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ANALYSIS OF COOLING METHODS

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Army Electronics Command
Fort Monmouth, New Jersey

March 1968

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by

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ANALYSIS OF COOLING METHODS

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March 1968

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FORT MONMOUTH, NEW JERSEY

Abstract

Experimental results have shown that a beam power density of 1667 Watts/ cm^2 can be dissipated in an electrode which consists of a narrow bore tubing, if the tubing is filled with copper mesh to a 20% density and water at a low rate is passed through the tubing. It is shown that this high power density can be dissipated because the mesh surface area is sufficient to drop the power density at the point of transfer to the coolant to a density less than or equal to 135 Watts/cm^2. The surface of the mesh is effective due to some combination, yet to be determined, of thermal conductivity of the mesh and vapor transport. An experiment designed to verify the proposed mechanism and determine the contribution of the mesh thermal conductivity is planned for the next phase of the study. The results of this experiment will allow the extrapolation of the results to other electrode geometries.

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ANALYSIS OF COOLING METHODS

INTRODUCTION

Electron tube*power generation capabilities are limited by a number of factors. One of the prime limitations is the total power or the power density dissipated in anode or collector structures. The amount of power that can be dissipated is in turn limited by the means available to cool the electrodes. As the frequency of operation of the electron tube is increased, the cooling problem becomes increasingly important since the electrode sizes scale inversely with frequency, and power density necessarily increases if an attempt is made to maintain the power output. At a point in power versus frequency space, which is a function of the particular type of electron tube and its particular electrode design, the tube designer reaches a point where either radiation cooling or metallic thermal conduction will not serve to maintain the electrodes at a safe operating temperature. At this point, the designer resorts to water cooling or to vapor cooling to handle the required amount of power. Both of these methods are of limited use when the electrode to be cooled is basically a small bore tubing, as will be shown below. Experimental results on a contractual study[1] placed by the Electron Tubes Division of the Electronic Components Laboratory have demonstrated a method of increasing the power density dissipated in such tubing by a significant factor. It is the purpose of this analysis to determine a mechanism that accounts for the empirical results. Once a mechanism has been established the tube designer will be able to extend the range of application of this cooling technique. In order to arrive at an appropriate mechanism, the available facts on water cooling and vapor cooling were reviewed. A summary of these known facts is included in this report.

No matter what method of cooling is used the thermal design must take into account both the total power that is being dissipated and the power density of dissipation. If the amount of coolant used is insufficient to handle the total power being dissipated, the entire body will rise in temperature until destruction takes place. If the power density exceeds the ability of the coolant to take power away from specific locations, then hot spots will form, again resulting in destruction of the electron tube. In pulse operation, an additional problem is introduced in that a temperature drop may exist between the actual surface on which the electron beam impinges and the surface at which heat transfer to the coolant takes place because of the time constant of the system. This analysis will be limited to problems involving either continuous dissipation or where the peak to average power dissipation ratio is such that a significant temperature rise does not take place during the on-pulse at the beam-electrode interface.

TOTAL POWER LIMITS

The total power dissipated in a heat transfer system using any liquid coolant, assuming turbulent flow, is:

---

* Statements apply equally well to other active devices such as solid state power generators.

$$P_L = C_p Q_w \Delta T \quad \text{---------} \quad (1)$$

where C_p = Specific heat of the liquid,

Q_w = Flow rate,

and ΔT = Temperature difference between input and output.

When vapor cooling is used the total power dissipated is:

$$P_V = C_L Q_V \quad \text{------------} \quad (2)$$

where C_L = Latent heat of vaporization,

and Q_V = Rate of vaporization.

When water is used as the coolant, equations (1) and (2) can be expressed in practical units as:

$$P_L = 264\ Q_w \Delta T \ \frac{\text{Watts}}{{}^{\circ}\text{C} \cdot \text{gal/min}} \quad \text{-----} \quad (3)$$

and

$$P_V = 1.42 \times 10^5 Q_V \frac{\text{Watts}}{\text{gal/min}} \quad \text{-----} \quad (4)$$

respectively.

Equation (4) includes only the contribution of the heat of vaporization at a constant temperature, the boiling point, to the heat transfer process. The power required to heat water to the boiling point from, for example, a 20°C input temperature would provide an approximate 14% increase in the capability of a non-recirculating water-to-vapor cooling system.

POWER DENSITY LIMITS USING WATER COOLING

The heat transfer capabilities of a cooling system in terms of the density of power transferred has been expressed in empirical relationships by many experimenters. The works of Grass,[2] Hansen,[3] and Schack and others have been compared by Schack[4]. These empirical relationships involve a number of parameters, which will not be discussed here. The results of these studies are better summarized for our purposes by comparing them with experimental results and the practical rules-of-thumb used by electron tube manufacturers. At the water temperatures usually associated with electron tubes, the experimental results fall in a range of 0.22 to 10.8 watts/°C/cm^2. The derived equations predict values toward the low end of this range. Using an allowed temperature drop of 30°C, the literature would predict a range of 6.6 to 324 watts/cm^2. One electron tube manufacturer[5] uses a factor of 100 W/cm^2 as a typical value for water-cooled electron tube design. This factor may or may not include an area multiplication factor, i.e., the area available for transfer of heat to the coolant is larger than the beam cross-sectional area. This practical factor thus falls well within the experimental range. Recent results in high power density electron tubes, however, have exceeded this conventional tube cooling factor by more than an order of magnitude. In the L-65[6] cooler design over $1\frac{1}{2}$ kilowatt/cm^2 of both active beam power density and cooler transfer power density has been accomplished experimentally. Similar power densities have been reported using "Vortex" cooling in which the cooling water is directed along the wall of the cooling tubing at high velocities rather than directly through the pipe at high velocities. Although no exact calculations were found in the open literature covering this case, the heat transfer equations provide a clue as to the process involved.

Basically there is no limit to the amount of power per unit area that could be transferred to a stream of water that moves sufficiently rapidly over the transfer surface in a turbulent manner. If turbulence is not present, however, the only mechanism available for heat transfer to the water not in direct contact with the transfer surface is by thermal conductivity of the water. In normal fluid flow in pipes, no matter how large a velocity is used and no matter how great the average turbulence is, as measured by the Reynolds number, a layer, which moves in a laminar manner, forms near the surface of the pipe, i.e., the layer has no radial velocity component. The actual heat transfer is thus limited by the thermal conductivity across this thin layer of water. In "Vortex" cooling where the flow is directed helically along the surface of the pipe, this "stagnant" or boundry layer must be reduced in thickness by at least an order of magnitude, thus providing an order of magnitude improvement in power density capabilities.

POWER DENSITY LIMITS USING VAPOR COOLING

The limits for vapor cooling heat transfer density cannot be expressed by a single equation, but the experimental results are much more straight forward than is the case for water cooling. The relationships have been summarized in curves attributed to Nukiyama.[7] The curves are drawn for both a logarithmic and linear scale in Figure 1:

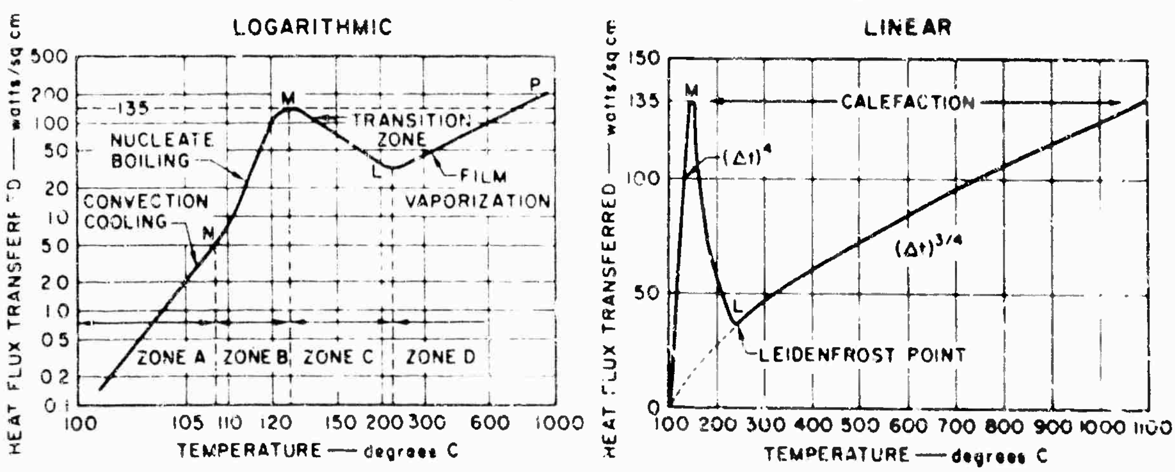

Figure 1. Nukiyama heat transfer curve

Figure 1 shows that the maximum power density at the transfer surface that can be handled by vapor cooling is 135 watts per cm^2. This refers to the surface area in contact with the liquid that is being vaporized. The power density in the beam cross-sectional area may be increased by an area multiplication process provided that the thermal conductivity of the metal cross-section is sufficient to achieve the power density transfer. In normal vapor cooled electron tubes, a system of pyramidal protuberances from the anode into the liquid achieves an area multiplication factor of about four, thus permitting an active beam area power density of approximately 500 watts per cm^2 to be transferred by the vapor process.

TEST RESULTS

With this background in cooling techniques, the results obtained in the study referred to previously[1] may be examined. In the experiment a one-inch length of 0.005-inch wall copper tubing having an outer diameter of 0.065 inch was bombarded with an electron beam. The total power dissipated in the anode was 700 watts. Tests were performed with a variety of cooling techniques for comparison purposes. With no coolant flowing through the tubing immediate destruction of the tubing took place. With water flowing through the tubing at 10 gallons per minute, the anode melted in two to three seconds. With the same water flow rate introduced through a vortex generator, melting did not occur until 10 seconds. When the tubing was filled with 0.003-inch-diameter copper strands (or mesh) to a 20% density, the 700 watts could be dissipated continuously with a water flow as low as 0.0106 gallons per minute (40 cm^3/min) with all or most of the water emerging as steam. The beam power density dissipated using this technique was 1667 watts/cm^2, which is approximately equal to that achieved on the L-65 program. These results are significant in two respects: the coolant flow rate is extremely small; and the cooling technique succeeded in a geometry (small bore tubing) where vortex cooling failed. The specific results are clear in themselves. In order to extrapolate the results to other geometries, however, a working model of the mechanism of heat transfer is required. The nature of the mechanism may be deduced from an analysis of the test results.

ANALYSIS OF THE TEST RESULTS

The total power dissipated in the experiment, 700 Watts, can be handled by a comparatively small flow rate of water whether water cooling or vapor cooling is the primary mechanism. This can be determined by solving equations (3) and (4) for the quantity of coolant required in either case:

$$Q_w = \frac{700}{264\,\Delta T} \text{ gal/min} \times {}^{\circ}\text{C}$$

for a permitted temperature rise of 30°C

$$Q_w \approx 0.088 \text{ gal/min}$$

for a permitted temperature rise of 80°C (assuming that water entering at 20°C is raised to the boiling point)

$$Q_w \approx 0.033 \text{ gal/min}$$

and

$$Q_V = \frac{700}{1.42 \times 10^5} \text{ gal/min}$$

$$Q_V \approx 0.005 \text{ gal/min.}$$

Thus, if the water was completely vaporized 0.005 gal/min of water would be sufficient to remove the heat generated by a continuous dissipation of 700 watts. This is only approximately half of the flow used in the successful experiment using the copper mesh. The observed result that the coolant emerged from the system as a mixture of steam and water is satisfactorily explained by the total power transfer relationships.

The power density at the transfer surface when the copper mesh was not used is estimated at 1200 watts/cm^2. This estimate is based on the following calculations:

$$A_1 = \pi d_1 L \quad \text{------------------- (5)}$$

where A_1 = Total inside area,

d_1 = Inside diameter = 0.055 in.,

L = Active length = 1.0 in.,

and A_1 = 1.114 cm^2.

Since the electron beam impinges on the exposed front side of the tubing only, the inside portion of the non-exposed back of the tubing can only transfer to the coolant that amount of power conducted to it by the thermal conductivity of the copper tubing. The amount of power which is transferred by the back of the tubing can be calculated from equation (6).

$$Q = \frac{\sigma A \Delta T}{d} \quad \text{------------------- (6)}$$

where σ = Thermal Conductivity (Quantity of heat transmitted per second through a plate one-centimeter thick when ΔT is one $^\circ$C.)

A = Cross-sectional area

d = Transmission path length

ΔT = Temperature drop across transmission path.

Equation (6) may be expressed in practical units for a copper heat conductor as:

$$P \approx \frac{4.185 \, A \, \Delta T}{d} \quad \frac{\text{Watt} \times \text{cm}}{\text{cm}^2 \times {}^\circ\text{C}} \text{ . -------- (7)}$$

The amount of power transmitted to the back of the tubing may be calculated using equation (7) and Figure 2. Substituting the values shown in the figure into the equation we obtain:

$$P \approx \frac{10.66 \Delta T \; L (d_o - d_i)}{(d_o + d_i)} \; \frac{\text{Watt} \times \text{cm}}{\text{cm}^2 \times {}^\circ\text{C}} \quad \text{-------(8)}$$

For the values involved in this experiment and assuming that the temperature difference is not greater than a drop consistent with efficient vapor cooling (from Figure 1 the drop is estimated at 20°C i.e., $T_1 \approx 140$°C; $T_2 \approx 120$°C), the power which could be transmitted to the back is:

$$P \approx 45.1 \text{ Watts.}$$

Assuming that the remainder of the power is transferred through the front half of the tubing, the power density through the transfer area of 0.557 cm^2 would be greater than 1100 watts/cm^2. This exceeds the power density that can be handled by vapor cooling by a factor of almost 10. Even if there were a mechanism whereby the entire inside area of the tubing was effective in heat transfer, the power density would exceed the Nukiyama maximum by a factor of almost five. It is, therefore, not surprising that even with a flow of 10 gal/min, the tubing melted when tested without the copper mesh inside.

With the copper mesh included within the tubing, the surface area available for heat transfer from the anode to the coolant is increased. If the heat energy can be transferred from the tubing to the mesh then this larger area would be effective in reducing the power density to within the limits of the Nukiyama maximum. The surface area of the copper mesh may be estimated by assuming that a sufficient number (N) of single strands of wire are inserted in the tubing to occupy 20% of the cross-sectional area of the bore. The approximate number of wires used is:

$$N = 0.2 \frac{\pi r_i^2}{\pi r_w^2} \approx 67$$

where r_i = Inside radius of tubing

r_w = The wire radius.

The surface area of this number of wires is:

$$2 \pi r_w NL \approx 4.07 \text{ cm}^2.$$

The surfaces of the wire mesh can be used to transfer heat to the coolant if, and only if, heat is transferred from the inside of the front of the tubing to the wire mesh and the back of the tubing by either thermal conduction through adjacent copper strands or by some other transport mechanism.

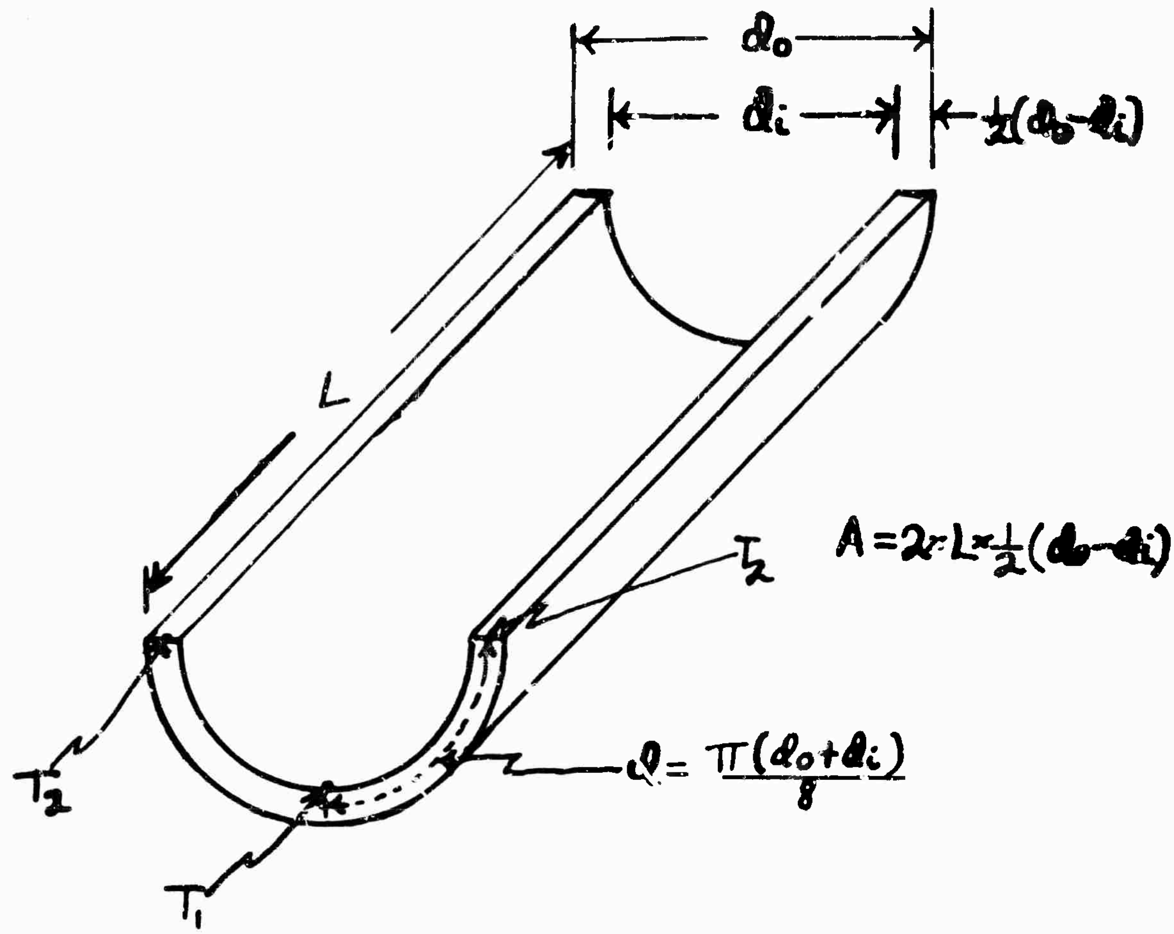

Figure 2. Model for calculation of front-to-back power transmission (front half of tubing not shown).

The thermal conduction can only be estimated since the exact contact area of wire strands to the copper tubing and wire strands to adjacent strands is neither controlled nor known. If the wires were touching over their entire length, L, with an effective contact region equal to one quarter of the wire radius, r_w, the temperature drop from one end of a string of wires to the other end would be a function of the number of strings present. Since there are a limited number of wires in the volume, the length of each string is a function of the number of strings. The transfer of heat to the coolant and to the back of the tubing can not be assumed to be effective, if too many strings are hypothesized. Thus, for the wire size and the tubing bore involved, with any more than five strings the far end of the back of the tubing would not be reached by thermal conduction. With five strings the temperature drop would be approximately 68.6° as determined by substituting in Equation (7). As many as nine strings would be required to reduce the temperature drop across the string to the maximum tolerable temperature drop of 20°C. Since the actual contact area will be much smaller than that assumed for these calculations and the volume will be filled more uniformly than would be possible if the wires were strung as required for the calculation, there is only a small likelihood that the conduction of heat from the front of the tubing to all of the mesh and to the back of the tubing is by a process of thermal conduction alone. The surface area required for efficient vapor cooling can, however, be utilizied by another process dependent upon the properties of the vapor itself. If steam is produced at the front end of the inner wall, it will transport heat to the cooler wires by convective flow and condensation at any surface area at a temperature less than the boiling point. Heat will be pumped by this process from the hotter inner wall to the cooler, wires tending to bring the temperature into equilibrium with a small temperature drop between the different portions of the surface area. The entire surface area would be available for interchange of heat with the coolant and the rate of exchange would be kept down to the point at which calefaction does not take place.

CONCLUSIONS AND RECOMMENDATIONS

While the analysis contains a number of assumptions that can only be verified by further experimentation, it has given an indication of a mechanism that accounts for the large improvement in the power handling capabilities of the length of copper tubing when a copper mesh is inserted into it. Furthermore, if it can be determined that the mesh thermal conduction path is not an important contributing factor to the utilization of the mesh area, then it should be possible to extend the technique used here to a wide variation in geometry. An experiment to both verify the analysis given above and to determine the contributions of the mesh thermal conduction path versus the vapor transport heat conduction path has been planned using the four-factor Box[8] experimental design shown in Figure 3. The four variables selected are:

Tube Bore Diameter
Tube Wall Thickness
Mesh Thermal Conductivity
Mesh Area for Specific Power Density.

The tests will be run at a constant beam density, thus requiring a variable total power for the different tubing diameters. The volume of mesh will be adjusted to give the values of power density required based on both mesh surface area and the area of the inside of the tubing. The selected levels of the variables are shown in Table I. It is anticipated that the results of this experiment will establish the range of usefulness of the mesh-vapor cooling method, which already shows promise of providing a new tube design capability with respect to beam power density dissipation limits and required coolant flow rates. Since this method provides an order of magnitude improvement in power densities, precautions must be observed, either in the experiment or in actual application of the techniques, to insure continued optimum operation or the test vehicle (or actual device) will be catastrophically destroyed. Methods of insuring reliable operation of the system will be explored in the course of the planned experiment.

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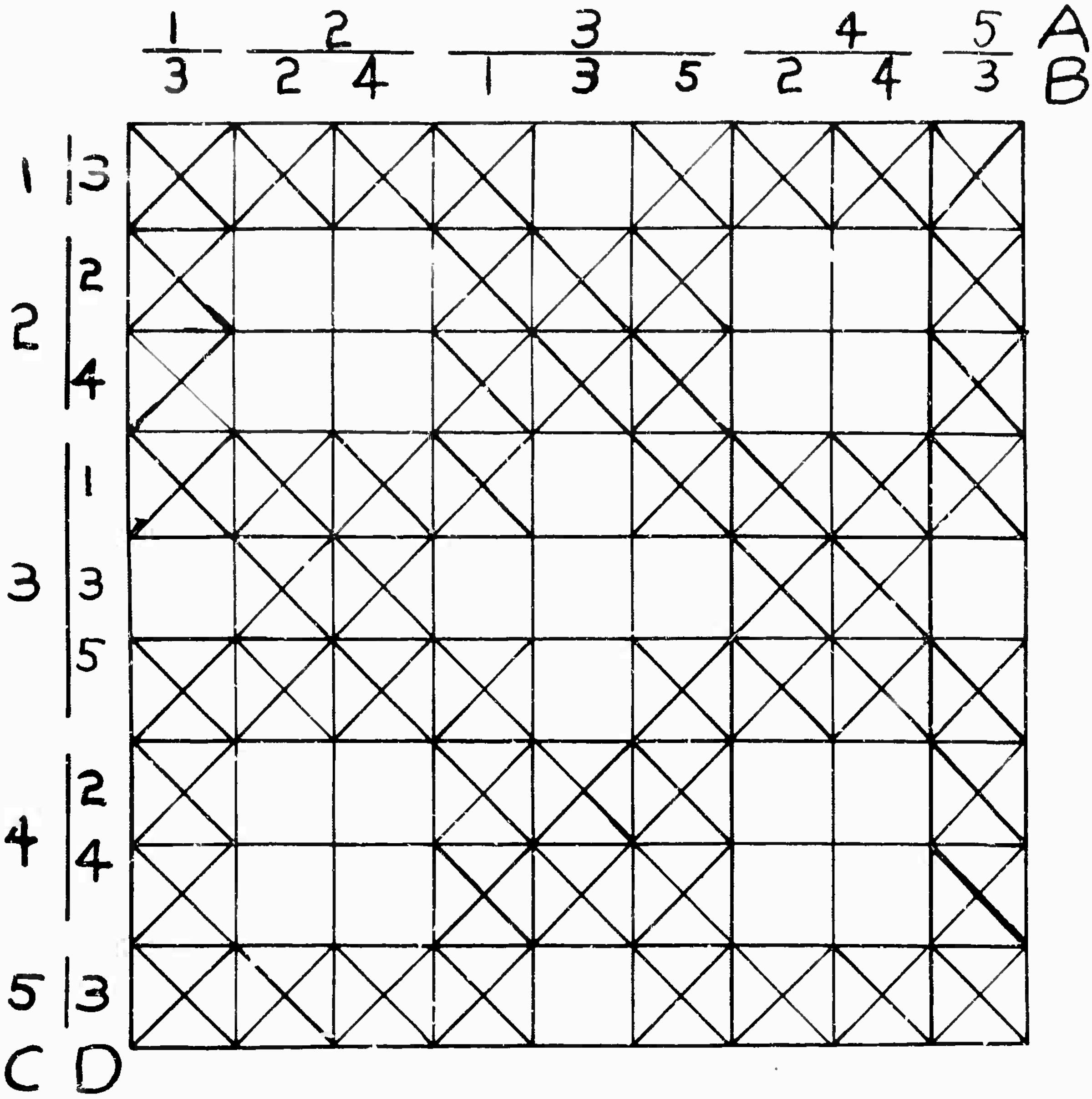

LEVEL	CODED VALUE
1	−1.4142
2	−1
3	+ 0
4	+ 1
5	+ 1.4142

TWENTY-FIVE EXPERIMENTS

TEN RESIDUAL DEGREES OF FREEDOM

Figure 3. A four-variable Box design

TABLE I

Levels of the Variables for Cooling Experiment

Level	Coded Value	A Tube Bore	B Tube Wall	C Mesh Mat./*	D Mesh Pwr **
1	- 1.4142	0.055"	0.005"	Silicon/.002	51 W/cm^2
2	- 1.0	0.080"	0.0103"	Nickel/.134	65 W/cm^2
3	0	0.140"	0.0125"	Alum./.450	100 W/cm^2
4	+ 1.0	0.200"	0.0178"	Gold†/0.776	135 W/cm^2
5	+ 1.4142	0.225"	0.020"	Copper/0.410	149 W/cm^2

* Thermal conductivity

** Desired Power Dissipation per cm^2 of surface area including inner surface of tubing

† A Gold-Copper or Gold-Silver alloy trimmed to a conductivity of 0.776 would be more accurate than pure gold with a conductivity of 0.70. The error introduced if gold were used, however, would be small.

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13. ABSTRACT

Experimental results have shown that a beam power density of 1667 Watts/cm^2 can be dissipated in an electrode which consists of a narrow bore tubing, if the tubing is filled with copper mesh to a 20% density and water at a low rate is passed through the tubing. It is shown that this high power density can be dissipated because the mesh surface area is sufficient to drop the power density at the point of transfer to the coolant to a density less than or equal to 135 Watts/cm^2. The surface of the mesh is effective due to some combination, yet to be determined, of thermal conductivity of the mesh and vapor transport. An experiment designed to verify the proposed mechanism and determine the contribution of the mesh thermal conductivity is planned for the next phase of the study. The results of this experiment will allow the extrapolation of the results to other electrode geometries. (Author)

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Heat Transfer						
Water and Vapor Cooling						