The Traveling-Wave Tube Amplifier for the Microwave Transmitter

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(Manuscript received January 18, 1968)

The traveling-wave tube is the final microwave power amplifier in the transmitter of the TD-3 radio relay system. The important requirements of this amplifier are to furnish 6 watts power output at 35 dB gain with less than 0.02 dB variation in gain over any 12 MHz channel, to be free of noise and distortion, and to have a long life.

The tube contains a Pierce-type electron gun, a helix slow-wave structure with a sputtered tantalum lossy section, and a conduction-cooled unipotential collector. This new radio-relay tube is packaged with a periodic permanent magnetic circuit as an integral unit, which eliminates the need for beam focusing adjustments in the field and reduces the size of the amplifier.

I. INTRODUCTION

Because a traveling-wave tube can provide substantial, stable, microwave power output at high levels of gain with very little noise or distortion, it is used as the transmitting amplifier for the TD-3 radio-relay repeater. The 461A traveling-wave tube, manufactured by the Western Electric Co. (for Bell System use only), has been developed to furnish 6 watts power output at 4 GHz with 35 dB of gain.* The same tube is used for all channels in the TD-3 frequency band. Adequate flatness of the gain-frequency characteristic over a given channel is achieved at the time of tube installation by a tuning adjustment in the waveguide adjoining the tube.

The tube operates at 2 to 3 dB below maximum power output to keep intermodulation effects resulting from gain saturation low. At this level, the amplifier is essentially linear in operation with distortion products down 15 dB or more.

It is desirable that a traveling-wave tube for a radio relay system

* Losses after the TWT may cause the repeater output to be as low as 5 watts.

be a completely packaged device, so that it can be given the optimum focusing-field adjustment at manufacture with no further adjustments required in the field. This avoids the need for special test equipment in the field and duplication of tube adjustment, thus lowering costs. The package should be returnable at the end of tube life so that the magnetic structure can be reused. It was therefore decided to design a device that is packaged during manufacturing.

This device uses the periodic permanent magnet technique for focusing the electron beam.[1–3] Figure 1 shows the entire amplifier

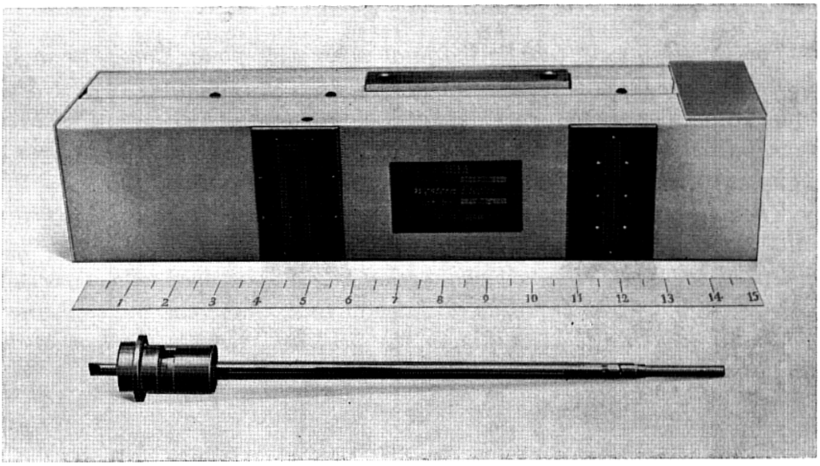

Fig. 1 — The 461A packaged traveling-wave tube.

which measures 3½ × 4 × 16 inches and weighs 16 pounds. Below the ruler is the vacuum tube* itself which contains the active elements of the amplifier.

System reliability is obtained through a combination of long tube life and provisions to monitor anode voltage for obtaining advance warning of tube failure. This allows scheduling tube replacement at a time when the channel is not in service. Improved cleaning and degassing procedures are used during manufacturing to obtain long life; whereas careful monitoring of shifts in tube characteristics during operation yield accurate failure warning.

RF input and output connections to the tube are made by nonstandard reduced-height waveguide. Tuning-screw impedance-match-

* By standard nomenclature, the entire device is an "electron tube."

ing devices, needed to obtain 0.02 dB (maximum) transmission flatness over the channel bandwidth, are part of the microwave transmitter rather than of the tube.

Power to run the tube is provided by a solid-state regulated high-voltage supply,[4] which in turn is driven by the nominal −24 volt dc input to the TD-3 bay.

Heat dissipated from the electron beam impinging on the collector of the tube is conducted to a heat sink which is an integral part of the TD-3 bay.

Table I summarizes the system requirements upon the 461A tube and typical device performance.

TABLE I—461A TWT REQUIREMENTS AND PERFORMANCE

	System requirement	Typical performance
Operating frequency, GHz	3.7–4.2	3.7–4.2
Operating power output, watts	5.9	6.2
Saturation power output, watts	—	11
Gain at operating power output, dB	32–38	35
Gain flatness in any 12-MHz band from 3.7 to 4.2 GHz, dB	0.02 max	0.02 max
Input return loss (with tuner), dB	—	20–25
Amplitude-to-phase-modulation conversion at operating power output, degrees per dB	4 max	3.1
Product of gain and noise figure, dB	62 max	59.4

The high-level spurious noise is required not to exceed by more than 10 dB the thermal noise (with the noise bandwidth fixed by the FM detector) in the output of the tube at low-level drive. This is typically the case.

II. ELECTRICAL DESIGN CONSIDERATIONS

Although the 461A tube's overall performance is superior to the 444A traveling-wave tube used as the transmitter power amplifier in the original TH radio relay system,[5] there are similarities in the electrical requirements for the two tubes.* Because considerable experience has been gained with the design of the 444A and with variations of this design, certain of the 461A design parameters have been chosen to be similar to corresponding 444A parameters. The beam current, the cathode current density and the beam voltage (helix-to-cathode potential) were chosen to be approximately the same as for the 444A.

* A prototype of the 444A, the M1789, is described in Ref. 6.

2.1 *Electrode Voltages and Beam Current*

It is desirable to depress the collector potential below that of the helix to reduce the beam power dissipated on the collector. Furthermore, since the collector must be cooled, it is convenient to operate it at ground potential. Because a depressed collector operates typically midway between cathode and helix potentials, the depression and grounding of the collector also simplifies power supply design by keeping the helix-to-ground and cathode-to-ground voltages low. Corona problems in power supplies become troublesome as voltages exceed about 1500 volts. For the 461A it was decided that the cathode should be operated at −1400 volts, the helix at +1200 volts and the anode at +1400 volts. With the beam voltage of 2600 volts, a beam current of 40 mA is sufficient for the required power output.

2.2 *Other Parameters*

With the beam voltage and beam current established, the other principal design parameters are:

Cathode current density $\approx$ 200 mA/cm^2
Beam-to-helix diameter ratio, b/a $\approx$ 0.5
Cathode temperature = 740°C (true)
Helix diameter, a = 0.1023 inch.

From these parameters, one may calculate values of helix[7] and gun[8] design constants. For the desired beam voltage, the helix must have 30 turns per inch and is calculated to give 9.8 dB gain per inch. This sets the required active length* at 5.33 inches. Adding the attenuation section and transitional turn makes the total helix length 6.86 inches.

With these values of helix and beam diameter, the gun should be designed to produce a minimum beam diameter (for 95 per cent of the beam current) of 0.0410 inches. This leads to gun design values of 12° 25′ for the convergence half-angle θ and 0.256 inches for the cathode-anode spacing, d.

2.3 *Magnetic Focusing*

In his work on periodic permanent magnet focusing, K. J. Harker demonstrated that the magnetic flux required for minimum beam ripple is related to the space-charge density and the magnetic shielding of the cathode.[9] Using his curves, minimum ripple in the 461A

* It is necessary also to allow for losses, particularly in establishing the circuit wave initially.

should occur when the peak value of magnetic flux is about 325 gauss. This theoretically optimum value of peak flux density calls for perfect beam launching and a perfectly straight magnetic structure. This is impractical, and little deterioration results in practice from the use of higher-than-optimum flux densities.

An extensive study of magnet structures giving a variety of fields has resulted in the adoption of an empirical value of 1000 gauss for the peak flux density in the 461A.* This value limits the helix intercept current to less than ¼ per cent of the beam current over a wide range of beam currents and voltages. The magnetic alloy Alnico 8 is used. This alloy has the advantage of not requiring compensation for temperature changes. The focusing field has a period of 0.550 inch with a polepiece inside diameter of 0.312 inch.

III. CONSTRUCTION

New techniques were developed for more economical and accurate helix construction, improved cooling, and to permit the use of reduced-height waveguide.

3.1 *The Helix*

The helix consists of 0.010-inch molybdenum wire, supported by three ceramic rods glazed to each helix turn. Helices are constructed by winding the helix on a mandrel, releasing the helix from the mandrel by partially annealing the wire and allowing it to "spring back" from the mandrel.

However, if the helix is not allowed to spring back, three advantages occur. First, it is cheaper to make, because fewer hand operations are involved. Second, higher electronic efficiency results because the exact pitch is maintained over the entire helix length (comparatively large dimensional changes accompany springback).

The input waveguide and output waveguide are a fixed distance apart. Best match is obtained when the ends of the helix are located the same distance apart and then positioned to be located at the respective waveguide. Therefore, a third advantage for a no-springback helix would be that an exact length could be more easily maintained, thereby simplifying the problem of obtaining simultaneously RF matches at both the input and output waveguides. This is very important with the 461A tube because of the increased difficulty of matching brought on by use of reduced-height waveguide.

* Corresponding, in Mr. Harker's nomenclature, to $\alpha/\beta > 3$ and $\beta < 0.06$.

Therefore, a no-springback helix has been incorporated into the 461A design. After being wound, the helix is prevented from springing back by a weighted fixture. The mandrel on which the helix is wound is coated with aquadag, which burns off during the glazing of the wire to the rods. With the aquadag coating gone, the mandrel can be removed even though springback has not been allowed.

3.2 *Applied Helix-Loss*

In order to keep the amplifier from oscillating, it is necessary to deliberately apply a lossy material to a section of the helix. Historically, a favorite material has been carbon, often in the form of sprayed-on aquadag. Usually, the input and output sections of helix are isolated by as much as 80 dB of loss.

Experience in the TH radio relay system has shown that many of the 444A traveling-wave tubes began to oscillate after 10,000 hours of operating life. This was traced to a decrease in the helix loss, presumably because of oxidation of the aquadag.

To avoid this problem in the TD-3 and TH systems, the lossy material used in the 461A and 444A is tantalum applied by sputtering. The required loss is easily obtained and all evidence to date shows that the helix loss does not deteriorate with use.

3.3 *The Periodic Permanent Magnet*

The advantages of a periodic permanent magnet structure are elimination of the need to adjust beam focus in the field and reduction of amplifier size. The periodic permanent magnet is assembled by stacking rings of Alnico 8 magnetized with alternating polarity between polepiece rings so that the field reverses at each polepiece. The input and output waveguides, which must carry RF energy through the stack, are made with reduced heights of 0.200 and 0.100 inch, respectively, to disrupt the stack geometry as little as possible.* Each waveguide is introduced between two polepieces. The polepieces used in the vicinity of the waveguide have offset flanges (see Fig. 2) to allow a maximum magnet thickness at the waveguide, without a change in the magnetic period. Compensation for leakage flux is acquired by adjusting the degree of magnetization of individual magnets.

The polepieces are aligned concentrically with a precise mandrel. The stack is potted by applying epoxy adhesive externally and is

* Standard waveguide for this frequency has a height of 1.145 inches.

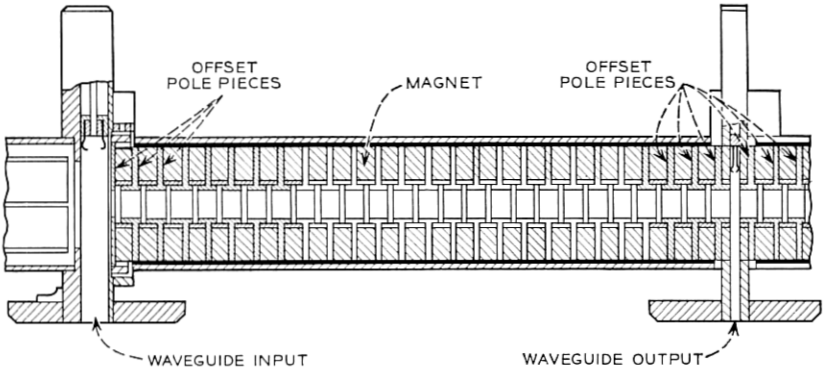

Fig. 2 — A cross section of the periodic permanent magnet assembly.

bonded with epoxy into monel supporting covers. No fasteners are used.

A special gun-end magnet is required to reduce the leakage field strength to 18 gauss at the cathode position. This was found to give best noise performance. In Fig. 3, typical curves for noise, helix intercept current, power and gain are shown as a function of peak flux density.

3.4 *Electron Gun*

The final 461A design configuration includes a spherical surfaced cathode in the electron gun. Previous devices were made with a "coned cathode." The effect of the cone at the center of the cathode was to produce a semihollow beam and thereby reduce the magnitude of ion oscillations which could modulate the beam. The cone was used in tubes using a uniform focusing field, but it was found in the course of this work that the cone is incompatible with periodic permanent magnet focusing, and increases ion noise, thermal noise, and helix intercept current.

Figure 4 shows the electron gun structure and a choke used to prevent RF power from leaking out of the tube through the gun.

3.5 *Cooling Block*

The TWT electron collector intercepts the 0.040 ampere beam at about 1400 electron volts so that some 56 watts must be dissipated. In the interest of preventing spurious ion oscillations and for the

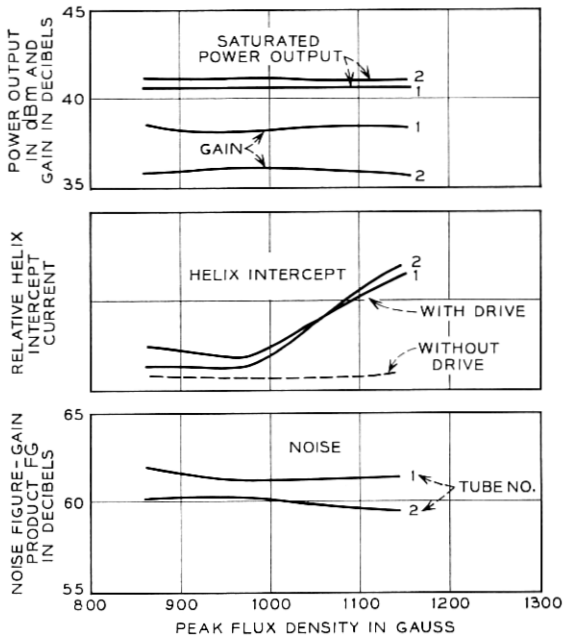

Fig. 3 — The effects of the magnitude of the peak flux density on several characteristics.

sake of long life, the collector must be maintained at a reasonably low temperature (below 150°C).

It was decided that rather than to use forced air, as is done in the TH system, the 461A collector should be cooled by conduction to fins mounted on the TD-3 bay.

In order to allow alignment of the electron beam with the magnetic field, the hole in a cooling block is made 3 mils larger than the collector. The small annular space between the collector and cooling block is filled with a silicon heat-conducting paste which provides excellent heat conduction from the collector to the cooling block.

The collector is held radially by a reference surface located between the magnet stack and the cooling block as shown in Fig. 5. The aluminum cooling block is itself conductively coupled to cooling fins which are part of the TD-3 bay.

3.6 *Enclosure*

The package is enclosed in a sheet steel container for RF shielding, strength, and mechanical protection.

IV. PROCESSING

The tube parts are kept in dustproof super-clean areas. All parts are water-washed with ultrasonic agitation. How long an unbroken film of pure water remains over the surface of the part after it is withdrawn from the bath is used as an indication of cleanliness. All parts are further cleaned by heating in wet hydrogen. The subassemblies of the gun and the helix are degassed by induction heating in a vacuum furnace. Normally the temperatures used for induction heating are limited by the softening points of glaze joints, braze joints, or ceramics.

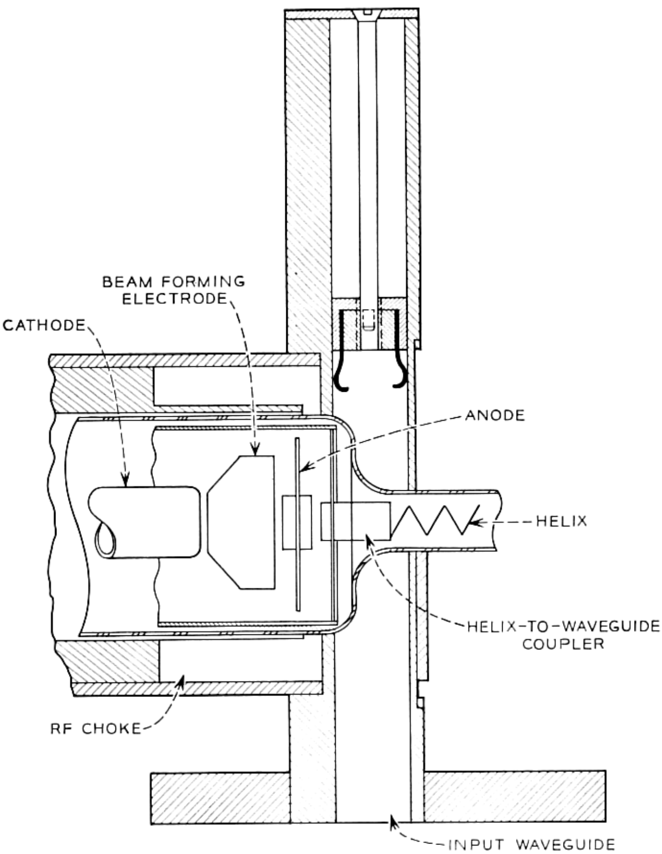

Fig. 4 — A cross section of the electron gun region of the 461A tube.

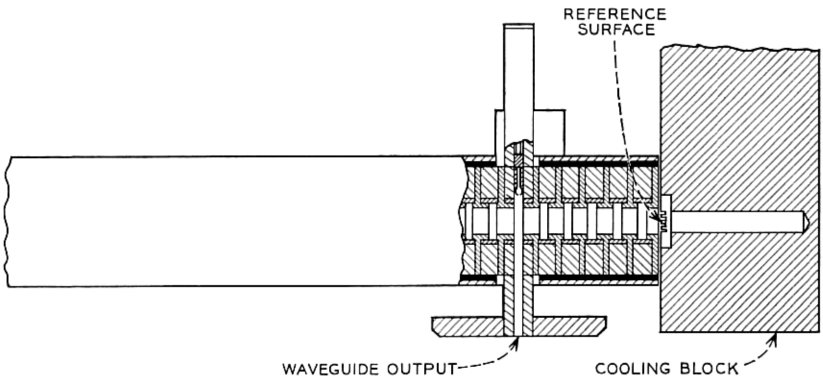

Fig. 5 — Cross section of the magnet stack, the cooling block assembly.

V. TUBE PERFORMANCE

5.1 *Power Output and Gain*

Although high efficiency is not a primary design objective for a radio relay tube, (especially since tube cost tends to be increased by designing for greater efficiency) the efficiency of the 461A for saturated operation is a quite reasonable 20 per cent. The saturated efficiency of the 444A tube used in the TH system is about 21 per cent. The traveling-wave tube in the *Telstar*® communications satellite was specifically designed for high efficiency and gives in excess of 30 per cent saturated efficiency.[10] The desired gain has been obtained with the typical tube-to-tube variation illustrated in Fig. 6. Through the use of waveguide tuners at the input and output ports of the tube, the transmission characteristic over any 15 MHz band can be flattened to less than 0.02 dB variation peak-to-peak.

The input and output matches must be such that reflections do not upset the characteristics of the bandpass filters facing the tube. For this reason, isolators are used at the input and output of the tube. However, the need to avoid gain ripple makes it important to achieve a good match at the input. The input return loss in the 461A is typically greater than 25 dB when the waveguide tuner is used.

5.2 *Thermal Noise*

Since TD-3 is a frequency-modulated system, limiters are used in every repeater to remove the AM component of noise modulation. Therefore, only FM noise is important.

Thermal noise has been determined by the standard technique of

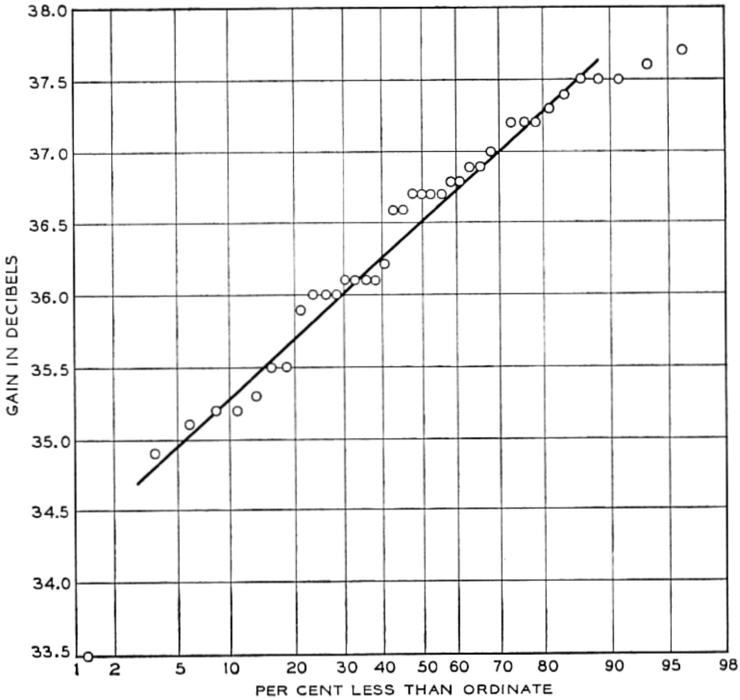

Fig. 6 — Distribution of 461A gain at midband.

measuring the noise power output through a 10 MHz bandpass filter. However, it is necessary to know the noise figure in the presence of a carrier at high level drive. The maximum carrier-to-noise ratio of which the 461A tube is capable is about 156 dB per hertz bandwidth. It is apparent from this that care must be used to filter out the carrier when measuring noise in the presence of a carrier. To do this, one sets the filter frequency away from carrier frequency making certain to obtain at least 100 dB of isolation at the carrier frequency.

The gain at the frequency (f_o), where noise power is measured, will be compressed because of the presence of the carrier at (f_c). If the ratio of low-level gain $(= G_o)$ to compressed gain is designated as C, and the high-level noise figure is designated as F_{38},* then

$$\frac{N_{oc}}{kTB} = \frac{F_{38} G_o}{C}$$

* The designation F_{38} is used because the nominal output power is 38 dBm (6-1/3 watts) at the output port.

where the output noise power is N_{oc}, measured through a filter of bandwidth B (k is Boltzmann's constant and T is absolute temperature).

The noise figure has also been determined by using the output of an FM detector and has been shown to be the same as that obtained using the method first described. Figure 7 shows the effect of changes in helix voltage on noise figure F, gain G and gain-noise figure product FG.

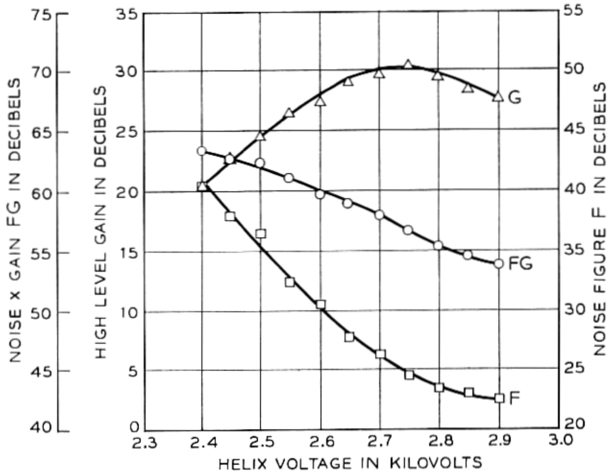

Fig. 7 — Typical variation of noise and gain with helix voltage.

The cathode must be immersed in a small magnetic field of about 18 gauss in order to inhibit the growth of a space-charge wave of noise. The nature of the variation of low-level noise and helix intercept current with cathode field is shown in Fig. 8. The measurements were taken using a coil over the tube in the cathode region. Increasing the cathode field coil current beyond 250 mA, which corresponds to a cathode field of 10 to 15 gauss, has no further effect on the gain-noise figure product FG,* even though noise figure continue to drop, because of the simultaneous increase in gain.

5.3 *Spurious Modulation*

The ion noise power in the output of the TWT is measured with respect to the thermal noise output with an FM detector. Thermal

* More important to system design than noise figure.

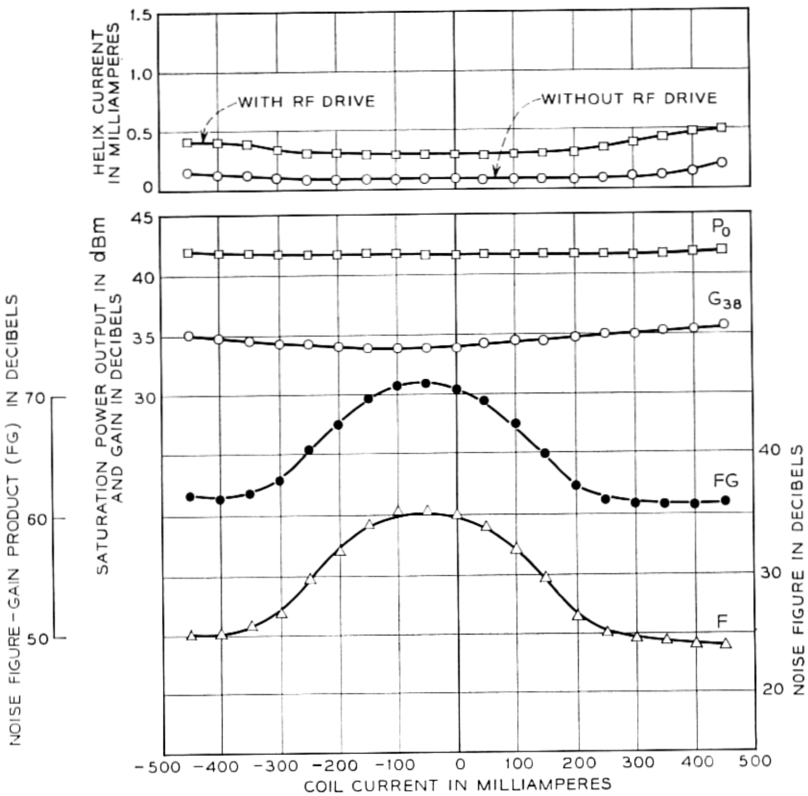

Fig. 8 — Noise and power versus cathode field.

noise power measured at baseband at the output of an FM detector varies in magnitude as the square of the baseband frequency. Ion noise will generally appear as a series of spikes riding above thermal noise.

Figure 9 is a plot of thermal noise vs tuned frequency of the noise analyzer. An ion-noise spike is evident at a baseband frequency of 7 MHz and a power output of 38 dBm. Since the response of an FM detector to a thermal noise input is proportional to the ratio of noise to carrier power, the magnitude of ion noise can be fully specified as being so many dB above thermal noise, for the detector bandwidth to be used, and for the nominal output power.

Ion noise appears in the output of most 461A tubes and is reduced to an acceptably low level by aging. The outgassing of helix parts by

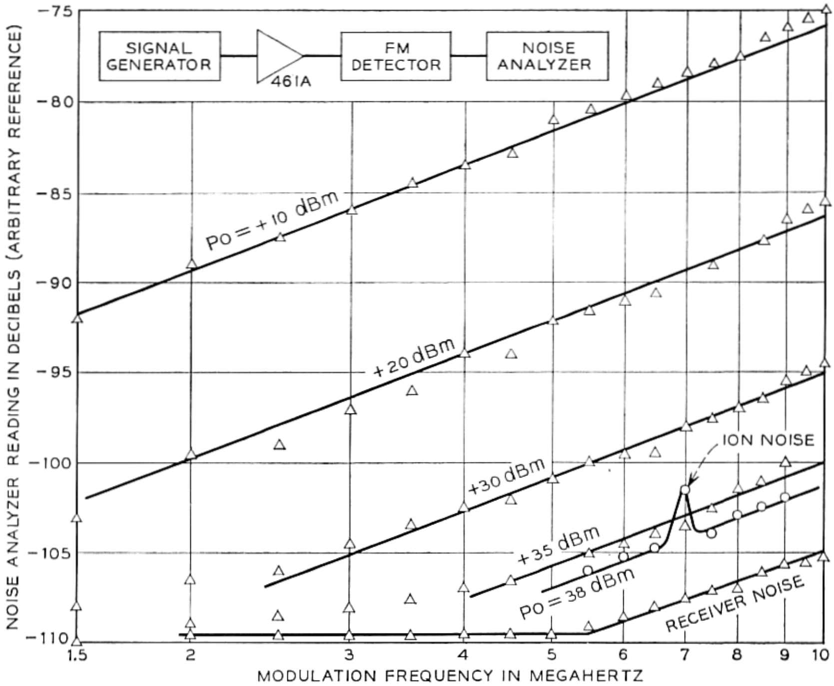

Fig. 9 — Thermal noise characteristics of a 461A TWT showing an ion noise spike at 7 MHz.

electron bombardment is the principal purpose of this aging process, which typically takes 100 to 200 hours.

Intermodulation in general refers to the fact that in active devices, it is normal to find extraneous frequencies in the output signal. For instance, if two signals enter the device at ω_A and ω_B, one finds in the output signals at ω_A, ω_B, $2\omega_A$, $2\omega_B$ and intermodulation products at $2\omega_A - \omega_B$, $2\omega_B - \omega_A$, and so on. Signals at $\omega = 2\omega_A - \omega_B$ are known as third order distortion products and those at $3\omega_A - 2\omega_B$ as fifth order distortion products, and so on. The harmonics at $2\omega_A$ and $2\omega_B$ can be removed from the output by using a low-pass filter.

If one assumes that only distortion products of the $2\omega_A$–ω_B type are obtained, by measuring them one can estimate the degree of AM-to-PM conversion as a measure of intermodulation.* This has been done using two input signals, one at ω_A and the other at ω_B.

* Although the basic device phenomenon is intermodulation, in systems work the parameter of concern is AM/PM conversion. Also see Ref. 6.

For output power levels ranging from 36 to 40 dBm, the AM-to-PM conversion in 461A tubes was found to be between 2 and 5 degrees per dB amplitude modulation.

5.4 *Life and Prediction of Failures*

In order to obtain good reliability for the system, sudden unpredicted failures should be infrequent. The traveling-wave tube is expected to have a field lifetime between 30,000 and 50,000 hours. Since other system components have expected lifetimes upwards of 200,000 hours, the end-of-life of the traveling-wave tube will be the most frequent cause of a system channel going off the air. System reliability can therefore be substantially improved if the failure of the traveling-wave tube can be predicted. A soon-to-fail tube can then be replaced by a new one while the channel is not being used.

In the TH radio relay system, a dip test has been used to predict imminent failure. This consists of determining the dip in beam current after suddenly reducing the heater voltage to zero, then restoring it to its original value after a specified number of seconds. However, studies of the TH system have shown that the approach of cathode failures can be predicted better on the basis of a record of the increase and rate of increase of anode voltage needed to give a 40 mA beam current during life. Therefore, an accurate anode voltage meter has been provided in the TD-3 TWT power supply, to permit a voltage record to be kept for each tube.

5.5 *The Power Supply*

The power supply[4] provides a well-regulated heater and helix voltage. The dc heater voltage is regulated to ± 2 per cent, which allows the cathode to operate at lower temperatures for long life without risking the instability which can occur if the cathode temperature becomes too low. The heater ripple is kept below 0.1 volt to prevent heater ripple from appearing as gain ripple. The anode and helix regulation is made small enough (± 45 volts, ± 12 volts, respectively) to permit the gain setting to be held to within ≈ 0.3 dB. However, the ripple requirement (1.8 volts, 0.4 volts) is governed by the requirement that the phase deviation resulting from the ripple be 67 dB below the signal deviation, as required for television. Collector voltage requirements are predicated mainly on an allowable increase in helix current over that at the optimum collector voltage.

Proper start-up contributes to the long life of the tube. To accomplish this, a built-in timer delays the application of high voltage and provides an overvoltage for the heater, so that when the high voltages are automatically applied, there will be sufficient cathode emission for good beam focus. This is especially important for older tubes.

VI. CONCLUSION

The desired TD-3 repeater power output of 38 dBm is obtained with a noise output of about 59 dB (24 dB noise figure) at a gain of 35 dB. The intermodulation distortion at this power level is equivalent to about 3 degrees per dB.

To achieve long life, the device has been conservatively designed at a moderate cathode loading. It is expected, from our experience with field performance of the 444A tube, and our laboratory life tests of prototype tubes, to achieve a field life of about 40,000 operating hours. In order to obtain optimum convenience in service, the device has been packaged for easy installation; periodic permanent magnet beam focusing is used to reduce weight and ease handling.

VII. ACKNOWLEDGMENT

A project of this complexity represents the work of many development engineers of the Reading Laboratory, each responsible for a vital contribution. We give a special word of thanks for the efforts of Messrs. L. K. S. Haas and H. P. Ross. These gentlemen were responsible for transforming the prototype device into the final design for manufacture, and for many valuable features of that final form.

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