

The AR6A Single-Sideband Microwave Radio System:

The Traveling-Wave-Tube Amplifier

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This paper describes the amplifier for the AR6A radio transmitter, which consists of a Traveling-Wave Tube (TWT), its magnetic focus system, and driving power supply. The amplification of single-sideband modulated signals requires an unusually low intermodulation noise level and relatively low thermal noise power at the amplifier output. Further, owing to the use of predistortion to achieve the overall repeater intermodulation level objective, the amplifier must perform at high stability. These objectives have been met by choosing suitable TWT design parameters, operating the tube far below its saturated power capability, and devoting close attention to the details of tube construction. The power supply provides well-regulated heater, helix, and collector voltages to control the TWT gain. The supply also regulates the beam current. Current detection circuits protect the tube and power supply from tube internal arcs.

I. GENERAL

The development of a traveling-wave-tube amplifier was undertaken to fulfill all proposed operating requirements for noise, signal intermodulation, gain, safety, and mechanical stability. Prior experience with Western Electric Traveling-Wave Tubes (TWTs)[†] indicated the

*Bell Laboratories.

[†]Acronyms and abbreviations used in the text and figures of this paper are defined at the back of this *Journal*.

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direction of design. Subsequent application in the AR6A* Radio System has shown that the device, designated the 473A TWT, when operated with the power supply described in this article, meets all detailed repeater requirements. The use of this TWT was discontinued following the decision to terminate the manufacture of all Western Electric traveling-wave tubes. An equivalent TWT obtained from a commercial source and meeting the same requirements is now used in production of the AR6A Radio System.

II. THE TRAVELING-WAVE TUBE

2.1 Requirements on the TWT

The 473A TWT includes the vacuum tube and the focusing magnetic circuit (Fig. 1). This combination must be united at the manufacturing location, so that optimum focus and Radio Frequency (RF) operating parameters are achieved.

The following list of major requirements specified for the TWT includes the operating conditions specified over the frequency band of 5.925 to 6.425 GHz (with full-load output power of 24.8 dBm and gain reduced 2 dB below the optimum value by increasing the helix voltage):

1. RF gain—40 to 48 dB.
2. Gain plus noise figure—69.5 dB maximum.
3. Third-order intermodulation (three-tone test method)¹— $M_{A+B-C} = -90.5$ dB maximum, and constant within ± 0.4 dB with the power per tone varied from 18 to 30 dBm.
4. Fifth-order intermodulation ($M_{2A+2B-C}$)— from 22- to 30-dBm output power, -180-dB maximum at 18-dBm output power, -160-dB maximum.

The device developed to meet these requirements consists of a helix-type, single-collector, convergent-flow, electron-gun traveling-wave tube, focused by a Periodic Permanent Magnetic (PPM) field.

As observed from the requirements, noise figure, signal intermodulation, and gain were the major operating parameters to be satisfied. Also, implied by the application, long operating life requires low cathode current loading and minimum interception of current from the beam by the helical slow-wave structure. Further, a critical need for this application is mechanical stability; it was verified that minute movement of the helix results in significant shift in intermodulation (IM) performance.

III. TWT COMPONENT DESIGN APPROACH

3.1 Focus circuit and tube envelope

The PPM focus circuit was adapted from an existing Western Electric manufactured circuit used on the 461A TWT. The existing

*Amplitude Modulation Radio at 6 GHz for the initial (A) version of the system.

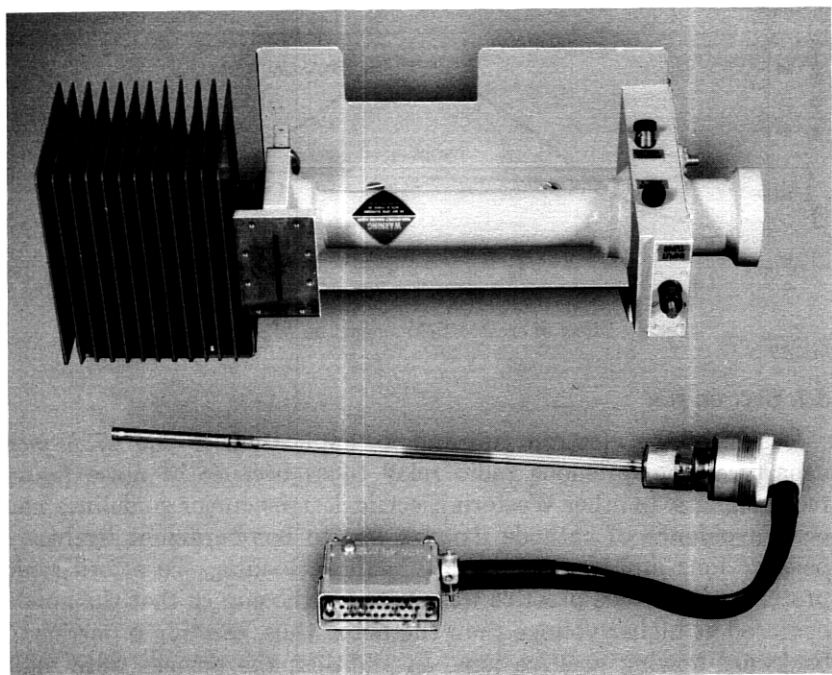


Fig. 1—Picture of AR6A 473A TWT.

glass envelope was also used so that it fit the magnet and pole piece parts. Since the TWT was required to be convection cooled by free air, a finned cooling structure was developed. An SMA coaxial RF input was specified and the coaxial-to-waveguide transition was made an integral part of the circuit.

Of major importance was the introduction of a cross-magnetic field in the collector region. The reason for this is that elastically reflected electrons or electrons emitted by secondary emission from the tube collector resulted in feedback to the input, which has a deleterious effect on intermodulation performance. The smoothing effect, with power variation, upon the third-order intermodulation, with and without the use of a cross field, is shown in Fig. 2.

The focus circuit is assembled from Alnico 8 magnets and soft iron pole pieces on precision mandrels so that no trimming of the magnetic field is necessary for tube focus. A movable pole piece near the input waveguide allows optimum focus to be reached. Cooling fins are coupled to the copper collector of the tube via a thin layer of conducting silicone grease. Adjustable tuning plungers in the waveguide optimize the RF impedance match between the input and output waveguides and helix.

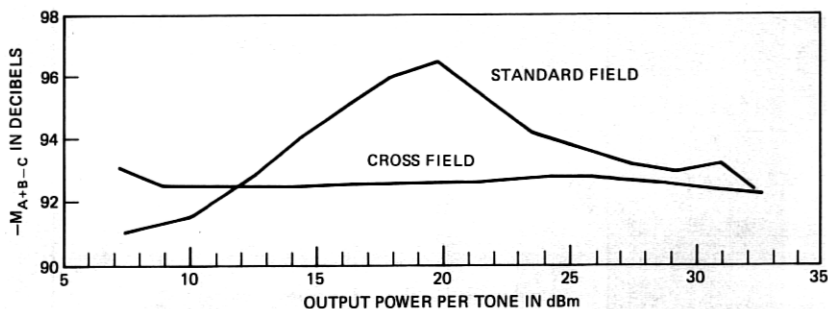


Fig. 2—Effect of crossed-field magnet on M performance.

3.2 Electron gun

Design of the electron gun and its application in the 473A is a departure from previous radio relay tubes because of noise figure requirements. In other Western Electric designs, major guidelines had been avoidance of cathode damage due to bombardment by heavy positive ions and use of moderate cathode loading. To afford ionic protection, previous practice was to design the gun so that the anode operated at higher voltage than the helix, thus, erecting a barrier to backward-flowing positive ions. In addition, the devices were built with highly convergent beam profiles, i.e., with the cathode diameter being much greater than the diameter of the beam projected through the helix. Typically, the emission density in such designs is $0.2A/cm^2$ of cathode area.

The effect on noise figure of both helix-voltage-to-anode-voltage ratio, E_w/E_c , and cathode current density, J_c , is shown in Fig. 3. The upper plot, evaluated at $J_c = 0.2$, shows the noise figures obtained with previous design rules. Clearly, lower noise figure can be obtained with $E_w/E_c > 1$ and with the cathode diameter smaller. A standard oxide cathode coating would be advantageous over other less proven, high-current types if the cathode loading could be reduced to allow its use. The anode voltage was set at 3150, nominal, so that $E_w/E_c = 1.3$. Diminishing benefit would be obtained from a higher ratio, and leakage problems on insulators would also increase. The resulting electron gun is a glass-rod supported triode that emits 70 mA dc from an oxide-coated cathode. The cathode-heater structure is designed to operate at 740 degrees Celsius (observed pyrometric temperature).

The life capability of the cathode has not been entirely confirmed. Based on calculation and extrapolation, greater than 30,000 hours is predicted. Limited facilities allowed five tubes to be run individually over times ranging from 3100 to 8500 hours. One of the five showed significant cathode degradation at 6000 hours; the other four were stable. No short-life problems have been encountered in application.

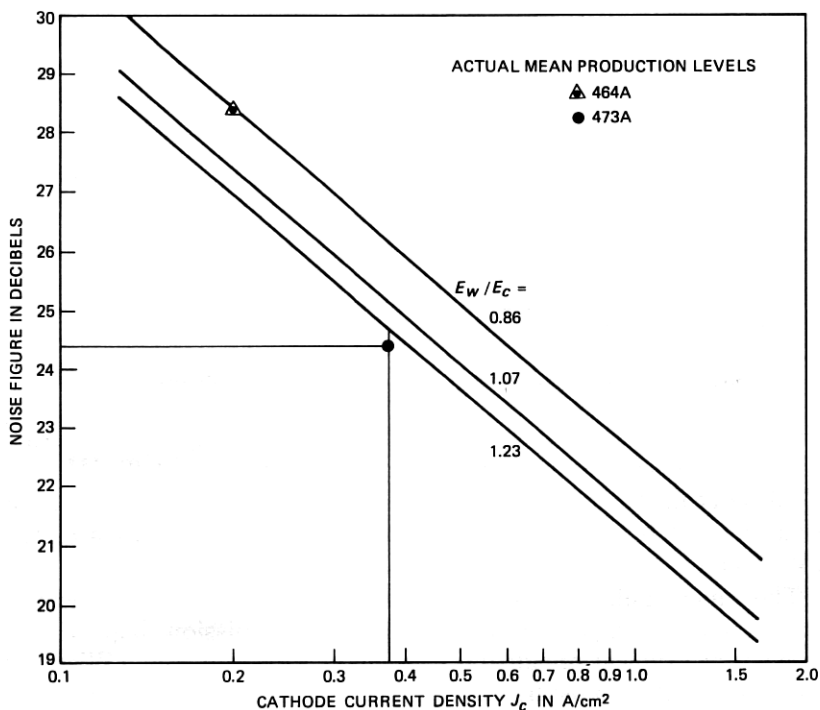


Fig. 3—Effect of cathode loading on noise figure for different voltage profiles.

3.3 Helical slow-wave circuit

Initial tests confirmed the work of Curtice,² showing that for lowest intermodulation distortion the helix RF loss should be minimized and the gain parameter C (which is proportional to the 1/3 power of beam-current-to-helix-voltage ratio) should be maximized.

Consideration of the effect of the gain parameter led to design of the helix to operate at 4100 volts. It is noted also that minimum helix loss is desirable for minimizing tube noise figure, although the effect is not as pronounced as it is on intermodulation. Low loss and mechanical rigidity tend to be opposed, because additional support material adds to RF losses.

The helix structure, therefore, utilized beryllium oxide rods. After refining the processing, rods with round cross section had nearly as low loss as those with modified T-shape cross section. The round cross-section rods were used and were bonded to the helix wire with glass frit (glaze). This arrangement was considered the best compromise from the standpoint of intermodulation and noise performance, mechanical rigidity, and heat dissipation.

The helix sever loss (i.e., the loss deliberately added to the midsec-

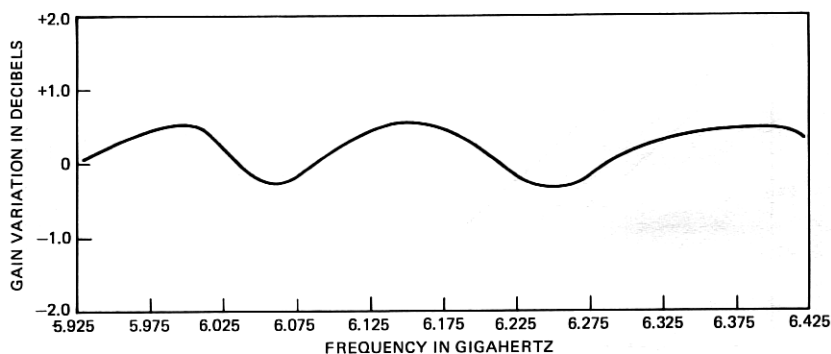


Fig. 4—Typical 473A traveling-wave-tube broadband gain variation.

tion of the helix to prevent self-oscillation and to provide good external RF matches) is a tantalum-aluminum sputtered film with Ta/Al ratio of 70/30 atomic percent.* This loss section is highly stable and not easily altered by bombardment with the 4000-volt electrons of the TWT beam.

The taper applied at the beginning and end of the sever loss is critical to achieving the desired broadband transmission shape. Figure 4 shows the typical broadband gain characteristic of the TWT. The required variation must be less than 1.2 dB peak to peak with no more than four cycles in the 500-MHz band.

3.4 Collector

Construction similar to that employed in other Western Electric designs was used. The material is copper, of a length such that the modulated beam is well within the collector before significant beam spread occurs. This point is important from the standpoint of secondary emission. As noted previously, control of secondary electrons and reflected electrons is obtained by a cross-magnetic field over the collector.

3.5 Processing

The design included careful attention to parts cleaning, degassing, and handling. Final exhaust was conducted with titanium gettering pumps and seal-off of each vacuum envelope was accomplished only after indicated internal pressure was in the region of 10^{-8} mm Hg.

IV. TWT DEVELOPMENT PROBLEMS

Performance of the TWT was evaluated on a number of models. Problem areas that would likely result in low yield in manufacture were identified and changes were made.

*This film was originally developed for film resistors.³

4.1 Electron gun interelectrode leakage

Initially, a gun structure using ceramic rod supports similar to that used in the Western Electric 461A⁴ TWT was used. It was soon found that the higher voltages resulted in electrical breakdown across the support rods. A glass rod support structure was designed, leading to much improvement in the leakage problem. It was also necessary to maintain careful parts cleaning and processing. To keep electric fields low, adjacent parts, such as the gas getter and leads, were precisely placed and an initial voltage treatment of the gun was incorporated. The power supply was designed, as later described, to be insensitive to arcs that may occasionally occur. These actions resulted in attaining control over leakage and arcing problems.

4.2 Low-frequency noise

The output of early tubes often showed noise at a few hertz and a few tenths of a decibel in amplitude. A rather elaborate computer-based study indicated that the noise was due to oscillation of ions trapped in potential depressions in the electron gun. The study also gave direction to gun design changes required. However, during the period of this study, the gas getter was changed from a nonevaporating type to an evaporating type; the change was actually made from the considerations of lowering cost and using less space within the envelope. It was found that the oscillation problem disappeared, presumably because the new getter reduced the pressure of the offending ion. Though attempts were made, the ion responsible for noise generation was never identified.

V. TWT RESULTS

The gain and third-order intermodulation coefficient were characterized using a special three-tone intermodulation test set.⁵ Several hundred tubes (including preproduction versions) were characterized. Typical results are shown in Figs. 5 and 6, which plot the gain and M_{A+B-C} versus power and helix voltage, respectively. These measurements versus power were particularly important because of the requirement for constant third-order performance, which is necessary for the application of the predistorter to the AR6A transmitter.

Sample distributions of three major operating parameters from production—gain, third-order intermodulation, and noise figure plus gain sum—are shown in Figs. 7 through 9. Excellent control within the specification requirements is demonstrated. The remaining important parameter, fifth-order intermodulation, was measured only occasionally and was always well below the specification limits.

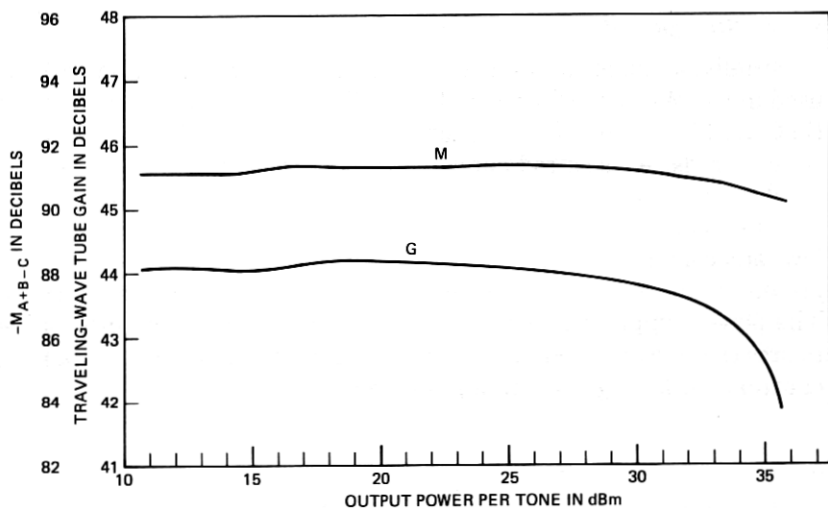


Fig. 5—Typical results of 472A TWT performance study showing third-order intermodulation coefficient and gain versus RF output.

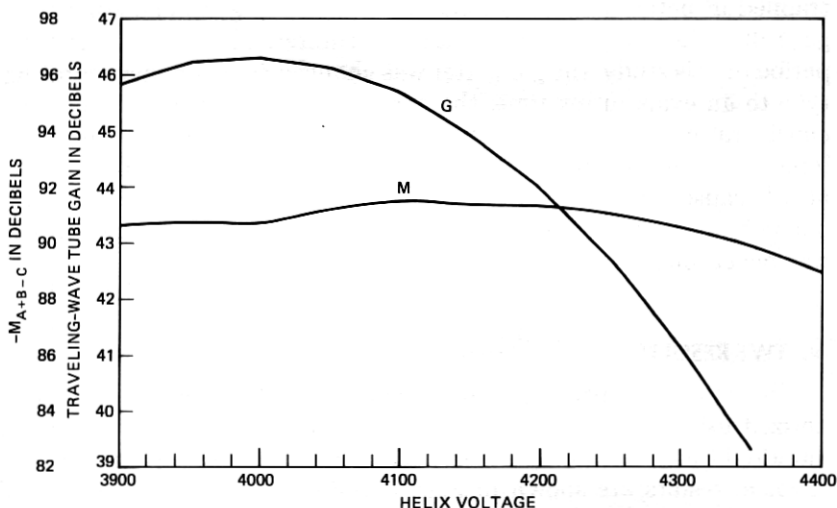


Fig. 6—Typical results of 472A TWT performance study showing third-order intermodulation coefficient and gain versus helix voltage.

VI. REQUIREMENTS ON THE POWER SUPPLY

The requirements for the TWT power supply, with emphasis on those features that directly interact with the TWT, are summarized as follows:

1. Well-regulated heater and helix voltages and beam current are required to control the TWT gain and intermodulation noise.

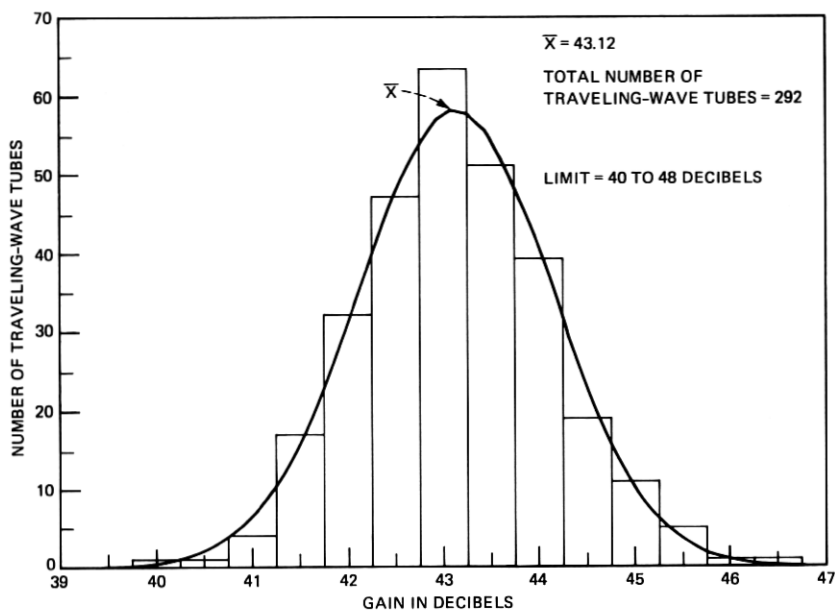


Fig. 7—473A TWT gain.

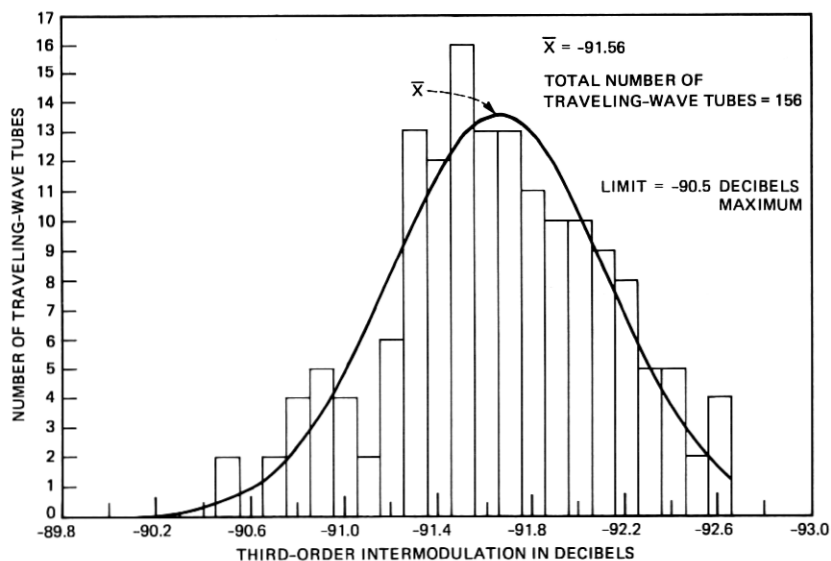


Fig. 8—473A TWT third-order intermodulation ($-M3$).

2. During turnon and turnoff, the electrode voltages must be sequenced so that damaging helix and anode currents do not occur.

3. Current detection circuits must protect the TWT and supply from tube internal arcs.

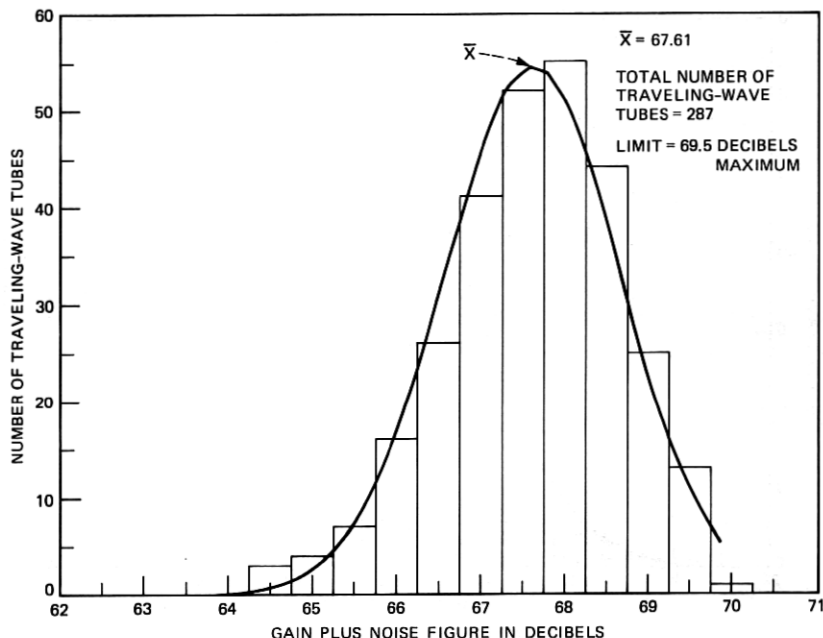


Fig. 9—473A TWT noise figure plus gain sum.

4. Side tones generated by the power supply and TWT combination must be more than 77 dB lower than a single-tone test signal.

VII. POWER ARRANGEMENT AND REGULATION APPROACH

Figure 10 shows a block diagram of the power supply. The power supply and TWT parameters are summarized in Table I. The heater/Beam-Forming Electrode (BFE) dc-to-dc converter supplies 6.3 volts at 1.2 amperes to the TWT heater. The heater voltage is regulated to ± 2 percent by controlling the duty cycle of the converter. During initial turnon, the current in the cold heater is limited to about 1.9 amperes by a limit circuit (not shown) within the converter.

The BFE supply is used to turn the TWT on and off electrically. When the TWT is running normally the BFE-to-cathode voltage is less than 1V (nominally 0V). During the time when turnon, turnoff, or internal TWT arcs occur, transistor Q1 is turned off. This causes the BFE potential to be approximately $-450V$, thus turning the TWT beam off. The BFE switching procedures are discussed in more detail in a later section.

Since the cathode is the common terminal of the TWT amplifier, electrode voltages are, therefore, normally specified with respect to the cathode (even though the collector is grounded). The collector

converter supplies +1800V. The 1800V output is controlled by the duty cycle of the converter to achieve ± 2 percent regulation.

The anode converter and collector voltages are applied in series combination to provide from 2800 to 3500V to the anode. The beam current is monitored and the output voltage of the anode converter is regulated to control the beam current to 70 mA ± 0.5 percent through control of the anode-to-collector voltage. The helix current (I_w) is also monitored. If I_w is less than 1.75 mA, the anode converter regulates the beam current as discussed. Should I_w reach 1.75 mA (corresponding to an unfocused TWT), the anode voltage (E_c) is controlled to hold I_w at 1.75 mA. However, this causes the beam current to fall out of regulation, and when it is 2 percent lower than 70 mA, a trouble indication is generated. This indication occurs when a TWT cathode has become deactivated.

The helix converter and collector converter are applied in a series combination to provide from 4000 to 4550V to the helix. The helix voltage is adjustable using a resistive voltage divider. Since the TWT gain is extremely sensitive to changes in helix voltage, the helix converter includes a series regulator to control the helix voltage to ± 0.5 percent. The converter being controlled supplies only the helix-to-ground voltage.

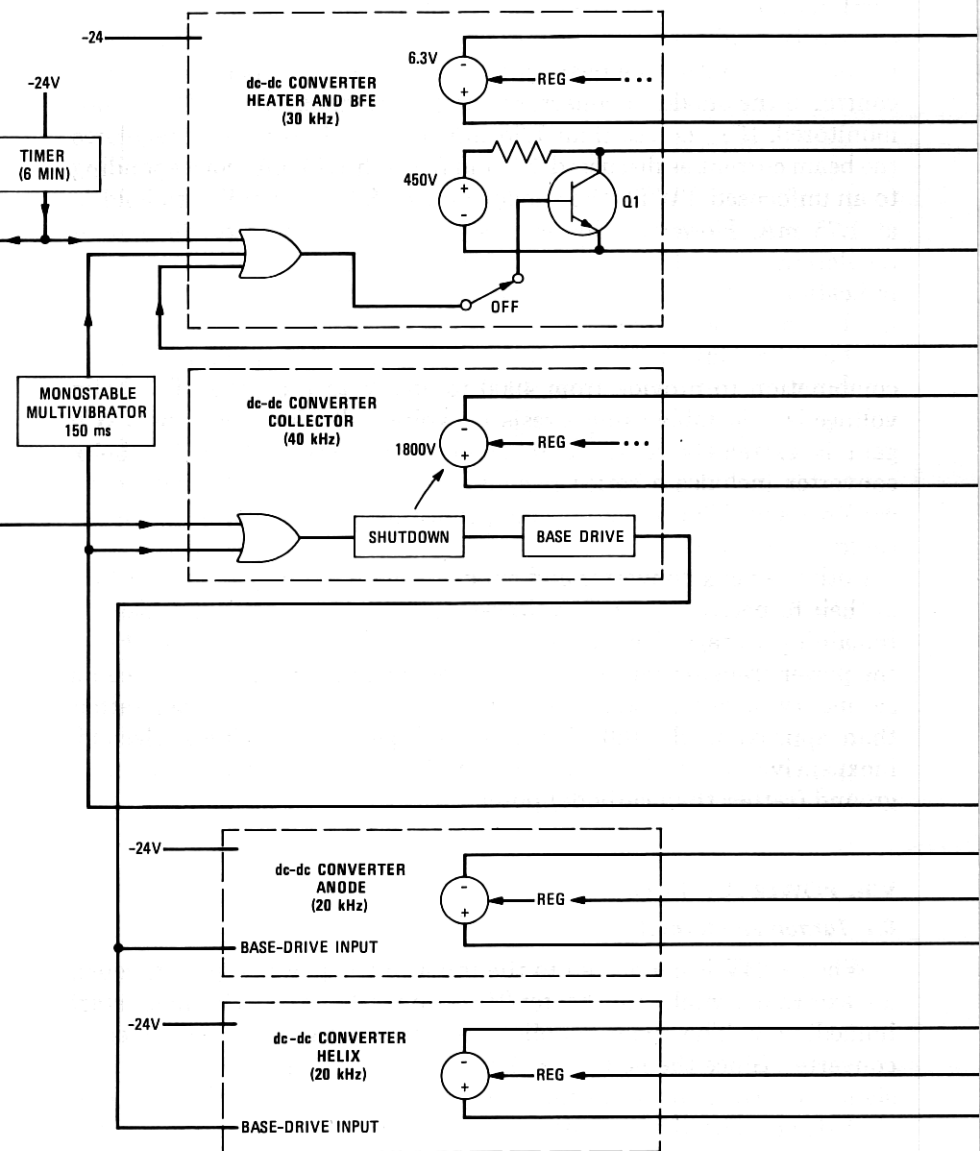
Both the helix converter and anode converter supply only a portion of their respective electrode voltages; the collector supply provides the remaining voltage. This arrangement is used for two reasons. First, the power transformer used in each converter is inexpensive since its secondary must withstand only the voltage it generates itself rather than approximately 1800V plus its self-generated voltage. Second, inexpensive monitoring circuitry may be used since it operates near ground (rather than cathode) potential.

VIII. POWER SUPPLY OPERATION

8.1 Turnon and turnoff

When $-24V$ is connected to the input of the power supply through an external switch, the heater/BFE converter and the timer start immediately. The timer supplies a shutdown signal to the collector converter. Since the helix and anode converters depend on base-drive signals for their inverters from the collector converter, they are also shut down. The timer continues to supply a shutdown signal for a nominal 6 (minimum of 5) minutes to allow the TWT to warm up. During this preheat period the timer also supplies a signal that causes $-450V$ to be applied to the BFE during warm-up to inhibit spurious emissions from the cathode.

At the end of the 6-minute warm-up period, the shutdown signal to



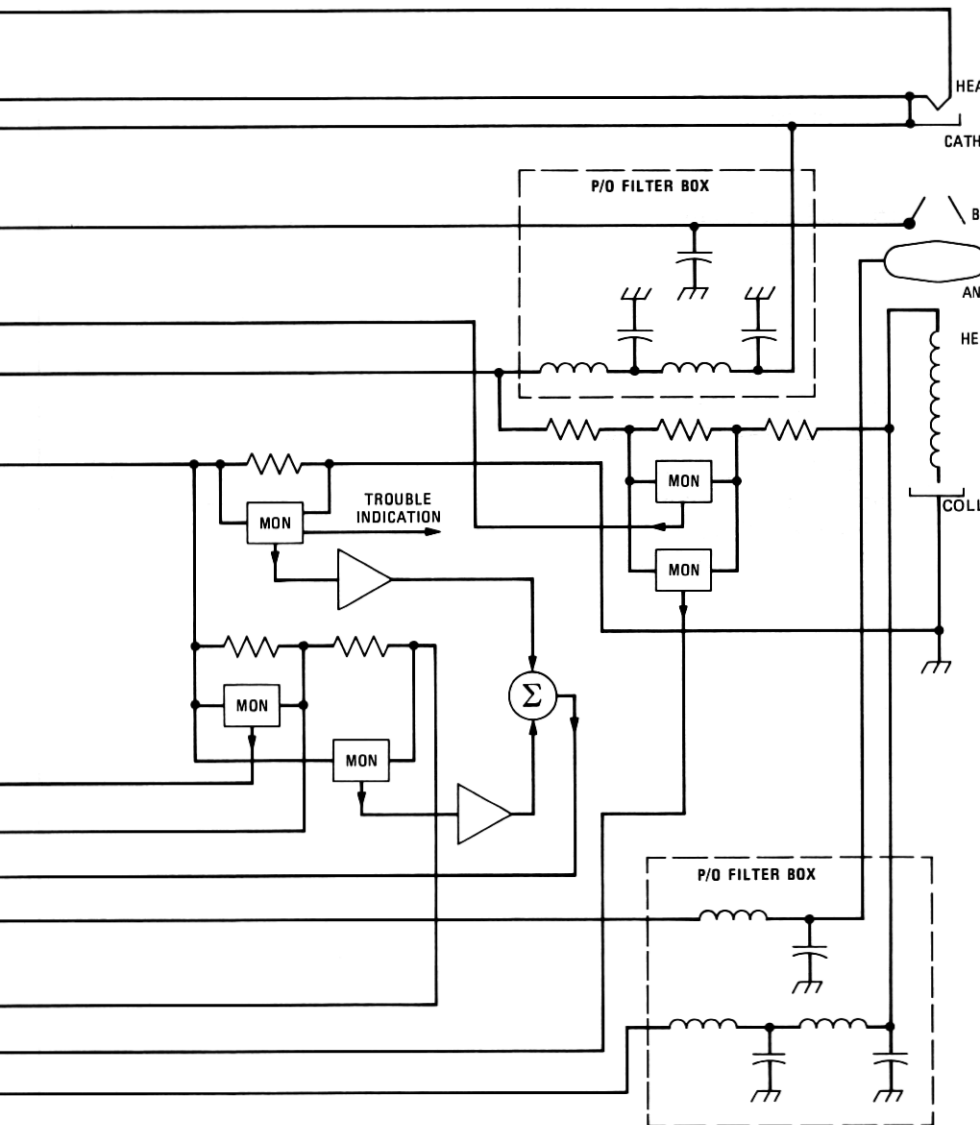


Fig. 10—Block diagram of the TWT power supply.

Table I—Parameters of TWT power supply requirements

| | |
|-------------------|--|
| Heater current | 1.2 amps maximum |
| Heater voltage | 6.3 volts ± 2 percent |
| BFE voltage | 0 |
| Anode current | 0.5 mA maximum |
| Anode voltage | As required for collector current |
| Helix current | 1.8 mA maximum |
| Helix voltage | Adjusted for 5 percent above synchronous operation; regulated to ± 0.5 percent after adjustment |
| Collector current | 70 mA |
| Collector voltage | 1800 volts ± 2 percent |

the collector converter is removed. The collector, helix, and anode converters then start. The time constants of each converter are designed so that these electrode voltages reach their respective final values in the order named above. The BFE voltage is not switched to zero until the collector converter has started, and the helix voltage has reached 4000V. This arrangement prevents excessive helix current while the TWT is turning on.

The external $-24V$ switch is used for normal turnoff. On removal of $-24V$, the electrode voltages decay, the timer resets, and the BFE supply loses its continuous source of energy. As soon as the helix voltage reaches 4000V, the remaining BFE voltage is applied. There is still enough stored energy in the BFE supply's internal capacitor to inhibit the beam until the other electrode voltages fall safely below levels that would otherwise cause damaging values of helix and anode currents.

8.2 Arc detection

On occasion a TWT arcs. Any combination of electrodes might be involved in the arc, but the direct or indirect result is almost always a large value of helix and/or anode current. When the helix plus anode current exceeds 10 mA, a shutdown signal is applied to the collector converter. Of course the helix and anode converters also shut down, since they depend on the collector converter for base drive signals. Decay of these voltages then causes the arc to extinguish. At this time the collector converter is again turned on and the tube voltages rise toward their respective normal values.

During the arc and subsequent shutdown, the RF output of the TWT is less than normal. When the TWT is turning back on, the process is controlled so that the AR6A protection switching system can operate properly. The RF output is held off by applying $-450V$ to the BFE for at least 150 milliseconds, thus allowing AR6A Radio System transients, which may occur during the arcing process, to subside completely before reapplying RF signal to the system.

The arc detection arrangement described above not only protects

the TWT by turning it off for the prescribed time period, but also has proved to be successful in protecting the supply. One particularly arc-prone TWT was life tested for 14 days. A total of 110 arcs occurred, but no supply damage resulted. The TWT parameters gradually fell out of specified limits, but the TWT performance did not change significantly as the result of any one arc.

8.3 Tones

The power-supply ripple requirements are not directly specified. Instead, they are implied by the requirement that the TWT sidetones must be more than 77 dB below the test tone.

Output filters are used in each converter. Additional Inductance Capacitance (LC) sections are mounted in a shielded steel box. A shielded cable connects the output of the filter box to the TWT.

The dominant sidetones occur at 20 kHz, the frequency of the helix and anode converters, and at 30 kHz, the switching frequency of the heater/BFE converter. These sidetones are caused by interwinding capacitance current that is generated in the power transformer in the helix, anode, and BFE converters. These currents are bypassed where appropriate, but they are still the dominant tone sources. In addition, special filtering is provided for transistor Q1 to prevent it from being turned off at a 30-kHz rate by interwinding capacitance current.

IX. AMPLIFIER OPERATION

The TWT and power supply are electrically connected by a shielded cable. At the TWT end, the cable is potted into the end of the tube. The cable connector mates to the power supply connector, which is accessible through a slot cut into the top cover of the power supply. A safety arrangement prevents power-supply operation when the TWT connector is disconnected.

The RF signal connections to the TWT are via an SMA coaxial connector at the input and a reduced height WR159 waveguide at the output. Adjustable shorts are provided for RF matching at the input and output.

Meters on the front panel of the power supply are supplied to measure the helix and collector currents. On the front panel, a helix-voltage adjustment (labeled RF gain) is provided. This adjustment is made during alignment of the amplifier so that the TWT operates at a helix voltage higher than the synchronous value, thus providing gain that is approximately 2 dB lower than that achievable at the synchronous helix-voltage value.

All amplifiers were tested in a bay environment. The gain-versus-frequency characteristic (transmission characteristic) of the amplifier embedded in the AR6A transmitter was measured for each amplifier

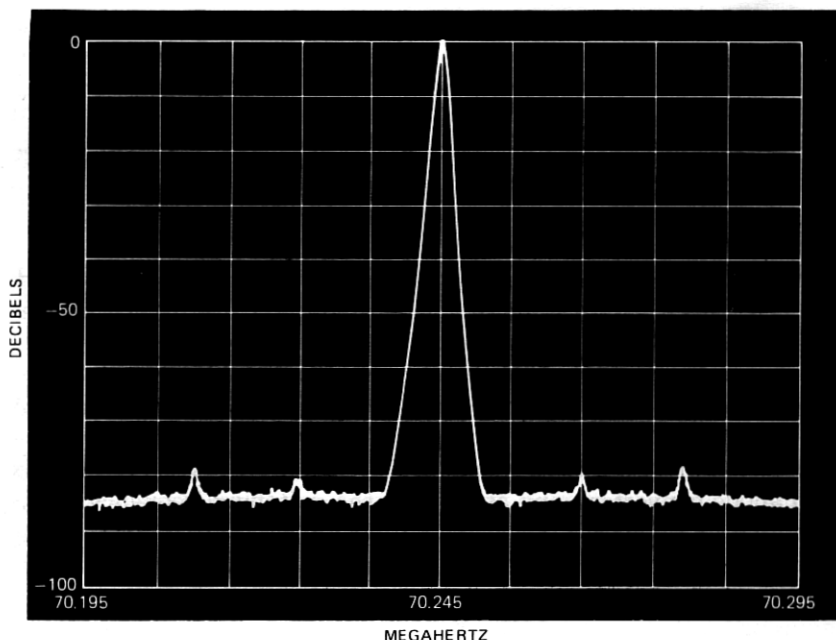


Fig. 11—Test tone with spurious modulation.

shipped for field application. The results of these tests were interpreted by subtracting out frequency characteristics attributable to other transmitter components. Such analysis shows that the average transmission characteristic for 100 amplifiers (with samples at every channel) has a bow of approximately 0.1 dB across the 30-MHz channel. (Note that any residual slope of the transmitter is equalized.) This is approximately what one would expect, considering the gain variation shown in Fig. 4.

Also, a test was made to check for a spurious modulation caused by very low ripple voltages at frequencies that are multiples of the 30- and 20-kHz switching rates of the power supply. A test tone was applied to the amplifier and sidetones were measured. The sidetones were required to be at least 77 dB below the level of the test tone. A graph extracted from a spectrum analyzer photograph shows a typical result (Fig. 11).

X. ACKNOWLEDGMENTS

J. R. Meszar and C. A. Waldron were highly instrumental in the development of the power supply and TWT, respectively.

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