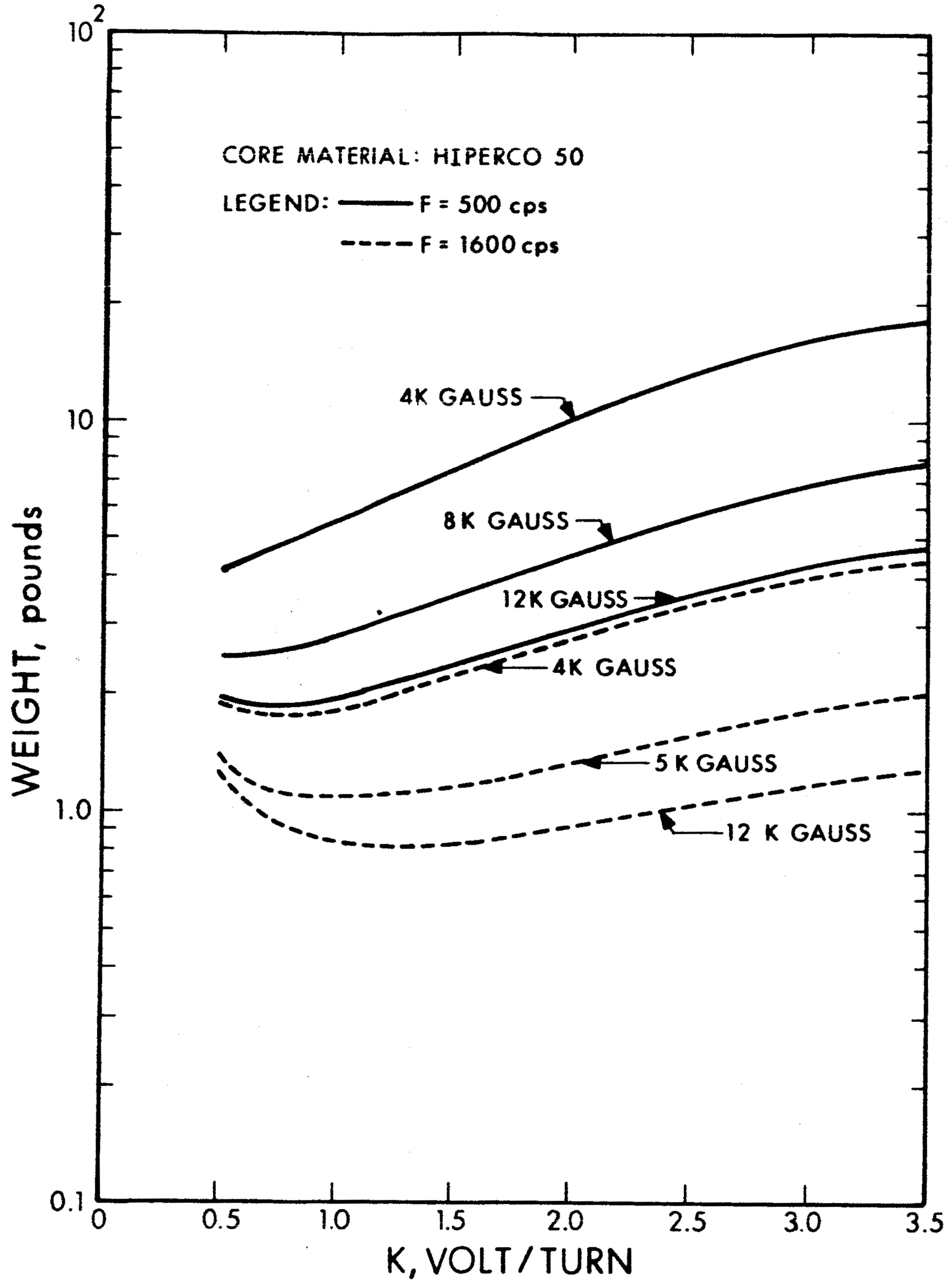


FIG. 7 TRANSFORMER WEIGHT VERSUS VOLT/TURN RATIO FOR VARIOUS FREQUENCIES AND FLUX DENSITIES

the 500 Hz operation is close to 3 pounds per transformer. In the event that the thyratron may operate at high currents and high cesium pressure and a 500-Hz frequency is used, enough material for operation at 500 Hz was ordered.

The laminations themselves are 0.004 inch thick and will be covered with 0.10 mil insulation on each side. For the DU-37 core, the total stack height including insulation will be 1.41 inches and for the DU-50 it will be 1.07 inches.

OFHC copper has been chosen for the conductors in the high-temperature transformer because of its superior electrical and vacuum qualities. Since the transformer will be operating in a vacuum, there is no danger of oxidizing the copper. The only material which would be better than OFHC is silver. Foil winding was chosen over wire winding because of the higher efficiency and the better packing of the windings on the core.

For the primary winding, a 1-inch-wide by 40-mil-thick OFHC copper strip will be used. To facilitate winding, the 40-mil thickness will be made up of eight layers of 5-mil-thick copper strip. The secondary winding will consist of 35 turns of 1 inch wide by 3-mil-thick copper foil. The primary, secondary, and insulating material will be wound into a single coil unit into which the core material will be inserted.

3.6.2 Insulation

Several insulating materials have been investigated for use with the high-temperature transformer. Since the voltages to be encountered in this transformer are quite low, it is felt that the insulation problem is not extremely critical even though the temperature involved is unusually high. The properties of materials considered are tabulated in Table I and shown in Fig. 8 which list resistivity and dielectric strength for various temperatures. The obvious choice would be alumina since it excels all the other materials in both resistivity and dielectric strength at temperature. However, it is very brittle and tends to flake off and is difficult to apply to any flexible metallic conductor. Therefore, a material that is more easily handled, if not quite as superior electrically, would be desirable from a mechanical point of view. Mica has very superior properties for electrical insulation at high temperatures and can stand temperatures up to 900°C without degradation of characteristics. Just as with the alumina, mica, in its natural form, is quite brittle and fragile and is not easily adapted to the winding that is needed for the transformer. However, a special material called Isomica, consisting of 80 percent muscovite mica flakes and 20 percent polyester fiber heat-bonded resin has become available which, presumably, can be used at least up to 480°C in air, and probably higher in vacuum. One problem might be that the polyester fibers will leave a residue which could cause trouble after a long period of time of operation at high temperature. Another material considered is ordinary glass fiber tape. This is the most readily available and most easily used insulating material. However, reference to Fig. 8 shows that at 600°C the resistivity of soda lime glass is quite low and even with the low voltages to be expected, some ohmic conduction may take place and contribute either to heating of the transformer or deterioration of the insulation itself. Most glass tape is made of soda lime glass. If, however, higher temperature glass tape is available, it would be the best choice for insulation.

TABLE I

MATERIAL PROPERTIES

Material	Temperature (°C)	Resistivity (ohm/cm)	Dielectric Strength (V/mil)	Remarks
Muscovite Mica	20	2×10^{13} to 10^{17}	3000-6000	Shows no apparent change in physical characteristic at 400-600°C can be fired to 900°C
Isomica	120	10^{14}-10^{15}	400	80 percent muscovite mica plus 20 percent polyester fibers, heat-bonded
Alumina 99%	25	$> 10^{14}$	600	Data for sintered Al_2O_3
	300	10^{13}		
	500	6×10^{10}		Probably lower for powdered layer
	1000	2×10^{6}		

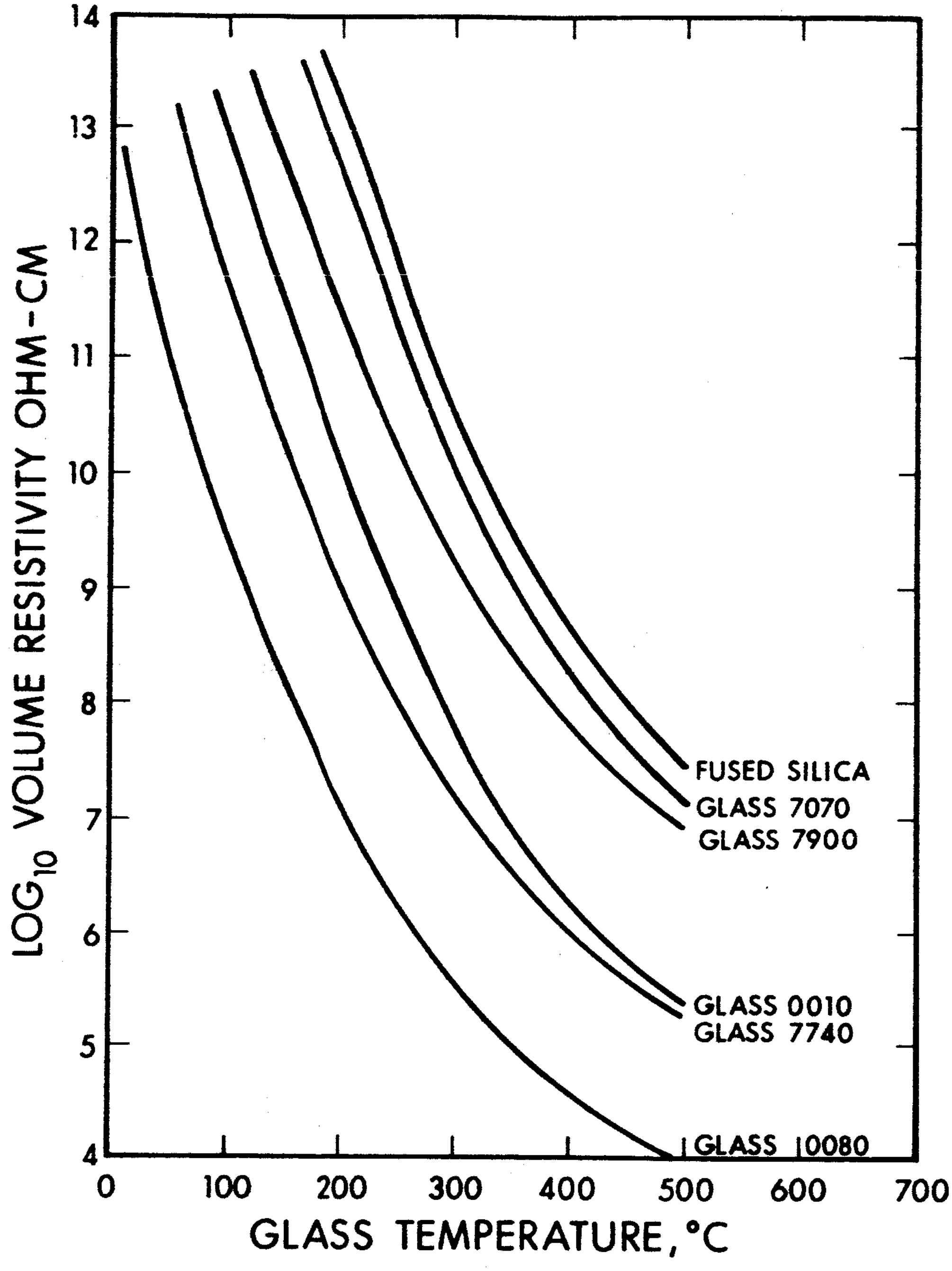
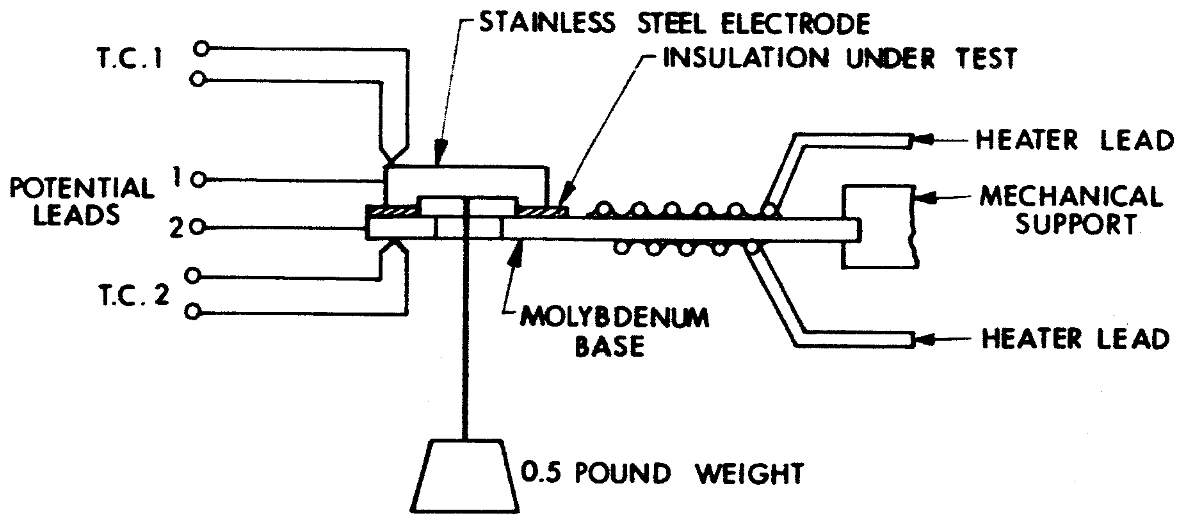
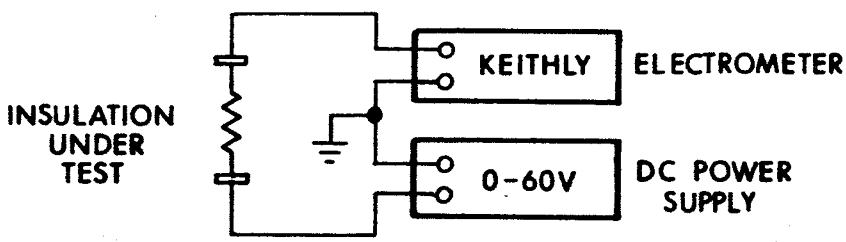


FIG. 8 VOLUME RESISTIVITY AS A FUNCTION OF TEMPERATURE FOR CORNING GLASSES 0010, 0080, 7070, 7900, AND FUSED SILICA

Vacuum insulation tests were run on two of these materials, namely, the Isomica and glass cloth insulation. The purpose of these tests was to attempt to simulate approximately the winding pressure and the voltages that might appear on the transformer and apply these to the insulation at temperature in vacuum. A schematic of the test configuration which was mounted in an ion-pumped vacuum system is shown in Fig. 9a and the measuring schematic in Fig. 9b. A voltage of about twice the expected operating voltage was applied to the insulation and the temperature was varied between room temperature and 650^{o}C in a vacuum of 6 x 10^{-7} torr. The current through the insulation was measured with a Keithly electrometer. In the tests on both materials at temperature, the total current through the sample was on the order of 10^{-9} amps which indicates a resistance on the order of 10^{10} ohms. This is far above that required for operation of the transformer. These were short time tests and conceivably extended operation would show degradation of the resistance of the material. However, extended tests will be run later when the final material is selected. Both materials showed a browning or discoloration after operation at temperature and the Isomica had a tendency to crumble after exposure to temperature. It was the mechanical property that deteriorated rather than the electrical properties of the material. Because the Isomica mechanically deteriorated more than the glass fiber and because the glass fiber is so much easier to handle and even though at 500^{o}C Fig. 8 shows unfavorable resistivity characteristics for soda lime glass at temperature, it is felt to be worthwhile to run a long time test on the glass sample. If a long time test on this material proves satisfactory, no further work will be done on the insulation for the transformer. If it is not satisfactory, investigation of the other materials mentioned here will be made in greater detail to test their suitability for this application.



(a.) MECHANICAL ARRANGEMENT



(b.) ELECTRICAL CIRCUIT

FIG. 9 600°C INSULATION TEST

3.7 Circuit Design

All circuit work done in this period has been oriented toward developing the best arrangement for taking recovery time and voltage hold-off data. No additional work on the inverter circuit itself has been done beyond that which was reported in the Phase I final report. The test circuits used for obtaining the data of the starting voltage curves and two starting voltage curves in addition to those obtained in the last period are shown in Fig. 10. The curves were obtained by setting the grid voltage at the desired level and raising the collector voltage until the tube fired. The low pressure curve was taken to look for the hump observed in the higher pressure cases. A slight hump was actually seen which may be evidence of elastic scattering of electrons. A curve was obtained for 0.3 torr also since it is the upper pressure limit of interest. Since the exact relationship of one curve to another depends on series resistances and absolute pressure equilibrium, this series of curves yields only a quantitative comparison. They will be repeated more carefully over the pressure range of interest.

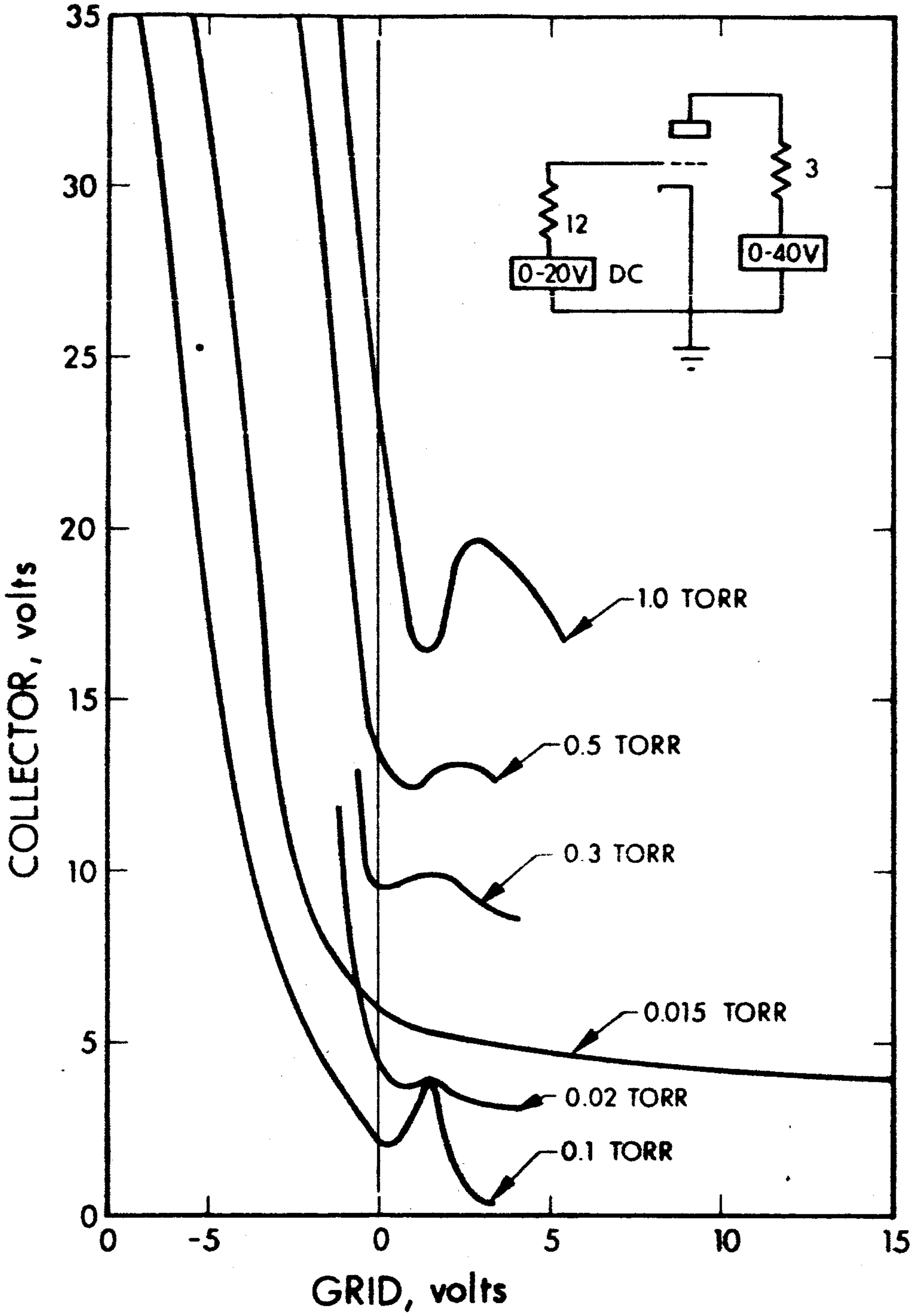


FIG. 10 ANODE STARTING VOLTAGE VERSUS GRID VOLTAGE FOR SEVERAL CESIUM PRESSURES

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4. PLAN FOR NEXT PERIOD

1. Continue testing deionization time device for additional data.
2. Complete thyratron design, order materials, and begin fabrication of materials on hand.
3. Set up long term test for transformer insulation.
4. Begin transformer fabrication if core material arrives.

Man-Hours Expended

A total of 3293 man-hours has been expended on this program as of May 31.