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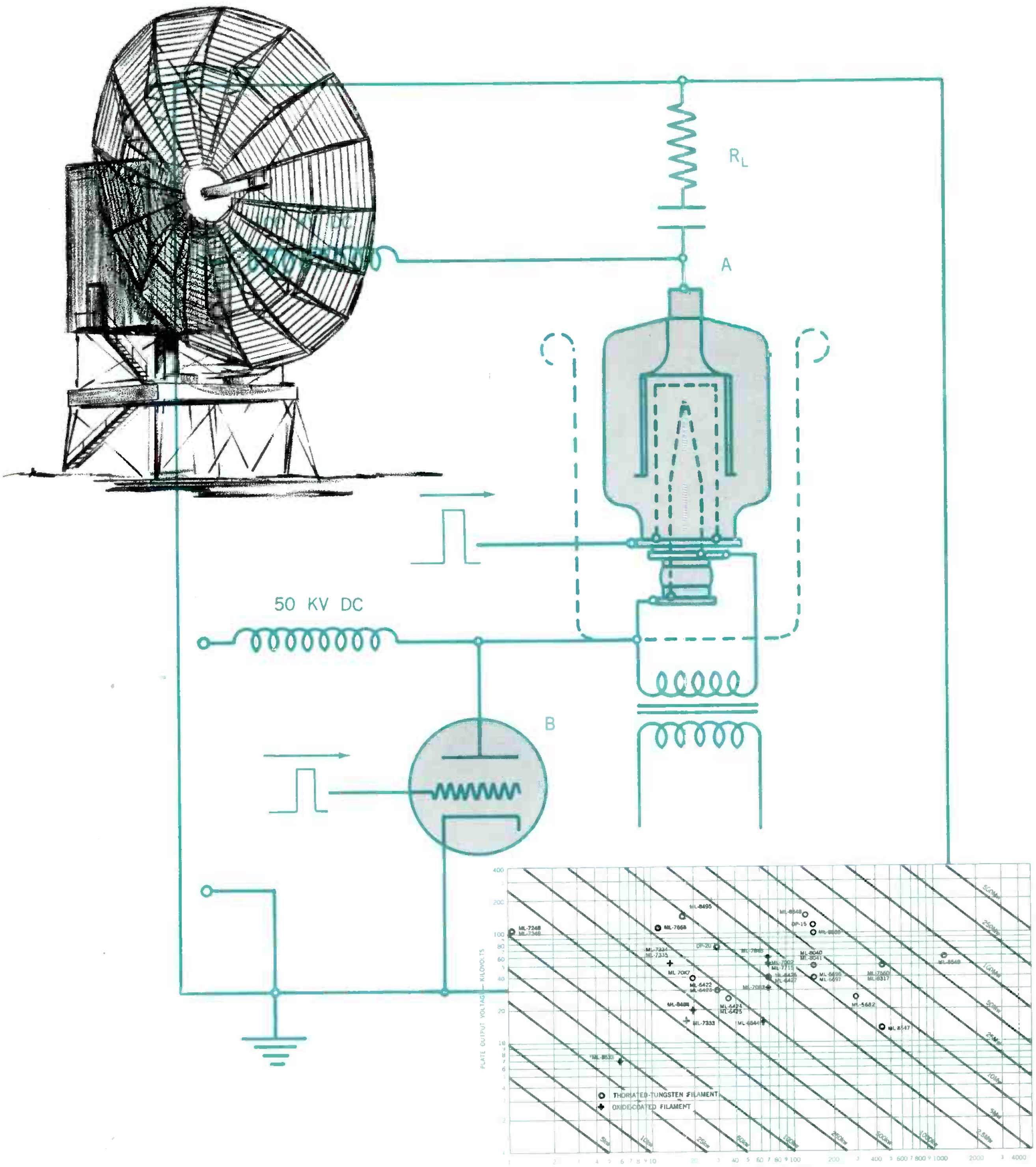

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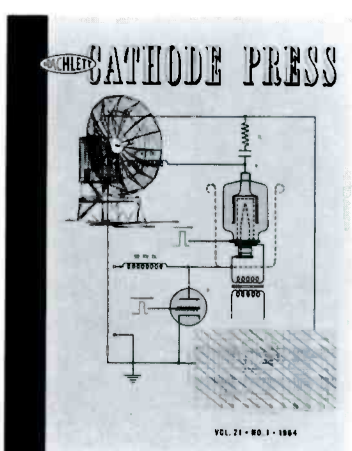

COVER . . . is a representation of the design and application aspects of pulse tubes for high voltage, high power video and rf pulsing. Part I of a two-part article on this subject begins on Page 2.

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IN THIS ISSUE

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- Small Power Tubes
- Photosensitive Tubes

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Editor's Note:

This is Part I of a two-part article which is an unusually complete compilation of design and application data on this subject. Part II, "Interactions Between Pulse Modulation Tubes and Circuits" is scheduled for CATHODE PRESS, Vol. 21, No. 3. Both parts are to be reprinted in Machlett's brochure "Pulse Tubes for High Voltage, High Power Video and RF Pulsing" (1964 Edition).

Vacuum Power Tubes for Pulse Modulation

by Dr. H. D. DOOLITTLE
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Part 1

Design, Theory and

The generation of high voltage and/or high power pulses is essential for most radar or other applications involving pulses of electromagnetic energy. The generation of power pulses requires an electrical energy storage element which can be either a capacitor or an inductance. For practical reasons a capacitor is nearly always used. In order to transfer the energy from the storage device to the pulse energy generator, some type of switch is required. Gaseous devices such as thyratrons, ignitrons or spark gaps may be used. Similarly vacuum tubes may be used. The principle difference in these two types of control devices is that the gaseous devices are capable of being turned on only, whereas vacuum tubes allow complete control over the transfer of energy. Gas tubes are used extensively with pulse forming networks to generate high power pulses. Whenever pulses must be spaced close together, or the pulse shape must be carefully controlled, hard tubes, i.e., high vacuum tubes, must be used.

Since Class C operation of transmitting tubes is quite similar to a high duty cycle pulse modulator, power transmitter tubes can easily be applied to pulse generation. In more recent years vacuum tubes have been designed especially for pulse operation.

The principle design features for tubes to be used in pulser operation are high voltage stability, high output current, good efficiency and precise control of the output power. The transition from the non-conducting to the conducting state must be accomplished in a time short compared to the pulse width. These various factors will be discussed in the following paragraphs.

Principal Design Factors of High Vacuum Pulse Modulator Tubes

1. The basic equations governing the flow of current.

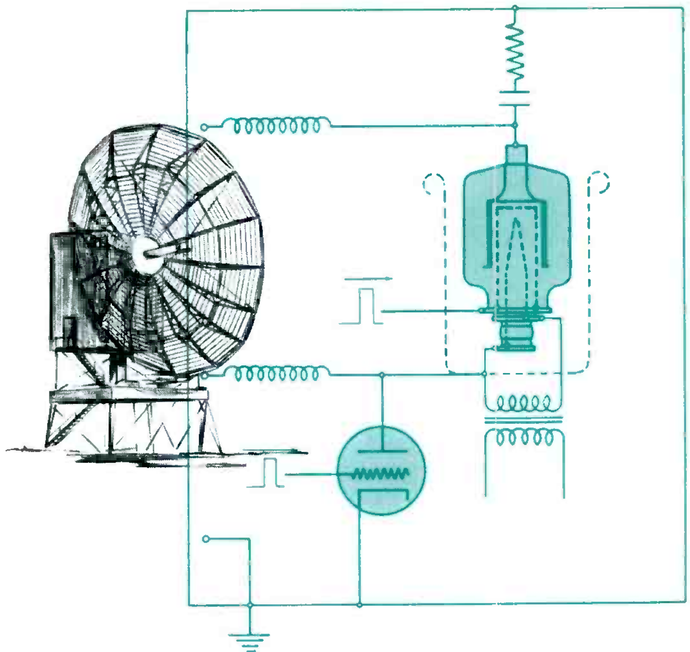
All vacuum tube cathodes emit-space-charge limited current according to the formula:

$$i_k = i_p + i_g + i_{sg} = \frac{2.33 \times 10^{-6}\, \alpha A}{S^2}\left(e_g + \frac{E_{sg}}{\mu_{sg}} + \frac{e_p}{\mu_p}\right)^n \quad (1)$$

where i_k = instantaneous cathode current in ma
i_p = instantaneous plate current in ma
i_g = instantaneous grid current in ma
i_{sg} = instantaneous screen-grid current in ma
α = a constant dependent on geometry of tube
A = cathode emitting area in cm^2
S = equivalent diode spacing in cm
e_p = instantaneous plate voltage in volts
E_{sg} = dc screen-grid voltage in volts
e_g = instantaneous control-grid voltage in volts
μ_p = plate amplification factor
μ_{sg} = screen-grid amplification
n = very nearly 3/2 for most geometries

Instantaneous values are given for currents and voltages because it is not possible to take dc readings in the positive grid region due to problems of electrode dissipation. The screen voltage is given as dc since that is the usual operating condition.

For a simple planar electrode triode this formula reduces to:



Operational Characteristics

$$i_k = i_p + i_g = \frac{2.33 \times 10^{-6} A}{S^2}\left(\frac{e_p}{\mu_p} + e_g\right)^{3/2} \quad (2)$$

where A is the actual cathode area, S is approximately the grid-cathode spacing, e_p and e_g are the plate and grid voltages and μ_p is the amplification factor. The basic definition of the amplification factor is given by the ratio of the active grid to cathode capacitance to the plate to cathode capacitance. These capacitances refer only to that portion of the cathode structure which is emitting; i.e., the passive or tube structure capacitances are not to be included in the above ratio. Obviously, for a given grid-cathode spacing, μ_p increases as the plate to grid distance increases and it decreases if the grid wire mesh or helix is more open. μ_p is not affected by the grid cathode spacing in a well designed tube.

For a cylindrical triode like the conventional radio transmitting tube using thoriated-tungsten wires in a birdcage structure (See Figure 1), it is not possible to achieve a precise formula for i_k. However, equations which are accurate to a few per cent can be used. The form is essentially the same as for a planar triode:

$$i_k = i_p + i_g = \frac{2.33 \times 10^{-6} \alpha A}{S^2}\left(\frac{e_p}{\mu_p} + e_g\right)^{3/2} \quad (3)$$

where α is a constant depending on the spacing between cathode and grid, the diameter of the cathode wires and the spacing between cathode wires, A is the cathode emitting area and S is the equivalent diode spacing. The latter is about 10% to 20% greater than the actual grid-cathode spacing. α is unity for solid cylindrical cathodes when S << cathode diameter. α is between 2 and 10 for most cathodes consisting of a number of parallel wires spaced many wire diameters apart.

In addition to the above equations, one needs a formula to calculate the division of current between the plate and the grid for various electrode potentials. Again no exact expression can be found. Approximate formulas are available. The simplest expression which gives fair results for $e_p/e_g > 2$, i.e., where anode current is less than j_o in equation 5, is given by:[1,2]

$$\frac{i_p}{i_g} = \delta \sqrt{\frac{e_p}{e_g}} \quad (4)$$

where δ is a constant depending on the interelectrode spacings and the screening fraction of the grid.

Another equation which is vital to tube design is that giving the maximum current which can cross the space from grid to anode in triodes or the screen grid to anode in tetrodes. This current is limited by the total space charge in the grid-anode or screen-grid-anode region and accounts for the high grid current and low plate current at low plate voltages seen on the characteristic curves of all tube types. This maximum current[3,4,5] in ma. per square centimeter of the active anode surface, j_o, for triodes is given by the equation:

$$j_o = \frac{2.33 \times 10^{-6} (e_p^{1/2} + e_g^{1/2})^3}{d^2} \quad (5)$$

where e_g is replaced by E_{sg} for tetrodes
d = grid or screen-grid to anode spacing in centimeters

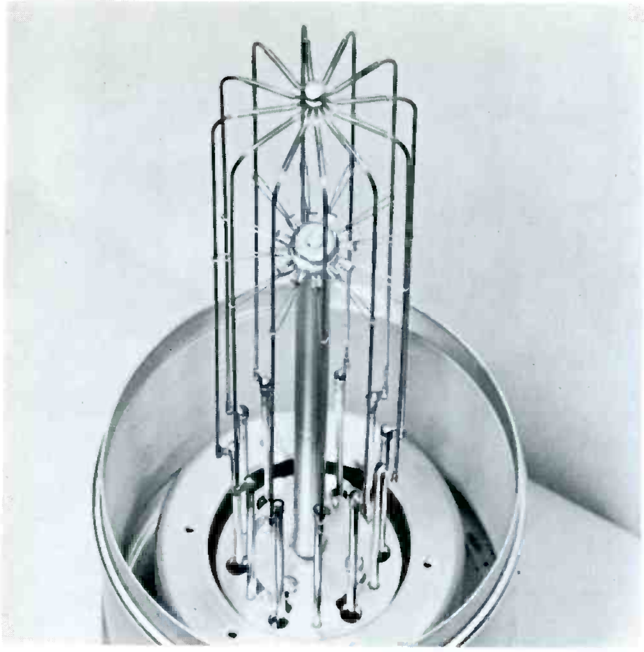


Figure 1 — A typical thoriated tungsten wire cathode — cathode of ML-7480 above.

Equation 3 for the total cathode current in a triode can be simplified to

$$i_k = i_p + i_g = K\left(\frac{e_p}{\mu_p} + e_g\right)^{3/2} \qquad (6)$$

where K is a constant called the perveance, which is dependent on the total cathode emitting area, the form of the cathode, and the grid-cathode spacing. For high perveance the cathode area must be as large as possible and the grid-cathode spacing must be as small as is feasible. Typical values of K vary from 1 microperve or one microampere per volt 3/2 for a gun of a klystron transmitting tube to 10,000 microperves or 10 milliamperes per volt 3/2 for a large radio transmitting tube. Even in the latter case, it is easy to see that e_g must be driven of the order of 2000 volts positive in order to get a few hundred amperes of emission current from a cathode. This is so since e_p must be small during conduction of current, i.e., the tube drop must be low. Figure 2 shows the effect of grid-cathode spacing on the effective drive voltage $\frac{E_{sg}}{\mu_{sg}} + \frac{e_p}{\mu_p} + e_g$ for tetrodes. For triodes the same data can be used but $E_{sg} = 0$. (As noted above $\frac{e_p}{\mu_p}$ is usually negligible in either case). Figure 2 also shows that the effective grid drive voltage must be increased in order to draw higher emission current density from the cathode.

The numerical value of perveance depends on grid-cathode spacing, cathode area and also on the form of the cathode. A squirrel-cage type of cathode of a length, L, with 16 wires on a two-inch bolt circle spaced a distance, S, from a grid will have a certain perveance. Doubling the number of cathode wires on the same bolt circle will raise the perveance by only 30%, but require twice as much cathode heating power. A cylindrical cathode of sheet metal 2-inches in diameter and the same length will have only about twice the perveance of the 16-wire cathode and require many times the cathode heating power. Of course, if the length of the cathode is doubled in any case, the perveance is doubled; but otherwise, when wire cathodes are used, the perveance does not necessarily increase linearly as the number of cathode wires is increased. This is the reason for the α in equations 1 and 3. It is also the reason why wire cathodes are used so extensively; that is, in order to obtain the highest perveance per watt of cathode power. The total cathode current density is limited by the required life of the cathode. Since emission density increases and cathode life decreases as an exponential function of cathode temperature, and since pulsed radar requires high peak powers, a compromise must be made between tube size and cathode life.

2. High Voltage Stability

The equations given above permit calculation of tube data with an error of 10% or less. However, in order to complete the design of a tube, it is necessary to consider one factor; i.e., will the peak voltage between electrodes cause excessive field emission and internal tube breakdown or flash arcing? Fortunately, closer grid-to-cathode spacings require less positive grid drive voltage, and it happens that there is no problem in designing tubes which do not initiate arcs between grid and cathode. The control-grid to plate, or screen-grid to plate spacing is another matter entirely. Here a compromise must be made between higher tube efficiency and voltage stability. From equation (5) it is obvious that, d, the outer grid to anode spacing, should be made as small as possible to have the lowest possible e_p or plate voltage drop during the pulse. However, this spacing, d, must be large enough so that the vacuum insulation between outer grid and plate does not fail at the maximum plate to grid potential for which the tube is rated. In order to design a tube it is necessary to know what the maximum electric field gradient at the grid can be without danger of excessive flash arcing. Kirkpatrick[6] has given a summary of the empirical data on breakdown between plane parallel electrodes. His data is given by curve A in Figure 3 showing voltage against spacing. Since electron tubes using cylindrical structures with wire grids have higher voltage gradients at the grid wires than do parallel plane sheet metal electrodes, the maximum voltage for practical tubes is lower. Since low-amplification-factor triodes have fewer wires and usually finer wires, the maximum plate voltage hold-off capabilities depend somewhat on the amplification factor. For this reason a shaded area, B, on Figure 3 indicates roughly the values of plate hold-off voltage for tubes with thoriated-

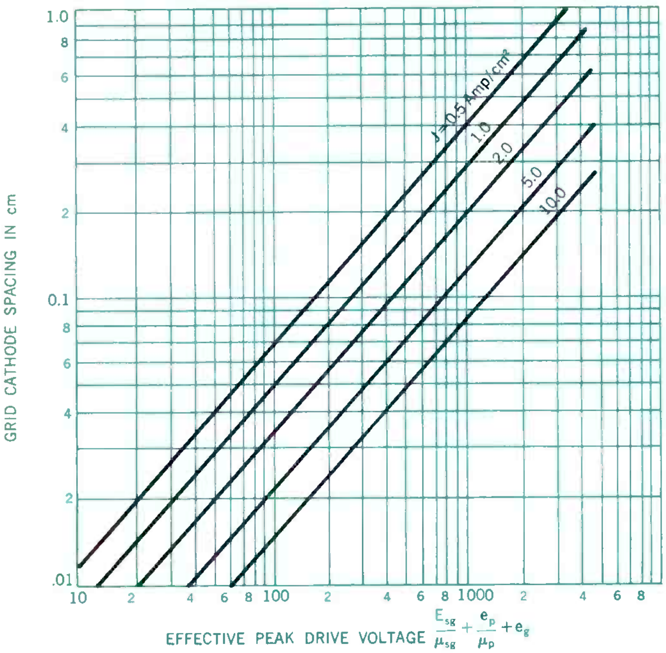


Figure 2 — Effect of grid to cathode spacing on required drive voltage for various cathode current densities, J.

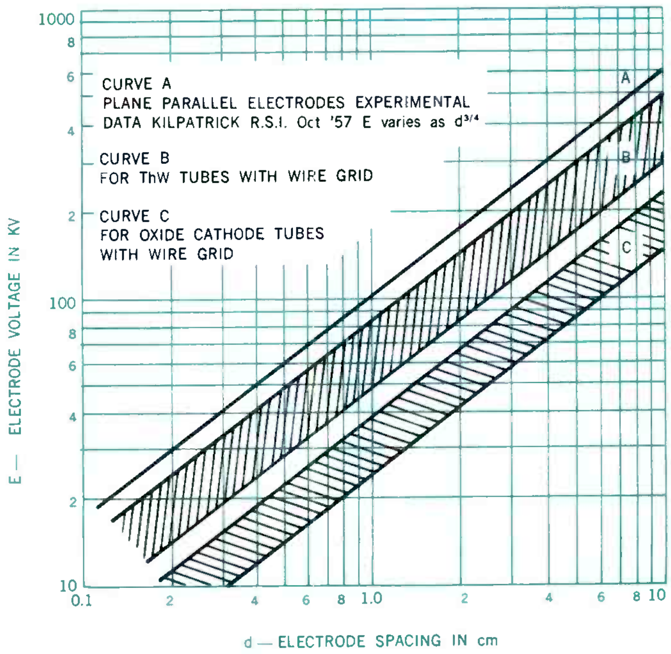


Figure 3 — Anode Voltage Rating versus Outer Grid to Anode Spacing.

tungsten cathodes and cylindrical structure grids. Another area, C, at still lower voltages is shown for tubes using oxide cathodes. In the latter case it appears that the products of decomposition of the oxide cathode cause the grid to become contaminated with a surface layer which has either a lower work function or has a greater roughness. It is well known that the maximum voltage gradient which any surface can support without sparking depends on the surface conditions. The best possible polishing will certainly improve the situation. In large tubes with many feet of wire, however, it is not feasible to perform optical polishing of grids. Furthermore, the result of a single tube arc could destroy the effect of such polishing.

One can read from the upper curve of Figure 3 the maximum permissible voltage gradients, E, for the parallel plane sheet metal case, since here the gradient is simply the voltage divided by spacing. It should be noted that this curve follows the equation $E \propto d^{3/4}$ and therefore at the higher voltages the maximum permissible gradient is lower. The lower curves are based on the calculated voltage gradients at the wire grids and on observations obtained from a series of tubes. Of course one has to know the actual geometry of a given tube in order to calculate the voltage gradients.

3. Cathodes for Pulse Modulator Tubes

At the present time only oxide and thoriated-tungsten cathodes are generally used. Extensive experience with thoriated-tungsten cathodes, see Figure 1, in transmitting tubes has demonstrated that the life of such cathodes is predictable.[7] The usual large transmitting tube cathode delivers 30 milliamperes per watt of cathode power with a safety factor of two in order to permit satisfactory operation at the rated —5% on filament voltage. Under such conditions cathode life is greater than 10,000 hours. If the filament voltage is closely regulated, say ± 1%, cathode currents up to 60 milliamperes per cathode watt can be obtained without much sacrifice in life. Higher emission can be had only at a corresponding reduced life. Peak cathode emission density of 3 amperes per square centimeter is compatible with the 10,000 life figure given above. With round wires it is seldom feasible to pull uniform emission density all around the circumference of the wire and therefore the average emission density will be less. Emission from thoriated-tungsten cathodes is independent of pulse width. The usual limiting factor on pulse width in such a tube is the rise in grid temperature. Excessive grid temperature causes the grid to emit; that is, to become a cathode with consequent loss of control by the grid.

Oxide cathodes have been used in switch tubes with maximum plate voltages of 75 kilovolts. (See Figure 4.) The advantages of the oxide cathode tubes are: smaller size, lower heater power for a given emission level, and better mechanical strength. Such tubes can be made so that they can be mounted in any position, and at least one design, the 7333, at the 300 peak kilowatt level has operated at rated power output on the vibration table from 30 to 2000 cycles per second at 10 g. On the other hand, it is not yet possible to predict the life of an oxide cathode over widely varying conditions. The 6544 operates at 2 amperes per square centimeter and 200 milliamperes per cathode watt. This tube has been evaluated on life test with pulse lengths of a few microseconds and a duty of about .0015. Under such operating conditions in laboratory life test equipment using a resistance load, average life is in excess of 3000 hours. In

Figure 4 — ML-6544 oxide cathode structure with grids and anode.

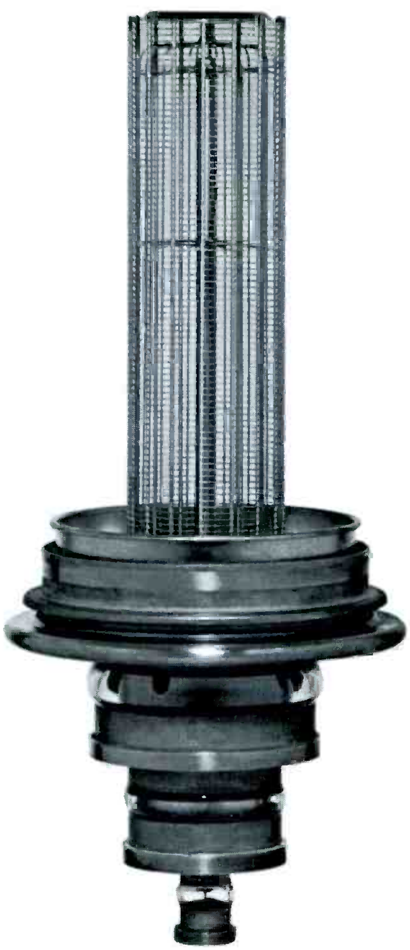


Figure 5 — A typical helical grid structure mounted over thoriated-tungsten cathode, ML-5682.

the case of the 6544 at .0015 duty, the grid dissipation is only about one-tenth the maximum capability of the grid. It appears feasible in this tube to extend pulse lengths to several hundred microseconds and/or increase the duty.

In oxide cathodes, life is dependent on cathode temperature, emission density, type of cathode nickel and residual gases. Improvements in cathode base nickels, tube processing and quality control can be expected to produce higher peak and average emission levels for very long life. Such development work requires continuous life test evaluation. Similarly it is necessary to monitor tube life on production sampling at the maximum ratings. Present life capability is purely empirical. For the above reasons commercial tube data sheets specify values of peak emission, pulse width and duty cycle for which the tube is monitored. Whereas any individual tube may operate satisfactorily under conditions considerably beyond the published limits, one cannot be sure that any tube bearing the same type number will do likewise.

4. Grids for Pulse Modulator Tubes

Grids usually consist of meshes or helices wound on vertical stays. (See Figure 5). The grids are almost invariably of tungsten or molybdenum, although they may be coated with platinum or gold or other materials to make them operate at higher dissipation levels without becoming emitters themselves. The screening fraction of the grid, i.e., the ratio of the area obstructed by the grid wires to the total area of the grid structure varies from 5 to 25%. The grid wires are usually made as small in diameter as is mechanically feasible. They must also have enough thermal capacity so that a localized arc will not result in the melting of a short section of wire. The spacing between grid wires is

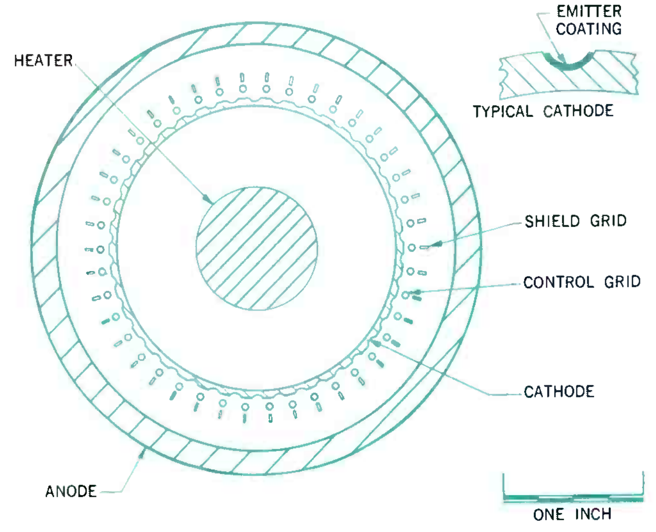


Figure 6 — Right section through active electrode area of ML-6544 showing beamed grid and cathode structures.

usually about equal to the grid cathode spacing in order that the grid have uniform control of the entire cathode emitting area[8]. This latter restriction means the use of a closer knit mesh and finer wires as the grid cathode spacing is reduced.

Typical "end-of-load-line" values for plate and grid currents depend on the screening fraction of the grid. Very roughly the percentage of the cathode current which goes to the grid will be about 1.5 times the screening fraction in per cent. Consider two tubes using the same cathode structure and interelectrode spacings but with different grid screening fractions. The low amplification factor tube, about 20, will have a screening fraction of about 10% and the grid current will be about 15% of the cathode current. The tube with a high amplification factor will have about 25% of the cathode current going to the grid. Conversely, the low amplification factor tube will require more negative bias to prevent plate current flow during the interpulse period. As far as grid driving power is concerned, it is very nearly the same for either tube.

Some triode tubes have been made with very low amplification factors, about 5. These tubes can pass reasonably high plate currents without driving the grid positive; see equation (6). Although a large negative bias is required in the inter-pulse period, the driving power can be quite low. Unfortunately, this cannot easily be done with high voltage tubes, since the large grid-anode spacing required to provide adequate high voltage insulation raises the amplification factor too much, even with low screening fractions on the grid.

The maximum permissible grid temperature determines the maximum dissipation rating of the grid. It also determines the maximum width of a single pulse. Neglecting radiation loss from the grid, and assuming the entire volume of the wire is heated instantaneously, the maximum rise in temperature of a grid during a pulse would be given by,

$$\Delta T = \frac{0.24\,P}{(s)\ (m)}\,\tau \qquad (7)$$

where ΔT = temperature rise in °C
P = watts dissipated in the grid
τ = pulse length in seconds
s = specific heat of the grid material
m = mass of the grid in grams

Since grids can operate to temperatures as high as 1400°C, radiation losses are significant and make possible higher grid dissipation ratings than the above formula indicates. This subject of grid dissipation will be discussed further in a later section. For the usual transmitting type of tube, the maximum length of a single pulse at rated power output is usually limited to 10 milliseconds or less.

Since grid current is undesirable and grid dissipation may be a limiting factor in tube operation, tubes have been made with grids so positioned as to substantially reduce grid current. (See Figure 6.) These tubes utilize a type of gun structure with relatively long strip cathodes set in a focusing groove. The grids consist of relatively large diameter rods parallel to the emitting cathode strips. These grid wires are spaced on either side of, and somewhat forward to, the cathode emitting area such that they are not in the path of the main electron beam[9, 10]. Such tubes are capable of extremely long pulses as far as the grid is concerned. Since such grids intercept much less space current, the driving power for such a tube is lower than the type of triode discussed earlier, although the amplification factor may be from 50 to 500. The 6544 tube has a μ of 90, hold-off capability in excess of 20 kilovolts, and the grid current is less than 10% of the cathode current.

In the case of conventional tetrodes, control-grid dissipation is not a problem, since intercepted grid current is kept low and so is the positive grid drive voltage. In this case the screen-grid dissipation is the limiting factor and is subject to all the restrictions of the control grid of a triode.

5. Anodes for Switch Tubes

Anodes for radiation cooled tubes are usually of molybdenum sprayed with a zirconium getter powder. The use of copper for forced-air or liquid cooled tubes is general. Although radiation cooled tubes have been built for 3 kilowatts of dissipation, they are only usable if the associated circuit components are several feet away. In general, any rating over 100 watts is objectionable due to space problems. For copper anode tubes, anode dissipation presents no serious problem since liquid or forced-air cooling can be used.

Equation 7 with appropriate values is applicable in evaluating anode dissipation density. Of course one has to consider conduction cooling, anode wall thickness and temperature gradient through the copper[11, 12].

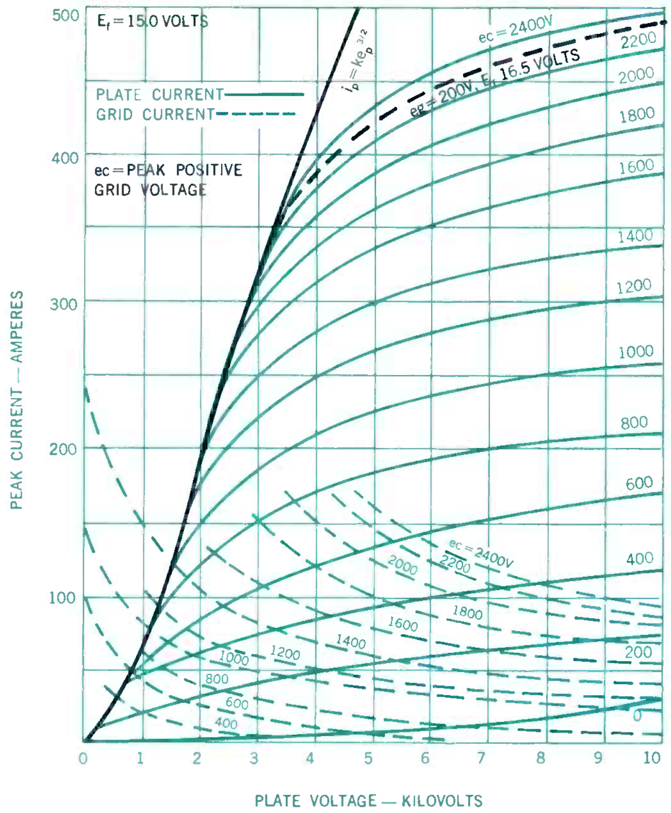


Figure 7 — Constant Grid Voltage Characteristic Curves of ML-7560 showing End-of-Load Line Point and Diode Curve $i_p = ke_p^{3/2}$.

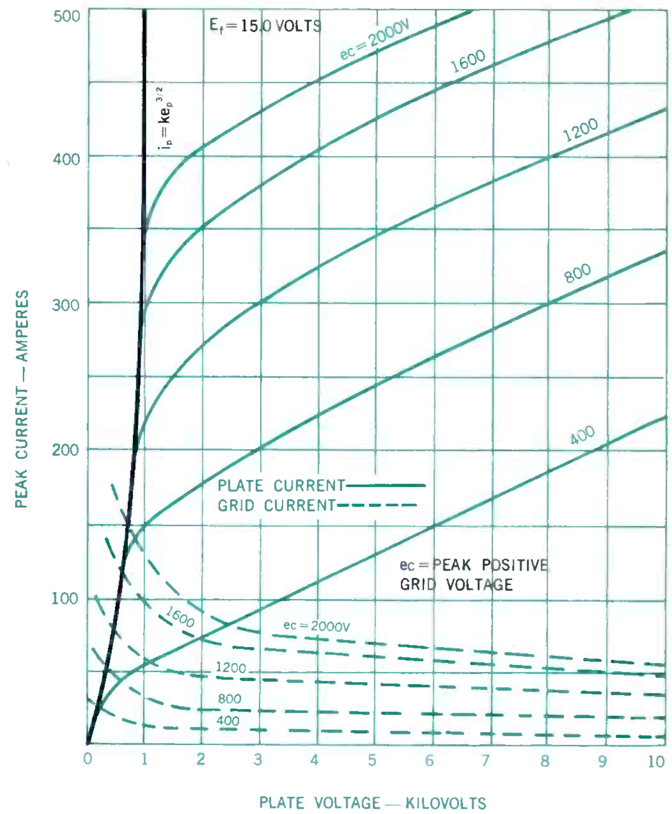


Figure 8 — Constant Grid Voltage Characteristic Curves of ML-8547, showing effect of reduced grid anode spacing on the Diode Curve $i_p = ke_p^{3/2}$.

6. Interelectrode Capacitances and Amplification Factor

The grid (or screen-grid) to anode spacing and the anode surface area determine the grid-anode (or output) capacitance. It has been shown that the outer grid to anode spacing is determined by voltage breakdown considerations. Furthermore, it has been shown that the anode area is determined by the minimum acceptable tube efficiency. In other words, the grid to plate capacitance of a triode or the output capacitance of a tetrode is not an arbitrary design parameter. It is fixed by other considerations except insofar as the capacitance of the electrode support structures and tube envelope can be kept to a minimum. Similarly, the grid cathode capacitance of a triode or the input capacitance of a tetrode is determined by the choice of the quantity, S, the equation (1). If it is required to minimize the peak positive value of e_g in equation (1) for the maximum value of $i_k/\alpha A$, the only independent variable that can be selected is S, the effective grid-cathode spacing. It should be recalled that $i_k/\alpha A$ has a limited maximum value based on the required cathode life. In order to decrease the maximum value of e_g (to reduce the grid drive voltage and power), it is necessary to increase the input capacitance. Although the input tube capacitance increases as the grid is moved closer to the cathode, the total energy stored in this capacitance, in order to raise the grid potential to the desired value, decreases approximately linearly with the spacing. Since both the driving power and the capacitance charging energy decrease with decreasing grid-cathode spacing, it is obviously desirable to make this spacing as small as possible, even though it causes a loss in plate current density (equation 5). Practical grid-cathode spacings are determined by how small a grid wire can be used at how close a spacing and still maintain a uniform grid-cathode spacing throughout life.

The only capacitance in a triode which can be varied appreciably by the tube designer is the plate to cathode capacitance. For a fixed grid-anode spacing this capacitance determines the amplification factor of the tube. As shown in section 4, the net result is that either type of tube requires about the same driving power. As regards to capacitance charging currents, again there is a balance. The lower amplification factor tube may have a little lower grid-cathode capacitance, but it requires a higher total grid voltage swing. In general, the choice of amplification factor will depend on other circuit considerations such as driver tubes, use of pulse transformers, etc. For tubes designed to operate at low plate voltage, the outer-grid to anode spacing can be made smaller and, by equation (5), the current density in the grid-anode space can be higher. (See ML-7560 data vs. ML-8547, Figures 7 and 8). Even so, the grid-anode capacitance will increase due to this closer spacing, and the $\mu\rho$ will decrease unless the screening fraction of the grid is also increased at the same time.

The input capacitance of a tetrode will be higher than that of a triode of the same cathode emitting area, since the capacity from the control-grid to the screen-grid is in parallel with the control-grid to cathode capacitance. As regards the capacity charging currents and drive power, both will be reduced, since the total grid voltage drive from cut-off to maximum positive drive is substantially reduced over triodes. Where fast rising pulses are encountered, the tetrode seems attractive since its plate to control grid capacitance is much lower than for triodes. In order to consider the effective total input capacitance, it is necessary to write an equation for the "Miller Effect" for triodes or tetrodes:

$$C\text{ in eff} = C_{in} + C_{gp}\left(\frac{e_p}{e_g} + 1\right). \quad (8)$$

where = C in eff = effective total input capacitance
C_{gp} = plate to control grid capacitance
C_{in} = measured tube input cap. from grid to cathode (and screen-grid), anode grounded
e_g = pulse input grid voltage
e_p = pulse output voltage

Since the ratio of e_p to e_g for a tetrode is increased by about the same amount as the capacitance, C_{gp}, is decreased over that for a triode, effective total input capacitance of a tetrode is about double that of a triode. Of course the necessary grid swing is smaller for the tetrode.

Characteristic Curves and Principal Data for Some High Vacuum Pulse Modulator Tubes

The preceding paragraphs discussed briefly the design consideration for Vacuum Tubes. From these sections one can calculate all the pertinent data required for the circuit engineer. It is conventional to present absolute maximum ratings on such items as plate voltage, grid voltage, grid dissipation, plate dissipation, etc. Similarly interelectrode capacitances, filament voltage and current are given. Since it is not feasible to give an analytical relation between electrode voltages and currents, a graphical presentation is made. Usually these "Characteristic Curves" are given for 1, plate current and grid current vs. plate voltage with constant grid voltage curves as a parameter; or 2, grid voltage vs. plate voltage with constant plate and grid currents as parameters. The data for these curves are taken with microsecond pulses at a low repetition rate. The curves are referred to as static characteristics, since they give instantaneous values of currents for corresponding values of electrode voltages. It is possible to determine the dynamic characteristics for any load conditions from these static characteristics.

With vacuum tubes it is necessary that the plate current be negligibly small during the interpulse period. For this reason, a curve of plate voltage versus grid bias for cutoff conditions or a value of μ for cutoff is given (Figure 9). Since the interpulse period may be very long compared with the pulse duration, a plate current of a few milliamperes can cause an appreciable anode dissipation. Pulse modulators should have a sharp cutoff characteristic because the required negative bias voltage must be added to the positive grid drive in order to determine the total grid swing. Also the range of cutoff bias voltage for different tubes of the same type should be small, since the circuit designer must accommodate the poorest tube. The cutoff bias will vary with the plate voltage of a triode and with both the plate and screen-voltage of a tetrode. The pulser must be designed to provide a bias voltage large enough to be effective for the highest plate and screen-grid voltages that may occur in operation of the pulser, particularly when load inductance may cause the instantaneous plate voltage to go considerably more positive than the dc voltage. It is usually not practical to specify that the tube shall be biased to zero plate current, particularly in high voltage tubes. A compromise must be made between added grid drive power and plate dissipation. If there are oscillations on the grid drive following the pulse, it will be necessary to bias sufficiently such that plate current does not flow at the positive going peaks of such oscillations.

High voltage tubes may have some field emission from the grid. In such cases it is not possible to reduce this current by the use of additional bias since this current comes from the grid facing the anode. Tube specifications should give a maximum value for such currents. It should also be noted that plate current flowing at high plate voltages continuously in the interpulse period will give rise to appreciable x-rays. It is necessary to shield high voltage equipment for personnel protection.

1. Characteristic Curves of Triodes.

In order to illustrate the typical regions of the characteristic curves of triodes, the ML-7560 tube will be discussed. This tube uses a thoriated-tungsten wire cathode (Figure 1). Constant positive grid drive voltage curves are given in Figure 7, showing plate current and grid current as a function of plate voltage. It is to be noted that the area to the left of the line marked $i_p = K\,e_p^{3/2}$ defines a region where it is not possible to get any current to the plate. From the grid current curves it is obvious what is happening. It is seen that the grid current rises as the plate current decreases while the sum of the two currents is nearly constant. The reason for this situation is that a virtual cathode is established in the grid-anode space, i.e., the effective potential somewhere between the grid and the anode has dropped to zero (cathode potential) or below. When this happens, the current arriving at the plate is determined by the plate potential and the position of the virtual cathode as follows:

$$i_p = 2.33 \times 10^{-6}\,A\,e_p^{3/2} \;\; /s^2 \quad (9)$$

where i_p = current to anode in ma.
A = area of virtual cathode in cm^2

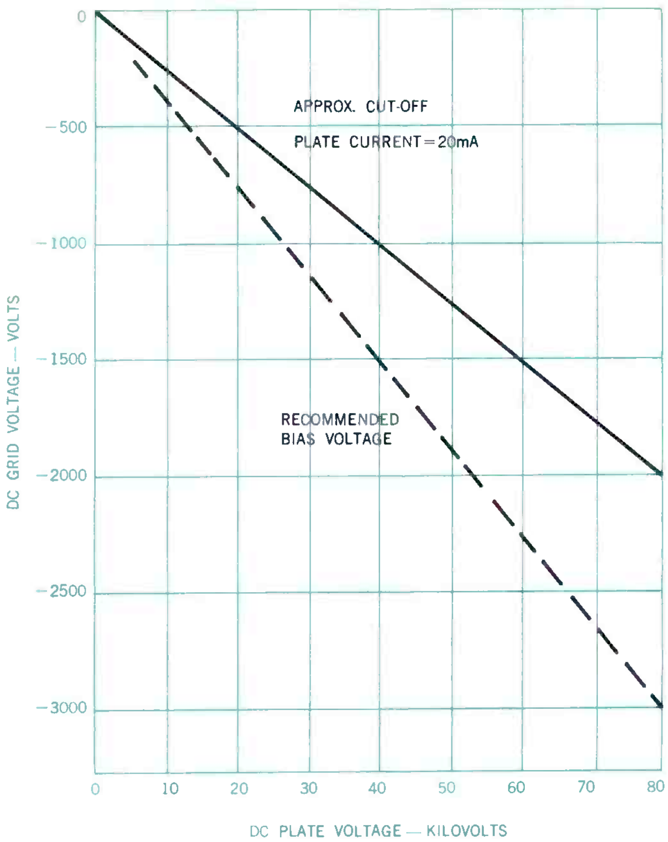


Figure 9 — Grid Bias versus Plate Voltage for cut-off in inter-pulse interval — ML-7560.

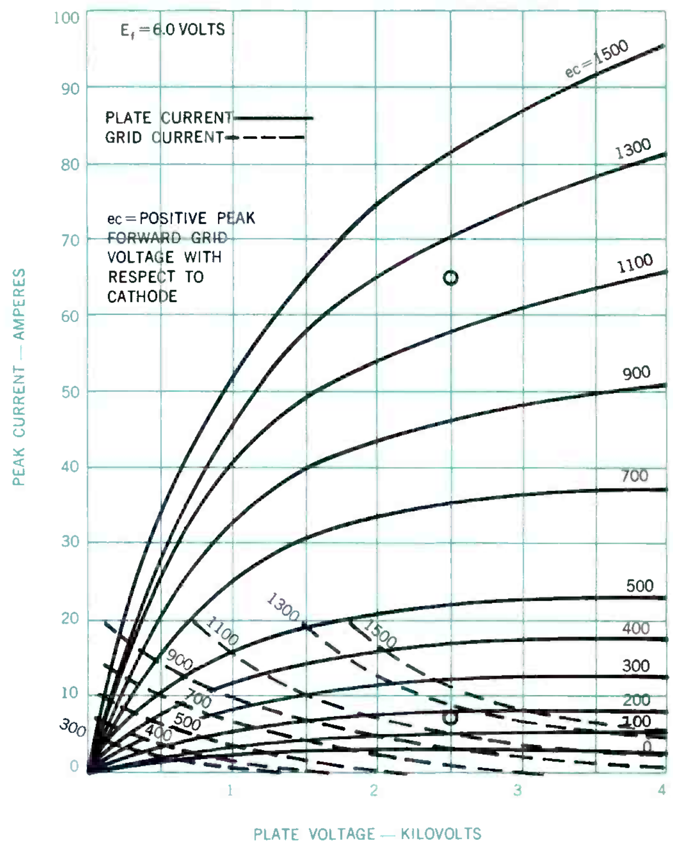


Figure 10 — Constant Grid Voltage Characteristic Curves of ML-6544.

e_p = plate voltage in volts

s = spacing from virtual cathode to anode in cm.

The area of the virtual cathode in this cylindrical electrode tube is the area of an hypothetical cylinder approximately half-way between the grid and the anode, and of length equal to the cathode length. When such a virtual cathode is formed, electrons passing through the grid are brought to rest and those that do not go to the anode (equation 9) are returned to the grid. This result is predictable from equation 5. This tube was purposely picked to illustrate equation 5, since the grid-anode spacing is large enough to hold off 60 kilovolts and the effect of the virtual cathode is more obvious than in closer spaced lower voltage tubes. Comparison of these data with those for a similar tube with a much smaller grid anode spacing and a lower value of maximum plate voltage (Figure 8) emphasizes the increase in "tube drop" with increased spacing. The overall plate efficiency does not change much since the dc plate voltage is correspondingly higher for tubes with greater spacings. The actual current density arriving at the anode at the end of the load line point, P, on Figure 7 is about 0.5 amperes per square centimeter of *anode* surface. Assuming that more cathode emission was available, it would be necessary to raise both grid and anode potentials in order to increase the total anode current. Such a procedure would mean that the tube drop would have to increase and the efficiency would decrease, since the maximum dc plate voltage is fixed. In other words, the use of more cathode wires or even a solid cylindrical sheet cathode without increasing either cathode length or diameter, cannot substantially increase anode current without materially lowering the tube efficiency. A properly designed tube balances total available cathode emission against that current which can cross the grid-anode space at reasonable plate efficiency, i.e., about 90%.

Another feature of the curves of Figure 7 is the gradual upward slope of the plate current curves to the right of the space-charge knee, and the corresponding downward slope of the grid current lines. Three factors contribute to these slopes. The most prominent effect is due to the term $e_p/\mu\rho$ in equation 6. It is seen from this equation that even if e_g is held constant, the total cathode current must increase, as the anode voltage increases. The higher the amplification factor of the tube, the flatter is the plate current versus plate voltage curve at fixed grid drive. A second factor is that the ratio of i_p to i_g increases as the ratio of e_p to e_g increases (see equation 4). This means that the plate current will rise while the grid current decreases. A third factor is secondary grid emission which becomes more pronounced at higher plate voltage. At low grid drives, that is a few hundred volts positive, the ratio of secondary electrons to primary electrons may exceed one. If the plate voltage is high enough, all these secondary electrons go to the plate and a negative grid current results (See Figure 13).

It should also be noted that the spacing between plate or grid current lines for a constant increment of grid drive voltage is fairly constant except at the higher grid drives. When plate current does not increase as could reasonably be expected by an appropriate increase in grid voltage, it is because one is running out of cathode emission. That part of the cathode closest to the grid becomes saturated in emission, and increased grid drive results only in reaching around to the back of the cathode wire where the field is not yet strong enough to take all the available emission. Raising the filament voltage will now give increased emission. Note the line marked Ef + 10% at 2000 volts in Figure 7. Such an increase in filament voltage reduces cathode life appreciably.

2. Characteristic Curves of Shielded Grid Triodes

Another type of triode switch tube is the shielded grid type with a beamed cathode structure. This type of triode has a high amplification factor and yet takes very little grid current. Examples of this type are the 6544, 7003, 7845. For discussion here we consider the 6544 (See Figures 4 and 6).

This design uses about 40 straight cathode strips .060″ wide, spaced with about .080″ separation between adjacent parallel strips. These cathode strips are arranged to form a cylinder of about 2″ in diameter. Located outwardly and slightly in front of the gaps between these cathode strips is a squirrel cage grid of .070″ molybdenum wire. On a somewhat larger bolt circle is a molybdenum shield grid also using .070″ molybdenum wires. This shield grid is tied to one end of the cylindrical cathode by a metal disc. The control grid wires feed through this disc to the external grid electrode terminal. Surrounding the shield grid is a copper cylindrical anode with about a 0.2″ radial spacing between it and the shield grid.

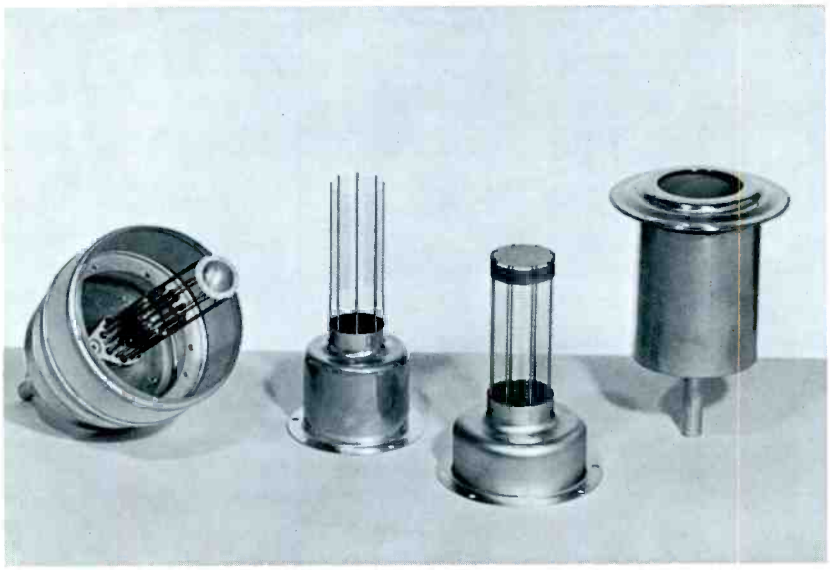
The principal arguments in favor of this design are: (1) by proper cathode shaping one can keep control grid current low, (2) shield grid current will be zero since this grid is at cathode potential, (3) any arc to the shield grid will not transfer to the cathode since lead impedance between shield grid and cathode is zero, (4) the shield grid can withstand heavy arcing if necessary without distortion, (5) neither grid will be required to stand appreciable dissipation, i.e., there will be no question of primary emission troubles even with abnormal use, (6) the structure is rugged, (7) no screen grid power supply is required, (8) the amplification factor is high and only a modest negative control grid voltage is required for cut-off.

Although the grid current is low in this tube, it is seen that at low plate voltage the grid current rises rapidly. The drop in plate current equals the rise in grid current; i.e., a virtual cathode is forming between shield grid and plate. The slope of the plate current versus plate voltage curve at constant grid drive is determined by the amplification factor of the tube, with μ about 60, the curves are fairly flat from 3 to 20 KV (See Figure 10).

3. Characteristic Curves of Tetrodes

A well known pulse tetrode is the 7007. Since this tube has been widely used and it exhibits typical tetrode characteristics, it will serve as an illustrative example of this class of tubes. Figure 11 shows the tube, and Figure 12 shows the

Figure 11 — View of cathode, grids and plate of the ML-7007 tetrode.



grid drive voltage versus plate voltage for constant plate and control grid currents at a screen grid voltage of 3000 volts. Since the screen-grid shields the cathode from the high plate potential, the cut-off bias is determined primarily by the screen grid voltage and its amplification factor of 10. See equation 1. The total grid swing required to obtain the rated cathode emission is less than for a triode, and little control grid current is drawn. The grid current is not appreciably affected by plate voltage variations. However, when the plate voltage is decreased far enough, a virtual cathode forms between the screen grid and anode with the resultant decrease in anode current and corresponding increase in screen-grid current, just as in the case of the triode for the control grid to anode region. The plate and screen grid current curves clearly show virtual cathode formation. For plate voltages higher than twice E_{sg}, the slope of the plate current curves reflect the high plate amplification factor of this tube. The spacing between the screen-grid and anode in this tube is about the same as that of the 6696 and considerably less than that of the 7560 triode. The 7007 tube is rated to hold off only 25 kilovolts compared to 45 kilovolts for the 6696. This relatively low voltage rating on the 7007 is due to the length of the ceramic envelope and not to internal electrode spacings. Some further problems on voltage stability will be discussed later.

Use of the Characteristic Curves to Determine Dynamic Operating Conditions

A "load line" is selected on a set of grid voltage versus plate voltage static characteristics in much the same manner as is done with Class C operation of CW amplifiers or oscillators. [13] For a first approximation, it is assumed that the load impedance is to be pure resistance. In this case the load line on the above characteristic curve will be a straight line. In order to select a tube it is necessary to first specify the required pulse voltage and pulse current for the load. If a pulse transformer is used, then the peak pulse power can be used to select a tube as the transformer will permit stepping up or down the voltage delivered from the tube (See Appendix I). If it is desired to work from the pulse modulator tube directly into the load, then a modulator tube must be selected such that the maximum dc plate voltage is approximately 10% greater than the required pulse voltage to be delivered to the load. It is also necessary that the tube selected be capable of delivering the required output pulse current. (Of course two or more tubes may easily be used in parallel). Having found a tube or tubes capable of the required output voltage and current, the next step is to determine the cut-off bias required during the interpulse interval when the modulator tube is supposed to be passing no current, i.e., the switch is open. Usually (Figure 9) a curve will be included with the tube data showing recommended bias voltage for various plate voltages. If such a curve is not included, a good rule is to use approximately 30% more bias voltage than for Class B amplifier operation. This additional bias is required to assure that plate current is negligibly small in the interpulse interval and to make certain that any oscillatory conditions at the end of the grid pulse do not give rise to appreciable plate current pulses following the desired output plate current pulse. The cut-off end of the load line has now been determined. See Figure 13. Next one picks a point of positive grid drive which from the grid voltage vs. plate voltage characteristic curves gives the required plate current to the load. This is the switch on condition. Selecting this point involves a compromise on grid driving power and plate efficiency. If such a point is picked at very low plate voltage, the output circuit will attain the highest efficiency, but the grid drive power may well be excessive. The result may be to overload the control grid or screen grid. Hence, if such a point were picked, the grid dissipations should be checked to see that these maximum ratings are not exceeded.

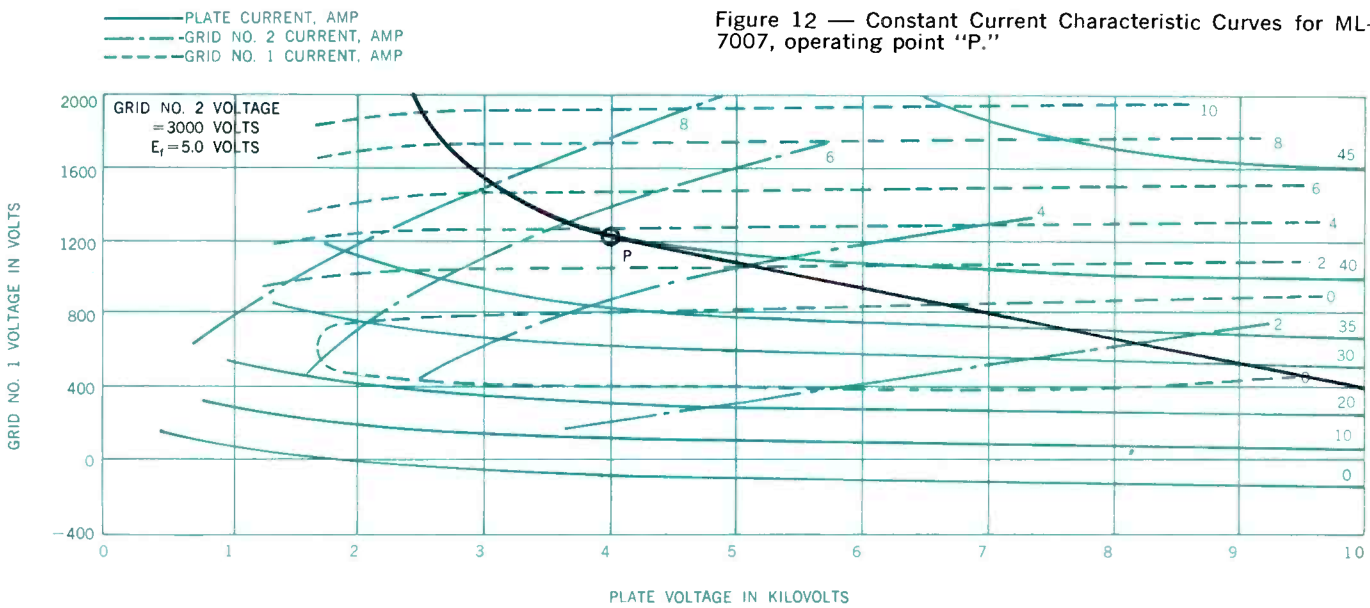


Figure 12 — Constant Current Characteristic Curves for ML-7007, operating point "P."

In the case of triodes, the operating point will usually be where the peak grid current is from 10 to 30% of the peak plate current. In tetrodes, the operating point should be picked such that the screen grid current is not excessive as regards the screen grid dissipation limit. (See Figure 12) When these two points have been spotted on the characteristic curves, a load line can be drawn as a straight line terminating on these two points. This line shows what the instantaneous plate current, grid current and plate voltage will be for any specified grid voltage wave form (Figure 13).

In equipment operation it is necessary to consider effects of variation of dc plate voltage, dc screen voltage and the effect of variations of amplitude of the grid driving pulse. (For a more detailed analysis see Ref. 14.) The effect of variation in grid voltage on the output pulse of the pulser may be illustrated by drawing the load line on the plate-current plate-voltage characteristic curves for fixed grid drives. An examination of the characteristics of triodes, shielded grid triodes and tetrodes, for example, Figures 7 and 10, show that the form of these curves follow a general pattern. For an approximate solution to the problem of regulation, i.e., variation of grid pulse amplitude or flatness of the top of the driving pulse, a simplified set of curves may be used as shown in Figures 14, a and b, where A, B, C . . . represent different constant grid drive voltages. These curves can be expressed mathematically by the equation:

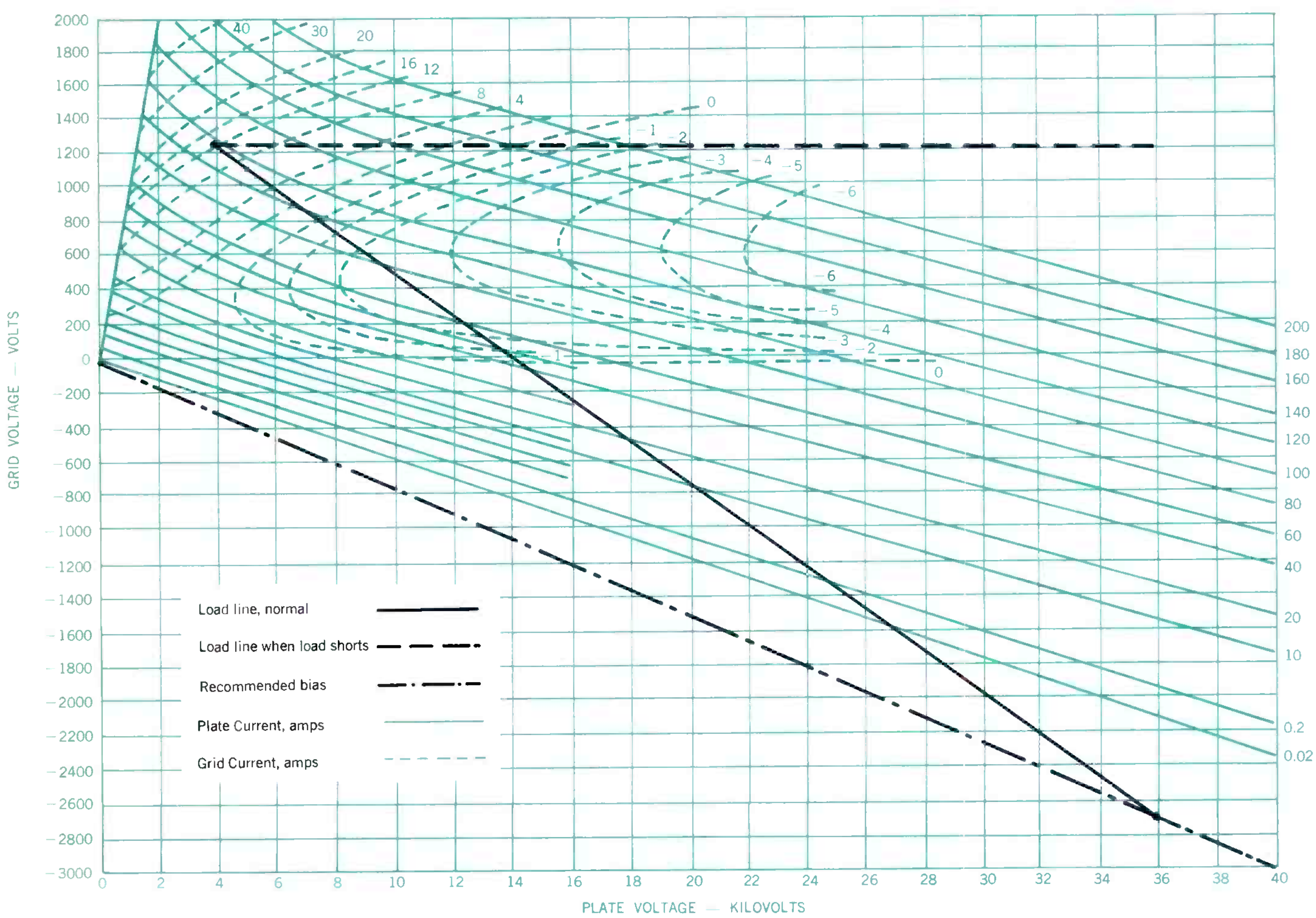
$$i_p = c\,(e_g + E_{sg}/\mu_{sg} + e_p/\mu_p) \qquad (10a)$$

with the following restrictions:

$i_p < \sigma e_p$
$i_p > 0$
$e_p > 0$
σ = conductivity of diode line
c = constant obtained from end of load line on characteristic curves.

Two load lines are drawn on the curves shown in Figure 14a. Line $E_{bb} - E_d$ — Opl corresponds to a low resistance load in series with a bias voltage, E_S, to simulate magnetron operation, where $E_{bb} - E_d = E_S$. The straight line connecting E_{bb} and Opl corresponds to a fixed resistance load of the same magnitude as the static resistance of the biased diode for the operating point, Opl. From this diagram it is evident that a change in the grid driving voltage corresponding to the curves A, B, C has no effect on the operating point for the switch tube. For actual tube characteristics the various

Figure 13 — ML-6696 Constant Current Characteristic Curves showing Reverse Grid Current Area, recommended dc bias, typical Load Line and Load Line when load shorts.



grid drive lines represented by A, B, C, etc., do not all follow down the diode line given by $i_p = \sigma e_p$ and curves A, B, C . . . are more or less rounded off as they approach the limit line on minimum plate current. Nevertheless, these curves can be used to determine with fair accuracy the effects of variations in grid drive, screen grid voltage and plate voltage, provided the changes are small.

If adequate positive grid voltage is provided to keep the operating point for the tube (Op1 Figure 14a) somewhat below the knee of the characteristic curve, irregularities in the top of the grid driving pulse are not observed on the output pulse. This consideration is of considerable importance to the design of the driver circuit. Since such operation results in high grid currents in a triode and high screen-grid currents in a tetrode, care must be taken to assure that excessive grid dissipation does not result. Furthermore, such operation requires a well regulated dc plate voltage supply for the pulser tube.

If the operating point Op2 is on the curve C of Figure 14b, and the grid voltage changes over the range from B to D, a different situation obtains. In this case both the load voltage and the load current are affected by variations in grid drive voltage. For the low-resistance biased diode load, a change in the e_g from C to D results in a load voltage change of ΔV_1 and a change in load current of Δi_1. Similarly, for the higher resistance load without a biasing voltage, the corresponding changes are ΔV_2 and Δi_2. Because of the upward slope of the constant grid drive curves above the knee, the change in current is greater for the low-resistance biased diode load and the change in voltage less. When a switch tube is operated in this manner, irregularities in the grid-voltage pulse are transferred to the load pulse.

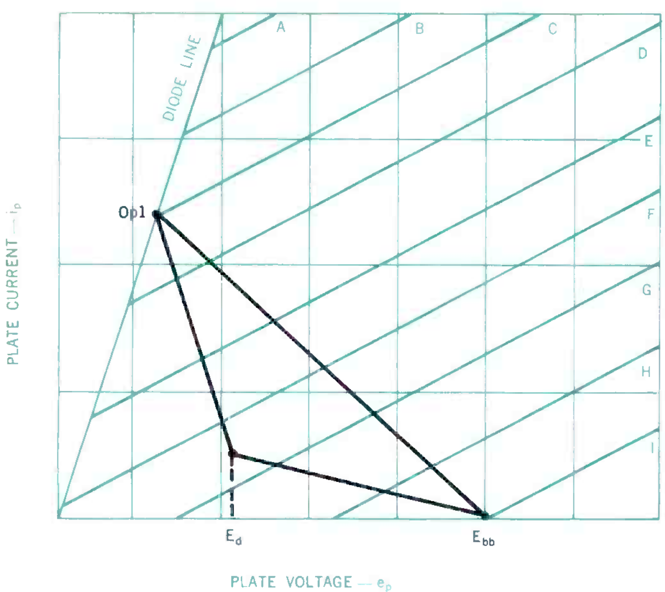
Of course if the load has reactive components, See Figure 16, the load line will depend on the instantaneous impedance and will form a loop of some sort. Since the curves of Figures 14 a and b include the effect of both screen-grid and control-grid variations, it should be pointed out that the combination of variations of both screen-grid voltage and pulse grid drive must be considered in regard to the critical drive line C, Figure 14a. Because of the flow of pulse current to the screen-grid and the plate to screen-grid capacitance, it is necessary to provide a large bypass capacitor between the screen-grid terminal and the cathode. If fast rising pulses are used, the self-inductance and the load inductance of this capacitor must be made small enough to give a low impedance at the maximum useful frequency component of the pulse. The use of grid drive saturation to give flat top pulses is usually confined to low or medium power stages. It tends toward excessive screen-grid dissipation in tetrodes, and excessive driver output current and grid dissipation in triodes. In shield-grid triode devices, the use of grid drive saturation is usually satisfactory even in high power tubes, because the grid is capable of handling high dissipation compared to that of its normal pulse amplifier rating.

If the operating point is taken above the knee of the curves, Op2 on Figure 14b, the effects of variation in grid drive voltage, screen-grid and/or plate voltage can be found by rearranging equation 10a and differentiating;

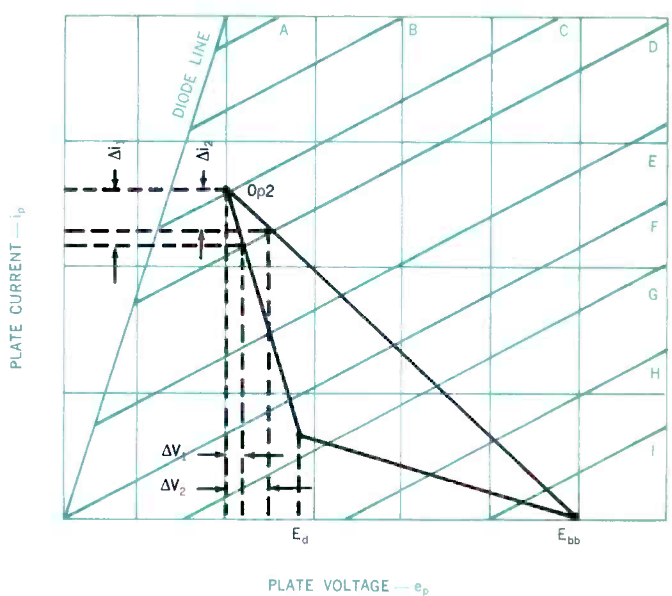
$$i_p = \frac{1}{\frac{i}{c} + \frac{rl}{\mu_p}} \left(e_g + \frac{E_{sg}}{\mu_{sg}} + \frac{E_{bb} - E_s}{\mu_p} \right) \qquad (10b)$$

Figure 14 — Simplified Constant Grid Voltage Characteristics for any vacuum tube:

a) load line to operating point below knee of plate current curve



b) load line to operating point above the knee of plate current curve.



where rl is the dynamic impedance at the Op2 point, Figure 14b, E_S is the starting voltage of a magnetron or the dc value of a biased diode load.

$$\frac{\partial i_p}{\partial e_g} = \frac{1}{\frac{1}{c} + \frac{rl}{\mu_p}} \tag{11a}$$

$$\frac{\partial i_p}{\partial E_{sg}} = \frac{1}{\frac{1}{c} + \frac{rl}{\mu_p}} \frac{1}{\mu_{sg}} \tag{11b}$$

$$\frac{\partial i_p}{\partial e_{bb}} = \frac{1}{\frac{1}{c} + \frac{rl}{\mu_p}} \frac{1}{\mu_p} \tag{11c}$$

$$\partial i_p = \frac{1}{\frac{1}{c} + \frac{rl}{\mu_p}} \left(\partial e_g + \frac{\partial E_{sg}}{\mu_{sg}} + \frac{\partial E_{bb}}{\mu_p} \right) \tag{12}$$

when rl/μ_p is small compared with $1/c$,

$$\partial i_p \approx c \left(\partial e_g + \frac{\partial E_{sg}}{\mu_{sg}} + \frac{\partial E_{bb}}{\mu_p} \right) \tag{13}$$

The above equations hold for all tubes whose characteristics can reasonably be described by equation 10a in the general region of the end of the load line for electrode voltage variations of a few per cent; i.e., ∂e_g, ∂E_{Sg} and ∂E_{bb}. If the tube is a triode, equation 11b is omitted, and the corresponding term is dropped from equations 12 and 13. From these equations one can determine the maximum variations permissible for e_g, E_{sg} and E_{bb} for a given maximum dip or the change in the total load current diL which is rl dip. Since the screen-grid amplification factor is usually of the order of 5, regulation of this voltage will probably be necessary in most cases. With tetrodes it is possible to "correct" the screen-grid voltage for changes of plate voltage, a practice that may be simpler than regulation of the plate supply voltage.

The power supply voltage may vary because of changes in either the ac input voltage to the pulser or changes in the dc average current from the power supply. The change in average current may be brought about by variations in the duty ratio that occur as a result of changes in either the pulse duration or the pulse recurrence frequency, or both. Variations of the ac line voltage input to the pulser causes a change in all the voltages in the pulser, and therefore changes the bias voltage as well as the other factors in equations 10 and 12. In order to make a complete analysis it would be necessary to consider the effect of bias changes, effects caused by the partial discharge of coupling capacitors, and current build-up in shunt inductances across the load. Another factor to be considered would be the regulation of the driving pulse supply, i.e., the effect of the internal impedance of the driving pulser due to variations in grid current of the following stage as drive is varied from C to A.

In order to compare the operation of tubes both above and below the knee of the curve, the effect of one variable, the plate voltage or E_{bb}, on the plate or load current will be investigated. To simplify the problem we will consider a triode. In the equations developed below $\left(e_g + \frac{E_{sg}}{\mu_{sg}}\right)$ can be substituted for e_g to cover the case of a tetrode. This problem is of interest in the operation of magnetrons since the magnetron frequency shifts as its current changes, i.e., the "pushing figure," df/di.

For a triode operating above the knee of the characteristic curves, equation 11c can be divided by equation 10b omitting the term E_{sg}. These equations give

$$\frac{dip}{i_p} = \frac{1}{1 + \frac{\mu_p e_p - E_S}{E_{bb}}} \frac{dE_{bb}}{E_{bb}} \tag{13}$$

For a triode operating below the knee of the curve, equation 10a reduces to

$$i_p = \sigma e_p = \partial\,(E_{bb} - \partial E_S - i_p\, rl)$$

which gives,

$$\frac{dip}{i_p} = \frac{1}{1 - \frac{E_S}{E_{bb}}} \frac{dE_{bb}}{E_{bb}} \tag{14}$$

In order to compare magnetron operation under the two conditions, consider the 725A magnetron which is to be operated at 11 KV and 10 amperes. Under these conditions E_S will be 9700 volts. For a 4PR60 tube operating below the knee of the curve, the plate voltage, E_{bb}, will be 11.7 KV, the screen-grid voltage is taken as 1250 volts, e_g will be 0. According to equation 14,

$$\frac{dip}{i_p} \approx 6 \frac{dE_{bb}}{E_{bb}}$$

For operation above the knee of the curve, constant grid voltage drive curves are drawn tangent to the characteristic curves for $e_g = 0$ and -50 volts at $e_p = 2000$ volts. E_{bb} will be 13 KV, $e_g = -35$ volts, $\mu_{sg} = 4$, $\mu_p = 70$ and

$$\frac{dip}{i_p} \approx 0.55 \frac{dE_{bb}}{E_{bb}}$$

From these results it is apparent that the regulation in plate current due to variations in E_{bb} is improved by a factor of 10 when the operating point is above the knee as compared to operation below the knee. Of course for operation above the knee, it is necessary to regulate e_g and E_{sg}. If the load had been a pure resistance, i.e., $E_s = 0$, the comparative values are reduced to 1 and 0.4 or a ratio of 2.5 instead of 10.

(Continued on Page 37)

Editor's Note:

CATHODE PRESS is pleased to reprint here an article on a topic of considerable interest: cable sheathing by electronic means. A recent development, in a relatively new field, electronic high frequency resistance welding, has been reported previously by CATHODE PRESS (Vol. 15, No. 1, 1958). The Thermatool process, as this high frequency resistance welding is known, employs induction heaters which use the Machlett ML-6696 coaxial terminal triode.

Acknowledgment:

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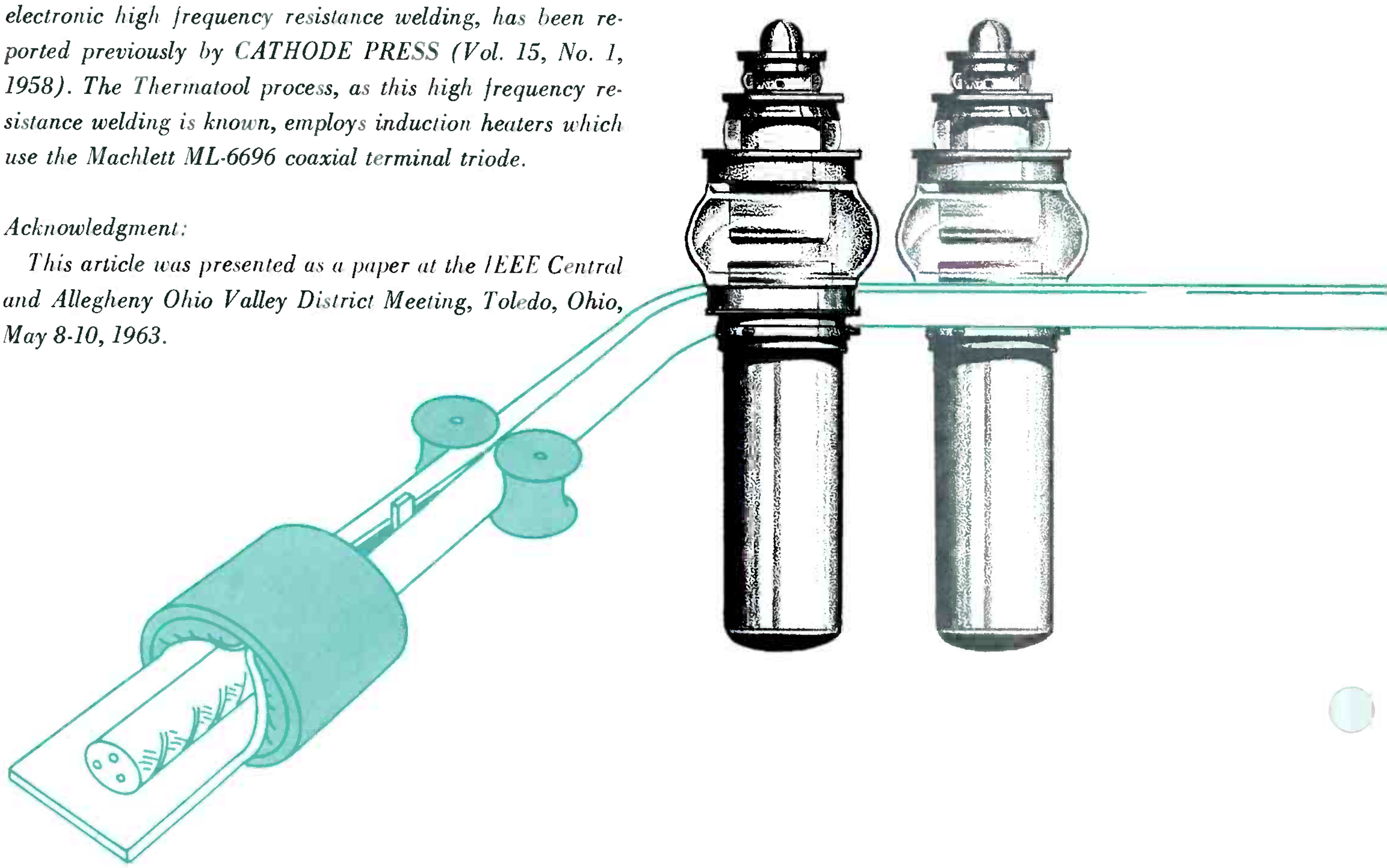

Thermatool Corporation, New Rochelle, New York, a subsidiary of the American Machine and Foundry Company, has developed a new method of applying metal sheaths to power and communications cables. This method is an outgrowth of Thermatool's widely used high frequency resistance seam welding process for metal tubes and pipes. Interestingly, the first production installations of this novel process have been in Europe, rather than the United States. The purpose of this paper is to describe the electrical features of this new cable sheathing process.

Cable Sheathing Materials

Lead and aluminum have been used traditionally for sheathing cables. Lead has the advantage that it is relatively easy to extrude. In addition, its extrusion temperature is not so high that it damages the cable insulation. It is possible to extrude lead cable sheath continuously. But lead is heavy and soft. Its dimensional stability over long periods of time is not ideal.

Aluminum makes a better cable sheath than lead. It has superior physical properties and is, of course, much lighter. However aluminum is more difficult to extrude. Both the pressure and the temperature required are higher than for lead. Special provision must be made when extruding aluminum around an insulated cable to avoid damaging the insulation. Continuous extrusion of aluminum cable sheathing has not proven commercially practical. Of course this limits the length which can be made at one time, determined by the amount of material in a single billet. It is possible to sheath cables with aluminum by first making an empty aluminum tube and then drawing the cable into it. But thin-wall aluminum tubes are difficult to handle without kinking and damaging. Furthermore the continuous length possible by this method is again limited.

Advantages of Method

The high frequency resistance welding process of sheathing cables which was developed by Thermatool elimi-

Cable Sheathing by High Frequency Resistance Welding

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nates the disadvantages of the older methods. Not only can cables be sheathed in any desired length, but also with any desired material. Copper and stainless steel, for instance, possess properties which are outstandingly favorable for cable sheath. Certainly these materials could not be applied to an insulated cable by extrusion, but they can be by the new process.

Skin Effect

Thermatool's process for cable sheathing utilizes two phenomena which have been usually considered as undesirable by most electrical and electronic engineers. These are skin effect and proximity effect. Skin effect is the tendency of alternating current to be more concentrated at the surface of a conductor than inside the conductor. The degree of skin effect depends upon four factors: frequency, conductor conductivity, permeability, and size. Increasing any one of these quantities will cause skin effect to be more pronounced. Skin effect is present to some degree in every alternating current circuit, as illustrated in Figure 1. Most engineers regard skin effect simply as a phenomenon which increases the resistance (and therefore the losses) in a conductor carrying alternating current. But, as will be illustrated in more detail later, skin effect is a desirable and essential adjunct of high frequency resistance welding.

It is customary to express the degree of skin effect numerically by using a quantity known as reference depth (sometimes called skin depth). The ratio of conductor diameter to reference depth is a measure of degree of skin effect, the effect being more pronounced when this ratio is large. If the conductor is rectangular, the ratio of the smaller dimension to reference depth is significant. When this ratio is equal to or greater than 10, skin effect is very pronounced. A solid conductor then has substantially the same resistance as a hollow conductor of the same outside dimensions and with a wall thickness equal to reference depth.

A complete discussion of the theory of skin effect is outside the scope of this paper, but it is interesting to display the equation for reference depth, which is

$$d = 3160\sqrt{\frac{\rho}{\mu f}}$$

where, d = reference depth, in inches
ρ = conductor resistivity in ohm-inch
μ = conductor relative permeability
f = frequency in cycles per second

For aluminum at room temperature, and with a frequency of 450 KC (which is what is commonly used for high frequency resistance welding), reference depth is approximately .005 inch.

Proximity Effect

The second phenomenon upon which high frequency resistance welding of cable sheaths relies is proximity effect. Proximity effect manifests itself when two conductors in which skin effect is very pronounced form a go and return circuit, and are located physically close to each other. Actually they must be close enough so that the external magnetic field which they set up is appreciably more concentrated between them than elsewhere. This causes the magnetizing force to be greater between them than elsewhere. As a result the current, already flowing in a thin surface layer because of skin effect, rearranges itself over the surface of the conductors in such a way as to supply the higher magnetizing ampere-turns per inch required for the restricted space between the conductors. When skin effect and proximity effect are both pronounced, substantially all the current flows along the opposing edges of the conductors, as illustrated in Figure 2a. The effect can be even further enhanced by the addition of a magnetic core which serves to increase the ratio of magnetizing force between the conductors to the magnetizing force elsewhere, as in Figure 2b.

High Frequency Resistance Welding

High frequency resistance welding of metal cable sheath is illustrated schematically in Figure 3a. The sheath is formed from flat strip in a special die-forming mill (not shown). The open seam passes continuously beneath a pair of sliding contacts. High frequency current is introduced through one

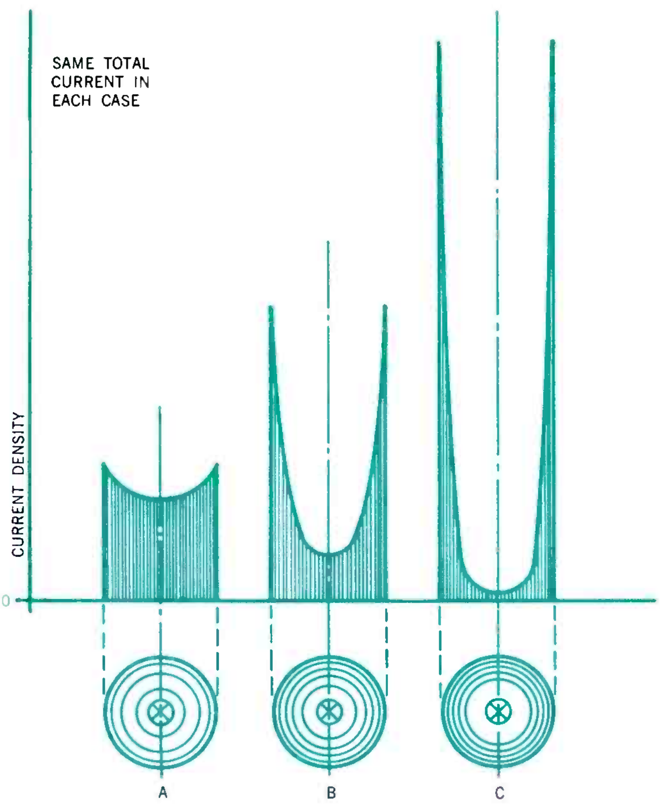


Figure 1 — Various degrees of skin effect.

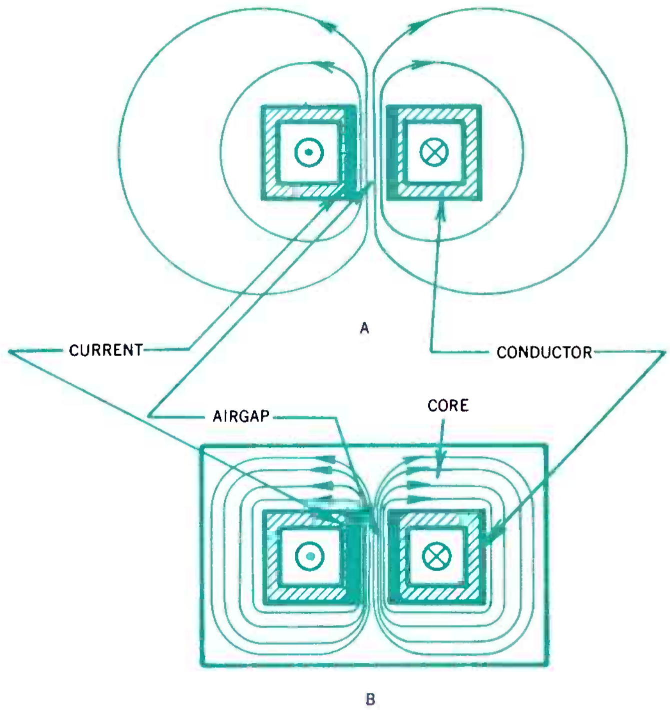


Figure 2 — Proximity effect in go and return circuit.

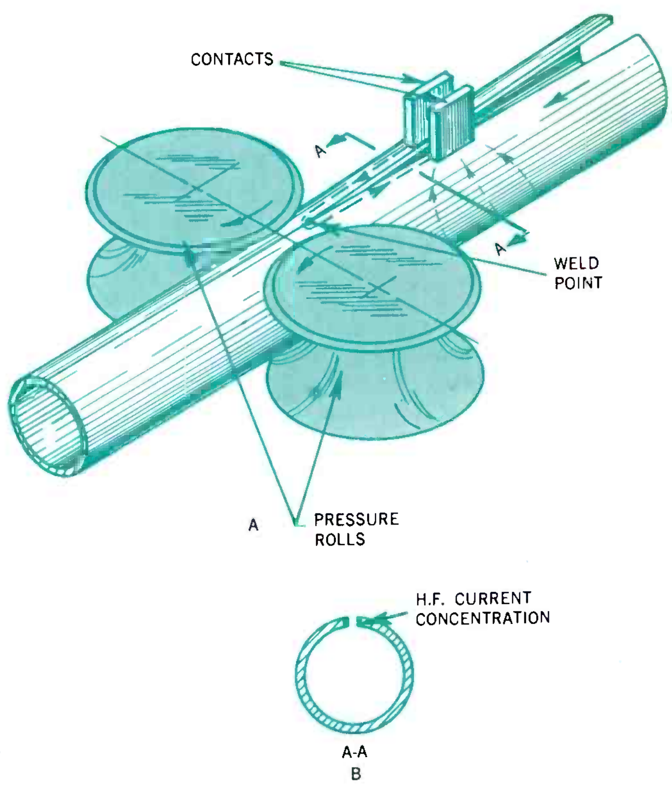


Figure 3 — High frequency resistance tube welding.

of these contacts, and flows (because of skin effect and proximity effect) along the strip edge to the point, slightly upstream from the pressure rolls, where the opposing edges come together. The current returns to the other contact along the other edge of the "vee"-shaped opening.

The high frequency current traversing the edges of the "vee"-shaped opening is compressed into a small cross sectional area, as illustrated in Figure 3b, and the resistance which it encounters is high. The result is rapid heating of the edges of the strip, with negligible heating elsewhere. This is best illustrated by a numerical example. Assume that the cable sheath is to be made of aluminum strip, .030 inch thick, and that the frequency is 450 KC. Reference depth will therefore be approximately .005 inch. Assume also that the RMS value of the current is 1000 amperes. Under these conditions, the resistance is the same as if the entire current of 1000 amperes were flowing with uniform current density in an aluminum conductor whose cross section is .005 inch by .030 inch. Heat will be developed by I^2R at a rate of approximately 7.5 KW per linear inch.

With power of this order of magnitude developed in the strip edges, their temperature rapidly rises to welding temperature as they traverse the relatively short distance from the contacts to the closure point. The hot edges are pressed together by the pressure rolls. A forge type weld results which is physically sound, as well as pressure tight.

There is a second path which high frequency current can traverse from one contact to the other, illustrated by the dotted lines in Figure 3a. This path, around the back of the tube, is not only widely spread out, but also has a higher inductance than the path along the narrow "vee" gap. The net result is that the portion of the contact current which goes around the back of the tube is not only small, but also causes very little heat loss.

Production Rate

A typical production rate when welding .025 inch thick aluminum sheath using a 60 KW 450 KC Thermatool electronic generator is 60 to 70 feet per minute (FPM). It is interesting to note that the faster the rate, the better is the efficiency. At 60 FPM, and assuming that the contacts are one inch upstream from the "vee" apex, it takes a spot on the strip edge only .0833 second to traverse the "vee" and be heated. But the temperature differential between the edge and the remainder of the strip is so great that even in this short interval of time an appreciable amount of heat travels away from the edge by conduction. If the rate of travel were to be doubled, the power would not have to be quite doubled, as there would be less time for heat to be conducted away. Higher welding rates have the further advantage that the material behind the edges is colder and stiffer, which causes the pressure rolls to be more effective.

Mechanical Features

Although this paper has to do primarily with the electrical aspects of cable sheathing by high frequency resistance weld-

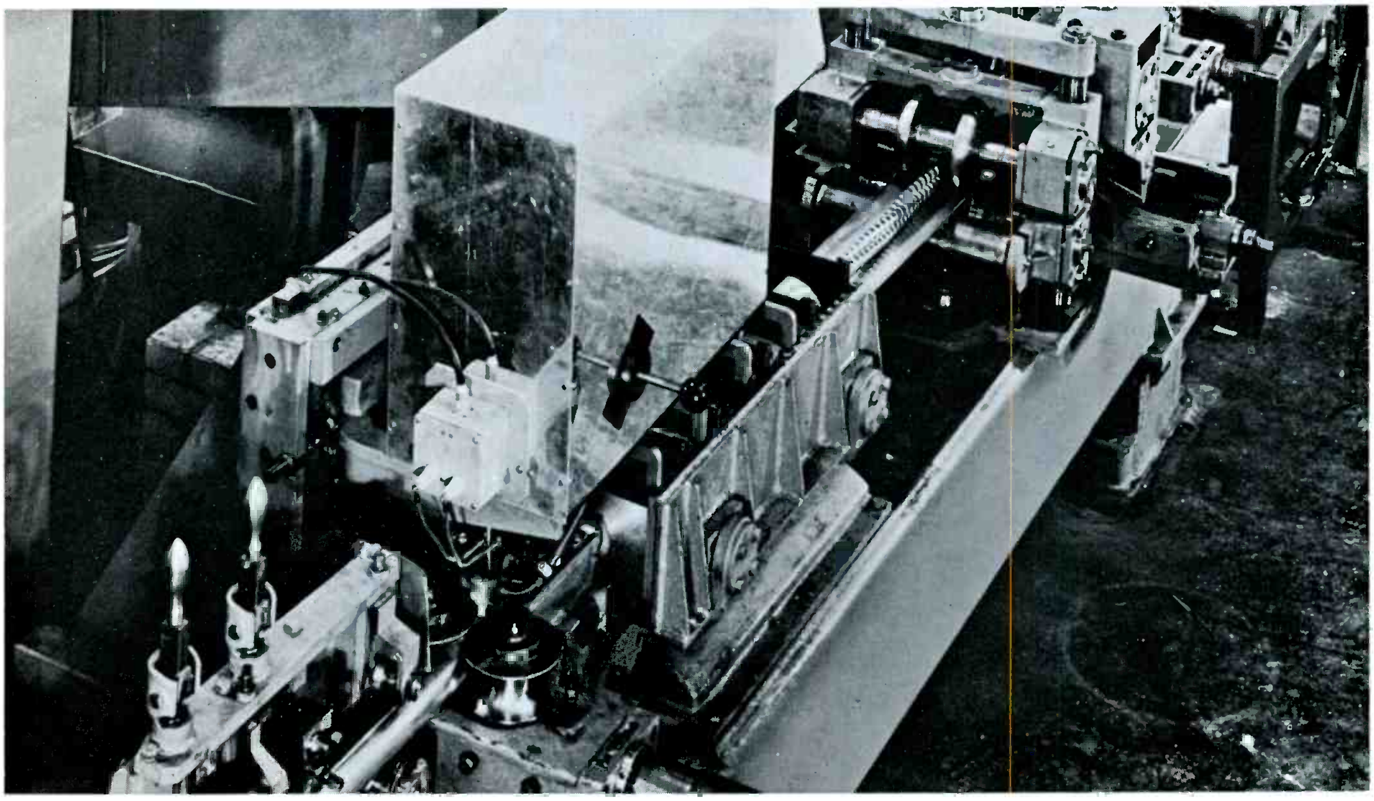


Figure 4 — High frequency cable sheathing mill.

ing, a word or two about the mechanical features is appropriate. Most tube and pipe forming mills utilize solid forming rolls. In successive stands, they gradually form flat strip into a circular shape with an open seam. Thermatool welding units are in production the world over on this type of mill, making tubing and pipe. Sizes range from one-half inch or less to three feet in diameter, and wall thicknesses is from a few thousandths to a half inch. The high frequency electronic generators range in output rating up to 560 KW.

When welding cable sheathing while the cable is inside, it is not practical to utilize solid rolls for the forming. The rolls and the cable cannot be in the same place at the same time. Therefore a die-forming mill, shown photographically in Figure 4, was developed. This enables the strip to be formed into tubular shape while the cable is inside, travelling forward at the same speed as the strip.

After the die-forming section of the mill, and just ahead of the sliding high frequency contacts, there is a seam guide. Its function is to ensure that the open seam between the strip edges is in proper registration relative to the contacts and also to ensure that the "vee" shaped opening between the contacts and the weld point has the optimum angle of opening. The seam guide is made of wear resistant material. For cable sheathing applications it is usually of the sliding type, and is insulated so as not to provide an additional electrical path between the contacts.

Downstream from the weld point, there is a tandem pair of scarfing tools which remove the external bead. There is also a thin device inside the tube between it and the cable which mechanically smooths the slight internal bead. At the weld point, the inside diameter of the sheath is usually about one-eighth inch larger than the outside diameter of the cable. This enables the welding operation to be accomplished without heat-damaging the insulation. Immediately after welding, therefore, the sheath is in the form of a loose metal tube surrounding the cable. But its diameter relative to the cable is such that it suits the subsequent corrugating operation, permitting the valleys of the corrugations to be pressed firmly against the cable. Corrugating is sometimes a separate operation and sometimes is performed continuously as the cable and sheath emerge from the forming and welding mill.

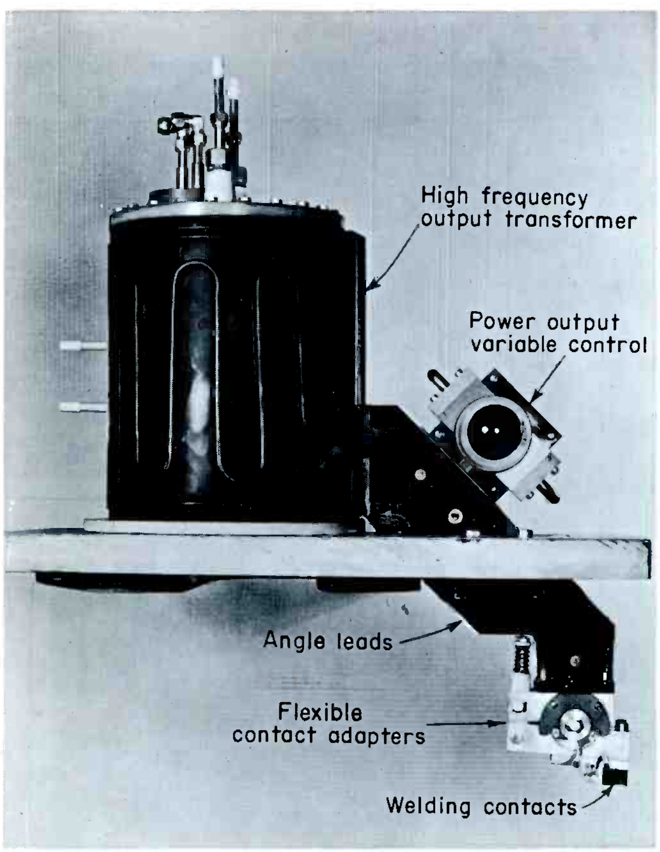


Figure 5 — Welding head.

Electronic Equipment

Most high frequency resistance welding installations for cable sheathing utilize 60 KW Thermatool electronic generators. Basically these are class "C" oscillators housed in rugged steel cabinets for industrial service. They feature hermetically sealed rectifier transformers, a capacitive voltage divider feedback circuit for grid drive, complete voltage regulation, filtering of rectifier output, and a power control device which permits the operator to alter the power steplessly even while the unit is operating.

The weld head (Figure 5), which is mounted on the cable sheathing mill, consists of a high frequency step-down transformer, its secondary leads, and the welding contacts. The stepless power control device, referred to previously, is an integral part of the secondary leads. One lead includes a one-turn series loop. A cylindrical member containing magnetic core material at one end and a copper slug at the other can be moved in and out of this loop by the operator by means of a handwheel. Continuous power control is thereby available from a minimum when the magnetic end is in the loop to a maximum when the copper end is in the loop.

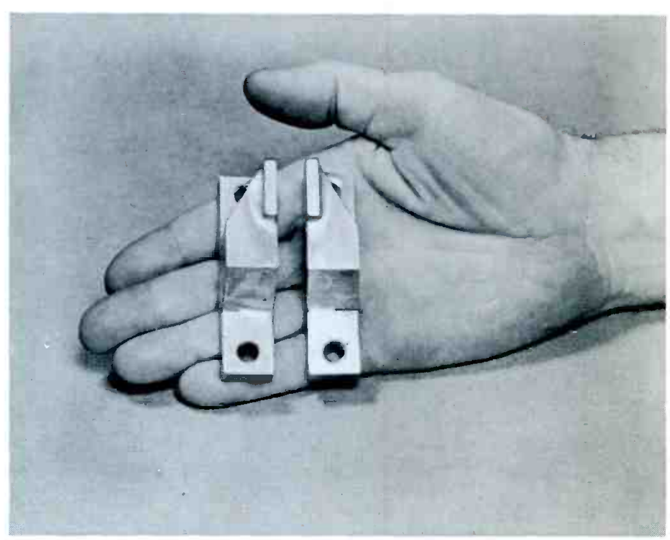


Figure 6 — High frequency resistance welding contacts.

The sliding contacts (Figure 6) are surprisingly small, considering the fact that they handle 60 KW at low voltage. They feature replaceable tips which can be replaced by a simple brazing operation after they are worn out. Average life of a set of tips is 50,000 feet of sheath or more. The contact bodies are water cooled. The cooling water is supplied through the secondary leads by means of a quickly made connection utilizing O-rings.

Future Developments

The next step in the development of this process will probably be mechanical. It will involve the development of methods for forming larger diameter thin-wall metal sheaths while still keeping the edges in proper registration and at the same time providing adequate welding pressure. (The edges of large diameter thin-wall tubes are prone to lap over each other when squeeze roll pressure is applied).

The future holds great promise for this process. As is the case in many new developments, conservative companies in the U.S.A. have hesitated, while their counterparts in Europe have gone ahead. It is anticipated that before long, high frequency resistance welded cable sheathing will be an established industrial process on both sides of the Atlantic.

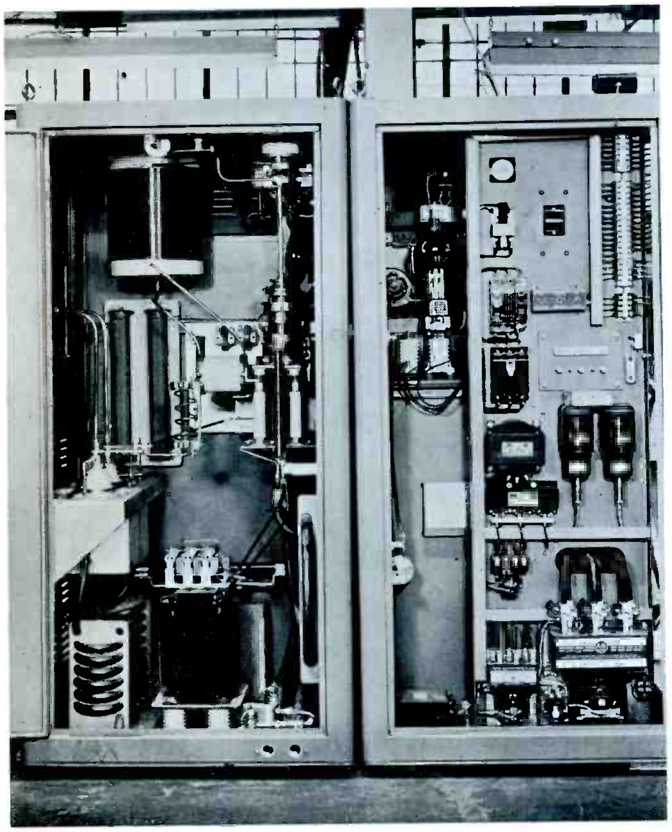
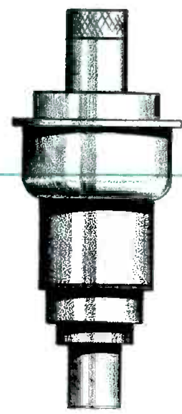


Figure 7 — View of 60 KW Thermatool High Frequency Generator, Model VT-60 with ML-6696 visible in rack to left.

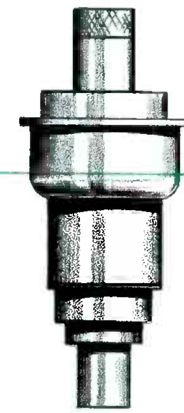
Operating conditions of final amplifier tubes of the Thermatool induction heaters, VT-60 (1 — ML-6696) and VT-140 (2 — ML-6696's), employed for high frequency resistance welding:

ML-6696

Frequency	450 Kc
Plate Voltage	11.7 kv
Plate Current	9.0 a
Grid Voltage	—1500 v
Grid Current	0,6 a



The Reliability of the Machlett Planar Triode



by NELLO ZUECH
Senior Production Engineer,
Small Power Tube Product Line,
The Machlett Laboratories, Inc.

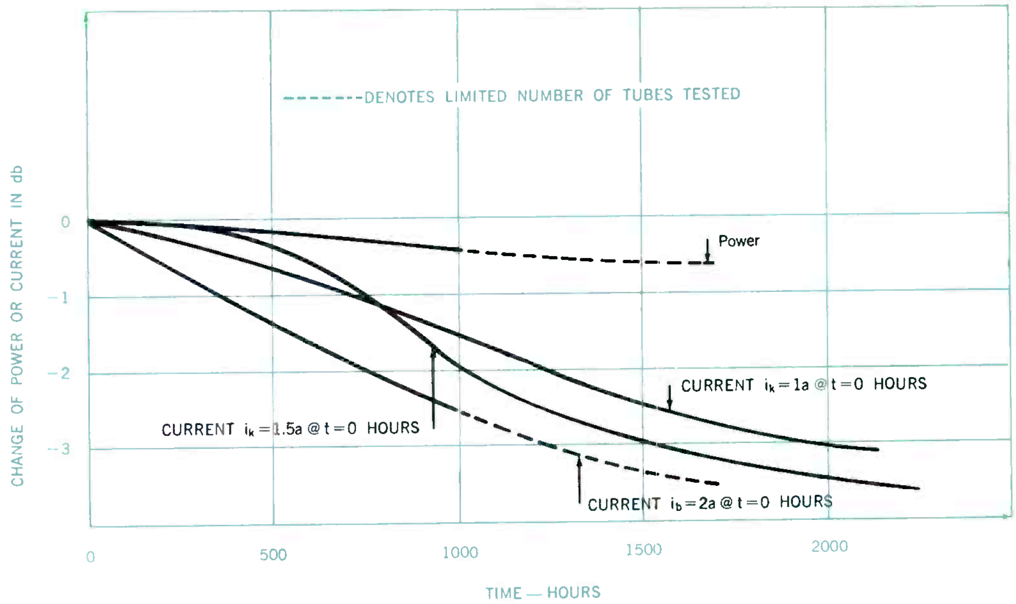
Much has been said in recent years about system reliability. The military, and therefore, industry has become reliability conscious. Since a system can exhibit a reliability only as good as the reliability of its least reliable component, the reliability of the electron tube aside from other components has come into question.

Unfortunately, planar tubes, like all tubes, are severely influenced by their environment, with respect to circuitry as well as ambient conditions. Because of this, it might be argued that the data upon which tube reliability figures are based, only reflect the reliability of the particular tube type, in the particular equipment specified, under a particular set of conditions. The truth of this will no doubt be debated many times over in the coming years. Nevertheless, if the conditions to which the tube is subjected during life test are more severe than normal or can be considered representative of the average application for which the tube was intended, the reliability data so obtained can be extrapolated to be meaningful for most field conditions.

The actual life test conditions to which a tube is subjected are governed in many cases by the pertinent military specifications. The philosophy upon which these conditions are based is generally in a state of flux. Recent emphasis is being placed on the filament stand-by life test for planar tubes, its proponents noting its success in its application on larger more expensive tubes as well as observations that this type of test is at least as rigorous, if not more detrimental than, rf life tests, provided the conditions have been properly chosen. Also in its favor is the argument that not all applications require continuous rf operation, and a large number are operating in a stand-by position often at a reduced filament voltage. Thus far, it has been the experience at Machlett, with respect to the ML-7698 and ML-7815, that the filament stand-by type of life test is more severe, perhaps as a result of the end point criteria (described later in this article), and results in a higher failure rate than would be the case under rf operational conditions.

What constitutes a failure? Either of two factors, as defined in military specifications: the inability of the tube to function, or the inability of the tube to meet certain predetermined test conditions. Consequently, while in a laboratory a tube may fail, that same tube in a field application under which the tube is not handled or disturbed once it is put in a socket, should give a longer life. Hence, reliability figures based on laboratory life tests can actually be considered pessimistic, provided the consumer has taken the necessary precautions to ensure against catastrophic or premature failure due to external circumstances.

The more familiar failure modes of planar tubes are essentially: (1) — emission failures due to cathode poisoning or cathode exhaustion at end of life, or (2) —catastrophic; that is, shorting between elements, filament defective either open or short, overloaded grid or anode due to operation in excess of ratings (either with the knowledge of the user or inadvertently as in the case of a failure in auxiliary equipment which is reflected back into the tube); leakers or loss of



vacuum due to extreme environmental conditions or to overheating because of improper cooling or of operation in excess of rating, and random failures which are virtually impossible to control.

Before proceeding, the following definitions should be embedded in the mind of the reader:

Reliability[1] — The probability that a device will perform as intended under design conditions for a specified period of time.

Confidence level[2] — The probability of rejection of material conforming to the specified failure rate. 90% confidence means certainty to 90% that the true mean time between failures is greater than the calculated limit and the true failure rate is less than its limiting value.

Failure rate[3] — The failure rate is expressed in terms of failures per unit of time. It is computed as a simple ratio of the number of failures f, during a specified test interval, t, to the total or aggregate survival test time of the articles undergoing test during the test interval:

$$r = \frac{f}{T}$$

MTBF[3]— Mean time between failure — During the operating period when the failure rate is constant, the MTBF is the reciprocal of the constant failure rate, or the ratio of the total operating time to the total number of failures:

$$m = \frac{1}{r} = \frac{T}{f}$$

There are essentially three rates of failure during the life of most components. Early in life failures, referred to as "infant mortality," period of constant failure rate, and wear-out phase period. Because of the nature of electron tube processing "infant mortality" is all but eliminated. And since most often a tube gives warning of impending failure by a change in operating characteristic making replacement at a somewhat predetermined time possible, all reliability data is generally based on a constant failure rate. This constant failure rate is further based on the assumption that the design is essentially constant and that a uniform manufacturing process is maintained. Assuming a constant failure rate in turn implies an exponential, or Poisson distribution of failures, namely:

$$R = e^{-\frac{T}{m}}$$

T — total operating time, m-MTBF, and R — reliability.

In the following tables for the individual tube types, two sets of failure rates are determined, one for a confidence factor of 90% — based on the recommendations of the Darnell report[9] — and one for a confidence factor of 60% — based on the recommendations of the Electronic Industries Association (EIA)[2]. Also included in the tables wherever possible are failure rates which are arrived at from data fed back from the field. As can be seen from the tables, the failure rates arrived at in the laboratory are, for the most part, in agreement with, or at least of the same order of magnitude as those based on information fed back to Machlett from various field applications. In other words, the failure rates are indeed realistic and the degree of reliability claimed is attainable.

High levels of reliability can be assured provided proper choices are made with respect to tube types and operating conditions. Because of the interrelationship between tube and cavity, effort should be expended to mate the two for optimum operation. Once the tube has been placed in the socket, it should be handled as infrequently as possible. Envelope and seal temperatures should be maintained at less than 175 degrees C[4], even though the tubes can actually withstand seal temperatures up to 250°C. Heater voltage should be at most at maximum rating and, if possible, optimized for the particular conditions (above 500 Mc transit time back-heating starts to have an effect). It has been shown on one Machlett tube type that life can be increased at least two and a half times by operating the filament at 5% below versus 5% above rating. In addition to optimizing, the filament voltage must be regulated to preferably 2% or better. Excessive plate dissipation should be avoided. Vibration should be held to a minimum.

If all the above precautions are taken there is no reason not to believe the reliability data is not valid and that the failure rates can in actuality be exceeded.

EXAMPLES OF CALCULATIONS[11]

Confidence bounds for the MTBF and failure rate for any given set of data may be estimated by various methods.

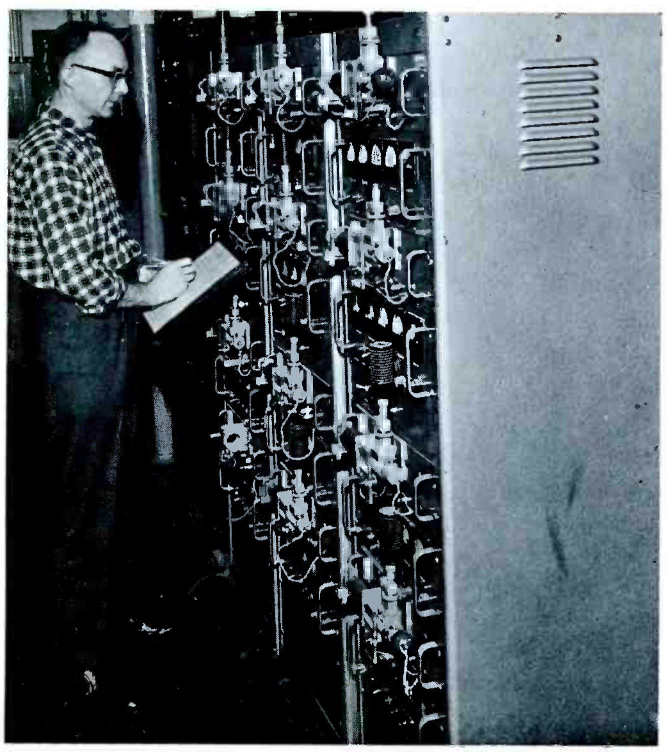


Figure 1 — Multiple unit life test equipment for ML-6442; contains plate pulse cavity oscillators. Test parameters: Pulsed Oscillation F = 3450 mc minimum; e_{py} = 3000 v; $R_g/1b$ = 2.5 mode; tpv = 1.0 usec ±10%; trv — 0.1 usec., maximum; tfr = 0.2 usec, maximum; prΩ/Du = 0.001 ±5%; E_f = 6.0 V.

Thus, the Poisson, the χ^2, or the F distributions, all well known to statisticians, may be used to calculate the confidence limits.

Example 1:

Given a total tube-hours of test equal to 100,000, with 2 failures; (a) what is the best estimate of failure rate? (b) what would be a failure rate limit which would include 90% of failure-rate estimates made under the same sampling conditions?

(a) $$\text{MTBF} = \frac{100{,}000}{2} = 50{,}000 \text{ hours}$$

$$\text{Failure rate} = \frac{1}{\text{MTBF}} = \frac{1}{50{,}000} = 0.00002$$ failures/hour or 2% failures/1000 hours.

These are "most likely," or modal estimates.

(b) *Using Thorndike Chart.*

Since we have made the assumption that the failure rate is constant this implies an exponential, or Poisson distribution of failures. We can therefore use Poisson tables or charts to place confidence limits on our estimates. (1)

The Poisson parameter in our case is $\frac{T}{\text{MTBF}}$, where T is total test hours.

If we look up the Poisson parameter on a Thorndike chart (2) for the 10% probability of occurrence of c = 2, or less, defectives, we find $pn = 5.3 = \frac{T}{\text{MTBF}}$.

$$\text{Then, MTBF}_{(.90)} = \frac{T}{5.3} = \frac{100{,}000}{5.3} = 18{,}900 \text{ hours}$$

$$\text{and, F.R.}_{(.90)} = \frac{1}{\text{MTBF}} = \frac{5.3}{100{,}000} = 0.000{,}053$$ failures/hour, or 5.3%/K hours.

We use the 10% probability point, since we want to be 90% certain that the true MTBF is greater than our calculated limit and the true failure rate is less than its limiting value.

Using Poisson Tables

We may choose to use a table of culmulative Poisson probabilities, such as Table II of Molina's Tables. (3) The Poisson parameter in these tables is denoted by a, and the probabilities are for *c or more* defectives occurring. Since we want to pick a limiting value of α, such that the number of defectives r = 2 or less will occur only 10% of the time, we look through the table for c = r + 1 = 2 + 1 = 3 defectives until we find the cumulative probability of a for 90%, c = 3. This value is approximately 5.3. Values for $\text{MTBF}_{(.90)}$ or $\text{F.R.}_{(.90)}$ are then found as in the calculations under the Poisson Chart above. We are then confident that the true MTBF under the same conditions will be equal to, or greater than, our limiting value of $MTBF_{(.90)}$, 90% of the time.

χ^2 Solution

If we conclude our testing after some time T total tube-hours, a one-sided 100 ($1-\alpha$) confidence interval for MTBF is given by the expression (4) (5)

$$MTBF_{(1-\alpha)} > \chi^2_{\alpha(2r+2)}$$

then, T = 100,000 hours (given)

r = 2 failures (given)

α = 0.10, since desired confidence 90% = 100 ($1-\chi$)

$\chi^2_{\alpha\,(2r+2)}$ is the upper 10% of the χ^2 distribution for 2r + 2 degrees of freedom. χ^2 tables are found in most recognized statistical texts.

$$\chi^2_{.10(6)} = 10.6$$

Substituting in the formula,

$$MTBF_{(.90)} = \frac{2 \times 100{,}000}{10.6} = 18{,}900$$

hours

$$\text{and, } F.R._{(.90)} = \frac{1}{MTBF_{(.90)}} = \frac{1}{18{,}900}$$

hrs. = 5.3%/K hours, which checks with the values found by using Poisson tables or charts.

Example 2:

100,000 tube-hours are achieved on a particular test, with no failures. What is the MTBF? The MTBF cannot be calculated in the usual manner, since $\frac{100{,}000}{0}$ is unsolvable because of the zero in the denominator. However, a median estimate (50% confidence) can be found, using the χ^2 formula in Example 1, and a value of χ^2 for 50%.

2r + 2 2 (0) + 2 = 2 degrees of freedom

$$\chi^2_{.50(2)} = 1.39$$

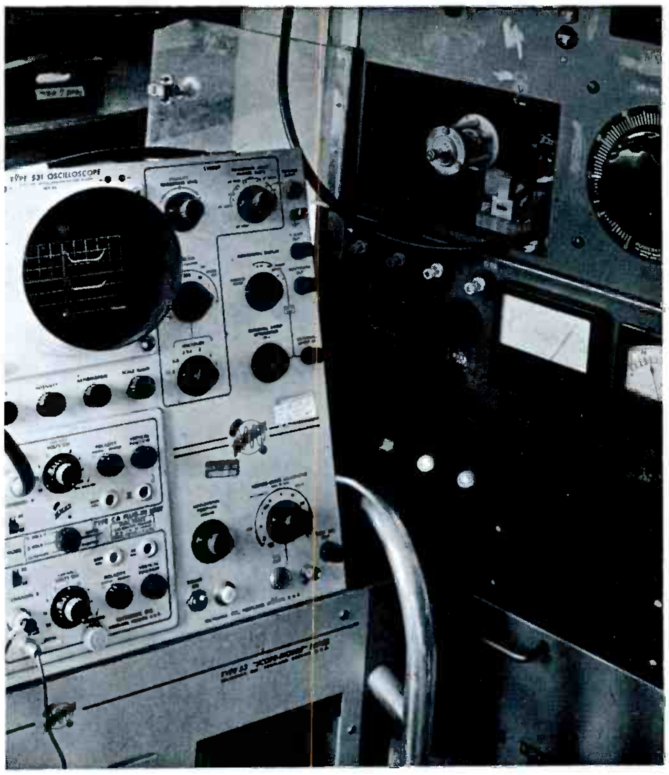


Figure 2 — View of End Point Test Set for ML-7815 and ML-7698; evaluates the deteriorating effect of filament standby life test by measuring the reduction in peak anode current under drive conditions established at 0 hours.

$$MTBF_{(.50)} = \frac{2 \times 100{,}000}{1.39} = 144{,}000 \text{ hours}$$

The median estimate of MTBF may also be found from the approximate relationship

$$MTBF = \frac{\text{total tube-hours}}{r + 0.693}$$

$$\text{Thus, } MTBF = \frac{100{,}000}{0.693} = 144{,}000 \text{ hours.}$$

We can of course calculate confidence limits at any desired level, using one of the methods suggested in Example 1 (b).

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[1]Allen, Gerald F., "Reliability Slide Rule," *Electronics*, September 6, 1963, p. 44.

[2]Finochi, Anthony J., "Ramifications of PSMR-1, the Darnell Report," *Electronic Products*, August 1962, p. 69.

[3]Calabro, *Reliability Principles and Practices*, McGraw-Hill, 1962.

[4]Henry, Robert S., "Thermal Design for Reliability," *Electro-Technology*, May, 1962.

[5]*Machlett UHF Planar Triodes* (Brochure), p. 16.

[6]Proposed Military Standard, "Life Qualification and Sampling Procedures for Use in Electronic Component Part Established Reliability Specifications" (Project Misc-0229) 11 March 1963.

[7]Edward, M. W., et al, *Subminiature Electron Tube Life Factors*, Reinhold Publishing Co., Elizabeth, N. J., 1961.

[8]Rath and Strong, "Notes on a Reliability Seminar."

[9]Parts Specification Management Report (PSMR-1), Department of Defense, May 1960.

[10]*Aero Geo Astro Reliability and Confidence Slide Rule Handbook*, October 1962.

[11]*Industrial Military Tube Reliability Data Report No. 3*, Raytheon Company, Industrial Components Division.

NOTE: Reliability Life Test Reports for ML-7289, ML-7815, ML-7698, and ML-6442 follow on Pages 30, 31, 32 and 33 respectively.

DATE ISSUED: 12/1/63

REPORT NO.: 1

SUMMARY OF TEST RESULTS	*No. Tested*	*Total Tube Hours*	*No. Failed*	*Failure Rate in % Per 1000 Hours Confidence Factor 60%*	*90%*
Total Failures — Electrical and Catastrophic — (2100 MC Life Test)	81	32,393	1*	< 6.1	< 11.9
Total Failures — Electrical and Catastrophic — (500 MC Life Test)	121	73,932	0	< 1.24	< 3.1

*Catastrophic-Leaker at 1791 Hours

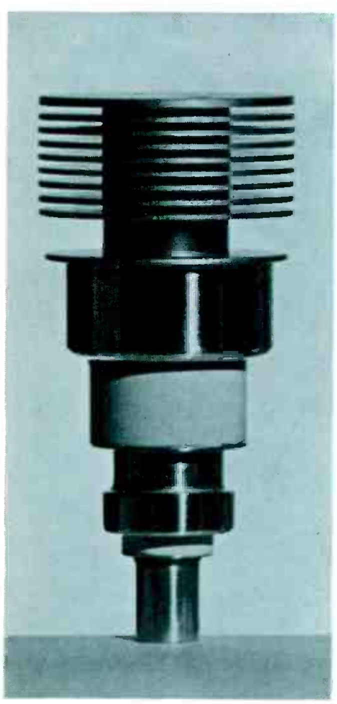
TEST DESCRIPTION: Per MIL-E-1/1120B

2100 MC: **Group C,** F = 2000 Mc Min;
Ebb = 1000 Vdc; Ib = 90 madc;
Ef = 5.0 Vac; initial Po = 15W Min.
Time = 200 Hours
ΔPo — 25% Maximum
Pulse Emission (2) Δi_k = 120 ma Max.

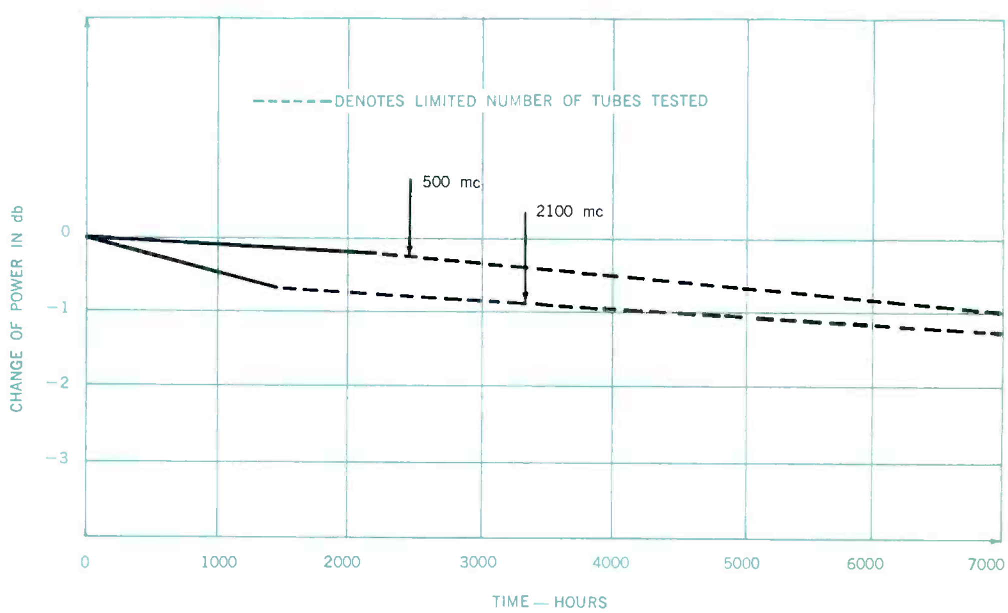
500 MC: **Group C,** F = 500 Mc Min;
Ebb = 800 Vdc; Ib = 80 madc;
Ef = 6.0 Vac; initial Po = 27W Min.
Time = 500 Hours
ΔPo — 25% Maximum
Pulse Emission (2) Δi_k = 120 ma Max.

APPLICATIONS: The ML-7289/3CX100A5 is a ruggedized, high-mu, Planar Triode of ceramic and metal construction designed specifically for use in equipment as an oscillator, amplifier or frequency multiplier at frequencies up to 2500 mc. It is well suited for pulsed operation at frequencies up to 3000 mc.

REMARKS: See Cathode Press Vol. 15, No. 1, 1958, "The Life and Times of the 2C39 in Microwave Radio Relays," P. 25.
Cathode Press Vol. 20, No. 1, 1963, "Atlantic Pipeline Company: Microwave User Since 1949," P. 25.
Based on these articles, the average life obtained in their application is 13,000 hours. Using this as the MTBF the failure rate is 7.5%/1000 hours.



POWER VS. LIFE



DATE ISSUED: 12/1/63 *REPORT NO.: 1*

SUMMARY OF TEST RESULTS	*No. Tested*	*Total Tube Hours*	*No. Failed*	*Failure Rate in % Per 1000 Hours Confidence Factor 60%*	*90%*
Catastrophic Failures	106	104,653	0	< .88	< 2.2
Total Failures (Catastrophic & Electrical)	106	104,653	0	< .88	< 2.2

TEST DESCRIPTION:

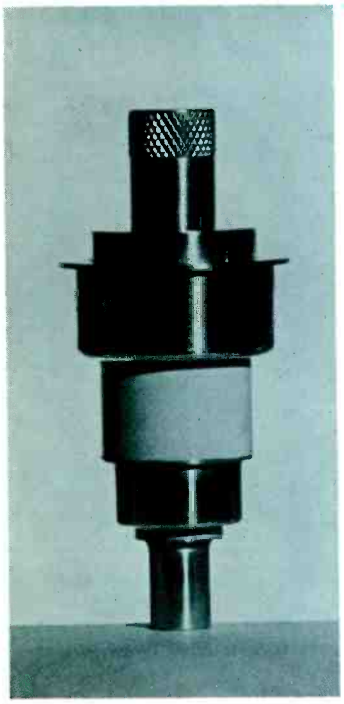
Per MIL-E-1/1429A (NAVY)
Group B — Ef = 6.0 Vac, Filament Standby; Time — 500 Hours
"At zero hours, establish the drive conditions necessary to obtain 2.0 amperes peak anode current with an anode voltage of 1000 Vdc and a bias voltage of —40 Vdc. The pulse width of the modulator shall be 2 μs (minimum) and the duty shall be 0.0025 maximum. With the drive level determined at zero hours check the anode current at the end of life. The maximum allowable drop in anode current is 25%."

APPLICATIONS:

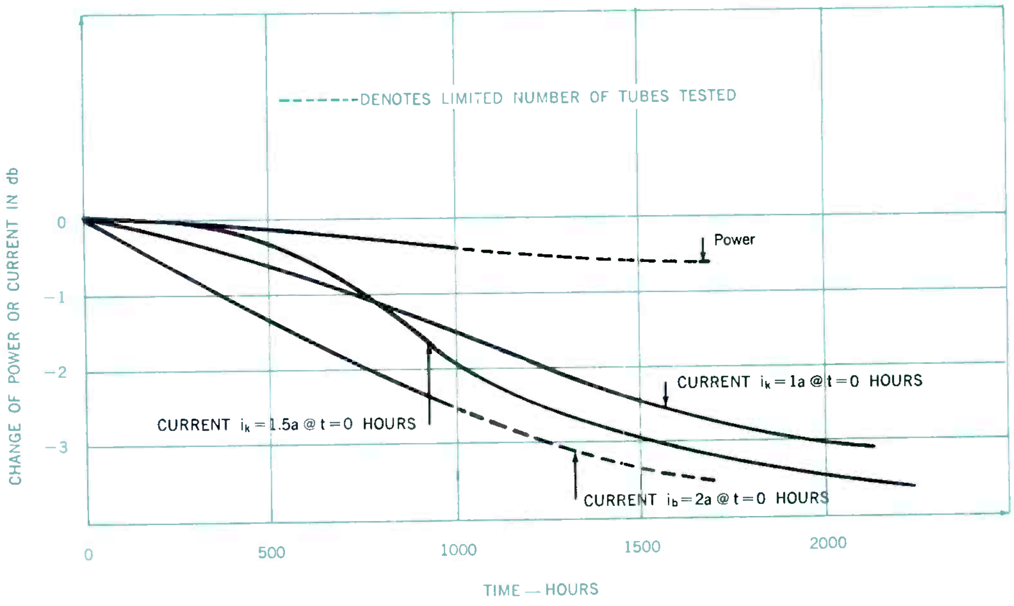
The ML-7815/3CPN10A5 is a high mu Planar Triode designed for use as a grid-pulsed or plate-pulsed oscillator, frequency multiplier or power amplifier in radio transmitting service from low frequency to 3000 mc.

REMARKS:

See Cathode Press Vol. 20, No. 4, 1963, "Evaluation of Negative Grid Tubes in Pulsed Applications for High Volumn Consumption in Phased Array Radar." P. 2. Claim 0 failures after total running time of 3700 hours per tube.



POWER AND CURRENT VS. LIFE



DATE ISSUED: 12/10/63

REPORT NO.: 1

SUMMARY OF TEST RESULTS	*No. Tested*	*Total Tube Hours*	*No. Failed*	*Failure Rate in % Per 1000 Hours Confidence Factor 60%*	*90%*
Catastrophic Failures	69	45,186	0	< 2.1	< 5.1
Total Failures (Catastrophic & Electrical)	69	45,186	0	< 2.1	< 5.1

TEST DESCRIPTION:

Per MIL-E-1/1470 (NAVY)

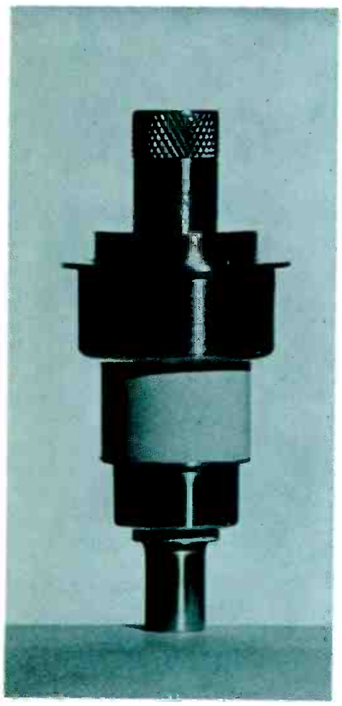
Group B

Filament Standby Ef = 6.3 Vac. Time — 500 Hours

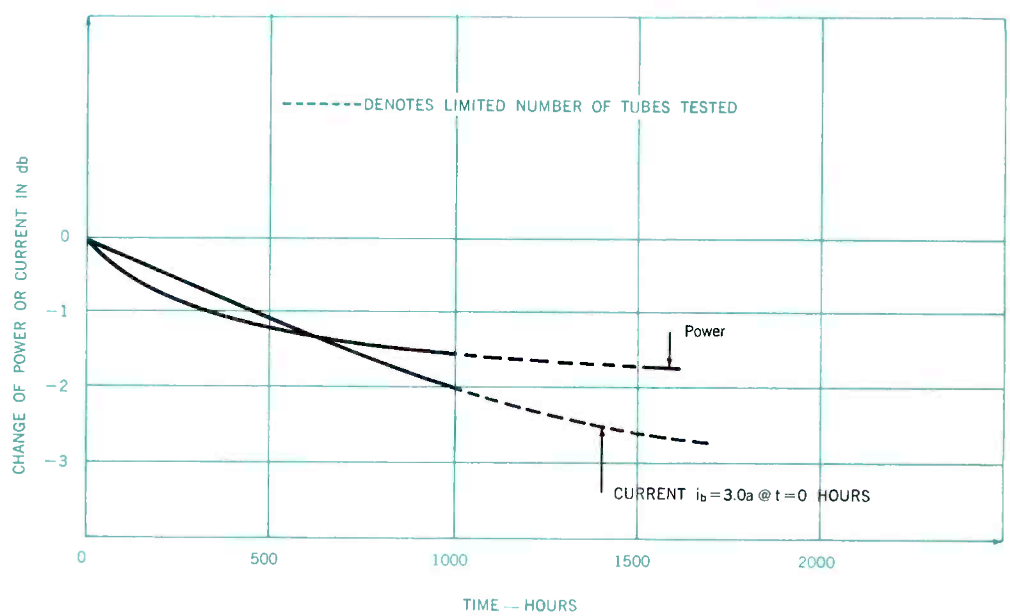
"At zero hours of life test establish the drive conditions necessary to obtain a peak plate current of 3a (minimum) with a plate voltage of 1000 Vdc and a bias of —40 Vdc. The pulse width of the modulator shall be 2 μs (minimum) and the duty shall be 0.0025 (maximum). With the drive level determined at zero hours, check the plate current at end of life. Maximum allowable drop in plate current shall be 25%."

APPLICATIONS:

The ML-7698 is a high-mu Planar Triode designed for use as a grid-pulsed or plate-pulsed oscillator, frequency multiplier or power amplifier in radio transmitting service from low-frequency to 3000 mc.



POWER AND CURRENT VS. LIFE



DATE ISSUED: 12/1/63

REPORT NO.: 1

SUMMARY OF TEST RESULTS	*No. Tested*	*Total Tube Hours*	*No. Failed*	*Failure Rate in % Per 1000 Hours Confidence Factor 60%*	*90%*
Catastrophic Failures	126	65,837	0	< 1.28	< 3.15
Total Failures (Catastrophic & Electrical)	126	65,837	1	< 2.75	< 5.08

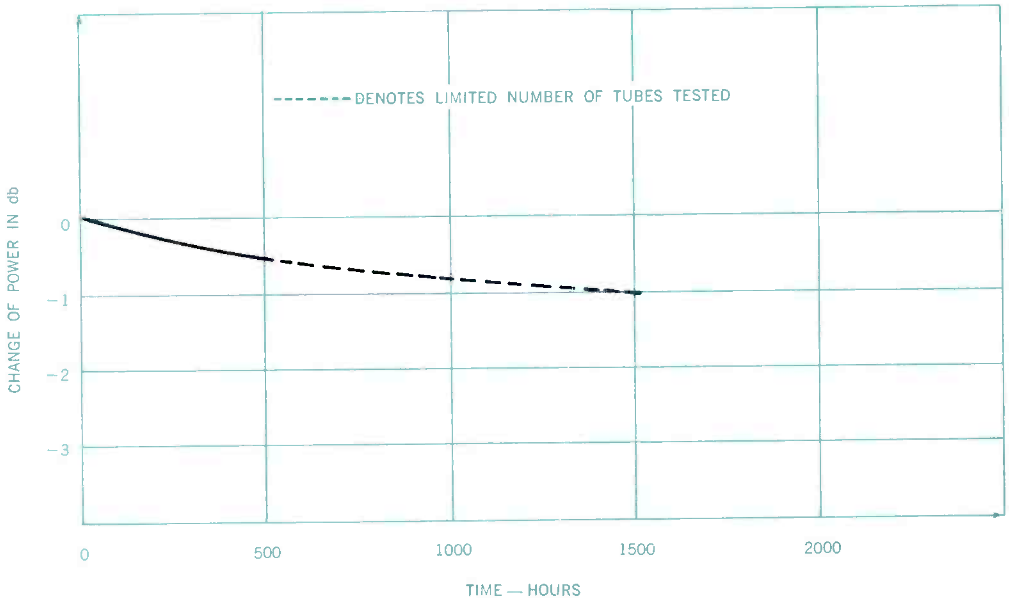
TEST DESCRIPTION:

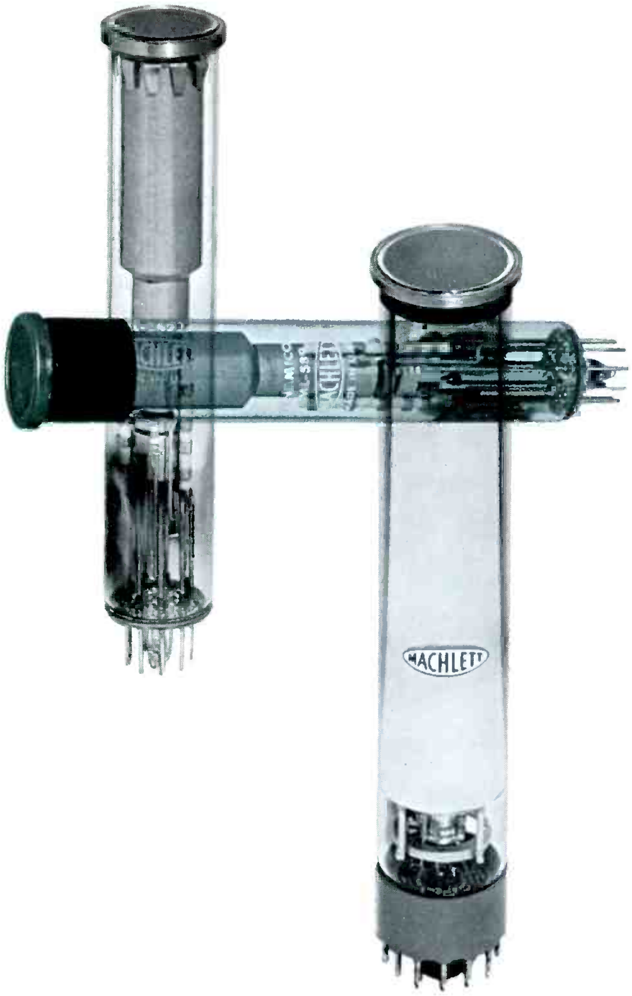
Per MIL-E-1/1055A
Group C
Time = 500 Hours
Pulsed Oscillation F = 3450 MC Minimum
e_{pg} = 3000 V; Rg/Ib = 2.5 madc; tpv = 1.0 usec ± 10%
trv = 0.1 usec, Maximum, tfr = 0.2 usec, Maximum;
prΩ/Du = 0.001 ± 5%
E_F = 6.0 V
ΔPo — 25% Maximum

APPLICATIONS:

The ML-6442 is a metal-ceramic envelope, medium-mu Triode of the Planar-Electrode type designed specifically for use as a plate-pulsed oscillator and amplifier at frequencies up to about 5000 mc. It can also be used as a cw oscillator, rf power amplifier or frequency multiplier at frequencies up to 2500 mc.

POWER VS. LIFE





Machlett Special-Purpose Vidicons

The design, development and production of specialized, high-quality TV vidicon camera tubes is a unique capability of The Machlett Laboratories. Since entering the vidicon field with a broadcast vidicon that provided "live" quality to film transmission in mid-1958, Machlett has continued to advance the state of the art with a succession of new and difficult-to-produce vidicons. The current Machlett line, described on succeeding pages, consists of exclusive, special purpose, high quality tubes. Each of these tubes represents a technological breakthrough which was the culmination of extensive research and custom engineering.

In addition to exclusively Machlett development programs, the Company is continually engaged in sponsored development on special or custom vidicons for the military, private research institutions and others. Machlett, with its staff of specialists, continues to solicit sponsored development programs.

Among the special Machlett vidicons, currently used in slow-scan systems in satellite applications, is the ML-7351A. It is highly sensitive in the red region, and has lag characteristics that make this tube particularly adaptable to CCTV systems viewing radar scopes, and the like.

Two tubes in the line — the ML-S522B and the ML-2128G — have spectral response which peaks near the ultraviolet region. Applications of these tubes include TV display of ultraviolet microscope images of specimens which could not be viewed, or would be changed by exposure to visible light.

The incorporation of fiber-optics faceplates as an integral part of the ML-2128G and the ML-2128U vidicons has significantly advanced the capability of TV systems. With fiber optics, images can be transferred over short or long distances (in this case, short) with high sensitivity, efficiency, and resolution, while a lens system is restricted by its focal length.

The development of two x-ray sensitive camera tubes — termed DYNAMICONS* — combines instantaneous, enlarged x-ray image reproduction with protection for observing personnel. Performance of both static and in-motion medical and non-destructive radiographic examinations are notable advantages of these tubes.

The two-inch vidicon — represented by the ML-2058G and ML-2135G — was developed for applications which required a wider input field than was possible with the conventional ½″ x ⅜″ scanned area of the 1″ vidicon. The 2″ tubes provide for a full 1″ x 1″ raster.

On the following pages are the essential details and characteristics of the current Machlett vidicon line. Further inquiry on these tubes as to applications and capabilities, as well as special developmental requirements, is invited.

*Trade name registered by The Machlett Laboratories, Inc.

ML-7351/ ML-7351A
1″ High sensitivity at low light levels

The ML-7351 and 7351A are 1″ TV vidicon camera tubes designed for low light level applications with limited subject motion. The slow-scan and target storage characteristics of these tubes are particularly advantageous in CCTV systems, viewing radar display scopes. Resolution is normally about 500 TV lines (over 800 lines with elevated focusing potential). Sensitivity is extremely high; scenes with as little as 0.05 fc illumination on the faceplate can be registered. For average scenes, this corresponds to 2.5 fc illumination on a scene when using an f/2 lens. Spectral response peaks at 6000 Å (in red region), and is somewhat dependent on dark current. Signal decay rate is approximately half that of standard light-sensitive vidicons. The ML-7351 has a side tip protrusion; ML-7351A does not have side tip, which permits use of longer deflection yoke.

ML-2128G
1″ High contrast; fiber-optics input

The ML-2128G is a 1″ TV vidicon camera tube with a fiber-optics faceplate. This faceplate permits the tube to be directly coupled to cathode ray, storage or image intensifier tubes provided with fiber-optics output. Fiber-optics combinations for such purposes greatly increase light transmission capabilities, are lighter in weight and utilize less space than comparable optically coupled devices. Spectral response is S-18. Resolution is 600 TV lines. High contrast is enhanced by means of extra-mural absorbtion in the fiber optics.

ML-S522B
1″ Fast, near UV spectral response

The ML-S522B is a 1″ TV vidicon camera tube which is sensitive to near ultraviolet illumination. It is ideally suited for TV systems coupled to devices such as the ultraviolet microscope, which provides increased resolving power with the advantages of fluorescence. The S-522B spectral response peaks at 4000Å. When used with monochromatic radiation at this wavelength, the tube has a sensitivity of about 4.5 $\mu a/\mu w$. Resolution is normally 500 TV lines, but may be higher with elevated focusing potentials. Signal decay rate is approximately double that of standard light-sensitive vidicons.

ML-2128U
1″ Near UV; fiber optics input

The ML-2128U is a 1″ TV vidicon camera tube that has a fiber-optics faceplate. It is sensitive to near ultraviolet illumination, and is especially suited for TV coupling to cathode ray, storage or image intensifier tubes which are provided with fiber-optics output. Such fiber-optics combinations are usually smaller, lighter in weight and have greater light-transmission qualities than comparable lens coupled devices. Spectral response peaks at 4000 Å, which permits increased over-all sensitivity when used with devices having ultraviolet-emitting output screens. Resolution is approximately 500 TV lines; high contrast is obtained by means of extra-mural absorption in fiber optics.

ML-2058G
2″ High resolution; 1.4″ diagonal image

The ML-2058G is a 2″ TV vidicon camera tube which provides high-detail resolution. It may be used with conventional image orthicon magnetic deflection coils. Length is 12″. Features include: a 1″ x 1″ raster (1.4″ diagonal working area); a limiting resolution exceeding 2000 TV lines, 1100 TV lines at 50% amplitude modulation; S-18 spectral response. Transfer Characteristics and Aperture Response Curves follow "Typical Operating Conditions." Development of a 2″ tube with a near UV response is both practical and feasible.

ML-589
1″ X-ray sensitive; High contrast image

The ML-589 DYNAMICON is a 1″ TV camera tube which is sensitive to x-radiation incident on its faceplate. It provides high-contrast images with detail resolution down to .0005″, and penetrameter sensitivities to 2% when used with an adequate CCTV system and x-ray source. This tube makes possible static and in-motion non-destructive examinations of metal weldments, encapsulated components, and biological specimens. Magnifications to 50X easily obtainable. Resolution of 300 ASA phosphor bronze mesh and .0005″ dia. single tungsten wires (at faceplate) can be obtained without additional absorber in x-ray beam. Tube has a low-absorption beryllium faceplate.

ML-2135G
2″ X-ray sensitive; 1.4″ diagonal image

The ML-2135G DYNAMICON is a 2″ TV camera tube which is sensitive to x-radiation incident on its faceplate. This tube permits high-contrast images, brightness intensification, remote viewing and improved x-ray protection. It has a 1″ x 1″ raster (1.4″ diagonal working area). Resolution of 300 ASA phosphor bronze mesh and .0005″ dia. single tungsten wires (at faceplate) can be obtained without an additional absorber in the x-ray beam. This tube is ideally suited for static and in-motion non-destructive examinations of metal weldments, encapsulated components, and biological specimens, especially for applications that cannot be adequately scanned by 1″ ML-589.

GENERAL CHARACTERISTICS	Units	ML-7351/ ML-7351A 1" High-Sensitivity
Heater, for Unipotential Cathode:		
Voltage (AC or DC)	V	6.3 ± 10%
Current	A	.6
Direct Interelectrode Capacitance, Signal Electrode to All Other Electrodes (Note 1)	pf	4.5
Spectral Response	—	See Curve
Photoconductive Layer:		
Aspect ratio of rectangular image	—	4 x 3
Maximum useful diagonal image	in.	.62
Orientation of quality rectangle	—	Note 2
Focusing Method	—	Magnetic
Deflection Method	—	Magnetic
Operating Position	—	Any
Overall Length	in.	6.25 ± .25
Greatest Diameter	in.	1.125 ± .010 (Note 4)
Bulb	—	T-8
Base, JEDEC No.	—	E8-11
Socket, equivalent to Cinch No.	—	54A18088
Weight, approximate	oz	2

FIBER-OPTICS CHARACTERISTICS

Fiber Diameter	microns	
Faceplate Thickness	in.	
Numerical Aperture, nominal	—	

Note 1 — This capacitance, which effectively is the output impedance of the vidicon, is increased when the tube is mounted in the deflecting-yoke and focusing-coil assembly. The resistive component of the output impedance is in the order of 100 megohms.

Note 2 — Proper orientation is obtained when the horizontal scan is essentially parallel to the plane passing through the tube axis and short index pin.

ML-2128G 1″ Fiber-Optics Input	ML-S522B 1″ Near-UV	ML-2128U 1″ Near-UV/ Fiber-Optics	ML-2058G 2″ High-Resolution	ML-589 1″ X-Ray Sensitive	ML-2135G 2″ X-Ray Sensitive
6.3 ± 10%	6.3 ± 10%	6.3 ± 10%	6.3 ± 10%	6.3 ± 10%	6.3 ± 10%
.6	.6	.6	.6	.6	.6
4.5	4.5	4.5	6.5	4.5	6.5
S-18	See Curve	See Curve	S-18	X-ray	X-ray
4 x 3	4 x 3	4 x 3	1 x 1	4 x 3	1 x 1
.62	.62	.62	1.4	.62	1.4
Note 2	Note 2	Note 2	Note 3	Note 2	Note 3
Magnetic	Magnetic	Magnetic	Magnetic	Magnetic	Magnetic
Magnetic	Magnetic	Magnetic	Magnetic	Magnetic	Magnetic
Any	Any	Any	Any	Face up to horizontal	Any
6.25 ± .25	6.25 ± .25	6.25 ± .25	12.0 ± .25	6.25 ± .25	12.0 ± .25
1.125 ± .010	1.125 ± .010	1.125 ± .010	2.25 ± .010	1.125 ± .015	2.25 ± .010
T-8	T-8	T-8	—	—	—
E8-11	E8-11	E8-11	B14-45	E8-11	B14-45
54A18088	54A18088	54A18088	—	54A18088	—
2	2	2	10	2	10
7		7			
.09		.09			
.84		.84			

Note 3 — Proper orientation is obtained when the horizontal scan is essentially parallel to the plane passing through the tube axis and base key.

Note 4 — ML-7351 has a side tip projecting beyond maximum diameter.

MAXIMUM RATINGS

	Units	ML-7351/ ML-7351A 1" High-Sensitivity
Absolute Values for a scanned area as noted	in.	½ x ⅜
Signal-Electrode Voltage	Vdc	75
Grid No. 4 and Grid No. 3 Voltage	Vdc	1000
Grid No. 2 Voltage	Vdc	500
Grid No. 1 Voltage:		
Negative bias value	Vdc	125
Positive bias value	V	0
Peak Heater-Cathode Voltage:		
Heater negative with respect to cathode	v	125
Heater positive with respect to cathode	v	10
Dark Current	uAdc	.1
Peak Target Current	ua	.55
Faceplate Temperature	°C	71
Faceplate Illumination	fc	100

TYPICAL OPERATING CONDITIONS

Signal-Electrode Voltage	Vdc	10 to 25
Grid No. 4 (Decelerator) and Grid No. 3 (Beam-Focus Electrode) Voltage (Note 7)	Vdc	250 to 300
Grid No. 2 (Accelerator) Voltage	Vdc	300
Grid No. 1 Voltage for Picture Cutoff (Note 8)	Vdc	—45 to —100
Minimum Peak-to-Peak Blanking Voltage:		
When applied to Grid No. 1	v	40
When applied to Cathode	v	10
Faceplate Illumination, highlight	fc	.3 to .7
Faceplate Temperature	°C	30 to 35
Dark Current	uAdc	.02
Target Current, highlight (Note 9)	uA	.32 to .42
Average Gamma for Transfer Characteristics	—	.65
For signal output current as given	uA	.02 to .2
Visual equivalent Signal-to-Noise Ratio, approx. (Note 10)		300:1
Field Strength at Center of Focusing Coil, approx.	gauss	40
Field Strength of Adjustable Alignment Coil	gauss	0 to 4

Note 5 — The maximum signal-electrode voltage is determined by the secondary emission first cross-over potential of the photoconductive layer. With a conventional deflection field rate of 60 cps, the cross-over potential will be reached, under no-radiation conditions, at a signal electrode voltage of between 35 and 50 volts. If the tube is operated above the first cross-over potential, the photoconductive surface will be stabilized by the G4 electrode. The potential across the photoconductive layer will then be the difference between the potentials applied to G4 and the signal-electrode.

If operated above the first cross-over potential during early life, this tube is very susceptible to picture and raster burns due to the high potential gradient across the layer. Although this effect becomes less apparent with increased operating hours, the manufacturer deems it advisable to limit the signal-electrode potential to a few volts below the cross-over point in order to prevent picture deterioration. The maximum signal-electrode potential is therefore given for each tube delivered.

With the beam off, the cross-over will be reached with a somewhat lower signal-electrode potential, as a result of the extended photoconductive storage time. It is important, therefore, to turn the beam on before increasing the signal-electrode potential above zero.

ML-2128G 1" Fiber-Optics Input	ML-S522B 1" Near-UV	ML-2128U 1" Near-UV/Fiber-Optics	ML-2058G 2" High-Resolution	ML-589 1" X-Ray Sensitive	ML-2135G 2" X-Ray Sensitive
½ x ⅜	½ x ⅜	½ x ⅜	1 x 1	½ x ⅜	1 x 1
75	40	40	75	Note 5	Note 5
1000	1000	1000	3500	1000	3500
500	500	500	350	500	350
125	125	125	125	125	125
0	0	0	0	0	0
125	125	125	125	125	125
10	10	10	10	10	10
.25	.02	.02	1.0	Note 6	Note 6
.55	.55	.55	2.0	.40	1.4
71	45	45	60	45	45
1000	—	—	1000	—	—
15 to 35	10 to 25	10 to 25	25 to 60	10 to 30	10 to 30
250 to 300	250 to 300	250 to 300	2900 to 3100	250 to 300	2900 to 3100
300	300	300	300	300	300
—45 to —100	—45 to —100	—45 to —100	—45 to —100	—45 to —100	—45 to —100
75	40	40	75	75	75
20	10	10	20	20	20
15	—	—	15	—	—
30 to 35	30 to 35	30 to 35	30 to 35	20 to 30	20 to 30
.02	.005	.005	.08	(Note 6)	(Note 6)
.32 to .42	.2 to .4	.2 to .4	1.2 to 1.6	—	—
.65	—	—	.65	—	—
.02 to .2	—	—	.08 to .8	—	—
300:1	300:1	300:1	300:1	300:1	300:1
40	40	40	60	40	60
0 to 4	0 to 4	0 to 4	0 to 3	0 to 4	0 to 3

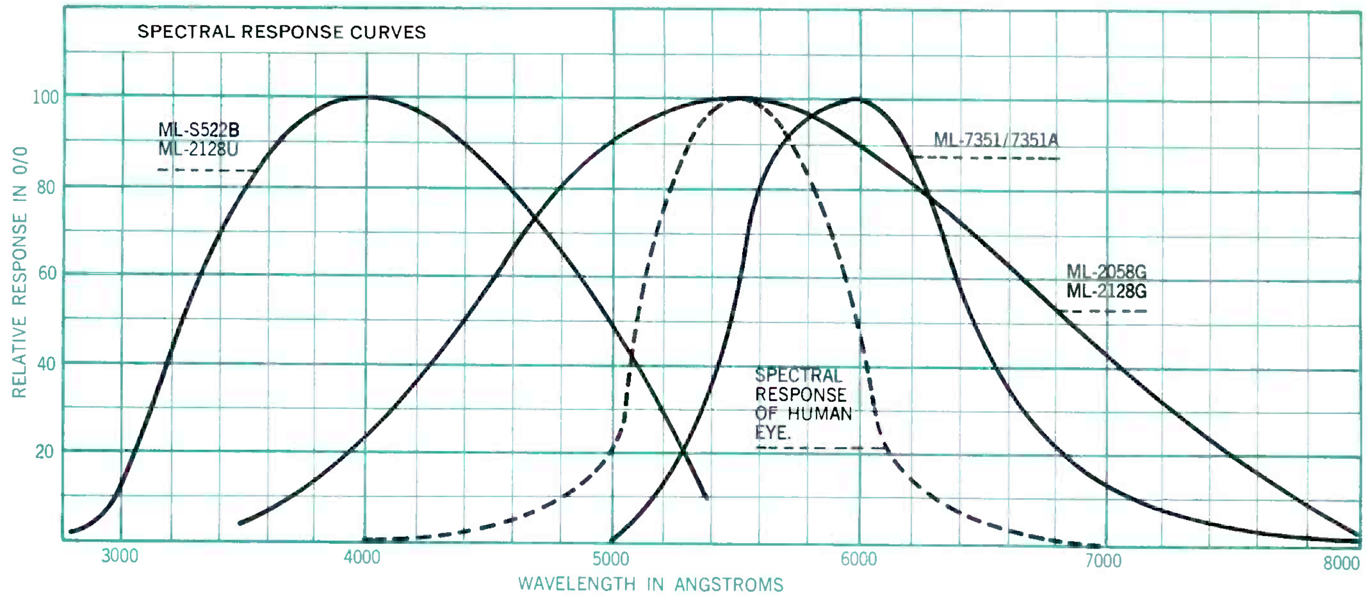
Note 6 — The characteristics of the photoconductive surface are such that the operating dark current is extremely small compared to that obtained with conventional light-sensing vidicons. It is somewhat difficult to measure due to the presence of leakage currents, and it is not therefore considered a useful operating parameter.

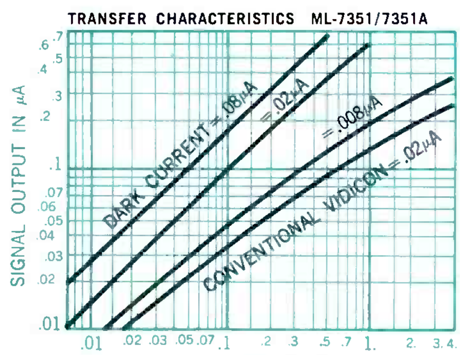
Note 7 — Definition, focus uniformity and picture quality decrease with decreasing Grid No. 3 and Grid No. 4 voltage. In general, Grid No. 3 and Grid No. 4 should not be operated below the lower value shown.

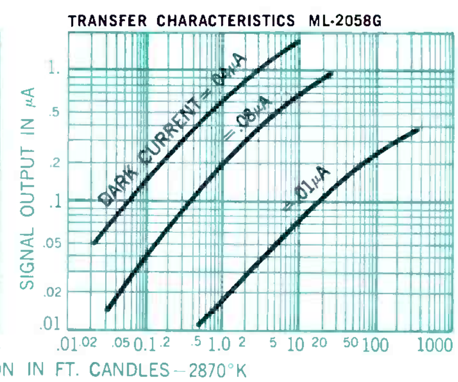
Note 8 — With no blanking voltage on Grid No. 1.

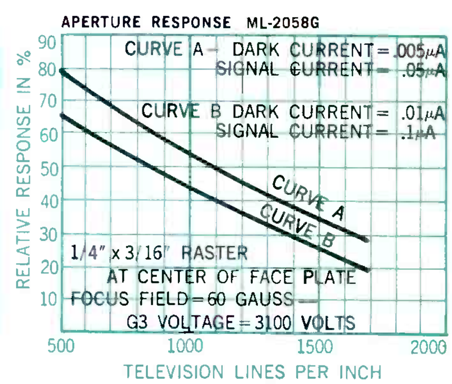
Note 9 — Video amplifiers must be designed properly to handle target currents of this magnitude to avoid amplifier overload or picture distortion.

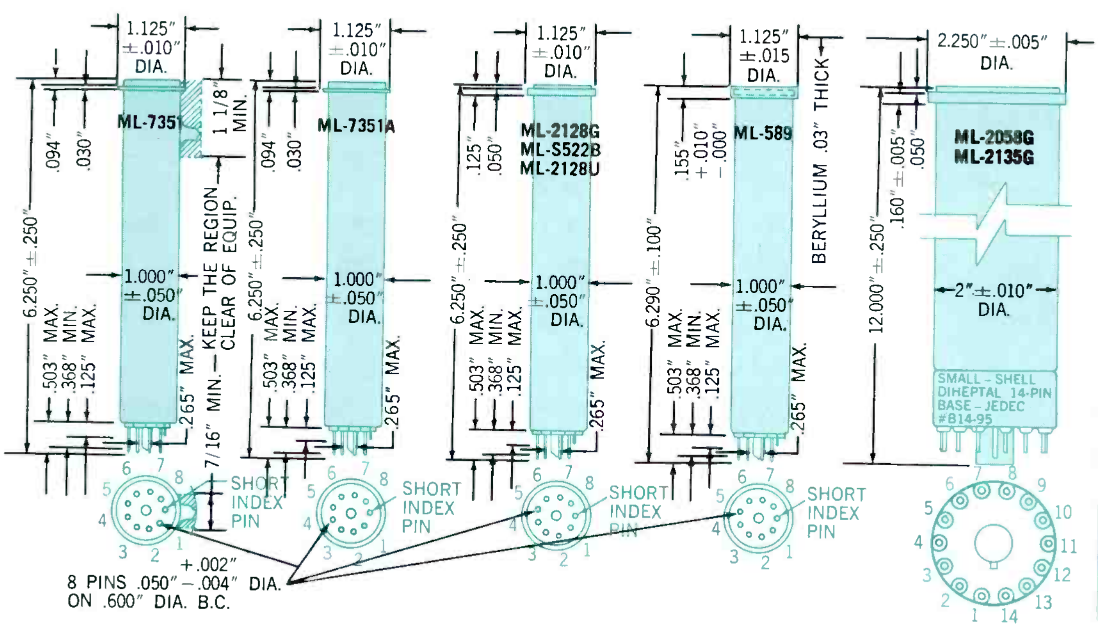
Note 10 — Measured with high-gain, low noise, cascode-input-type amplifier having bandwidth of 5 megacycles.











PIN CONNECTIONS FOR 1" TUBE	
PIN NO.	ELEMENT
1 & 8	HEATER
2	GRID NO. 1
3 & 4	INTERNAL CONNECTIONS–DO NOT USE
5	GRID NO. 2
6	GRID NO. 3 & GRID NO. 4
7	CATHODE
FLANGE	SIGNAL ELECTRODE
INDEX PIN	INTERNAL CONNECTION–DO NOT USE
2" TUBE	
2	GRID NO. 4
3	GRID NO. 3
4	INTERNAL CONNECTION–DO NOT USE
10	GRID NO. 2
13	CATHODE
1 & 14	HEATER
5 thru 12	GRID NO. 1

(Continued from Page 15)

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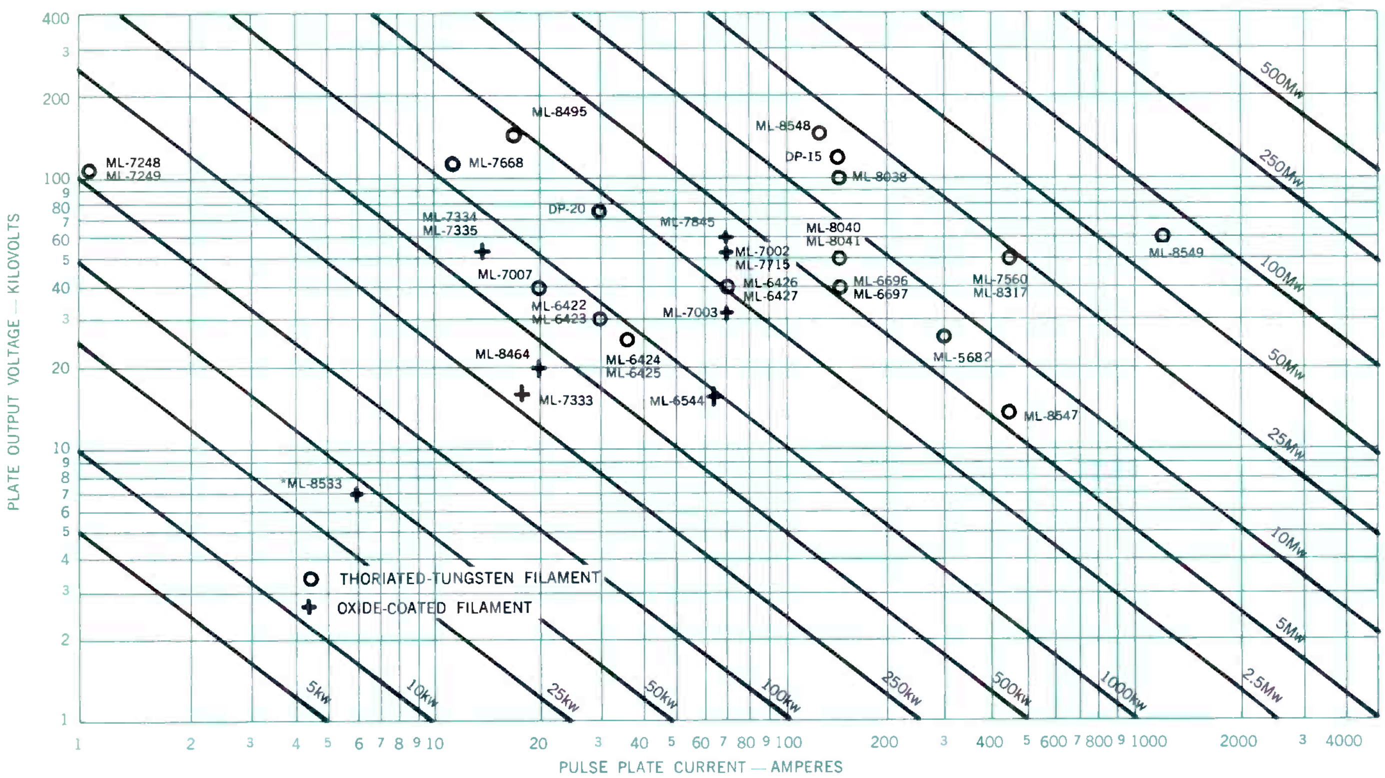
Appendix I

Switching Power of Machlett Pulse Tubes

Switching power of the current line of Machlett pulse tubes is indicated below. Each tube will deliver output current and voltage approximately up to values indicated by either an 0 or a +.

Lines of constant switching power through these coordinates show the range of current and voltage possible by the use of an output pulse transformer.



*UHF TRIODE. For data on other tubes of this type, Consult MACHLETT Engineering Department

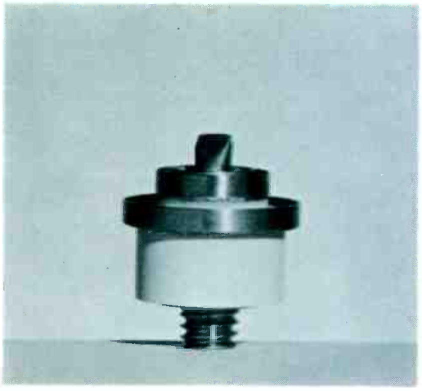
New Machlett Developments

Machlett announces a new line of miniature ruggedized, high-mu planar triodes illustrated below, ACTUAL SIZE. Performance of this miniature line is identical to that of the larger, conventional planar tubes.

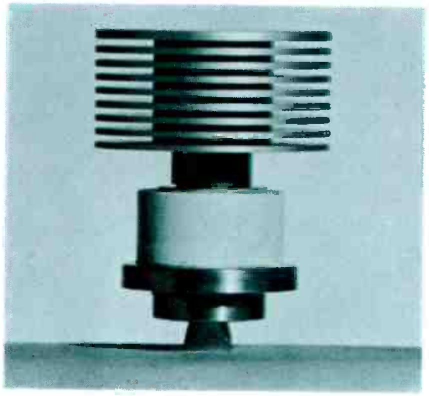
MAXIMUM RATINGS

	Units
Pulse Duration	usec
Duty Factor	%
Amplification Factor	—
DC Plate Voltage	kVdc
Peak Plate Voltage	kV
Peak Plate Pulse Supply Voltage	kV
DC Grid Voltage	Vdc
Instantaneous Peak Grid-Cathode Voltage	
Grid Negative to Cathode	v
Grid Positive to Cathode	v
Average Plate Current	mAdc
DC Plate Current	mAdc
Peak Plate Current from Pulse Supply	a
Peak Plate Current from DC Supply	a
Transconductance	mmhos
Average Grid Current	mAdc
Average Plate Dissipation	
Forced-Air or Heat-Sink Cooling	W
Conduction and Convection Cooling	W
Average Grid Dissipation	W

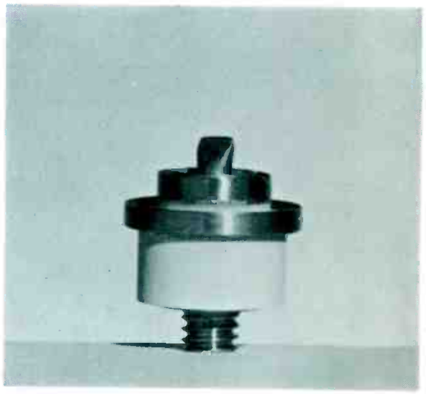
ML-8534



ML-8535



ML-8536



ML-8534 and ML-8535

For grid, plate-pulsed, or cw operation; frequency multipliers, oscillators, or amplifiers to 3 Gc. Both tubes employ **high current capability, phormat cathode, frequency stable anode;** and provide low interelectrode capacitance, and high transconductance.

ML-8536 and ML-8537

For grid, plate-pulsed, or cw operation; frequency multipliers, oscillators, or amplifiers to 3 Gc. Both tubes employ the **phormat cathode, frequency stable anode,** and provide low interelectrode capacitance and high transconductance.

ML-8538 and ML-8539

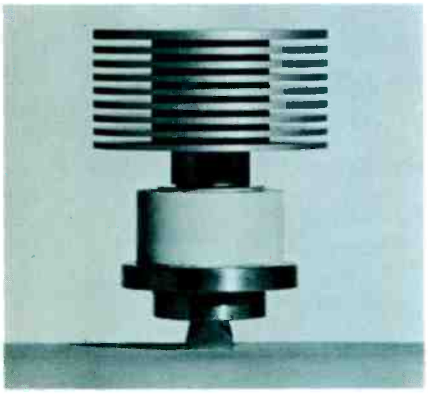
For use as **pulse modulators,** pulse amplifiers, grid-pulsed oscillators, or amplifiers and switch tubes. Frequency to 3 Gc. Tubes have **high current capability, and phormat cathode.**

• • •

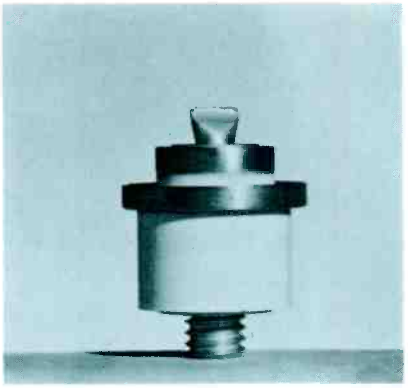
Switch tube to 30 kw max. at 0.0033 d

ML-8534/ML-8535: Pulsed UHF Oscillator & Amplifier, Grid-Pulsed	ML-8534/ML-8535: Pulsed UHF Oscillator & Amplifier, Plate-Pulsed	ML-8534/ML-8535: CW	ML-8536/ML-8537: Pulsed UHF Oscillator & Amplifier, Grid-Pulsed	ML-8536/ML-8537: Pulsed UHF Oscillator & Amplifier, Plate-Pulsed	ML-8536/ML-8537: CW	ML-8538/ML-8539: Pulse Modulator or Pulse Amplifier	ML-8538/ML-8539: Grid-Pulsed UHF Oscillator & Amplifier
6	6	—	6	6	—	6	6
.33	.33	—	.33	.33	—	.33	.33
80	80	80	80	80	80	90	135
2.5	—	2.5	2.5	—	2.5	8	7.5
—	—	—	—	—	—	10	—
—	3.5	—	—	3.5	—	—	—
−150	−150	−150	−150	−150	−150	−150	−150
−750	−750	−400	−750	−750	−400	−750	−750
+250	+250	+ 30	+250	+250	+ 30	+250	+250
16	16	—	10	10	—	—	16
—	—	150	—	—	100	150	—
—	5	—	—	3	—	5	—
5	—	—	3	—	—	—	5
—	—	30	—	—	25	—	30
6	6	45	5	5	45	—	6
33	58	100	20	35	100	100	100
10	10	10	10	10	10	10	10
1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5

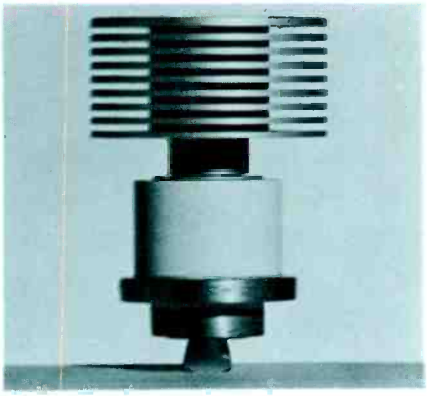
ML-8537



ML-8538



ML-8539



New Machlett Developments

ML-8464

Ruggedized shielded-grid triode for pulse generation to 2 Mw

Designed for operation while subjected to moderately high acceleration forces and is suitable for mobile radar applications. Delivers 400 kW pulse power output with less than 2 kW pulse driving power. Cathode is unipotential, oxide-coated; anode is liquid cooled.

Maximum Ratings, Pulse Modulator or Pulse Amplifier

DC Plate Voltage	25 kV
Pulse Cathode Current	25 a
Plate Dissipation	1.5 kW

Typical Operation

DC Plate Voltage	23 kV
DC Grid Voltage	—250 V
Pulse Positive Grid Voltage	1.1 kV
Pulse Plate Current	20 a
Pulse Grid Current	1.4 a
Pulse Driving Power	2 kW
Pulse Power Output	400 kW
Plate Output Voltage	20 kW

ML-8547

General-purpose, low-mu triode capable of 6 Mw pulse modulator service

ML-8547 is capable of switching 6 Mw in a pulsed modulator at relatively long pulse duration and high duty factor. Incorporates integral water jacket, sturdy coaxial grid and cathode mounting structures, and thoriated tungsten filament; provides low - inductance, high - dissipation, rf terminals.

Maximum Ratings, Pulse Modulator or Pulse Amplifier

DC Plate Voltage	16 kV
Pulse Cathode Current	550 a
Plate Dissipation	175 kW

Typical Operation

DC Plate Voltage	15 kV
DC Grid Voltage	—2000 V
Pulse Positive Grid Voltage	1.3 kV
Pulse Plate Current	250 a
Pulse Grid Current	70 a
Pulse Driving Power	235 kW
Pulse Power Output	3.5 Mw
Plate Output Voltage	14 kV

ML-2080G

9″ Light-Sensitive image intensifier with fiber-optics output

Primarily designed for medical applications. Has light sensitive photocathode with fiber optics output.

Input Diameter	Approx. 8.6″
Output Diameter	Approx. 1.0″
Photocathode	S = 20
Output Phosphor (Optional) (Other phosphor and optical flat glass on request)	P = 20
Brightness Gain (incl. minification)	10,000X
Photocathode Sensitivity	100 ua/L (min.)
Resolution at Photocathode	60 lp/in
Resolution of Output	500 lp/in
Fiber Optics Diameter	7 micron fibers (extramural absorption)
Operating Voltage (Nominal)	24 kV

About the Authors

Dr. H. D. DOOLITTLE

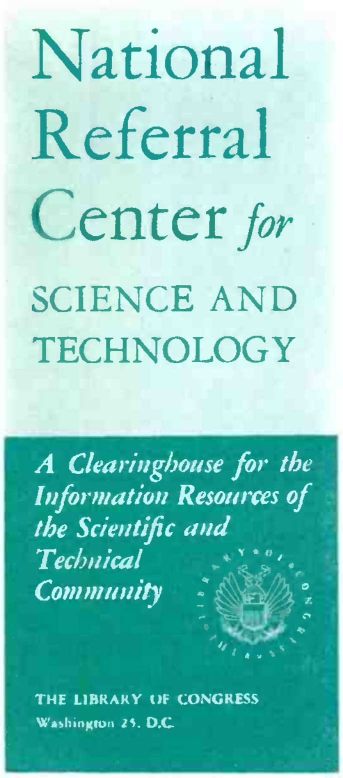
Dr. Doolittle is Manager of Technology of The Machlett Laboratories, Inc., and has been responsible for the development of UHF and high power triodes and tetrodes as well as research on cathodes and allied subjects. He is also responsible for over-all scientific work of the engineering staff with particular emphasis on new products and processes. Dr. Doolittle is a fellow of the American Physical Society, and a Member of IEEE and the Electrochemical Society.

C. A. TUDBURY

Mr. Tudbury has been Chief Engineer of the AMF Thermatool Corporation since 1958, and was previously associated with Tocco and Budd Induction Heating Division. He received his Bachelor's and Master's degrees in Electrical Engineering from MIT, and has taught Electronic Engineering at both Fenn College, Cleveland, and Wayne University, Detroit. Mr. Tudbury is past chairman of the AIEE Electrical Heating Committee and of the sub-committee of Induction and Dielectric Heating. He has written a textbook titled "Basics of Induction Heating".

NELLO ZUECH

Nello Zuech, who joined The Machlett Laboratories in 1960, was graduated from Catholic University of America, cum laude, with a B.E.E., and holds a M.E.E. from New York University (1962). A member of Tau Beta Pi and the IEEE, Mr. Zuech is now a Senior Production Engineer with the Machlett Small Power Tube Line.



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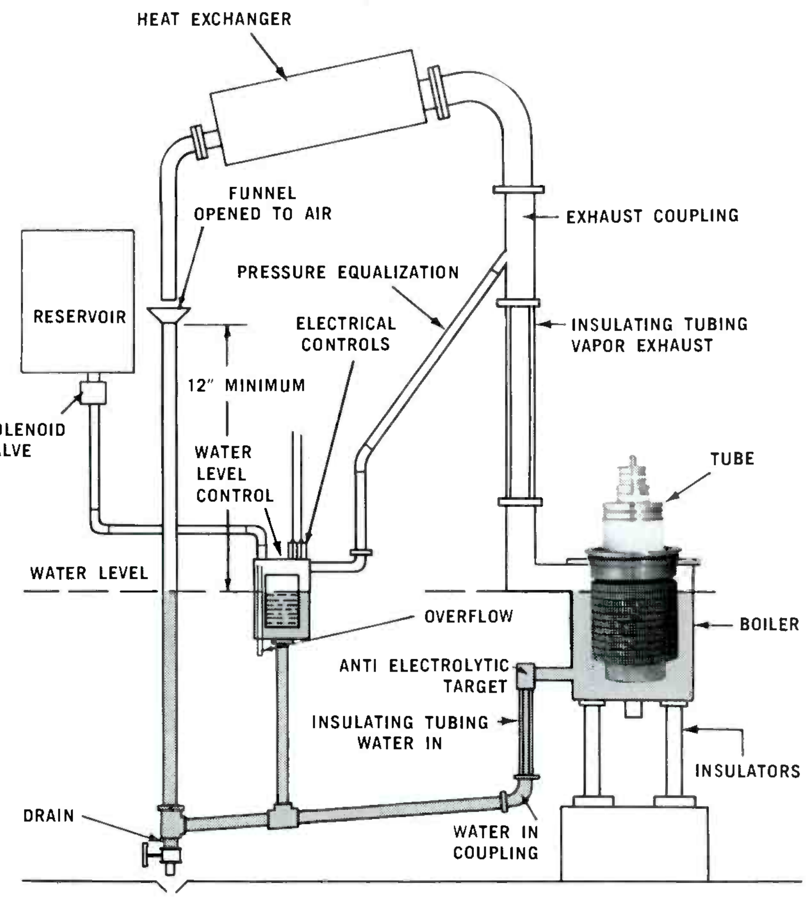
CONSIDERING VAPOR COOLING? SELECT ONE OF MACHLETT'S 4 BASIC SYSTEMS...



From 50kW to 500kW, Machlett offers four basic Vapor Cooling Systems for cooling high power electron tubes:

SYSTEM	TYPICAL APPLICATION
Vapor-Up (shown above)	General Broadcast (HF)
Vapor-Down	General & SSB Communications (HF)
Boiler Condenser	Industrial
Integrated	Special Service. Particularly suited to VHF.

System advantages include: 200-300% greater anode dissipation as compared to forced-air cooling; 10-20% greater anode dissipation over conventional water cooling; extremely large overload protection for anode; stable, quiet cooling; low water consumption; low operating costs.

Each of the above four systems is highly adaptable to a wide range of applications. Consider the advantages of each system—outlined in "Vapor Cooling," obtained by writing to The Machlett Laboratories, Inc., Springdale, Conn., an affiliate of Raytheon Company.

MACHLETT

ELECTRON TUBE SPECIALIST