High-Vacuum Oxide-Cathode Pulse Modulator Tubes

By C. E. FAY

Introduction

IN PRACTICALLY all pulsed oscillators such as those used in radar, some means must be provided to apply the pulse voltage to the oscillator circuit. In many early radars, a high-vacuum modulator was used for this purpose. The pulse was generated at low power level and then amplified by means of one or more stages employing high vacuum tubes. The final stage was required to block, or cut off the d-c supply voltage with no pulse applied, and to permit as much as possible of the d-c voltage to appear on the oscillator during the pulse. Since most radar oscillators operate at pulse voltages of from 5 to 20 kv and require currents of several amperes during the pulse, the requirements of the modulator tubes are quite severe. Standard transmitting[1] tubes were used at first, the higher power tubes having the necessary voltage rating and having in general a fair amount of cathode emission. Tubes were operated in parallel to provide the required amount of current. Practically all of these tubes were of the thoriated tungsten filament type. For example an early army radar, the SCR268,[2] employed 8 tubes in parallel having a total filament power of 1040 watts to provide a pulse current of about 10 amperes. The use of such equipment in portable or airborne service would be obviously impractical because of the large power consumption, bulk, and weight. In an attempt to provide tubes more suited to this type of service, those described in this paper were developed.

Tube Requirements

The function of the high-vacuum modulator tube essentially is to act as a switch to turn the pulse on and off at the transmitter in response to a control signal. The best device for this purpose will be the one which requires the least signal power for control and which allows the transfer of power with the least loss, from the transmitter power source to the oscillator.

If the oscillator must be supplied with a pulse of voltage E_p and current I_p,* or power E_pI_p, then the voltage which must be supplied by the transmitter power supply will be $E_b = E_p + e_p$, Fig. 1, if e_p represents the voltage

* It is assumed here that the pulse is rectangular in shape. This is usually the desired shape and is fairly well approximated in most cases.

drop in the modulator tubes necessary to allow current I_p to pass. The plate efficiency of the modulator is then simply $\frac{E_p}{E_b}$ and the power dissipated in the modulator tube plate is $I_p e_p$ during a pulse. The average power dissipated in the plate is then $I_p e_p$ multiplied by pulse length and by pulse frequency. The heat storage capability of the plate is ordinarily great enough that the average power is all that needs consideration.

The conditions imposed on the modulator tube are somewhat analogous to those of a class C amplifier at low frequency. The main difference is that the angle of operation is very small, and there is usually no appreciable backswing of plate voltage since the load is essentially a resistance. Typical

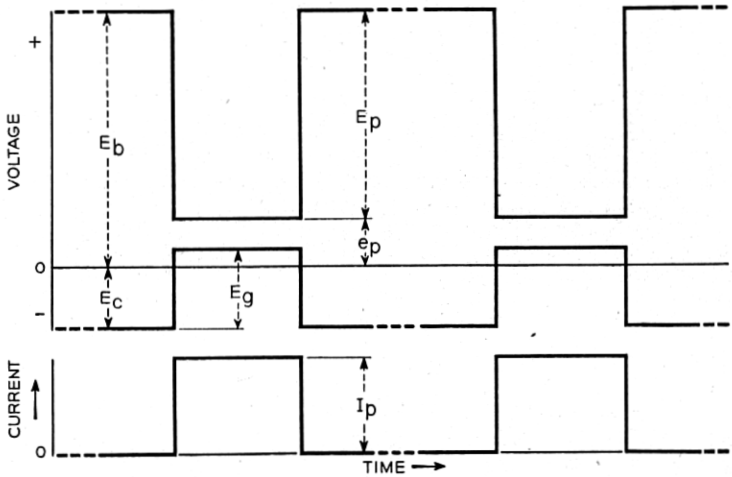

Fig. 1—Current and voltage relations in a pulse modulator tube.

modulator circuits are shown in Fig. 2. It is sometimes found desirable to employ a shunt inductance across the oscillator in the interest of a sharp cutoff of the pulse on the oscillator, particularly where capacitances to ground of various circuit components are appreciable. This results in an additional current demand on the modulator tube since the current through the inductance must also be supplied. The oscillator is often coupled to the modulator circuit by means of a transformer in order that desirable impedances are realized in each circuit.

Design Considerations

It was apparent on first consideration of the high-vacuum modulator problem that use of oxide coated cathodes would be of enormous advantage in keeping power requirements down. Heretofore the use of oxide cathodes in high voltage power tubes had been found very difficult, particularly where filamentary cathodes were employed. Any spark or momentary discharge in operation usually resulted in the burning out of the relatively fragile filaments. This result was caused mainly by the fact that a considerable amount of energy was of necessity available from the power supply equipment. However, in pulse service it is possible to limit the amount of energy available so that a momentary tube breakdown will not result in damage to a reasonably rugged equipotential cathode. Also, in the interest

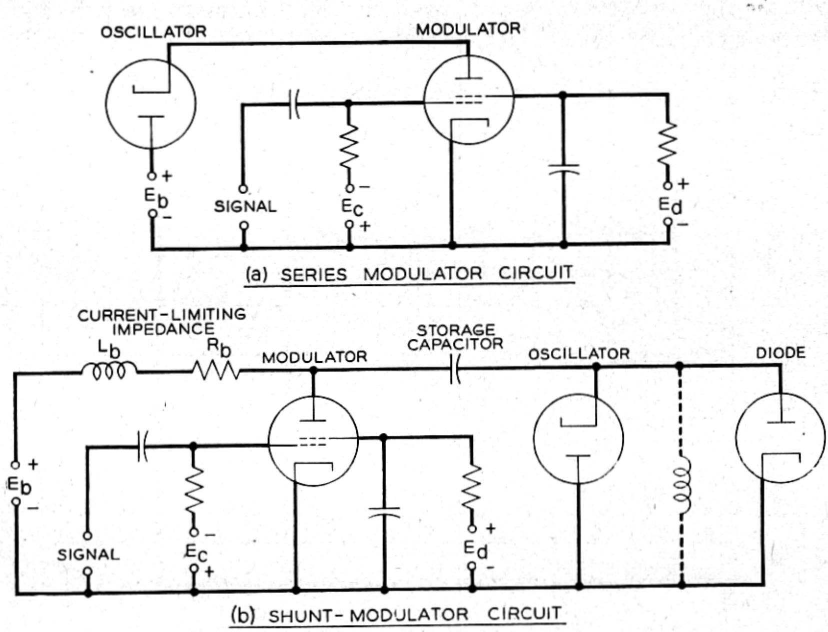

Fig. 2—Typical pulse modulator circuits.

of conserving control power it is desirable to build high perveance tubes which require very close control-grid to cathode spacings. This is much more easily accomplished with rigid cathode structures rather than filamentary cathodes, especially for service conditions under which extreme shock and vibration may be encountered.

Conservation of drive power requires that the modulator tube have high power-gain. This is most easily provided in the tetrode which provides a high over-all amplification factor with reasonable drive characteristics. Lining up the control-grid and screen-grid wires is of course advantageous in the interest of minimizing screen dissipation and getting the largest possible portion of the cathode current to the plate. The control-grid to plate capacitance is of little importance as long as it does not store much energy, there being little chance for oscillation in such a circuit. While it is desirable to operate with as low a minimum plate voltage as possible, it is of little additional advantage to bring the plate voltage below the screen voltage if the screen voltage is about 1000 volts and the supply voltage 15 kv. It was therefore thought permissible to increase plate to screen spacing beyond the optimum for best characteristics in the interest of high voltage and screen dissipation ratings.

The insulation in the tube between plate and other electrodes must be capable of withstanding the full supply voltage plus a comfortable margin. This dictates that if internal insulators are used they must have long path and that the bulb must have sufficient length to prevent flash-over externally.

The 701A Vacuum Tube

At the time of this development a tube was very urgently needed for a Navy radar application.[3] Since speed was of prime importance it was decided to take parts of a standard oxide-cathode beam-power tetrode, Western Electric 350A, and mount them in a structure capable of withstanding the required voltage; 12 kv in this case. Accordingly a cruciform structure was designed in which four sets of 350A electrodes were mounted on ceramic members attached to a molded glass dish-stem as shown in Figure 3. The four cathodes have a total coated area of approximately 14 square centimeters. A molybdenum plate of cruciform section mounted from a lead-in at the top of the bulb was used. This construction eliminated internal insulators between plate and grids other than the bulb. The control-grid of the 350A is normally gold plated to inhibit primary emission. This feature was retained in the 701A and the screen-grid also gold plated. The plate to screen-grid spacing was increased over that normally used in the 350A in order to allow somewhat better cooling of the grids and to allow greater clearance for high voltage reasons. This made the characteristics depart from good "beam tube" performance but at the high voltage condition of operation this was of little consequence. Characteristic curves of the 701A indicating performance under both high voltage and low voltage conditions are shown in Fig. 4. Since no experience was available at the time of this development to indicate what currents could safely be drawn from the cathodes under pulse conditions, the matter of rating these tubes was mainly guesswork since time was not available to await the outcome of life tests under various conditions. The ratings put on the 701A are as shown in Table I.

For the immediate application in hand, which required 12 ampere pulses at about 10 kv, it was decided to specify two 701A tubes operating in paral-

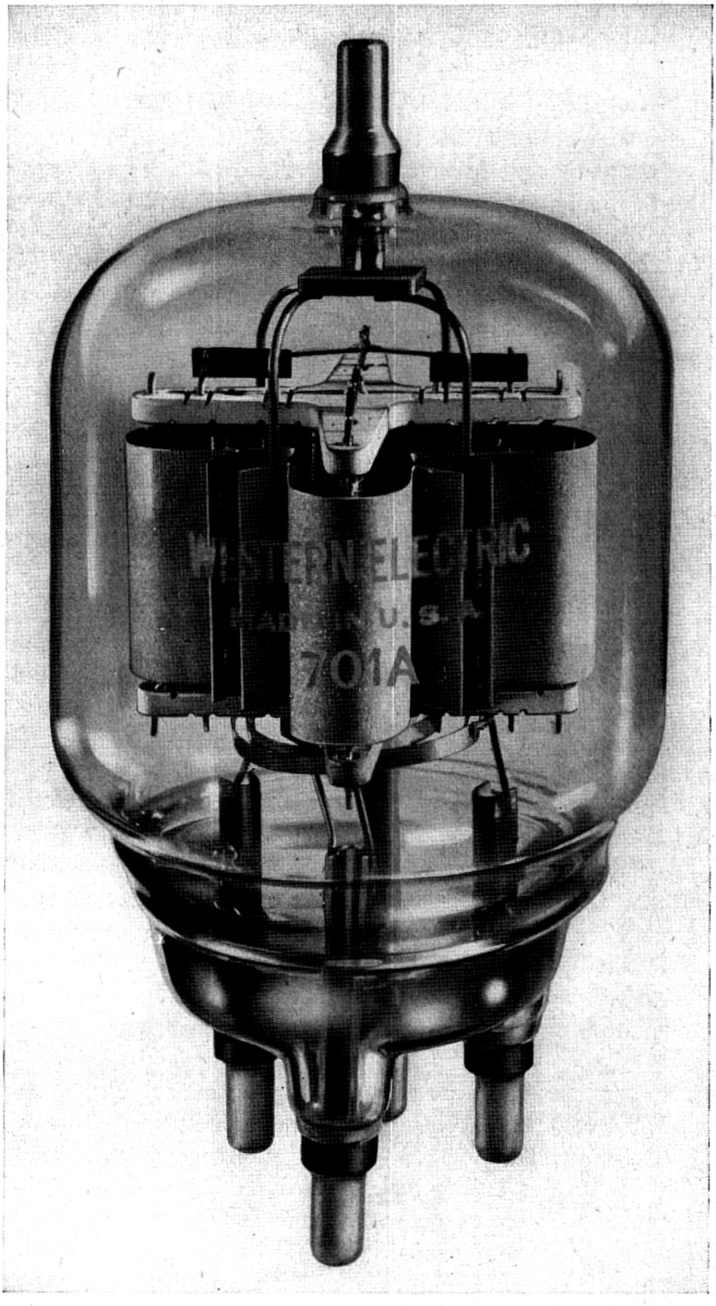

Fig. 3—The 701A vacuum tube.

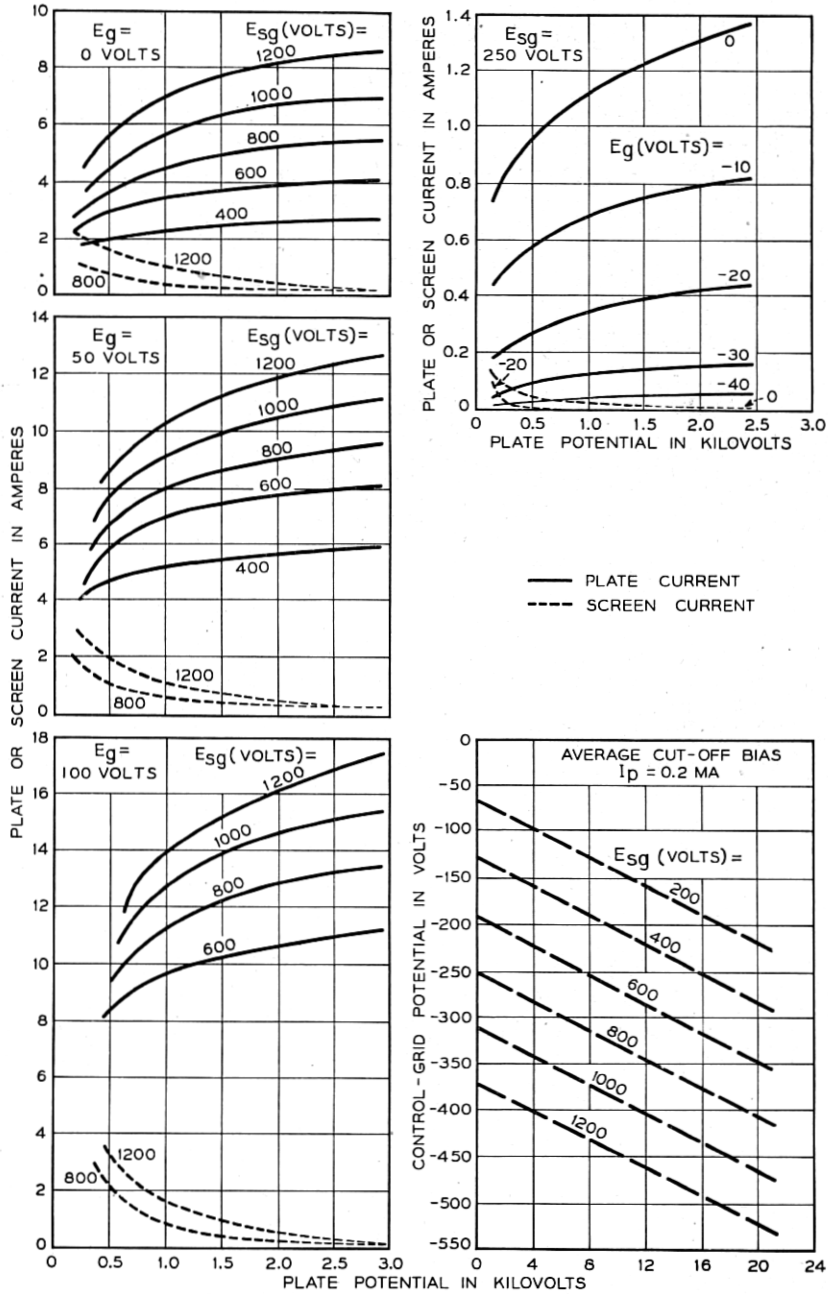

Fig. 4—Characteristics of the 701A vacuum tube.

lel. The pulse in this case was trapezoidal having a base width of about 4μ seconds and a top width of about 1.75 μ seconds; repetition rate was 1600 per second. When the tubes were operated under these conditions there was customarily some sparking within the tube in the first few minutes and then it apparently "aged in," and operated satisfactorily. At the rated heater voltage, the cathodes operated at about 800°C (brightness). This temperature would normally provide a cathode life of more than 1000 hours. Life tests in the laboratory indicated satisfactory performance for about 2000 hours. Reports from the Navy were difficult to obtain but those which were obtained indicated similar results. End of life was caused by both loss of cathode emission and by primary grid emission. Mechanically the tube proved to be reasonably rugged for normal service. However, shocks sustained in shipment of tubes caused mechanical misalignment in some cases, indicating a need for a more rugged structure for use in the armed services.

TABLE I
TABLE OF RATINGS OF OXIDE-CATHODE PULSE MODULATOR TUBES

Tube	Heater Voltage	Heater Current	Peak Plate Voltage	Peak Screen Voltage	Peak Plate Current	Plate Dissipation	Screen Dissipation	Max. Duty Cycle for Peak Plate Current	Capacitances		
									C_{in}	C_{out}	C_{gp}
	Volts	*Amperes*	*KV*	*KV*	*Amperes*	*Watts*	*Watts*		*mmf*		
701A	8	7.5	12.5	1.2	10	100	15	0.005	56	11.5	3.2
715A	27	2.15	14	1.2	10	60	8	0.002	35	7	1.2
715B	26	2.10	15	1.25	15	60	8	0.001	35	7	1.2
5D21	26	2.10	20	1.25	15	60	8	0.001	35	7	1.2
426XQ	8	7.5	25	1.5	20	150	15	0.001	46	7.5	0.6

THE 715A TUBE

The advent of airborne radar made the development of high power lightweight transmitters an urgent requirement. In this case long life was somewhat subordinate to lightweight and small dimensions. Ruggedness was also a requirement. The electronic properties of the 701A tube were well suited for airborne radar but the large bulk was an extreme disadvantage. Work was begun on a tube using the same cathodes as the 701A but having a simpler and more rugged mechanical structure. Out of this evolved the 715A tube. In this tube the cathodes were placed side by side and enveloped by a single control-grid, screen-grid and plate. In order to provide the necessary ruggedness and to keep the grids cool, heavier grid wires were used and they were wound on very heavy supports of high heatconductivity material. Both grids were gold plated as in the 701A. All electrodes were mounted between two specially shaped ceramic insulators which provided a relatively long path between plate and grids. This structure is shown in Fig. 5. Heat radiating fins were attached to the ends

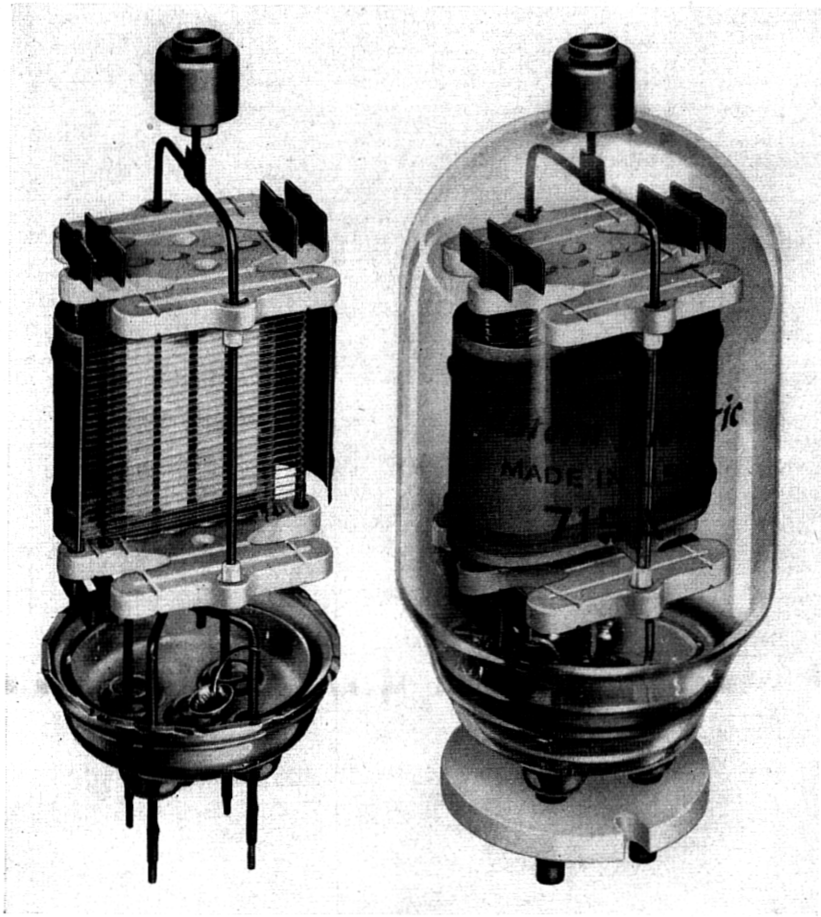

Fig. 5—The 715A vacuum tube.

of the control-grid and screen-grid supports. The plate is molybdenum with zirconium coating on its outside surface. This coating was employed to increase the thermal emissivity of the plate in the interest of a low operating temperature. It also serves to absorb some gas. The cathode, heater and grid terminals of the tube were brought out in the moulded-glass 4-Pin

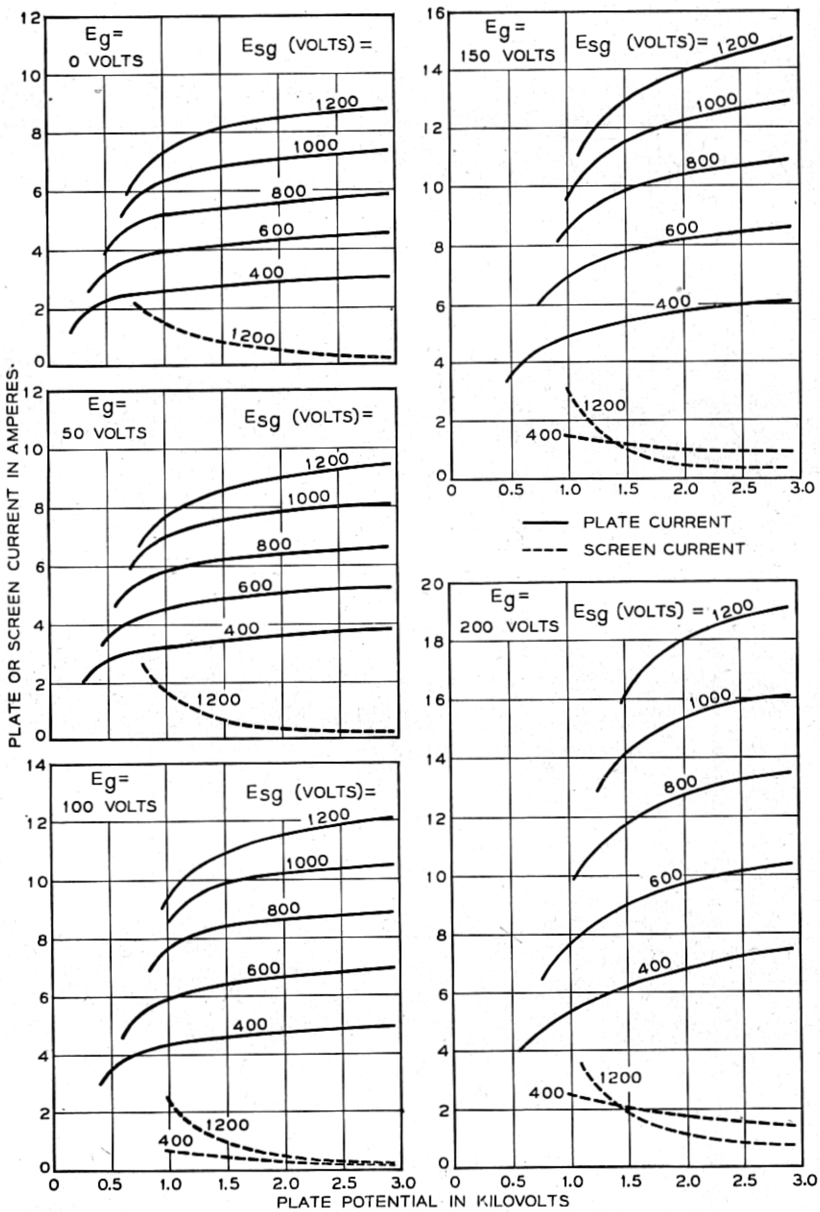

Fig. 6—Characteristics of the 715A vacuum tube.

base, and the plate terminal out the top of the bulb. This provided a very rigid structure which could stand extreme shock and vibration conditions. Although this structure sacrificed something in electronic performance over the 701A it still was quite satisfactory as a pulse modulator.

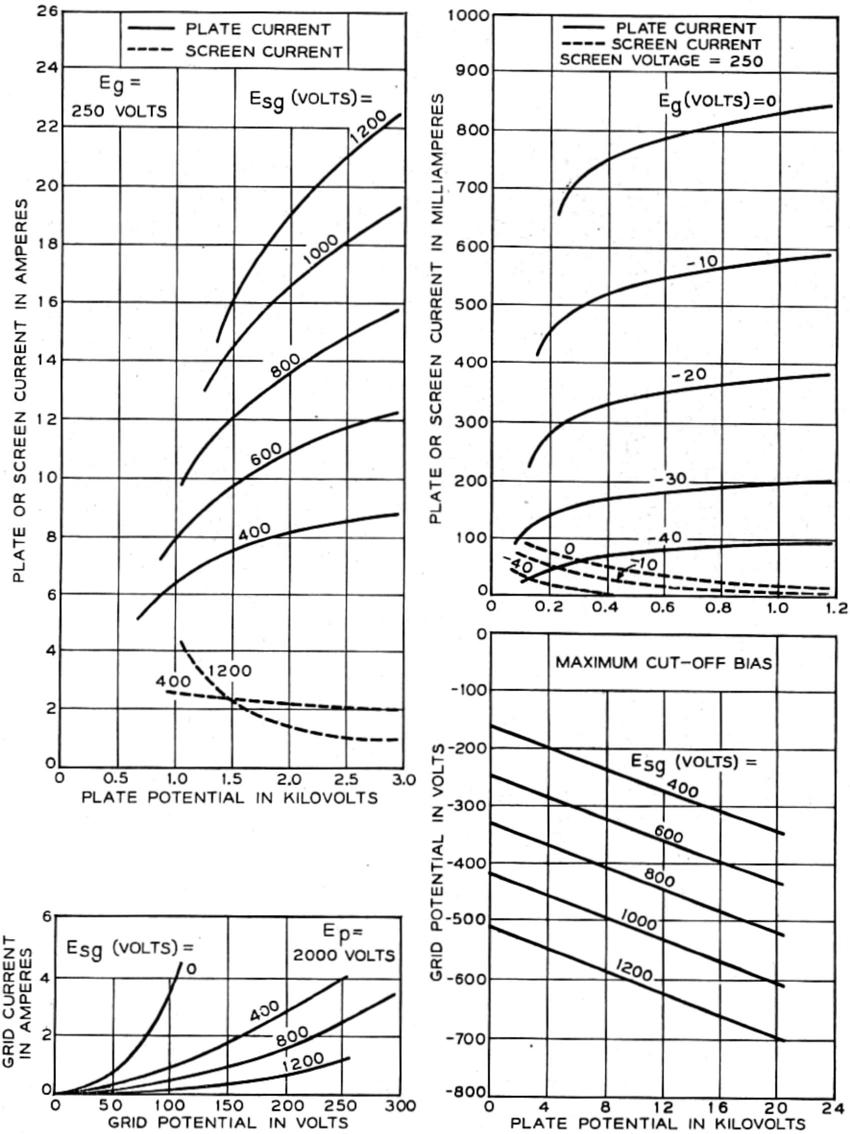

FIG. 6 (Continued)

The characteristics of the 715A tube applicable to both high voltage and low voltage operation are shown in Fig. 6. It was found that in spite of the internal ceramic insulators, satisfactory operation could be obtained at voltages as high as 15 kv. Since the 715A was designed primarily for airborne applications it was found desirable to design the heater to operate directly from the aircraft's storage battery which was a 24 volt battery.

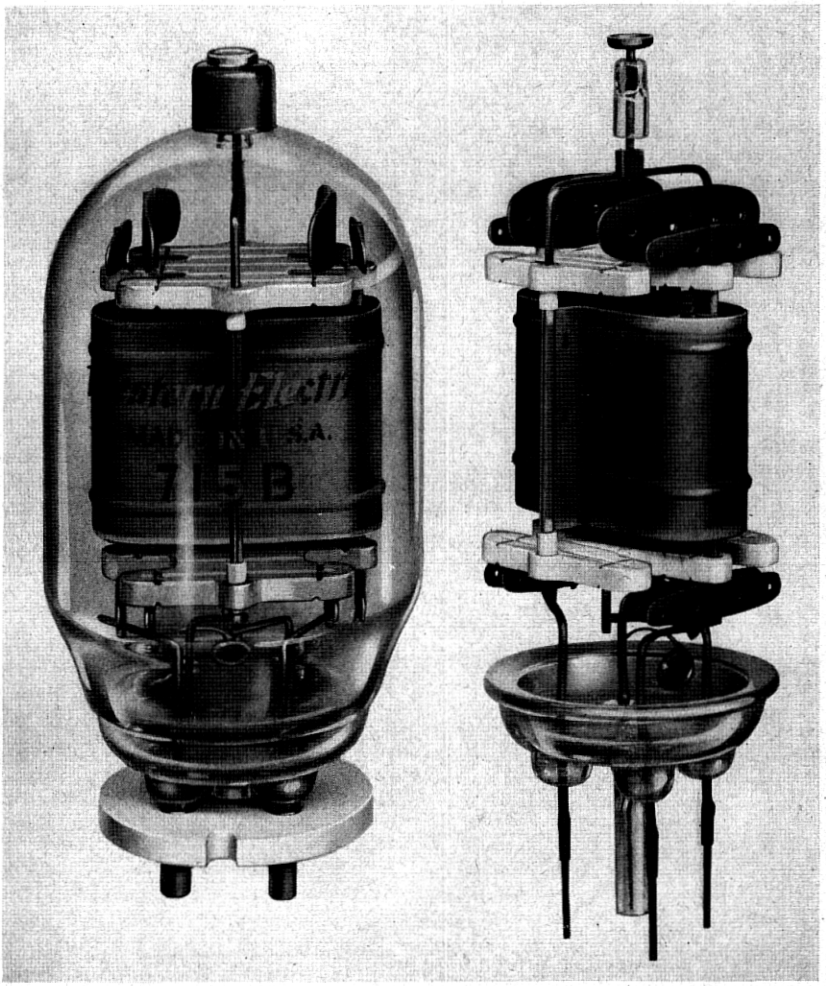

Fig. 7—The 715B vacuum tube.

It was also desirable that the equipment be operable when the charging generator was not running, at which point the voltage might be as low as 22 volts, and also when the generator was charging and the voltage as high as 28.5 volts. This required a compromise in the design of the heater which resulted in operation of the cathode at somewhat higher than normal temperature under rated conditions. The ratings of the 715A tube are given in Table I.

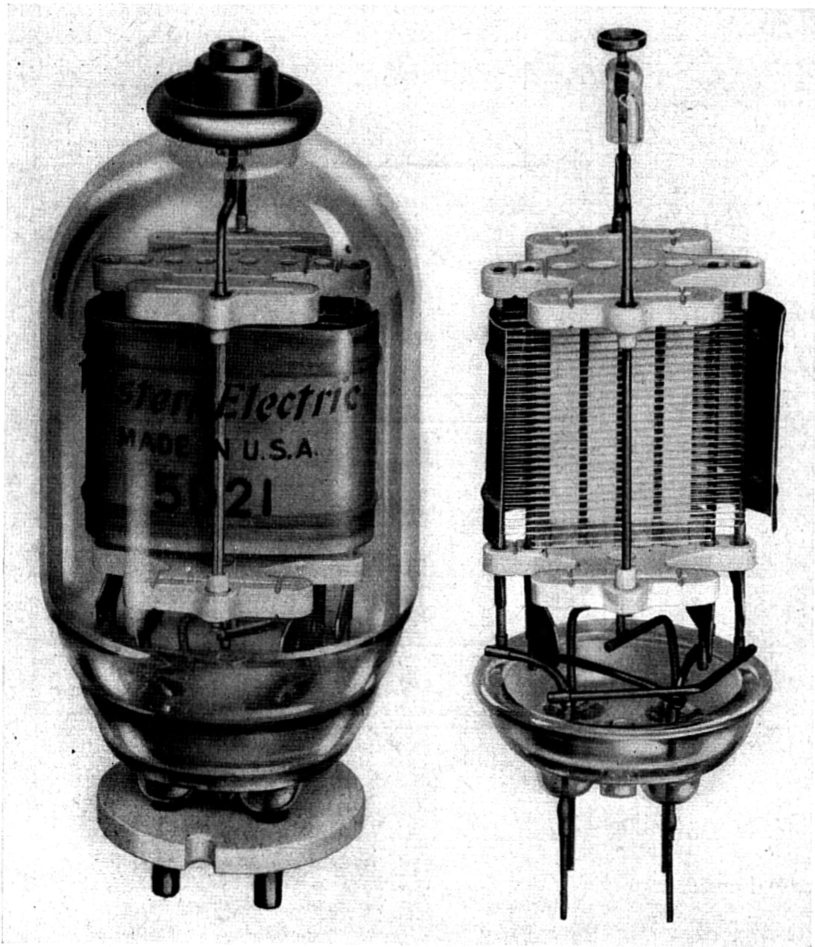

Fig. 8—The 5D21 vacuum tube.

The 715B Tube

Some applications developed which required a peak pulse current slightly greater and of longer duration than that for which the 715A was rated. Meanwhile more experience with the 715A and improvements in processing techniques indicated that a higher peak current rating was justifiable providing the grid temperatures were not increased.

The 715B tube is essentially the same structure as the 715A except that larger radiating fins are attached to the ends of the grid support wires. Figure 7 shows the structure of the 715B tube. The characteristics were identical but the ratings were changed, as indicated in Table I. The life obtained in laboratory life tests under rated conditions averaged between 500 and 1000 hours. Failure was usually caused by grid emission or loss of cathode emission.

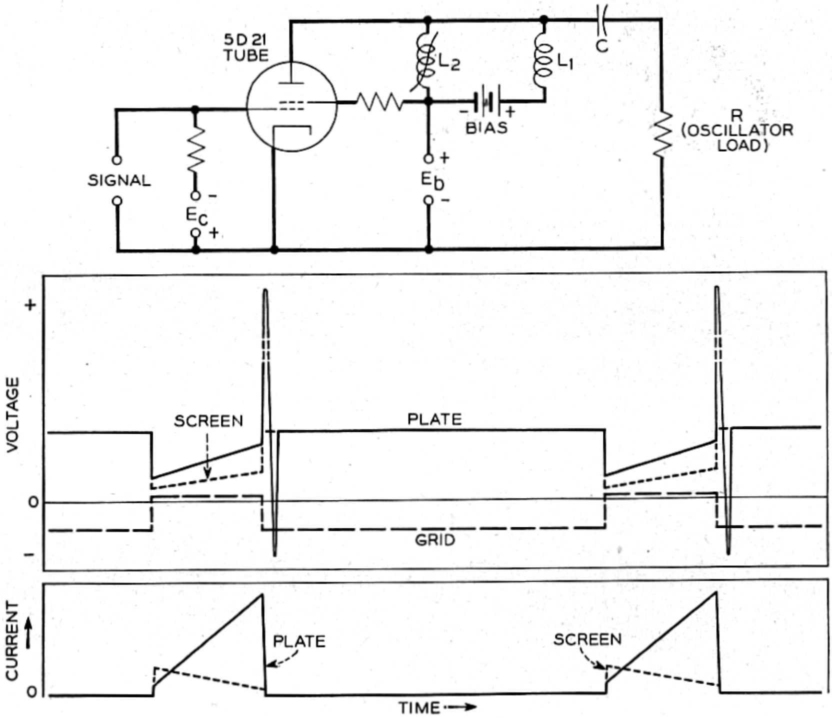

Fig. 9—Non-linear coil modulator circuit with illustration of the current and voltage relations in the 5D21 vacuum tube.

The 5D21 Tube

In response to the demand for further improvement of this structure in its ability to withstand higher voltage, the 5D21 tube was developed, Fig. 8. It is of the same family as the 715A and 715B. It was found that higher voltages could be used if the grid cooling radiators were removed from the top end of the tube. The cooling of the grid was maintained by providing copper wire connections from the bottom ends of the grid support wires to the base seals. This and the use of a specially designed plate terminal cap enabled the voltage rating to be raised to 20 KV.

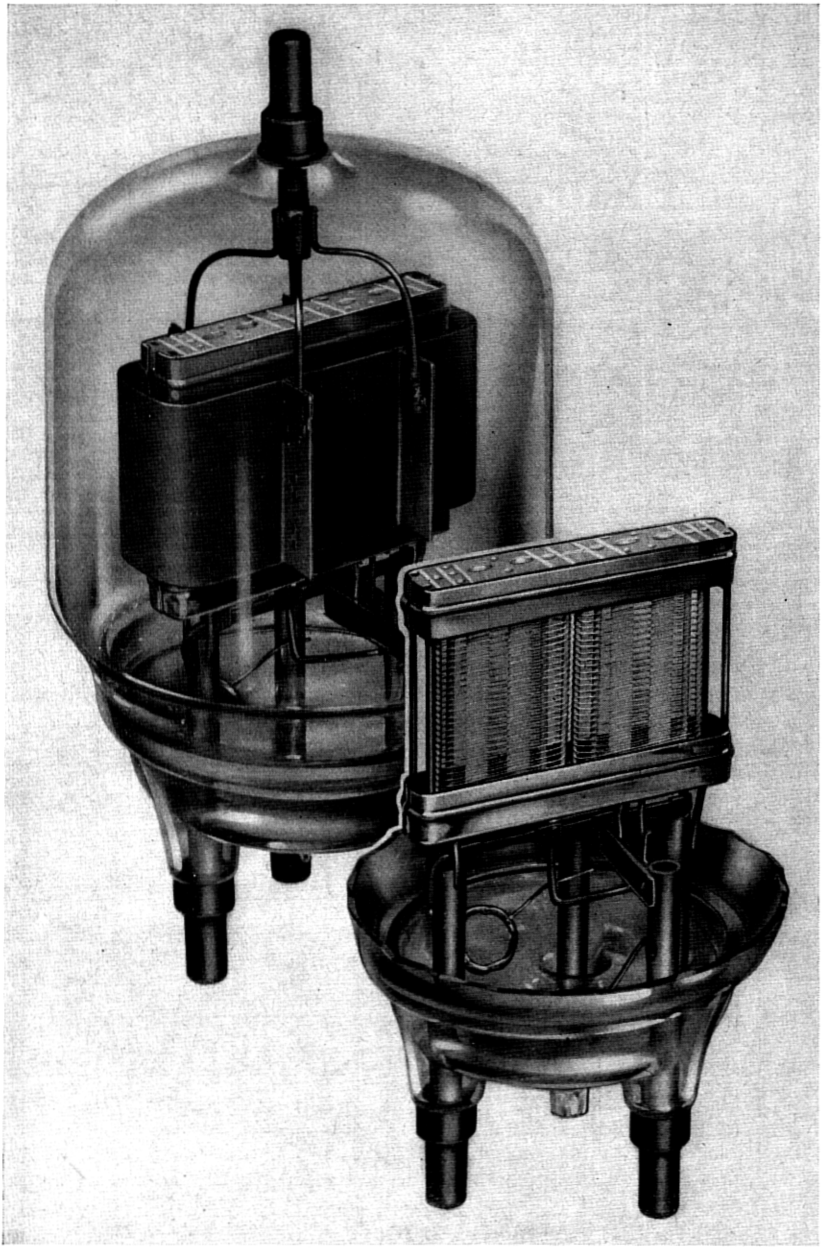

Fig. 10—The experimental 426XQ vacuum tube.

The 5D21 tube also found application as the control tube in non-linear coil type modulators.[4] Here the function of the tube was to permit passage

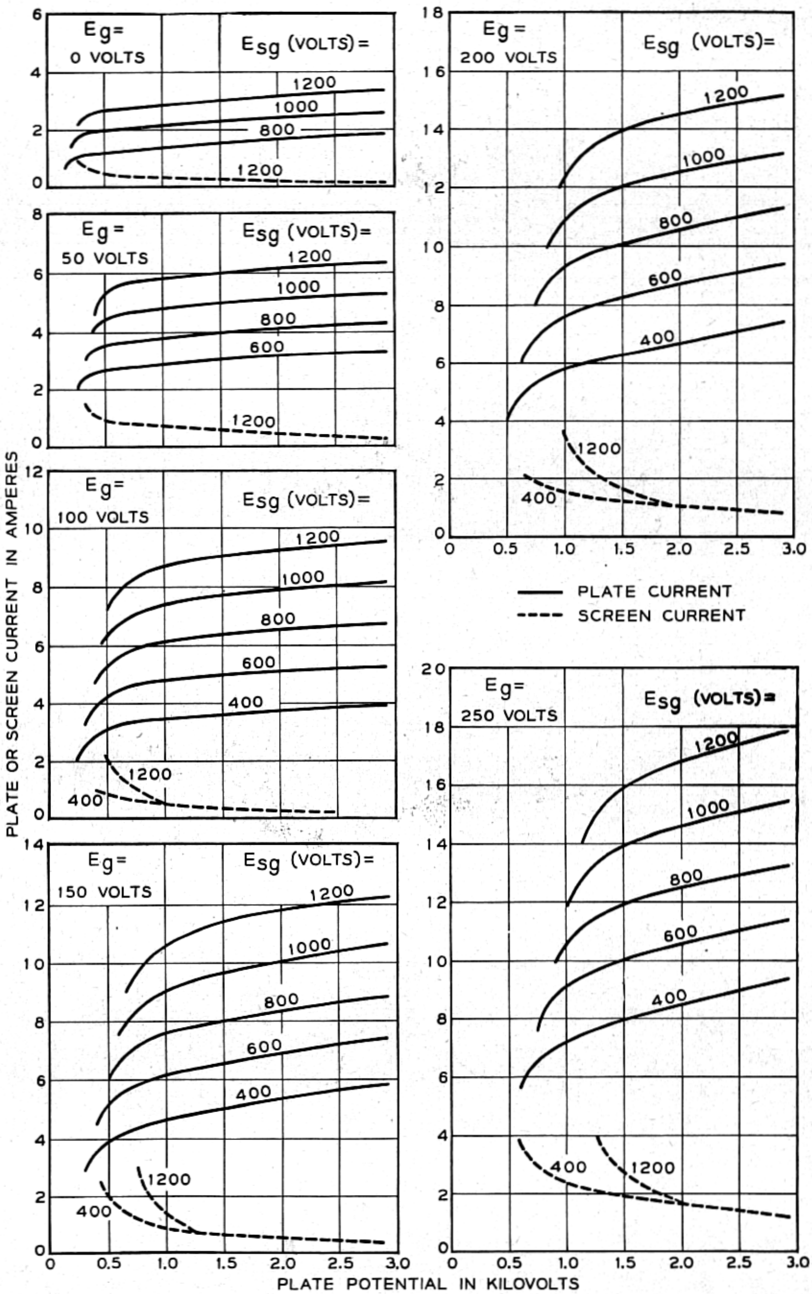

Fig. 11—Characteristics of the 426XQ vacuum tube.

of a moderately high current through an inductance and then suddenly to cut off the current and withstand the resulting voltage which built up across the circuit. A schematic of this type of circuit is shown in Fig. 9. In this circuit the tube is required to pass about two amperes peak plate current which builds up over a period of about 150 microseconds. The d-c. voltage under these conditions is about 1000 to 4000 volts and the screen voltage may be obtained from the same source through series resistance. The grid is driven only slightly positive. Screen-grid dissipation is one of the limiting factors in this type operation. Primary emission from the screen

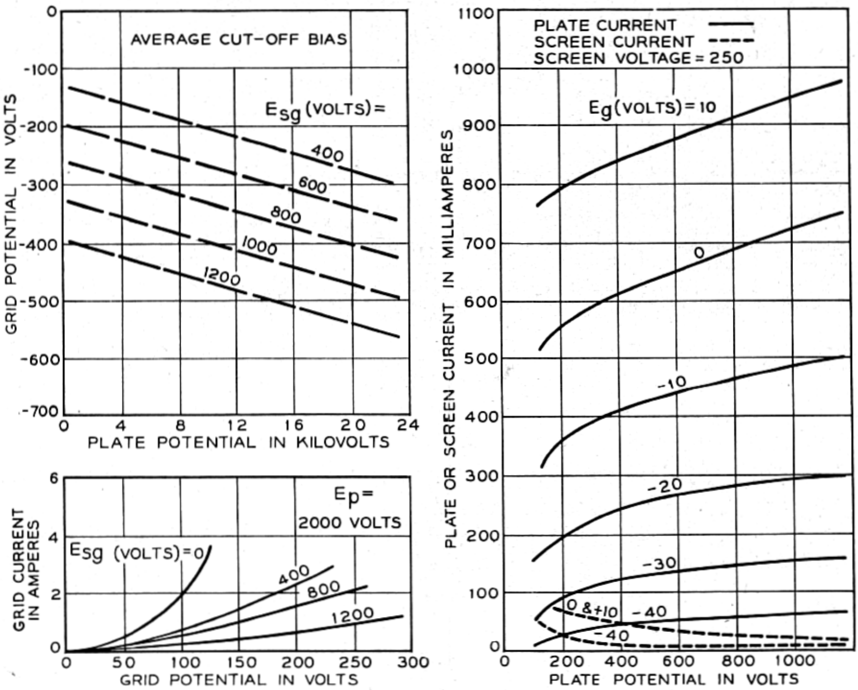

FIG. 11 (Continued)

grid, being present when the plate rises to its very high potential, tends to discharge the circuit prematurely, the energy wasted appearing as heat at the plate.

THE 426XQ TUBE

Since there was considerable demand for tubes capable of operating at voltages as high as 25 KV, a tube was developed to operate at this voltage. The limit of the 5D21–715B type structure seemed to have been reached at about 20 KV. It was also desirable to increase the current rating of the tube since in a laboratory test equipment a pulse power of 1.5 to 2 megawatts was needed. The laboratory number 426XQ tube shown in Fig. 10 was the result. Four of these tubes in parallel were capable of providing pulses of about 1.75 megawatts. In the 426XQ tube, the bulb used on the 701A was employed and the plate supported entirely from its terminal in this bulb. The same four cathodes were used, but were spaced farther apart than in the 715-type tube. Two separate control-grids and two screen-grids were used, each pair encompassing two cathodes. This allowed a reduction of dissipation per grid compared to the 715-type, otherwise similar techniques were employed. The characteristics are shown in Fig. 11.

The tentative ratings applied to the 426XQ are given in Table I. The allowable peak plate current was increased for this tube because the technique of processing had improved so that a higher level of cathode activity was consistently realized. Also the greater spacing between cathodes and use of two sets of grids resulted in better grid cooling. The tube was not used in any radar equipment, because by the time it was available the trend in radar equipment was toward small, compact apparatus in which spark gap and transmission line modulators[5] found considerable application. The 426XQ proved very satisfactory in laboratory test equipment. One set of these tubes operated for somewhat more than 2000 hours.

The Chief Problems

The difficulties experienced with this series of oxide-cathode pulse modulator tubes can be divided into three general classifications, namely: sparking, cathode emission, and grid emission.

The sparking in these tubes can roughly be divided into two types, which may be called inter-electrode sparking and cathode sparking. Inter-electrode sparking is a discharge between two electrodes of the tube caused by the momentary breakdown of the insulation between them or by a gas discharge. If the breakdown of insulation is caused by light deposited films, the resultant discharge usually causes removal of the film and cures the trouble automatically, provided no other damage is done to the tube. Gas discharges from isolated pockets may be initiated by the high fields or by bombardment by stray electrons. If these pockets are not numerous they are usually dissipated after a few minutes of tube operation such that further sparking is very intermittent and probably not of sufficient intensity to interfere with operation. The gas so released is ordinarily taken up by the getter in the tube so that operation is not subsequently impaired.

Cathode sparking may be caused by positive ion bombardment of the cathode or by poor adherence of cathode material when subject to electrostatic fields. This type of sparking usually does not clear up and when it becomes serious the tube must be replaced.[6] It can be aggravated by sparking in the oscillator part of the radar system. There is some evidence to indicate that very high rates of rise of the pulse current drawn from the cathode may tend to produce cathode sparking. At rates of rise in excess of about 50 amperes per microsecond per square centimeter of cathode area a tendency for increased sparking has been noticed.

Cathode emission, here as in any other tube, is governed by cathode temperature and other considerations such as quantity and kind of gas in the tube, the core material, coating material, and techniques of processing. No attempt will be made to consider these factors in this paper as they are sufficiently complex that no very clear cut dissertation can be given. Standard core materials and coatings were employed with good results. It was found that the double carbonates (Ba, Sr) were less subject to sparking than the triple carbonates (Ba, Sr, Ca). The cleanliness and previous treatment of the other parts of the tube seemed to be the major factor in determining the level of emission obtained.

Primary grid emission, or thermionic emission from the control-grid and screen-grid, was one of the most difficult problems in the development and production of these tubes. Many trials were made using different materials and coatings on the grids, but from all considerations gold was found to be the most satisfactory. The grids in all the tubes described here are gold plated or gold clad molybdenum. It is not considered that the use of molybdenum for the core material is necessary, it being used here mainly because it seemed to be the most economical material that had sufficient stiffness to maintain grid alignment. Materials that tend to alloy with gold easily are not suitable as it was found that gold alloys were not as good as pure gold on the grid surface. The limitation involved in the use of gold is that the temperature of the grid must be kept low enough that evaporation of gold is not serious. This temperature limit is probably about 700°C. If gold is evaporated, the grid soon loses its coating and primary emission builds up rapidly. Also, the cathode emission seems to be poisoned by the gold vapor.[7]

Acknowledgment

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