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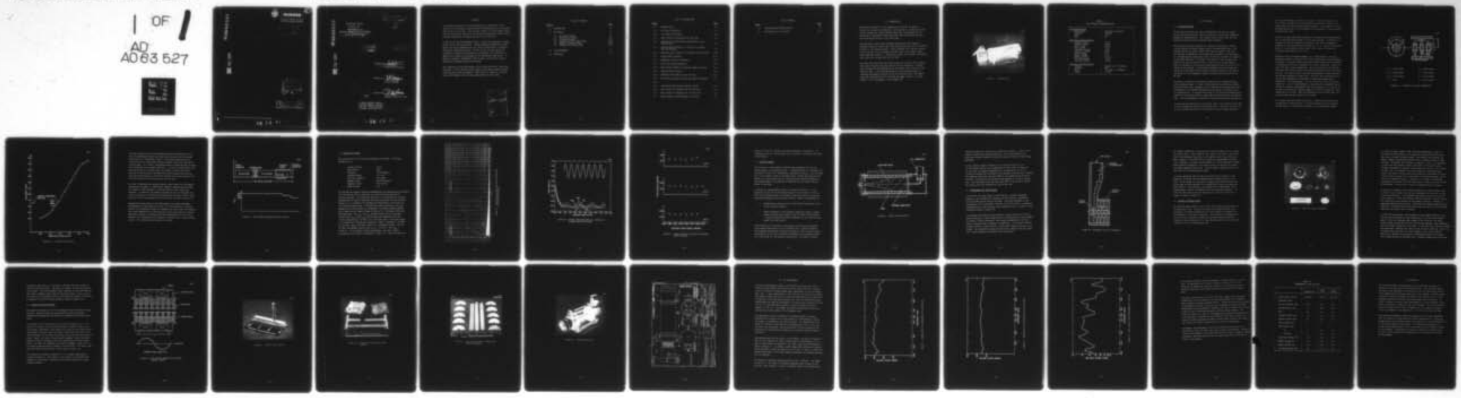

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3100 West Lomita Boulevard, Torrance, California 90509, Tel (213) 534-2121, TWX 910-347-6238

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Prepared by (10) K. W. Arnold
Senior Staff Engineer

Approved by J. P. Vaszari
J. P. Vaszari
Project Manager

Approved by R. A. Forbess
Manager, Power Tube Dept.

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ABSTRACT

The primary objective of the 914H program was to design and build a 200 watt CW, PPM focused, coupled cavity TWT operating over the frequency band of 30.0 to 31.0 GHz. This work was related to earlier Hughes developed millimeter-wave tubes, and the design and experience gained on these programs represented the design baseline for the 914H TWT.

As part of the early development effort, a study was performed to design the RF circuit and electron gun. Several computer programs were used to define the cavity dimensions and the circuit configuration to optimize efficiency, bandwidth and gain. The RF circuit was cold tested and optimized at X-band and then scaled up to Ka-band. The electron gun design was performed and evaluated in the demountable beam tester. In addition, windows, transformers, PPM focusing, collector and cooling systems were designed during this program.

Upon completion of the tube design, two RF tubes were built, tested and delivered. The two 914H TWTs were tested CW and demonstrated excellent beam focusing and RF performance. Power output in excess of 160 watts across the frequency band has been demonstrated on both tubes.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 INTRODUCTION

The general objective of this program was to develop and deliver 200 watt CW, Ka-band traveling-wave tube amplifiers. During the course of this program the required design effort was accomplished and the capability to manufacture these high power TWTs was demonstrated with the building and testing of two 914H tubes.

The 914H uses a unique high frequency construction that features a diffusion bonded RF circuit and a PPM focusing structure that is entirely external to the vacuum envelope. Other prominent tube features include an electron gun with an isolated mod anode and an air-cooled, single-stage depressed collector. Additionally, poker chip windows were successfully built and incorporated into the 914H.

Two tubes were fabricated and tested during the course of this program. Both tubes exhibited good beam focusing and RF performance: greater than 160 watts CW was demonstrated by the 914H's over the 30 to 31 GHz frequency band. A detailed discussion of the 914H tube design and operating performance is given in the following sections. The design operating characteristics for the 914H are shown in Table 1-1, while Figure 1-1 is a photograph of the packaged TWT.

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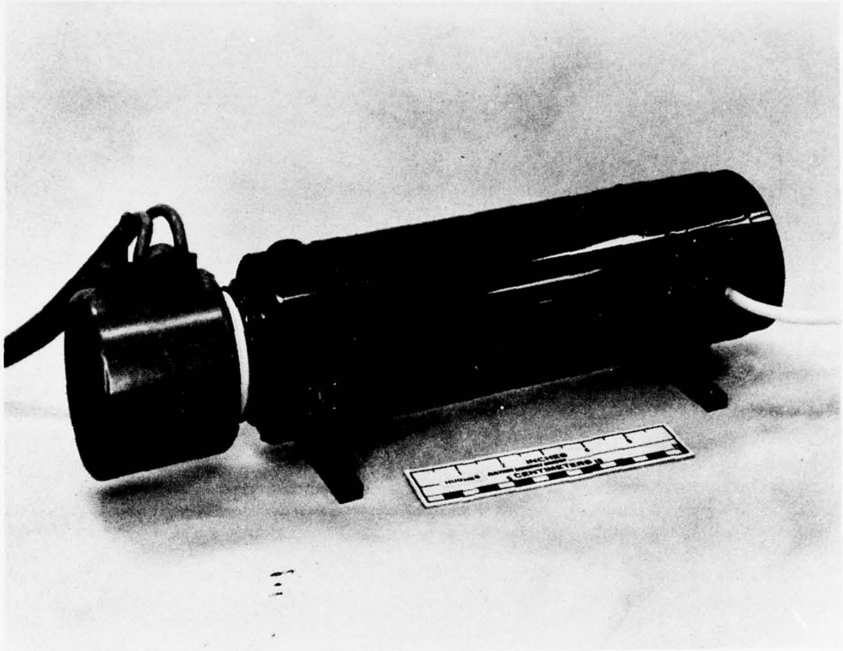


FIGURE 1-1 PACKAGED 914H.

TABLE 1-1

914H OPERATING CHARACTERISTICS

RF Characteristics	
Power output	200 watts (objective)
Frequency	30.5 GHz
Gain	35 dB
Duty	CW
Electrical Characteristics	
Cathode voltage	-16 kV
Cathode current	68 mA
Body voltage	ground
Body current	4 mA
Collector voltage	-8 kV
Collector current	64 mA
Anode voltage	0 kV
Heater voltage	6.0 V
Heater current	0.75 A
Ion pump voltage	3.0 kV
Ion pump current	<10 μA
Mechanical Characteristics	
Cooling	Forced air, 1.6 lbs/min
Focusing	PPM
Size	17" long x 5" diameter
Weight	13 lbs.

2.0 TWT DESIGN

2.1 RF CIRCUIT DESIGN

The RF circuit selected for this millimeter-wave TWT was the coupled cavity slow-wave structure, which is noted for its excellent thermal and mechanical characteristics. The coupled cavity circuit also provides efficient interaction with broadband width capability.

The slow-wave structure consists of a series of cylindrical cavities coupled together by kidney shaped holes in the separation walls. The coupling holes are usually rotated 180° from one cavity to the next. For the sake of simplicity, the RF wave may be thought of as traveling in a serpentine path through the chain of cavities, and thus its progress in the axial direction is retarded. The aim is to slow the wave down sufficiently that its phase velocity along the axis is approximately equal to the speed of the electron beam passing through the holes at the center of the cavities. An interaction between the electron beam and the RF wave then takes place in which the kinetic energy of the beam is converted into electromagnetic energy, increasing the amplitude of the RF wave.

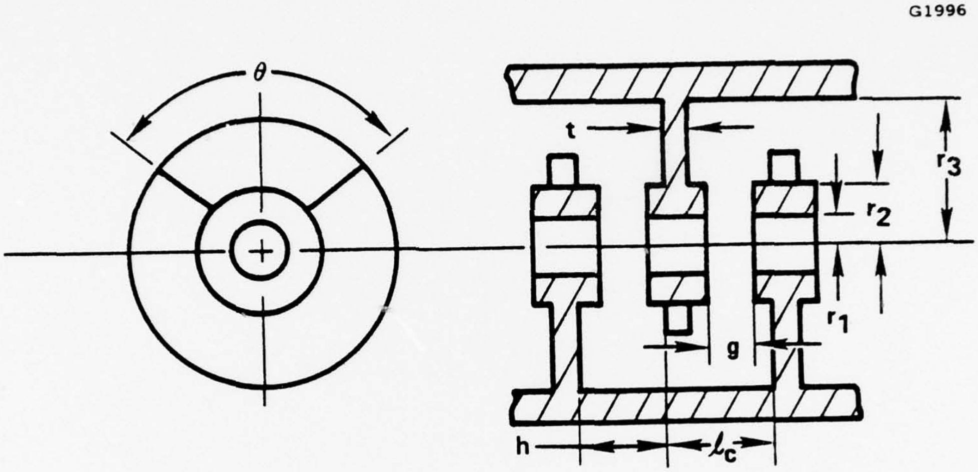
The chain of cavities is inductively coupled in the fundamental TM_{010} cavity resonance mode. It forms a filter-type RF circuit having a passband with upper cutoff frequency at the single-cavity resonance and with a bandwidth of the passband determined by the amount of coupling (size of coupling hole). In coupled cavity TWTs, it is the first forward space-harmonic of the RF wave which is made nearly synchronous with the electron beam. This space-harmonic, therefore, produces the effective interaction.

The basic design approach for the 914H RF circuit was essentially the same as that developed on other millimeter-wave TWTs. Initially, an effort was directed towards definition of the important circuit design parameters such as beam voltage, electron gun perveance, beam hole diameter, etc. The tentative designs were then extensively evaluated by means of the large signal and small signal computer programs. The design of the 914H has made maximum use of the performance and experience of related Hughes millimeter-wave TWTs.

In order to assure good beam focusing in this high power millimeter-wave TWT, an operating beam voltage of -16 kV was selected. In addition, to optimize the circuit interaction efficiency, the radial propagation parameter in the beam hole was optimized ($\gamma a = 1.1$). Based on the performance of similar Hughes millimeter-wave TWTs, a basic efficiency of 14 percent was assumed for the 914H.

Because of the low perveance design, $P\mu = .034$ micropervs, the cold bandwidth required to achieve the 1.0 GHz operating band is approximately 30 percent. The basic design procedure included using computer programs to optimize the RF circuit parameters and cavity dimensions. Figure 2-1 lists the final circuit dimensions. The final values for the coupling hole angle and ferrule gap were determined experimentally with an X-band circuit. All initial circuit work was accomplished at X-band because of the obvious advantage of larger size. Initially the coupling hole and ferrule gap dimensions are determined by performing phase versus frequency ($\omega - \beta$) measurements. An ω-β curve for the 914H is shown in Figure 2-2. With the establishment of the desired cold passband characteristics, impedance measurements were then performed on the circuit to be used with the aid of computer programs to predict the gain per cavity capability of the tube. With the finalization of the X-band work, the circuit design was then scaled up to Ka-band.

To increase the tube's basic efficiency, a velocity taper section was incorporated in the RF circuit. Velocity tapering is used to improve the efficiency of a TWT beyond the limits of a conventional design.



$2\,r_1 = 0.070$ inches

$2\,r_2 = 0.090$ inches

$2\,r_3 = 0.140$ inches

$\theta = 135^{\circ}$

$\ell_c = 0.095$ inches

$h = 0.065$ inches

$t = 0.030$ inches

$g = 0.025$ inches

Figure 2-1 Tentative RF circuit dimensions.

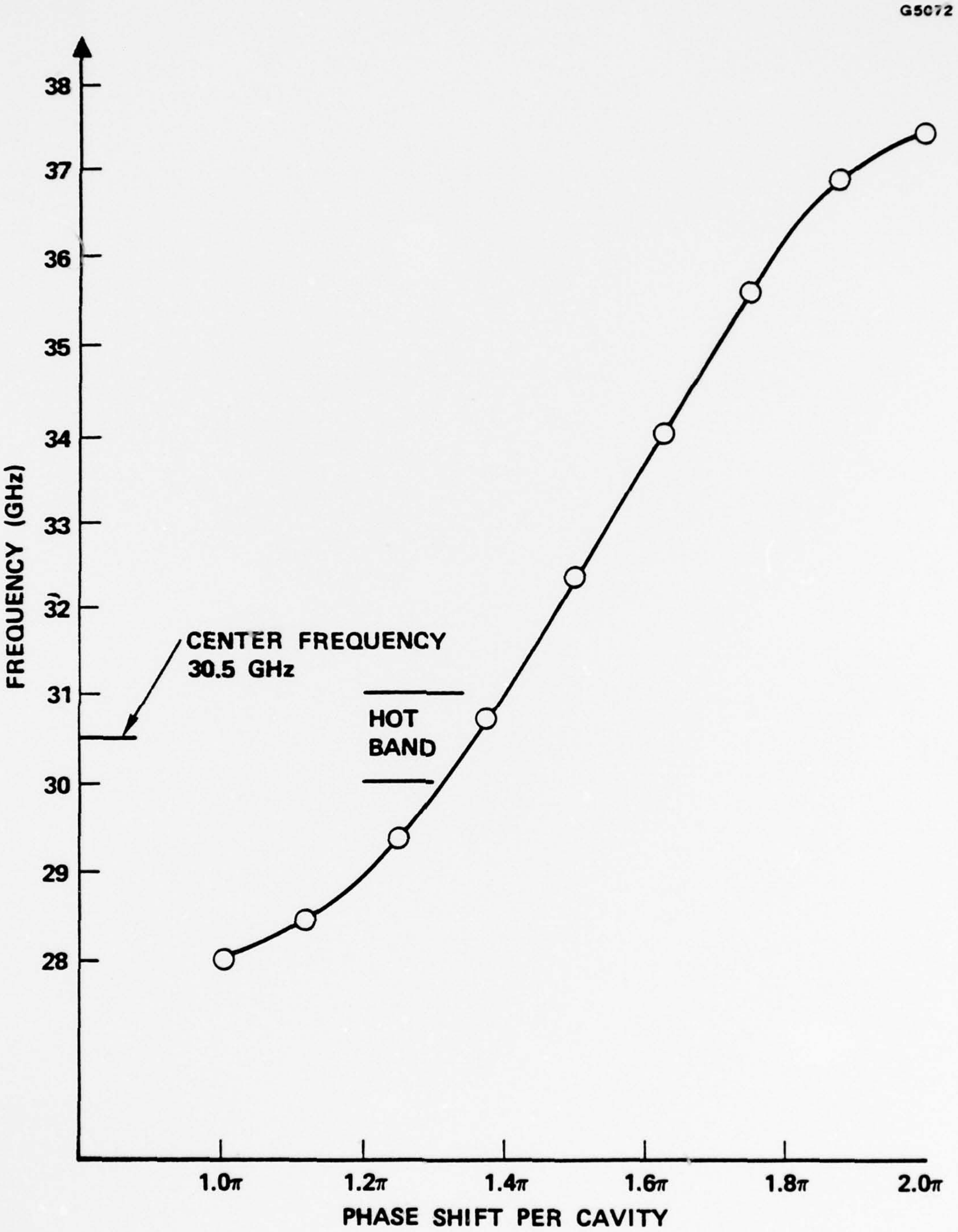


FIGURE 2-2 ω–β CURVE FOR THE 914H.

The basic limitation of the traveling-wave tube RF interaction is the loss of synchronism between the circuit wave velocity and the average beam velocity at large-signal levels. The average beam velocity is reduced below the circuit wave velocity because of the power extraction from the beam. As a result, the desired energy exchange between the beam and the RF wave can no longer take place. In order to resynchronize the beam and RF wave, a velocity taper is utilized to reduce the phase velocity of the circuit at the same rate as the average beam velocity. The taper was achieved on the 914H by reducing the circuit period in the last few cavities in the output section of the tube.

In order to determine the optimum velocity taper design for the highest interaction efficiency, a large signal computer analysis was performed. As a result of this analysis, a two step velocity taper design was achieved. In addition, the computer program was used to determine the cavity distribution to achieve the required gain and power output levels. The final circuit configuration used in the 914H is shown in Figure 2-3.

Because the cavity parts for the 914H require very tight tolerances, approximately 70 millionths of an inch, it is not practical to perform initial cold testing at Ka-band to determine the match cavity and termination cavity geometry and to determine the ferrule gap taper and coupling hole taper required to minimize the VSWR characteristic of the circuit. Therefore, all preliminary cold testing is conducted with a scaled X-band circuit. The results are then scaled to Ka-band.

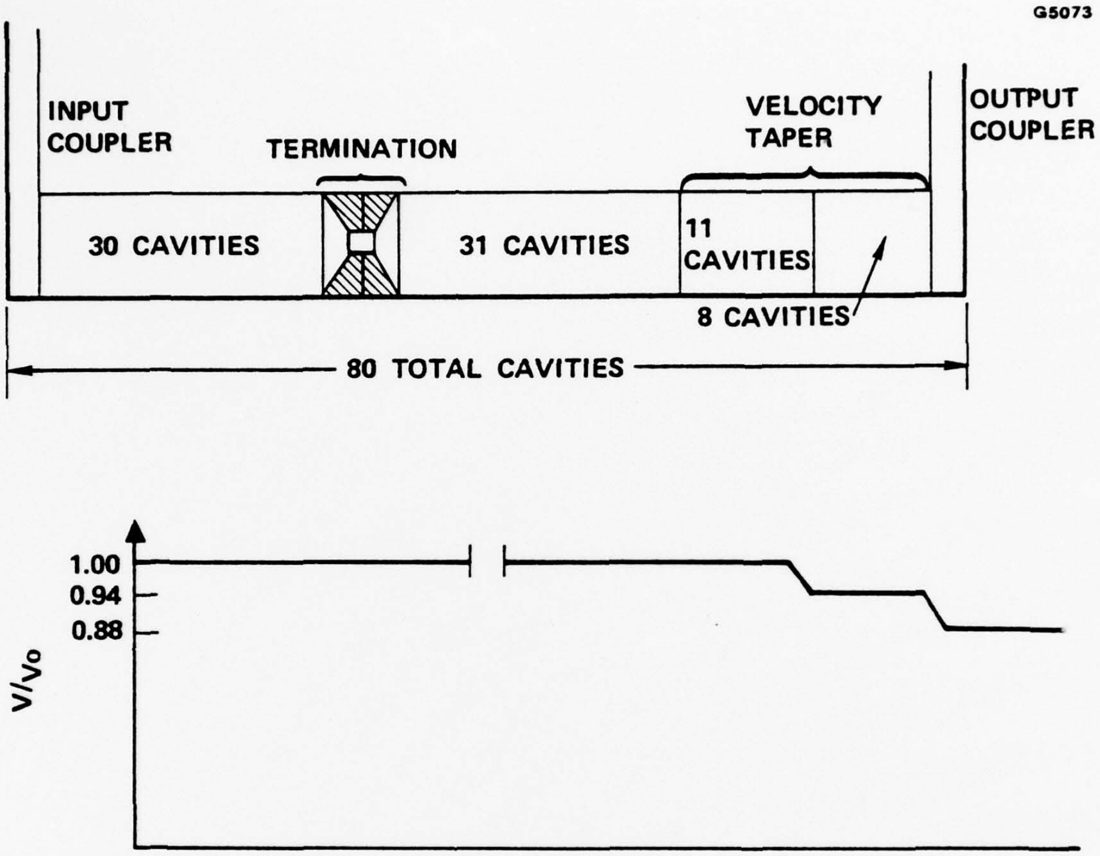


FIGURE 2-3 FINAL CIRCUIT CONFIGURATION FOR THE 914H.

2.2 ELECTRON GUN DESIGN

The electron gun for the 914H was designated the 227BMA. The design parameters are:

Cathode Voltage	-16 kV
Beam Current	.068A
Perveance	.034 Micropervs
Cathode Loading	1.54 A/cm^2
Beam Hole Diameter	.035 inches
Magnetic Field	PPM (2000 gauss)
Magnetic Period	0.576 inches
Anode Voltage	0 kV

The 227 BMA was designed using the Hermannsfeldt gun design theory and using the electrolytic tank to determine the electrode configurations and relative spacings. The design was analyzed by the Hermannsfeldt computer program which is used to determine the axial potentials and the perveance. Figure 2-4 is a computer plot showing the equipotentials in the gun and the electron trajectories. Utilizing these axial potentials, the given magnetic field and relevant gun parameters, the Amboss program computed the focused electron beam as shown in Figure 2-5. The figure shows five beam envelopes. The $r_{99.5}$ and r_{95} contain 99.5% and 95% of the beam current while $r_{1/10}$ and $r_{1/20}$ are the beam radii measured where the current densities are 1/10 and 1/20 of the peak value. The fifth radius, r_o is primarily of theoretical importance. When r_o exhibits no rippling in the drift region, the beam is said to be optimumly focused. For the 227 BMA, the maximum focused value of r_{95} = 0.0125 in. and $r_{99.5}$ = 0.0176 in. At the maximum focused beam radius, the radial current distribution in the beam is described by Figure 2-6. Since the beam hole

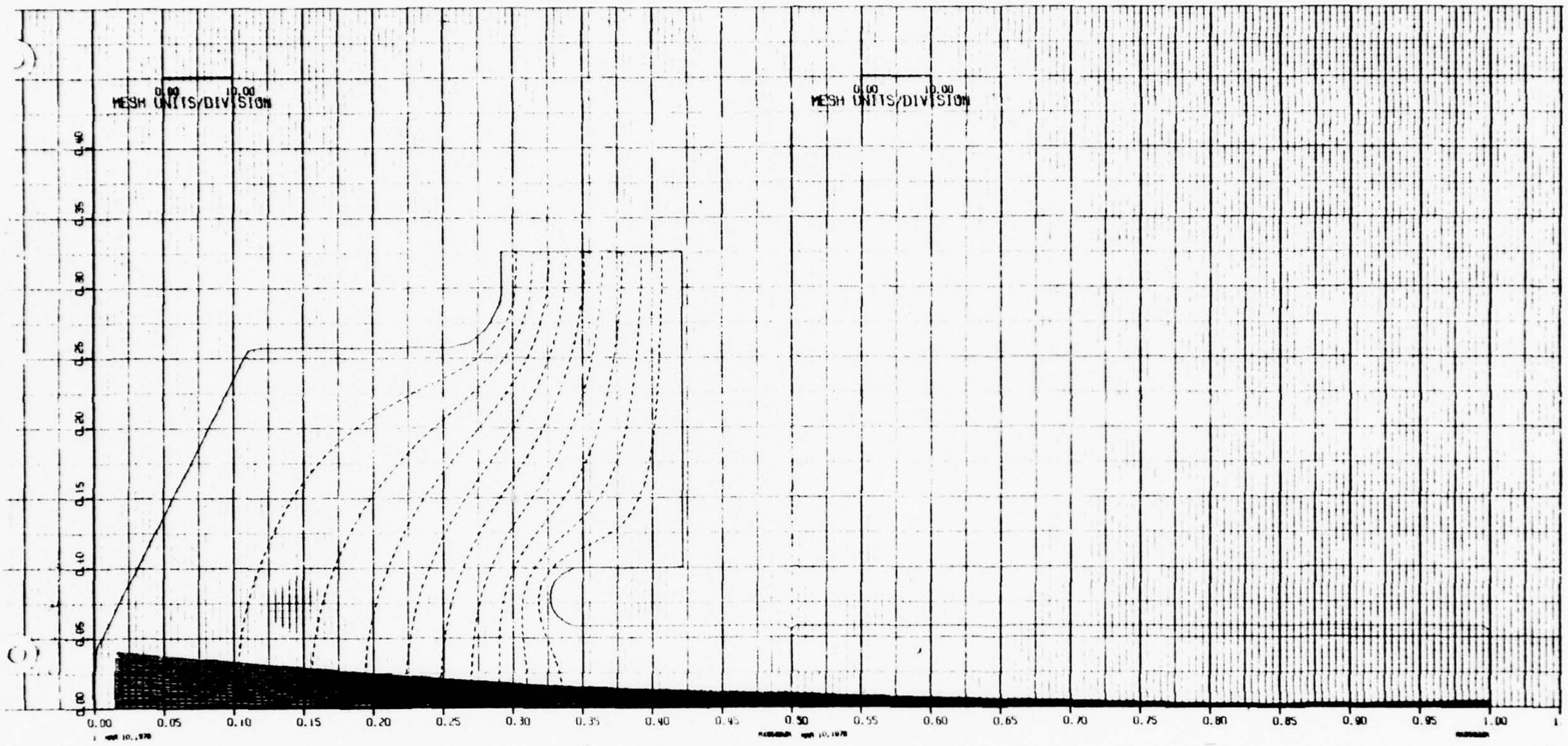


FIGURE 2-4 EQUIPOTENTIALS AND ELECTRON TRAJECTORIES IN THE ELECTRON GUN.

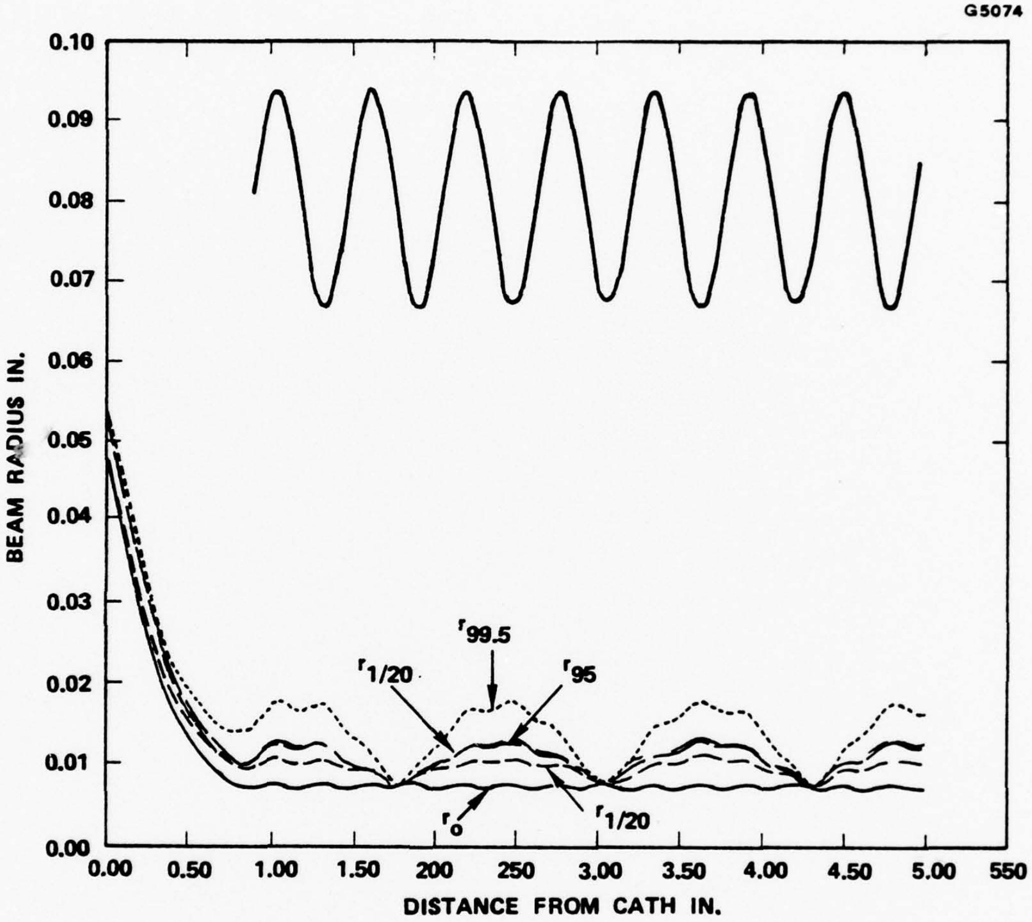


FIGURE 2-5 FOCUSED BEAM ENVELOPES AS A FUNCTION OF DISTANCE FROM THE CATHODE.

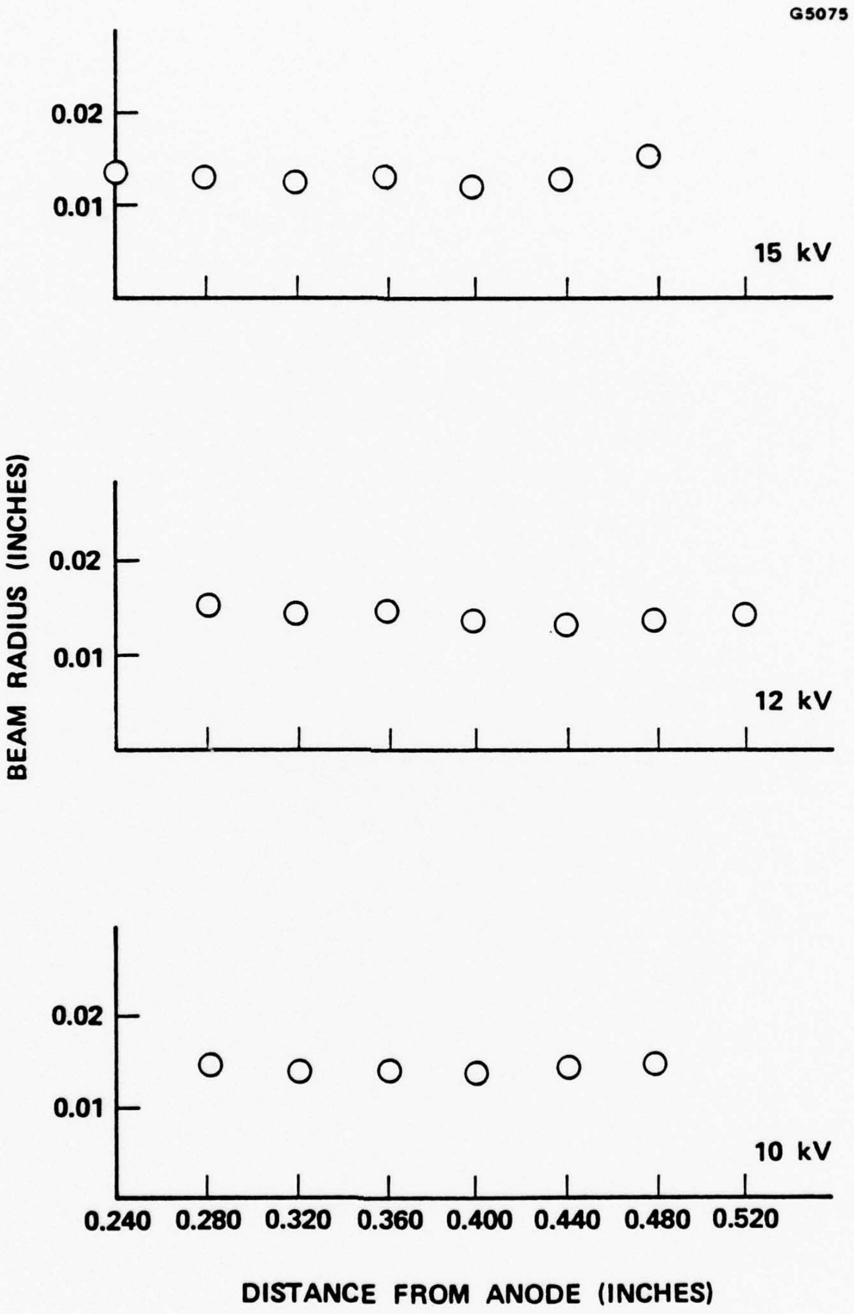


FIGURE 2-6 BEAM RADIUS AS A FUNCTION OF DISTANCE FROM THE ANODE.

radius is 0.0172 in., greater than 99% transmission is expected. The sinusoidal period of the focusing field is 0.576 in. and has a peak value of 2000 gauss.

2.3 COLLECTOR DESIGN

The collector is the section of the TWT that experiences by far the largest amount of intercepted power. A standard method of increasing the efficiency of TWTs is to incorporate a depressed collector. This recovers part of the kinetic energy in the spent beam, thereby reducing both the amount of dc input power that is required and the thermal dissipation. The maximum amount of depression is determined by the lowest electron energy in the beam.

A drawing of a single-stage collector is shown in Figure 2-7. The essential feature of the electrical design of such a device is that it must prevent backstreaming of secondary electrons produced by the beam electrons impinging on the collector surface. This is accomplished by:

1. Designing the collector for no direct beam interception close to the collector opening.

2. Taking advantage of the potential depression inside a bucket-shaped collector which results from the space charge density to deflect secondary electrons generated in the collector back toward the bucket walls.

These features were verified by calculating the electron trajectories and potential distribution in the collector with a computer program. This program evaluated the potential everywhere in the collector region, as determined by the exact electrode configuration and operating potential, and traced out the electron trajectories. The effect of space

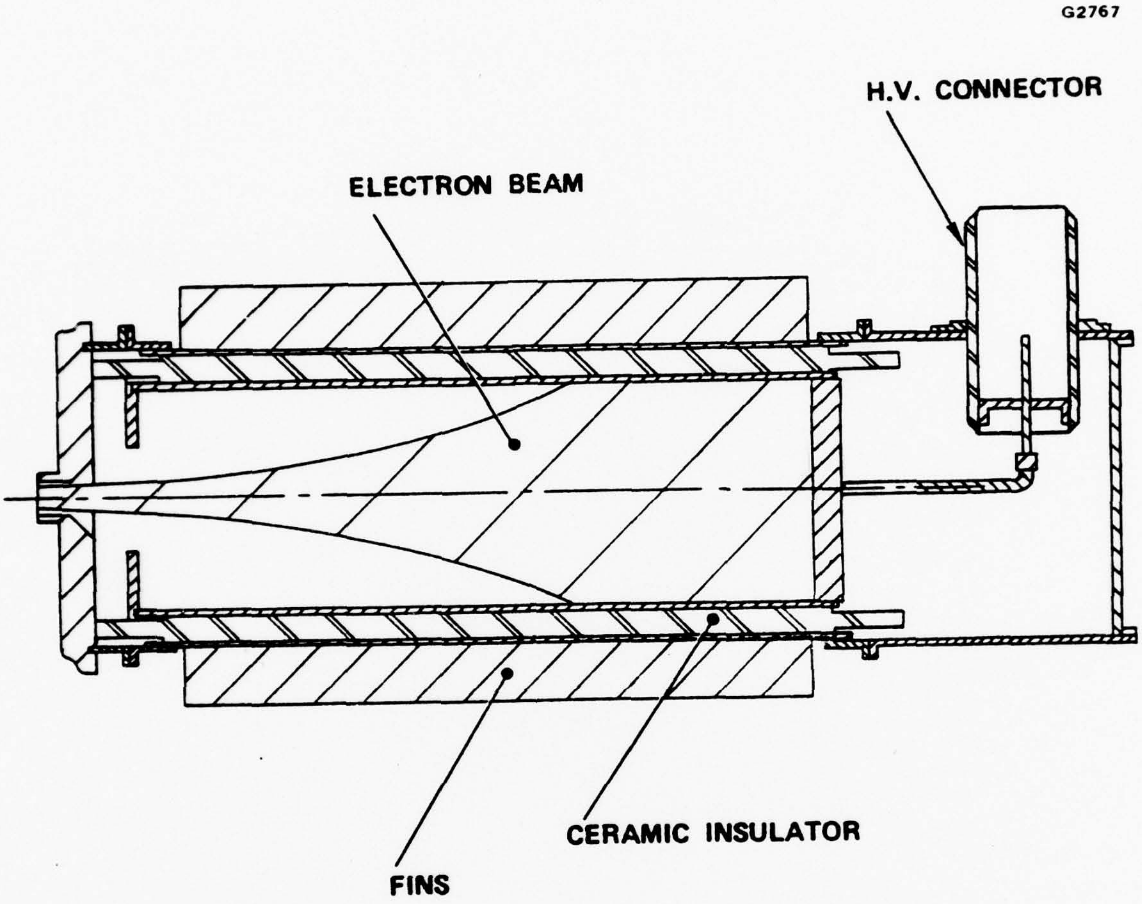


FIGURE 2-7 SINGLE STAGE COLLECTOR.

charge was taken into account by an iteration procedure. A plot of the electron trajectories and equipotentials, for a given geometry and electrode voltage, revealed how well the collector functions were being performed.

In the collector shown in Figure 2-7, if the flow rate of air is 1.6 lbs./minute and the inlet temperature is 40°C (after cooling the r-f circuit), the highest temperature to be expected on any of the collector surfaces was calculated on the computer using the TAP 3 program. The resulting value was less than 200°C at the parameters selected for the 914H. A worst-case run was made which assumed no collector depression: the calculated value was less than 500°C. The collector design was clearly more than adequate for use on the 914H.

2.4 TRANSFORMER AND WINDOW DESIGN

The RF input and output parts of the 914H has a standard waveguide connector, and provision for coupling from the external transmission line to the RF circuit must be provided. Since the impedance of the transmission line is different from that of the RF circuit, an impedance transformation is also required, which takes the form of a taper or step transformer shown in Figure 2-8.

The stepped transformer portion provides a smooth transition from full height waveguide to narrow height which is compatible with cavity height. To achieve a smooth transition, four steps are employed in the well-known, constant ripple, Chebyshev configuration. An available computer program provides a rapid solution to the rather complex problem of step design. The transformer design provided by the computer does not generally require empirical adjustment after fabrication.

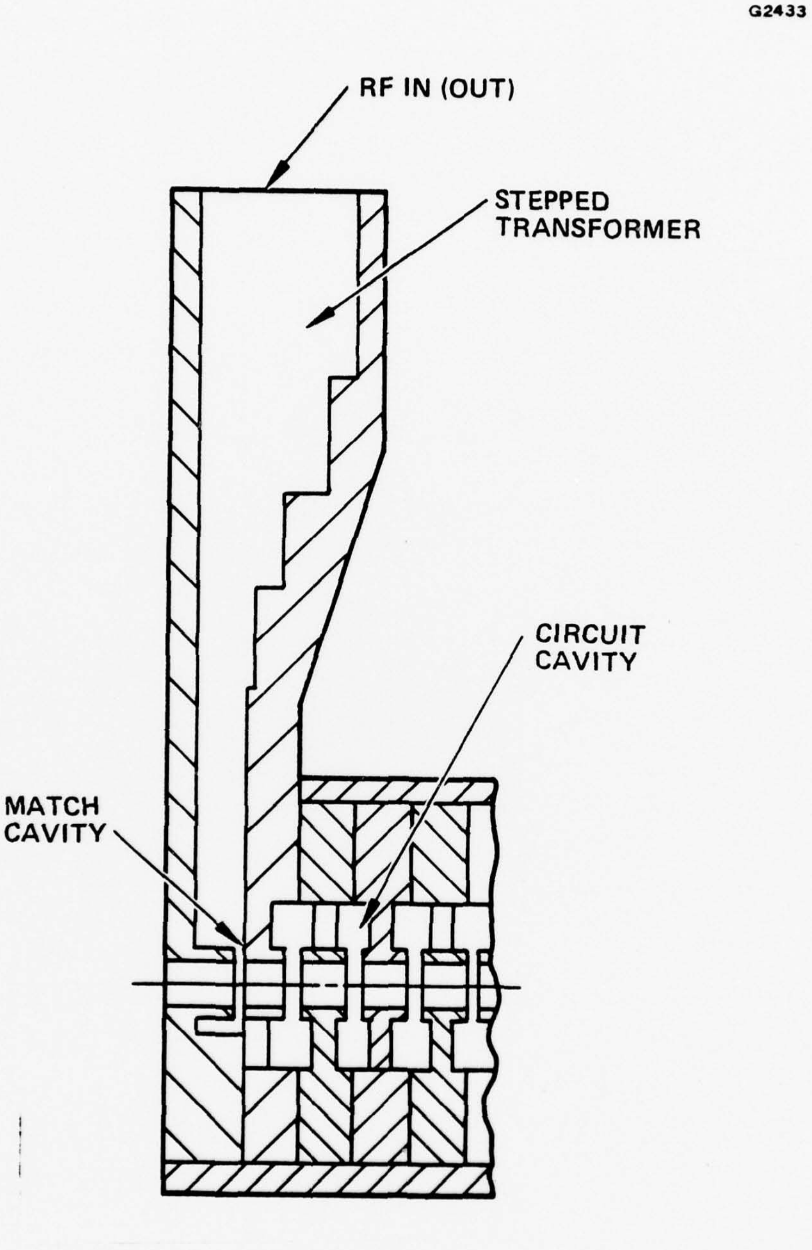


FIGURE 2-8 WAVEGUIDE TO CAVITY TRANSITION.

The stepped transformer is attached at its narrow height end to a hybrid (or match) cavity. The purpose of this cavity is to effect a mode transition from waveguide TE_{10} mode to the coupled cavity TM_{01} interaction mode. Design of the match cavity is largely an experimental exercise. It is convenient to perform the procedures at a scaled frequency (X-band). Three different geometries of the match cavity are adjusted to achieve an optimum impedance match area: the post height, distance from post to back wall, and coupling aperture angle.

It is also essential that RF input and output parts provide for the passage of RF energy without compromising the vacuum envelope of the tube. The RF window is a dielectric ceramic device which provides the vacuum seal and the capability for transmitting a high electromagnetic power density. These windows are designed for RF transparency with a minimum power reflected or absorbed over the operating frequency. The 914H TWTs developed during this program used the poker chip design window as shown in Figure 2-9.

2.5 MAGNETIC FOCUSING DESIGN

The electron beam focusing is one of the most critical design areas in the high power tube. In order to achieve the highest possible tube efficiency, the electron beam has to be well confined to minimize the interception of the circuit structure. In addition, the temperature of the RF circuit is directly related to the intercepted beam current; therefore, beam transmission is a very important factor in the life and reliability of the traveling-wave tube.

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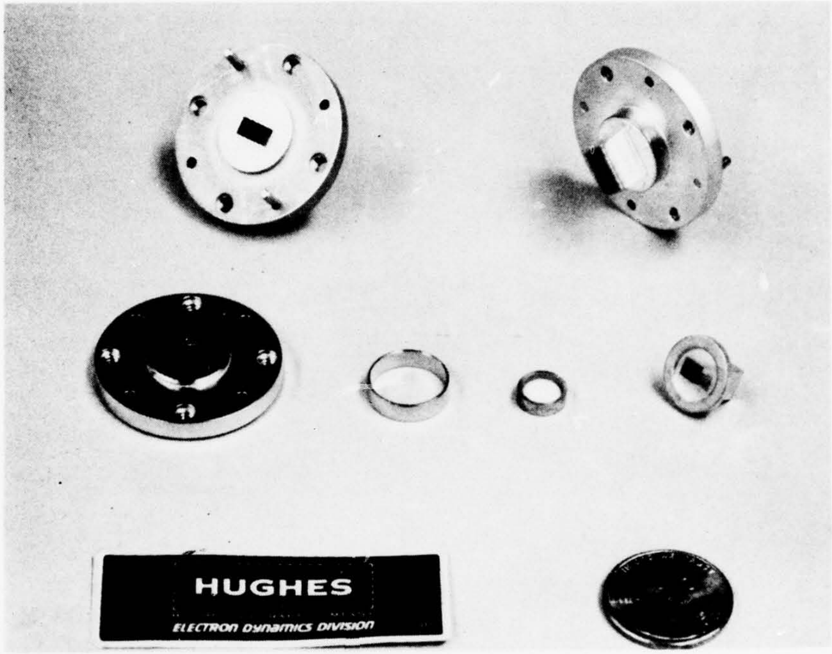

FIGURE 2-9 POKER CHIP WINDOW COMPONENTS.

A periodic permanent magnet (PPM) focusing configuration is used on the high power TWT because of its weight and overall efficiency advantage over a solenoid focusing scheme. The coupled cavity circuit provides a rugged, lightweight structure which is ideally suited for PPM focusing. Ordinarily, two criteria are applied: first, it is necessary to have sufficient magnetic field; and second, the ratio of plasma frequency wavelength to magnetic period should be at least 2.5 or higher. For TWTs with low perveance (as in this case) and large plasma wavelength, the second criterion should be replaced by considering the ratio of the electron scallop (due to the effect of transverse thermal velocities) to the magnetic period. A value of 1.5 is good, but sometimes, depending on the nature of the RF interaction, a ratio as low as 1.2 may be acceptable. If the ratio is unity, an unstable beam will result.

At X-band, for example, the focusing limitation in coupled cavity tubes in which the pole pieces form the walls separating the cavities is often pole piece saturation. At millimeter wavelengths, where the only practical scheme is to have the focusing structure external to the RF circuit, the limitation is the strength of the magnetic material. However, by employing samarium-cobalt (Sm-Co) a relatively new magnetic material which exhibits an extremely high energy product and coercive force the required peak field and period can be achieved.

In other TWT applications, the placement of Sm-Co magnet sections in the input section increased the beam transmission to the collector significantly. With the increased beam current to the collector, the interaction between the RF wave and the electron beam improved, thus increasing the power output capability of the tube. At the same time, the body currents were minimized, lessening the chance of the circuit to overheat. Also, the increased field provided by the Sm-Co magnets in the output section effectively improved the saturation RF defocusing effects of the beam. The focusing design was performed with a computer program that calculated statistical beam radii as a function of distance from the cathode in arbitrary focusing fields. The effect of thermal velocities was taken into account. The actual magnetic field required to focus the beam was 2800 Gauss, somewhat higher than the calculated value. This is due to the effect of RF defocusing forces in the saturation region of the tube. A schematic of the PPM focusing scheme is shown in Figure 2-10.

2.6 PACKAGE AND COOLING DESIGN

The mechanical design of the 914H encompassed several important considerations. These included the cooling method, structural design, operating environment and the electrical, mechanical and thermal interfaces.

The method of tube construction can be seen from Figures 2-11 to 2-14. Figure 2-11 shows a circuit section (vertical) brazed in place on an input/output transformer, while Figure 2-12 shows the two brazed stacks, transformer, stainless steel tube (which covers the stacks and is the valuum envelope for the circuit section), and the gun and collector pole piece. Figure 2-13 shows the pole pieces, magnets, ferrule and spacer assemblies and the stainless steel tube around which they are placed. Figure 2-14 shows the assembled tube before packaging. Figure 2-15 is the installation and control drawing for the 914H TWT. The final, packaged 914H TWT was shown earlier in this report (Figure 1-1).

The collector, discussed in Section 2-4, is a single stage design, cooled by forced air. The inside of the collector is insulated from ground by a thin sleeve of beryllium oxide, which however is a good thermal conductor.

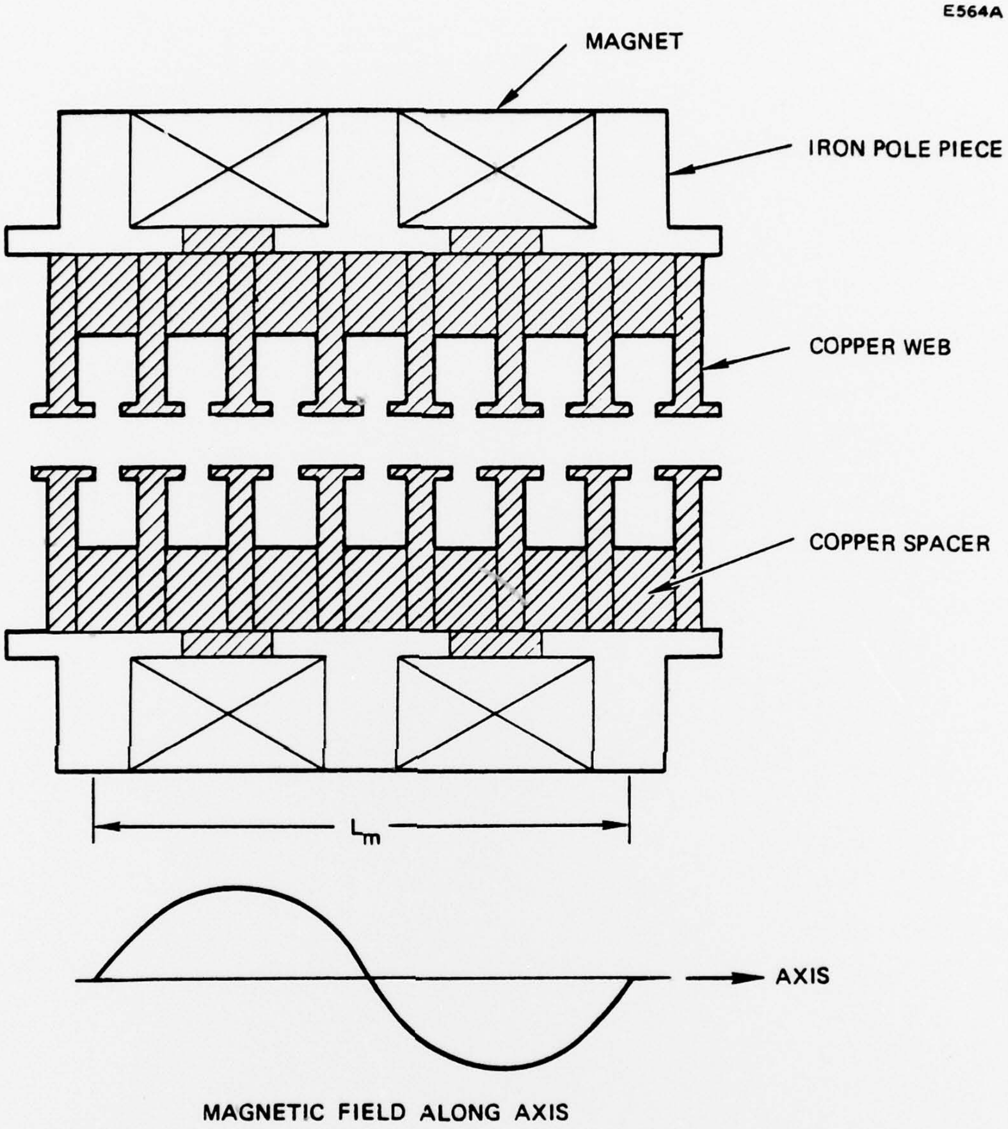

FIGURE 2-10 PPM FOCUSING SCHEME WITH EXTERNAL MAGNETIC CIRCUIT.

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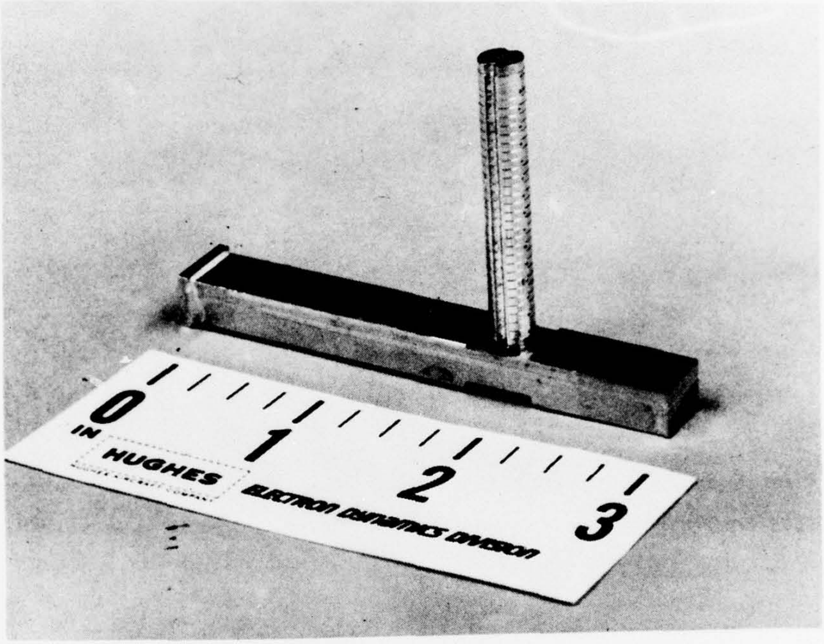

FIGURE 2-11 BRAZED CIRCUIT SECTION.

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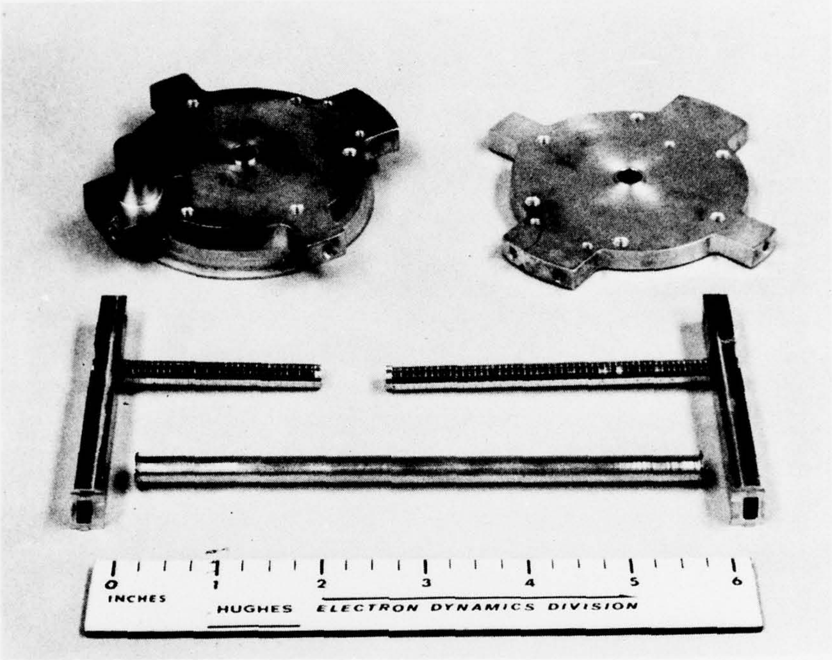

FIGURE 2-12 COMPONENTS AND BRAZED CIRCUIT SECTIONS.

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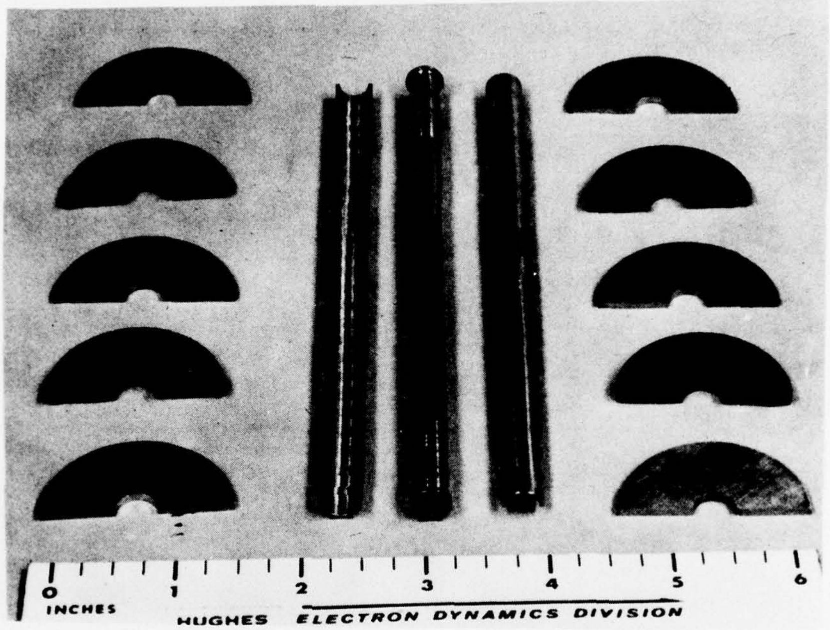

FIGURE 2-13 POLE PIECES, MAGNETS, FERRULE AND SPACER ASSEMBLIES.

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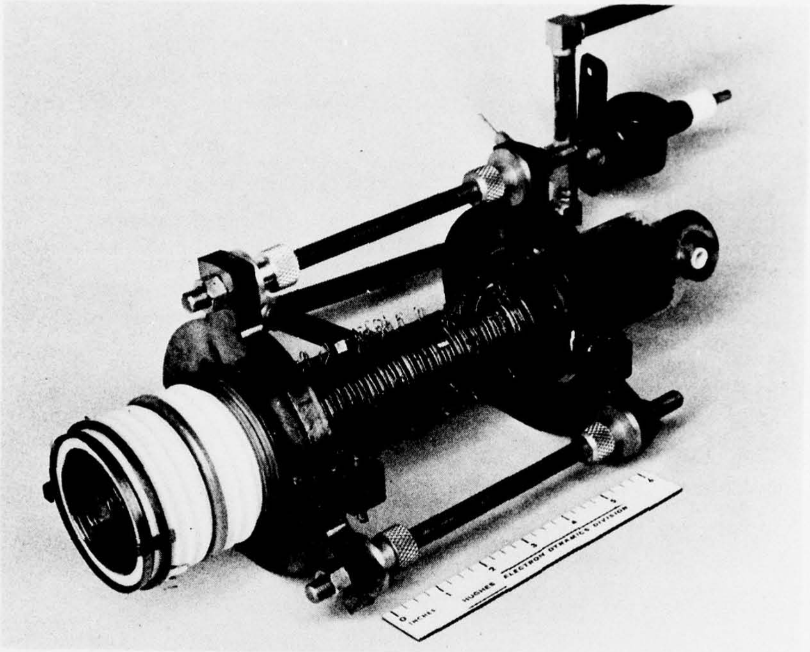
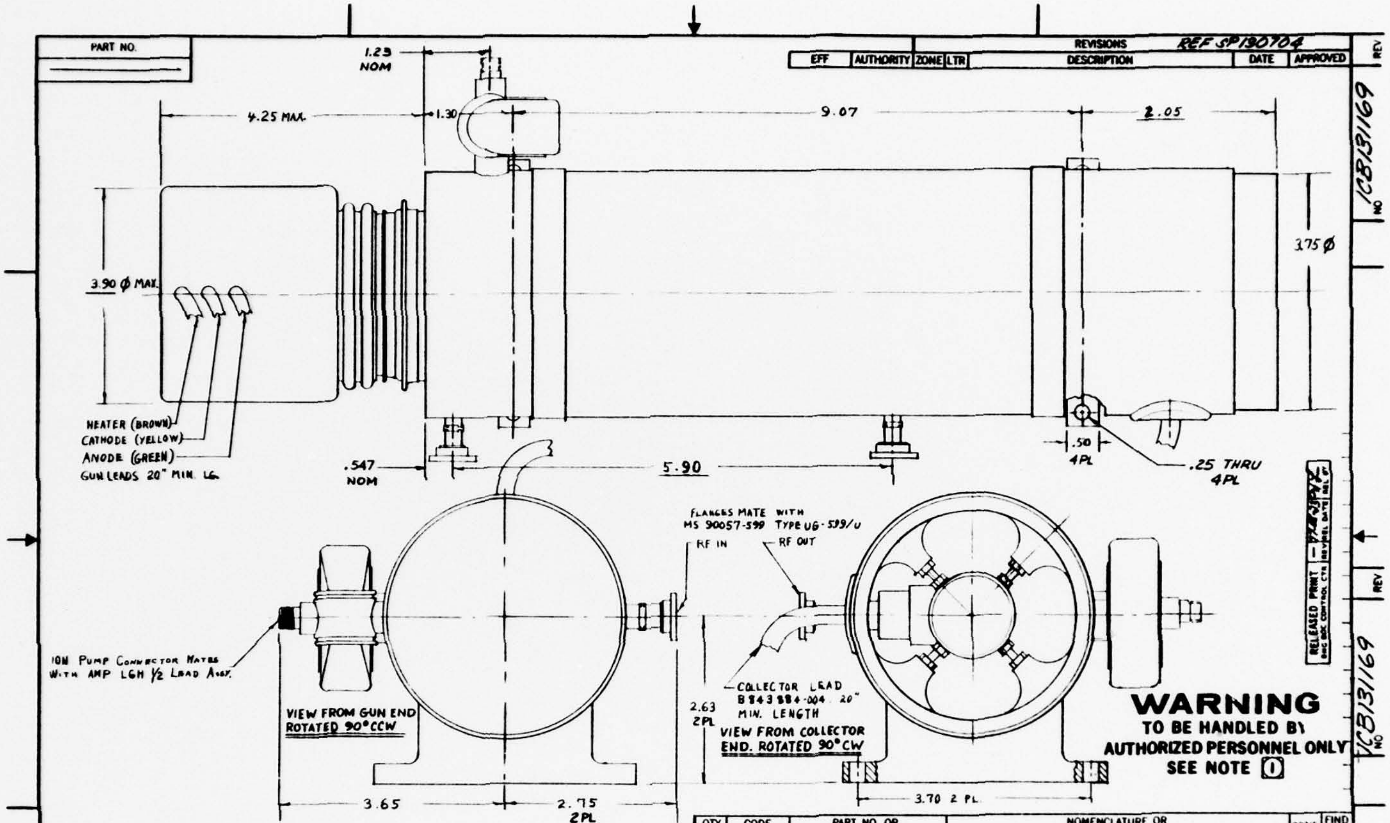


FIGURE 2-14 UNPACKAGED 914H TWT.



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APPLICATION	

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
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XX ③
ANGLES ±0° 30' FINISH 63/
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APPD		8/22/77

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TORRANCE, CALIF 90509

TWT, 914-H —
INSTALLATION CONTROL DRAWING

SIZE	CODE IDENT NO	DRAWING NO	REV
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3.0 TWT PERFORMANCE

During the development program, two 914H TWTs were built and tested. Excellent beam focusing was achieved on both tubes which was a prerequisite to meeting the high average power requirement of this millimeter-wave tube. A beam transmission to the collector in excess of 90 percent was achieved under worst case RF saturation conditions on both 914H TWTs. In addition to the good beam focusing, the first and second 914H tubes demonstrated very good RF performance. CW power output achieved over the 30.0 to 31.0 GHz bandwidth exceeded 160 watts average as shown in Figures 3-1 and 3-2. Tube number one actually demonstrated 200 watts average over a good portion of the frequency band.

With depressed collector operation, the minimum overall efficiency achieved was 27 percent on the 914H; however, an efficiency as high as 34 percent was achieved in the operating band. The demonstrated efficiency of the 914H is very high for a millimeter-wave tube of this type. The basic tube efficiency (without depressed collector operation) was measured at 15 percent which compares to an original design estimate of 14 percent.

The saturated gain of the 914H is 35 dB minimum. As shown in Figures 3-1 and 3-2, the flatness for fixed RF power input is approximately 1.0 dB peak to peak across the bandwidth. The small signal gain performance is shown in Figure 3-3. As shown, a small signal gain variation of approximately 5dB peak to peak was measured in the 914H. In order to reduce the inherent gain peaks in the small signal performance, an external equalizer will be required.

The electrical operating characteristics of TWT 1 and TWT 2 are shown in Table 3.1. As listed, the designed operating beam voltage for the 914H was -18kV; however, in order to properly center the operating band

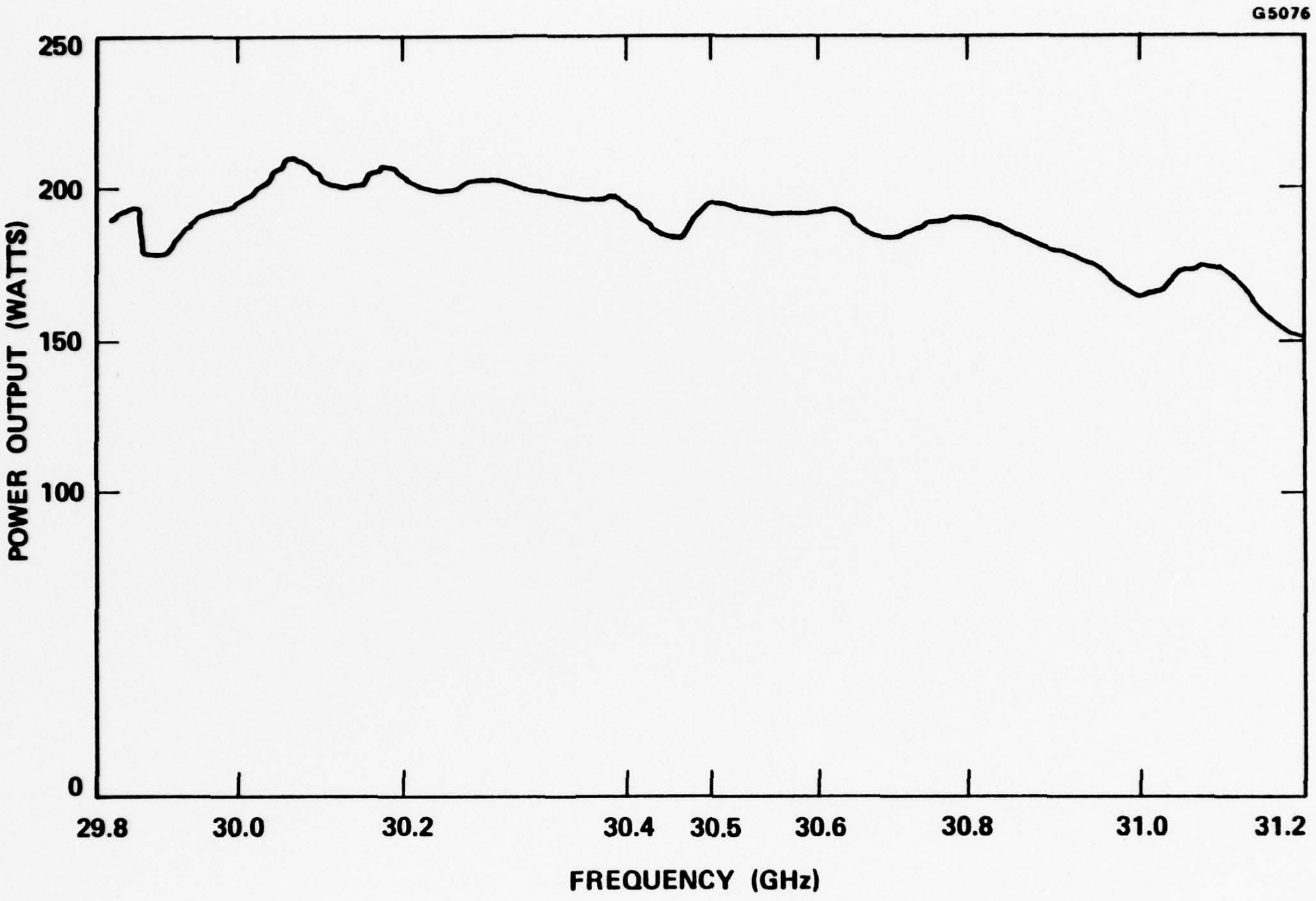

FIGURE 3-1 POWER OUTPUT VS FREQUENCY FOR THE 914H SN/1.

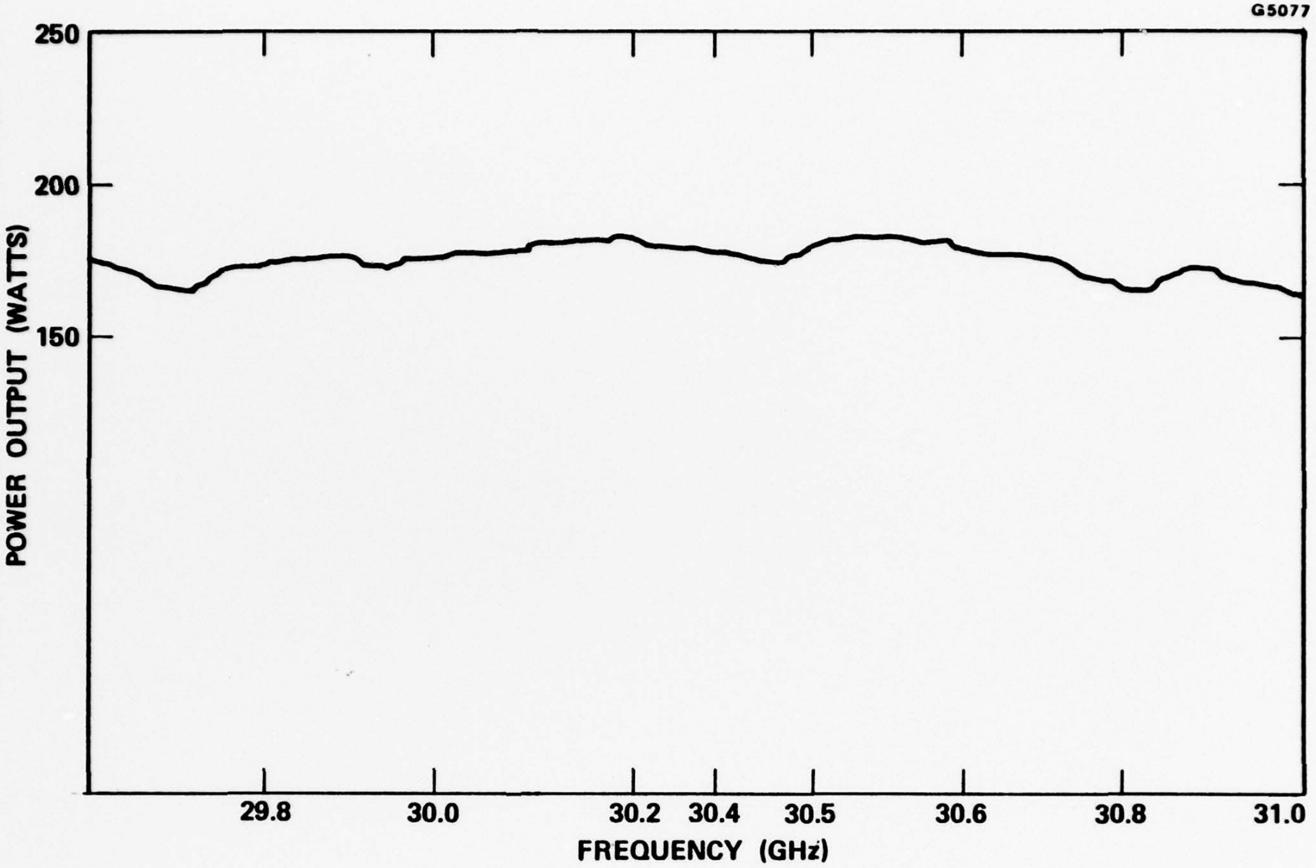

FIGURE 3-2 POWER OUTPUT VS FREQUENCY FOR THE 914H SN/2.

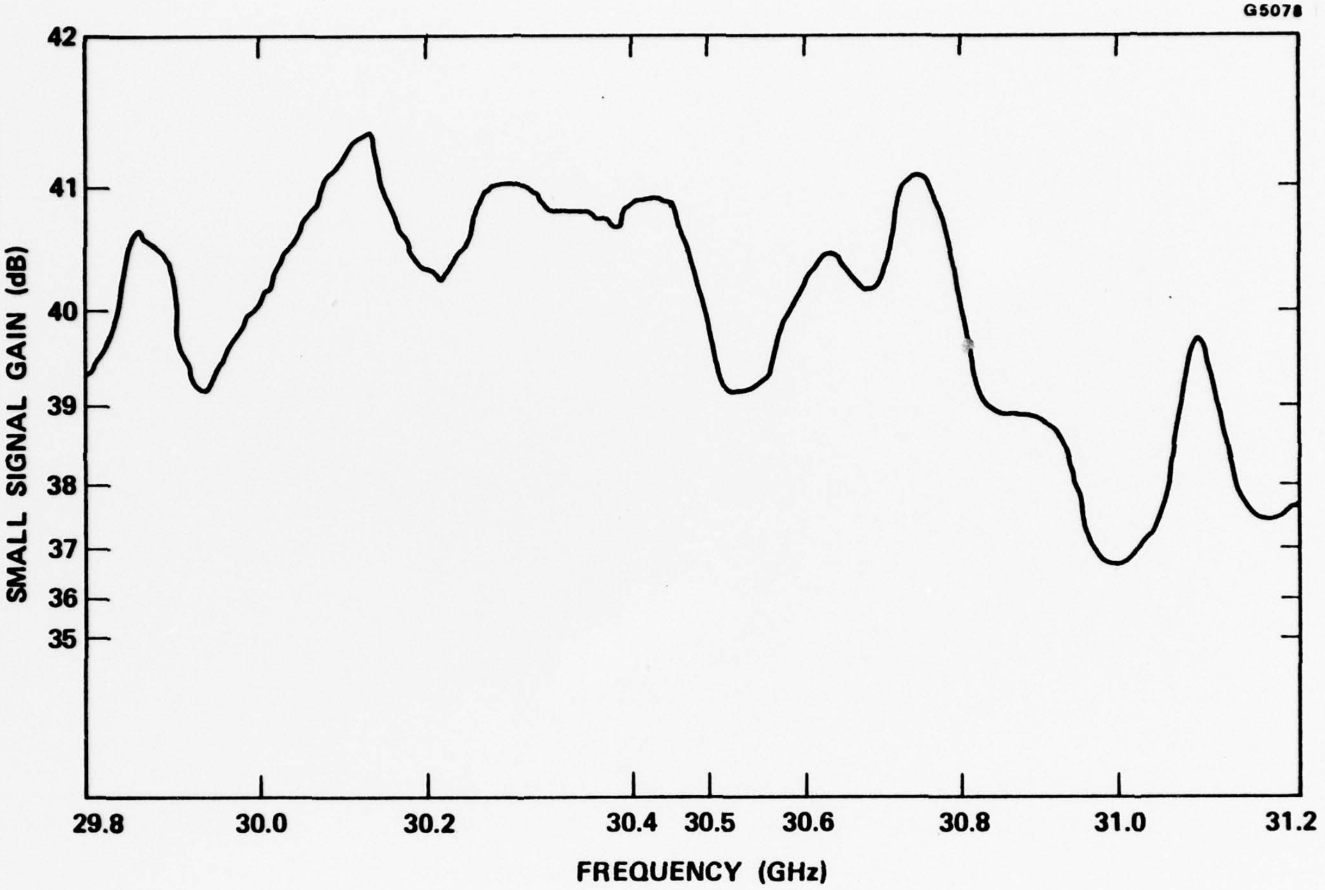

FIGURE 3-3 SMALL SIGNAL GAIN PERFORMANCE OF THE 914H.

and optimize the power output performance, a beam voltage of -16 kV was used. By adjusting the RF circuit design to operate at -18 kV and retaining the same basic efficiency design, it is anticipated that a minimum of 200 watts of CW power output can be achieved on a refined 914H.

Previous to the delivery of the two 914H TWTs, complete RF testing was accomplished with the exception of phase measurements which included phase linearity and phase pushing factors. During the last several months of performance testing, the special test equipment to perform the phase measurements was not available; therefore, the phase testing will be performed on the two 914H TWTs during the follow-on test program. The follow-on effort will consist of designing and building an external waveguide equalizer to improve the gain flatness of the tube and also will consist of performing detailed phase testing (phase linearity and operating factors) to further characterize the 914H tube performance.

In summary, the development of the 914H millimeter-wave TWT was very successful in that two tubes were built, tested, and delivered. Overall, the CW RF performance of the 914H including power output, bandwidth, gain, efficiency, and beam focusing look very good successfully achieving the goals of the program.

TABLE 3-1

PERFORMANCE OF THE 914H TWT

	Program Goal	Tube # S/N 1	Tube # S/N 2
Output Power (watts)	200(min)	165-210	165-185
Bandwidth (GHz)	1	1	1
Center Frequency (GHz)	30.5	30.5	30.5
Saturated Gain (dB)	35	35.5	36.5
Duty	CW	CW	CW
Cathode Voltage (kV)	-18	-16	-16
Cathode Current (mA)	79	67.3	67.9
Anode Voltage (kV)	0	0	2
Body Current (mA)			
dc	5	4.3	3.9
RF drive	8	6.7	5.55
Collector Voltage (kV)	-9.0	-8.0	-8.0
Heater Voltage (V)	6.0	6.0	6.0
Heater Current (A)	0.75	0.75	0.75
Ion Pump Voltage (kV)	3.0	3.0	3.0

4.0 CONCLUSION

The 914H development program resulted in the building, testing, and delivery of two high power millimeter-wave TWTs. Excellent beam focusing and RF tube performance was achieved on the two tubes which successfully demonstrated the design objectives of the program. CW power output in excess of 160 watts minimum was achieved over the 30.00 to 31.0 GHz frequency band with an overall efficiency higher than 27 percent. In order to improve the power output performance, a design refinement effort would be required to achieve the 200 watts minimum. This would primarily entail adjusting the RF circuit to operate at the originally designed -18 kV as compared to the operation at -16 kV for the first two tubes.

Both tubes were completely tested to characterize their TWT performance with the exception of measuring their phase characteristics. Phase measurements were not performed during this program due to the unavailability of the special phase test equipment. Detailed phase measurement of linearity and pushing factors will be performed during a follow-on effort to this program. Also during the follow-on program, an external equilizer will be built and tested to improve the gain flatness of the 914H TWT performance.