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TH-3 Microwave Radio System:

The Traveling-Wave Tube Amplifier

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The TH-3 radio system employs all solid state components with one exception. Because of the need for output power not obtainable presently from solid state devices, the sole exception is the traveling-wave tube power amplifier. This amplifier furnishes 40.5 dBm output power at 33.5 dB gain over any channel of the 5.925- to 6.425-GHz common carrier band.

This tube employs a long-life cathode made of zirconium-additive nickel. Also, it gives higher power output than traveling-wave tubes previously designed[2] for Bell System radio relay systems. This new tube and periodic permanent magnet circuit are packaged as an integral unit. It does not require focusing or other mechanical adjustments during the life of the tube.*

I. INTRODUCTION

Traveling-wave tubes are used as the transmitting amplifiers for the TH-3 radio system. The 464A traveling-wave tube, manufactured by the Western Electric Company for this application, is designed to provide a power output of 11 watts with 33.5 dB of gain in the linear region.

As is usual for such devices, the tube is operated at 2 to 3 dB below the maximum power output capability of 20 watts in order to keep intermodulation effects low. Also, it has been designed as a completely packaged device to reduce the number of tests and adjustments that are required at the installation site. The package is designed so that the magnet structure can be reclaimed at the end of the tube life for subsequent reuse.

The amplifier, shown in Fig. 1, measures 0.48 × 0.11 × 0.11 meter

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* Cathodes made from zirconium-additive nickel were used in the *Telestar®* traveling-wave tube; see Ref. 1.

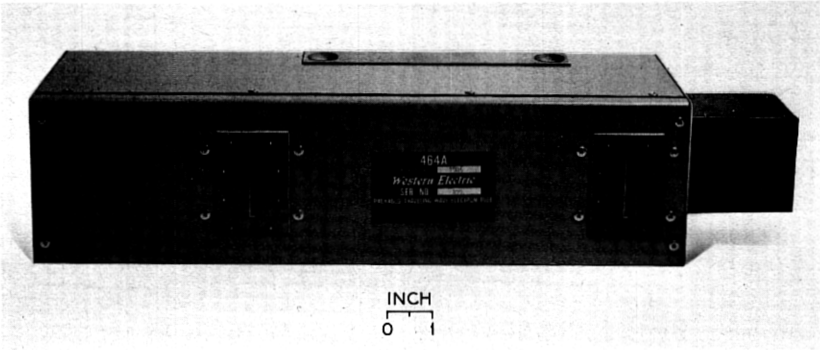

Fig. 1—The 464A traveling-wave tube power amplifier.

and weighs 8.2 kg. The evacuated tube is not visible after it has been packaged. Input and output RF connections are reduced-height (2.54 mm × 40.4 mm) waveguide. Power to run the tube is provided by a solid state regulated high-voltage supply.[3]

Table I summarizes the system requirements upon the 464A tube and typical device performance.

II. ELECTRICAL DESIGN CONSIDERATIONS

Since the power output for which this device is designed is higher than used previously for Bell System radio relay transmission, the internal structure has been changed from that of previous traveling-wave tubes.

Table I—464A TWT Operation and Performance

Operation	Design Requirement	
Operating frequency, GHz	5.925–6.425	
Operating power output, watts	11.2	
Operating beam current, mA	59.0	
Performance	Design Requirement	Typical Performance
Saturation power output, watts	$\sim$20	20
Gain* at operating power output, dB	31–35	33.5
Amplitude-to-phase modulation conversion at operating power output, degrees per dB	4 max	1.5
Product of gain and noise figure, dB	65 max	63.0

* See Section 2.4

2.1 *Electrode Voltages and Beam Current*

Calculations showed that in order to obtain a saturated power output of 43 dBm it would be necessary to use a beam current of 59 milliamperes, assuming a synchronous helix voltage of 3750 Vdc. The desired power can also be obtained using a somewhat higher helix voltage and lower beam current. However, this would result in a longer helix and more difficult helix intercept problems.

The collector efficiency of this device is 19 percent, typical for tubes of this type. The use of multiple collectors and tapered helix sections had been considered to further increase the efficiency, but it was concluded that such efficiency improvement added costs which were out of proportion to the advantages to be gained.

Thus, the current and voltage were chosen to be a good compromise, which allows for economy in magnet design, while still obtaining satisfactory gain and power output with a reasonable length of helix.

2.2 *Other Parameters*

With the beam voltage and current established, some of the other parameters of interest are:

Cathode current density = 200 mA/cm^2
Beam-to-helix diameter ratio =0.5
Cathode temperature = 740°C (true)

Helix:

mean diameter (wire 0.254 mm dia)	= 2.598 mm
turns per cm	= 9.48
active length	= 17.2 cm*
dielectric loading factor	= 0.782
gain per centimeter	= 3.08 dB
radial propagation constant	= 1.45.

In order to obtain higher operating power, the beam current has been increased as discussed in the previous section. This results in a higher current density in the helix region because the helix diameter is constrained by considerations of the design of the magnetic circuit and its space requirements. This also has the advantage that, without much change in beam convergence, the cathode current density is retained at the same value used in a previous tube,[2] the 461A, resulting in the long cathode life capability demonstrated by these other

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* It is necessary to allow sufficient length to overcome losses, such as the loss involved in establishing the wave on the helix.

devices. The beam-to-helix diameter ratio is a conservative value of 0.5; this is in comparison to higher ratios such as 0.8 or 0.9 which result in higher gain per unit length of helix, but can give problems in keeping the beam in focus and could result in requiring readjustment of the tube during operating life. The cathode temperature of 740°C is also a conservative choice; while greater cathode life might be achieved at temperatures closer to the edge of the temperature-limited emission region, 690°C to 710°C, the cathode life of 250,000 hours associated with the chosen operating temperature is more than adequate to meet the design intent, since in practice other factors limit the operating life below this figure.

The helix parameters listed above to complete the description of the tube result from the voltage and current decisions previously discussed.

2.3 *Magnetic Focusing*

To obtain satisfactory focusing (with Alnico-8 magnet material) the magnet period must be somewhat less than 16.13 mm. A value of 15.39 mm was chosen for this design. Calculations of the field required showed that magnetic field densities greater than 0.0970 T (tesla) are required, and a value of 0.1090 T was taken as the design figure.* Experimental values of helix interception current have been found to be below 0.7 percent of the cathode current. Because of the high energy of the electrons which are intercepted and because the helix structure depends on longitudinal conduction for cooling, it is important that this figure be low, preferably below 0.5 mA. Spot heating of the helix structure at helix currents greater than 0.5 mA begins to result in sublimation of helix materials, at these helix voltages.

2.4 *Operation*

The 464A has been designed for operation above the synchronous helix voltage. The advantages of this mode of operation are two: first, the helix voltage becomes a gain control, eliminating the need for the system to accommodate a specific tube gain. Second, the carrier-to-noise ratio is greater by 3 to 7 dB. This carrier-to-noise ratio advantage is gained even though the noise figure at the actual operating point may be above its minimum value. The minimum noise figure occurs at a helix voltage which varies somewhat from tube to tube,

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* Criteria arrived at in previous studies[2] have been applied here as well: $\alpha/\beta > 3$, $\beta < 0.06$.

and at a helix voltage greater than that for synchronous operation. The tube is run with the helix voltage increased above synchronous voltage until the output power decreases to 40.5 dBm with a constant input of +7 dBm.

The manner in which the power output varies with helix voltage under conditions of different input power is not very different for this device than for comparable tubes, as shown in Fig. 2. Figure 3 shows the saturation power capability, when calculated under the condition that the tube is run with the helix voltage increased to give 33 dB gain. Figure 4 shows the high-level gain, at midband, calculated from Fig. 2.

III. CONSTRUCTION

3.1 *The Helix*

Ceramic rods support a molybdenum wire helix which is glazed to the rods at each point of contact between rods and wire. When RF power is applied to the input of a medium- or high-power traveling-wave tube, the power output gradually decreases from the initial value over a period of from two to five minutes. This "fade" occurs

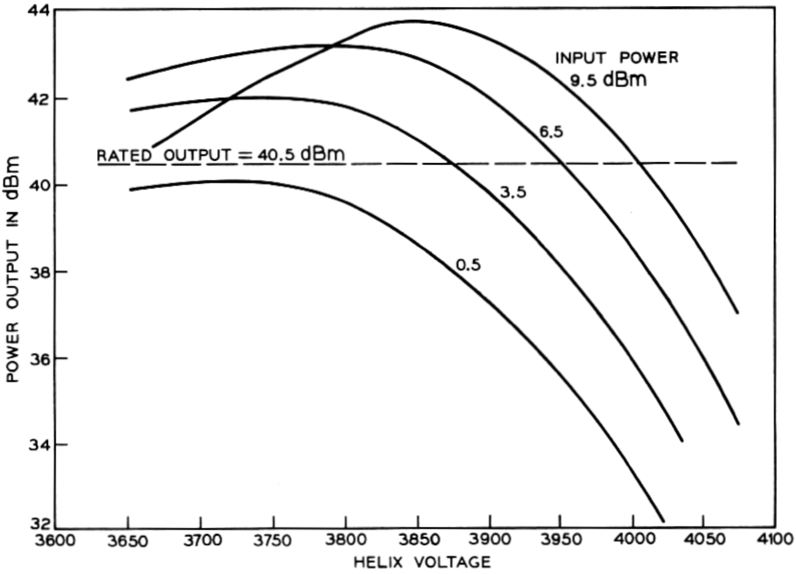

Fig. 2—Power input vs helix voltage curves for the 464A at midband.

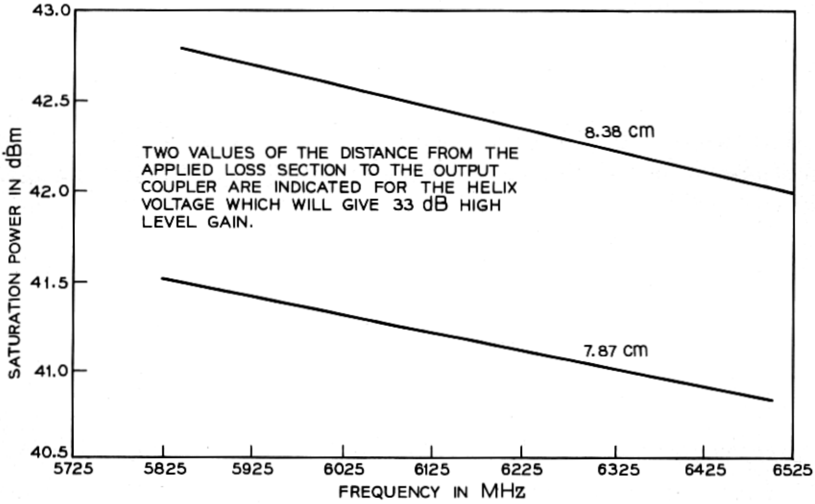

Fig. 3—Effect of loss pattern positioning on power capability.

because the dielectric properties of the helix support rods change as a result of heating of the rods.

Since the 464A has a beam power density 2-1/2 times as high as its predecessors, the degree of fade could become intolerable under some operating conditions. Therefore, fading was reduced by the introduction of a gap of 0.127 mm between the helix wire and ceramic support rods for a distance of ten turns away from the output coupler. The gap is produced by grinding a flat on each rod. This prevents excessive heating of the ceramic rods and associated glaze at the point where the (spot) heating is greatest. At 10 watts output, fade is only 0.2 dB with this provision.

The applied loss is a tantalum film applied by sputtering.[2] Since a loss of about 60 dB is required between the input and output sections to prevent oscillation, greater than 80 dB of loss is applied to provide margin for manufacturing variations and gain changes.

3.2 *The Magnetic Focusing Structure*

Use of a light and compact periodic permanent magnetic (PPM) circuit allows the tube and magnet to be shipped as an integral unit. Thus the beam focus and electrical characteristics can be optimized at the factory. At the end of the useful life of the tube, the entire package is returned to the factory for reuse of the magnetic circuit.

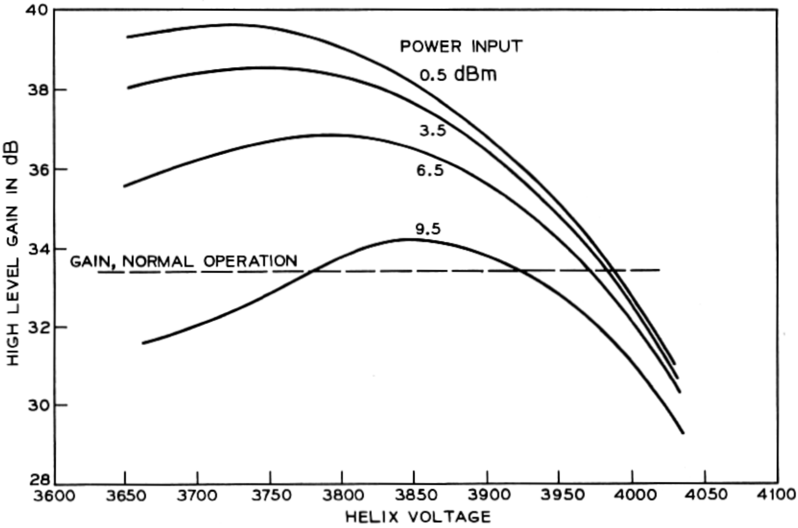

Fig. 4—High-level gain as a function of helix voltage, at midband.

The magnetic circuit consists of 36 Alnico-8 ring magnets stacked alternately with pure iron pole pieces (Fig. 5). The magnets and pole pieces are aligned using a precision mandrel. An epoxy adhesive is used to encapsulate the assembly within an aluminum housing. An RF choke is provided near the input to prevent leakage of the RF through the gun.

To achieve long life it is desirable that the collector be adequately cooled so that critical components of the tube are not overheated. The nominal heat dissipation of the collector is 110 watts. A maximum collector temperature of 150°C occurs for nominal cooling conditions for this dissipation. The collector fits into a hole in the copper cooling

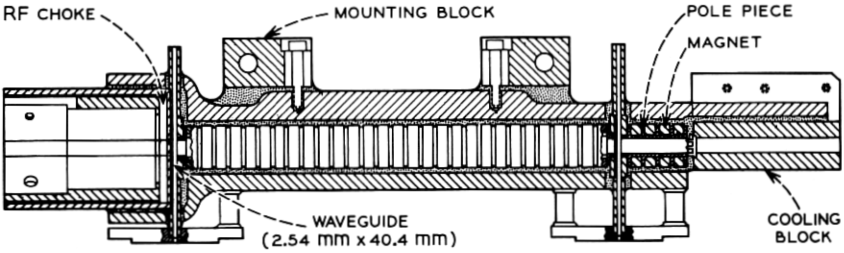

Fig. 5—A cross-sectional view of the 464A magnetic package.

block. The hole in the cooling block is 0.08 mm larger than the collector diameter to allow motion of the collector which in turn permits alignment of the electron beam with the magnetic field. This space is filled with a thermally conductive silicone paste. The collector is held radially (in a single transverse plane) by a reference surface located between the magnetic stack and the cooling block. Two cooling fins are attached to the cooling block during installation of the traveling-wave tube in the radio bay.

The tube is packaged in a sheet steel enclosure for RF shielding, strength, and mechanical protection.

3.3 *Electron Gun*

The 464A uses a convergent Pierce-type electron gun. The gun has a perveance of 0.207×10^{-6} amp/volt$^{3/2}$.

The cathode base material is a high-purity nickel with 0.1 percent zirconium additive. The diffusion rate of the zirconium in this nickel is lower[4] than that of the activating agents in "melt" nickel. Moreover, the arrival rate of zirconium at the nickel-coating interface is more nearly in balance[5] with the rates of the other processes essential to electron emission. The result of substituting the zirconium nickel for "melt" nickel is that the ultimate cathode and cathode coating life is increased and cathode sublimation virtually eliminated as a failure mechanism. Furthermore, the influence of gettering on barium production is decreased. Figure 6 shows the zirconium diffusion rate and coating depletion calculated for this cathode as a function of time.

Field experience with early designs of traveling-wave tubes indicated that one of the failure mechanisms has been associated with the glaze material used in the gun construction. It had been found that the glaze tended to electrolyze during the life of the tube, becoming conductive in high electric fields and leading ultimately to failures. The mechanical design of the 464A gun is such that no glaze material is used in its construction. One ceramic platform is used to support parts at high voltage and this is done so as to permit the use of stud and nut fastening. The basic gun structure is shown in Fig. 7.

IV. TUBE PERFORMANCE

4.1 *Gain and Power*

With an input power of 7 dBm applied, the desired output power of 40.5 dBm is achieved by adjusting the helix voltage to an appropriate value above the synchronous helix voltage. The nominal high-

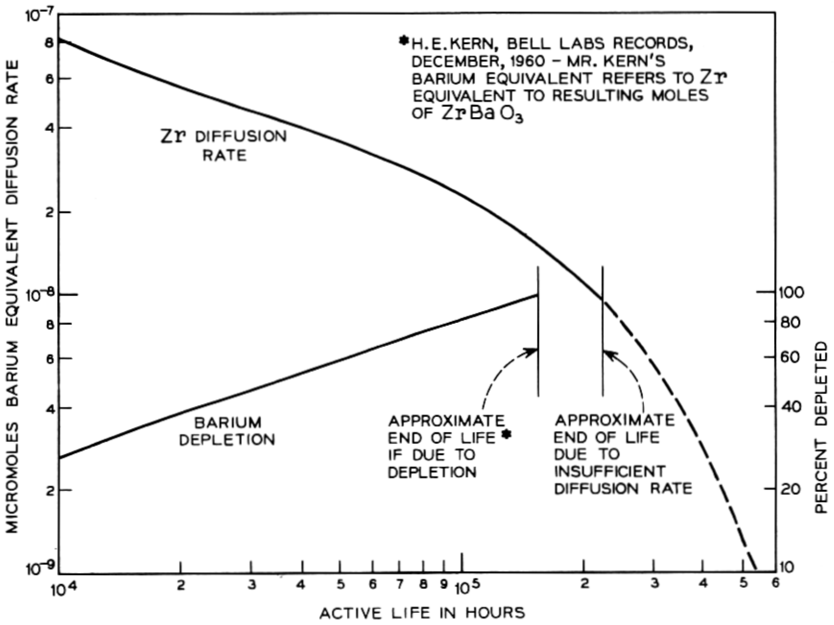

Fig. 6—Diffusion rate and depletion curves for the 464A cathode.

level gain is about 40 db when the helix voltage is set at the synchronous value.

The broadband gain flatness characteristics are optimized during the assembly of the package at the factory. Since the tube is preset for operation over the entire frequency band, complex impedance matching adjustments and measurements are not required for setting up the tube in the radio bay. Tuning adjustments are incorporated in the microwave integrated circuits which attach to the input and output ports of the traveling-wave tube. These are adjusted for maximum output in the particular radio channel in which the transmitter is operated.

4.2 *Noise*

The noise performance of the 464A traveling-wave tube is measured in terms of a noise-gain product (FG). This is defined as

$$FG = \frac{N_o}{kTB},$$

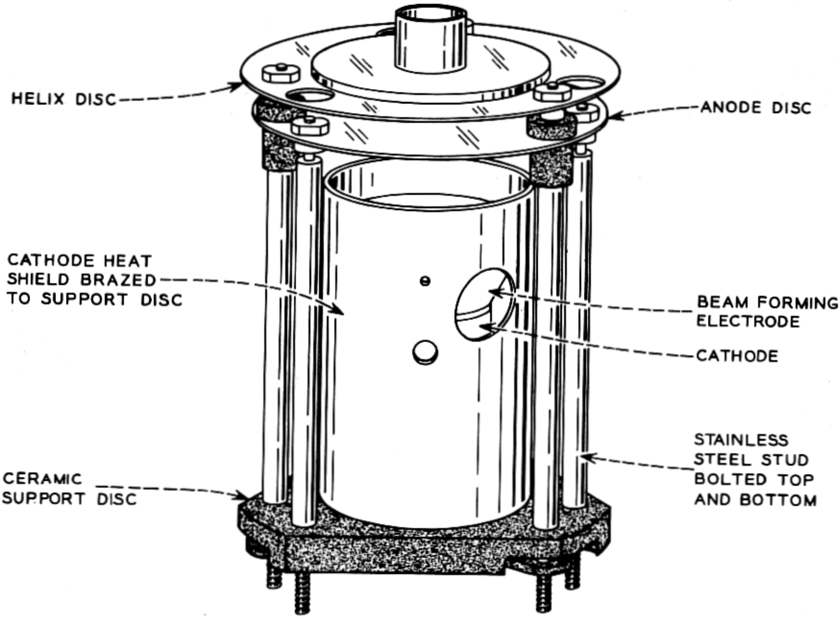

Fig. 7—A view of the electron gun.

where N_o is the thermal noise output of the traveling-wave tube, k is Boltzmann's constant, T is absolute temperature, and B is the bandwidth.

The noise-gain product is measured using an FM detector since FM noise is the important component in an FM system. The measurement is made with the traveling-wave tube driven to an output power of 40.5 dBm. A carrier nulling technique is used to increase the sensitivity of the measuring system.

Best noise performance of the device is achieved by immersing the gun in a small magnetic field. This has the effect of inhibiting the growth of a space-charge wave of noise. This small magnetic field is provided by a coil which surrounds the gun. The noise performance is optimized during the package assembly by adjusting a series resistance in the coil circuit.

4.3 *Life*

Since the reliabilities of other components in the system are designed for the long life achievable with solid state devices, this tube has been designed to be as compatible as possible.

The life of a tube can be discussed from a number of standpoints. In the early days of tubes, the life was most often limited by the cathode. In the present design cathode life no longer limits the life of a tube. In this traveling-wave tube, the zirconium-additive cathode yields an ultimate life greater than 17 years and the environment of the cathode has been kept as pure as possible to take advantage of its potential capability. However, a tube may fail for a number of reasons not directly related to the cathode; such as, foreign particles in the tube, gassy tubes, improper operating conditions, etc. For example, if the loss pattern in a tube degrades, the helix intercept increases causing the glaze to be excessively heated, which in turn increases the level of contaminants arriving at the cathode resulting in tube failure. From experience gained with related tubes, it is reasonable to expect that with the zirconium-additive cathode the median life will be greater than 50,000 hours.[1]

Requirements on the power supply[3] remain substantially the same as for the TD-3 case except for the higher voltage and higher dissipation needed. There is one major change. It has been found that the sequence in which voltages are applied to the tube has a strong effect on tube life. To ensure proper sequencing, the power supply has been designed with automatic turn-on such that the collector voltage has risen to nearly full voltage before the helix voltage is applied; similarly, helix voltage before anode voltage is applied. The same holds for turn-off except that the reverse order is necessary.

V. SUMMARY

The output power of 40.5 dBm required in the TH-3 system is supplied by this traveling-wave tube at a power gain of 33.5 dB. At this power level the noise figure is less than 29 dB and the intermodulation (AM/PM conversion constant) is about 1.5 degrees per dB.

To achieve long life, a cathode with an excellent reliability record in *Telestar®* has been employed.[1] Cathode loading is conservative, 200 mA/cm^2. To retain a favorable environment for the cathode, the gun is constructed without glaze; measures are employed to prevent power fading which would ultimately lead to cathode degradation. To obtain a stable loss pattern, tantalum is used rather than graphite. This reduces the possibility of a degradation[6] in the applied attenuation which in time would result in RF oscillation in the helix. Lastly, the tube-package design is such that focusing or other adjustments are not necessary upon installation or during service; the power supply is designed to turn the tube on with a minimum of adjustment and in a way most favorable to the tube.

Such measures are expected to result in a median life in excess of 50,000 hours, under operating conditions.

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