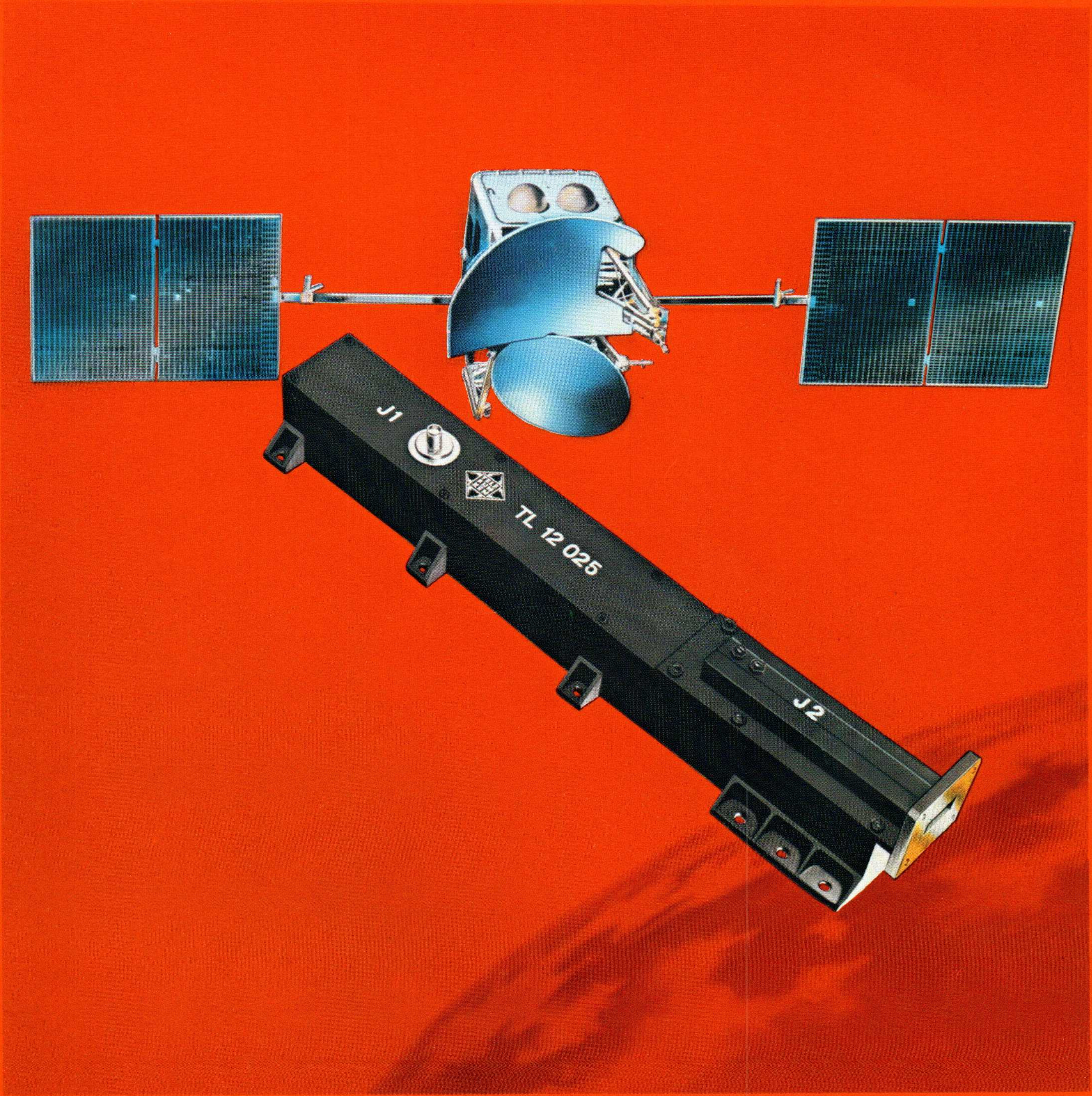
AEG-TELEFUNKEN

Microwave Tubes

Selected Papers on TWT's for Satellite Applications



Introduction

At the beginning of this century the wireless transmission of messages started with radio telegraphy.

The fast and impetuous development of this technology is well known. And it is also well known that the name TELEFUNKEN was closely associated with this development.

The rapid development of satellite communications clearly illustrates the importance and necessity of reliable communications.

In the extension of communications via satellites AEG-TELEFUNKEN are again playing a significant role.

Symphonie, the first European communications satellite, is equipped with the TELEFUNKEN traveling-wave tube TL 4003 which was developed specifically for this programme and has demonstrated its high quality in the interim with its exceptionally long life for example.

The successes achieved by AEG-TELEFUNKEN with this tube were the reason why so many international satellite communications systems are equipped with our traveling-wave tubes.

The following selection of papers and lectures about TELEFUNKEN traveling-wave tubes for communications satellites shall give you an impression of the contributions made by AEG-TELEFUNKEN towards reaching the present state of the art.

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Table I Communication Satellites Equipped with AEG-TELEFUNKEN TWT's

Programm	TWT Type	Sat. Output Power (W)	Frequency (GHz)	Efficiency (%)	Number of Collector Stages	Programm Status
Symphonie	TL 4003	13	3,7 – 4,2	32	1	in space
OTS	TL 12022	20	10,9 – 11,8	40	2	in space
Marats	TL 12022	20	10,9 – 11,8	40	2	11 GHz not applied
ANIK "B"	TL 12025 TL 4010	20 10	11,7 – 12,5 3,7 – 4,2	40 42	2 3	in space
TDRSS	TL 12030	30	11,7 – 12,2 und 13,4 – 14,05	41	2	in production
SBS	TL 12026	20	11,7 – 12,2	42,5	3	in production
ANIK "C"	TL 12016	15	11,7 – 12,2	42,5	3	in production

Traveling Wave Tubes for Communication Satellites

ROBERT STRAUSS, SENIOR MEMBER, IEEE, JORK BRETTING, AND ROBERT METIVIER

***Abstract*—Traveling wave tubes (TWT's) have contributed markedly to the development of communications satellites. As the prime-power consuming and transmitting device, the major transponder gain element, and the largest contributor to transmission nonlinearities, the TWT has been the focal point for continuous but carefully measured evolutionary improvements. Efficiency improvements continue to be made without compromising desired communications characteristics or tube lifetimes. These improvements have been made primarily in the RF circuit through loss reduction and phase-velocity tapering techniques, and in the spent-beam region through better multielement collector designs. Traveling wave tubes developed for satellites at 4 and 12 GHz are used as examples.**

Since TWT's are life-limited devices, emphasis has been placed on techniques ensuring long life in satellite applications. Both oxide- and dispenser-type cathodes are discussed and data on life characteristics are presented. During the past decade, while generally demonstrating excellent space lifetimes, operating TWT's continue to approach their potential cathode wear-out life, which is theoretically of the order of 10^5 h.

I. INTRODUCTION

SINCE the inception of active communications satellites, traveling wave tubes (TWT's) have played a fundamental role in their development. Typically, the TWT constitutes the major satellite power-consuming element as well as the sole telecommunications microwave power transmitter. It is also the transponder's major amplification element, and it is the largest contributor to transmission nonlinearities. Along with radiation-degradable solar cells, batteries, and station keeping fuel, TWT's remain among the satellite's basic life-limiting items. These features, in addition to the TWT's presently untaxed broad band capability, will continue to focus attention on this device.

The paper, after a brief review, discusses the most important design aspects of current space-type TWT's. First is the maximization of dc-toRF tube conversion efficiency at a given level of RF output power. The output-power operating point relative to saturation is drive selected, and is based on an acceptable level of intermodulation "noise" contribution to the total noise budget in the transmission path. Therefore, improvements in the tube's linearity which also preserve efficiency are of interest. The second major issue is the TWT lifetime and the techniques used to obtain acceptable life performance. The output power required (typically in the range of 4 to 20 W) determines, in part, the selection of the TWT's long-lived design. To date all *C*-band satellite TWT's have, for example, used oxide-coated cathodes with electron emission densities ranging from 100 to 300 mA/cm^2.

Although other TWT characteristics, such as gain (typically 40 to 70 dB), gain flatness, group delay, VSWR match, noise figure, overdrive response, dissipation, and weight, are important, each in its own way, they do not constitute sources of significant potential improvement at the present high level of device maturity. The major competitive incursion to TWT's comes from the longer lifetime potential and reduced weight of solid-state amplifiers. An indication of this trend is the use of solid-state driver amplifiers (3.7 to 4.2 GHz, 40-dB gain, ~1-W saturation power) to "back up" or replace driver TWT's. The recently launched SATCOM and COMSTAR satellites, for example, carried bipolar, transistor driver amplifiers. Future satellites are gradually expected to have ever greater complements of solid-state microwave devices as advances in power handling, combining, and efficiency occur.

II. BACKGROUND

In the early 1960's, when the first experimental active communications satellites (TELSTAR, RELAY, and SYNCOM) were launched, TWT's provided the RF output amplification. By that time, the TWT (invented 20 years earlier by Kompfner [1]) was already an established device. It had been mathematically characterized by Pierce in 1950 [2], and by the mid-1950's "line-of-sight" radio relay stations began using TWT's as transmitter output amplifiers [3], [4]. These early TWT's typically housed the electron gun, the helix slow-wave structure, and the beam collector in a glass envelope surrounded by a beam-focusing solenoid. This format, although usable in maintainable ground applications, was not attractive for weight-constrained space applications.

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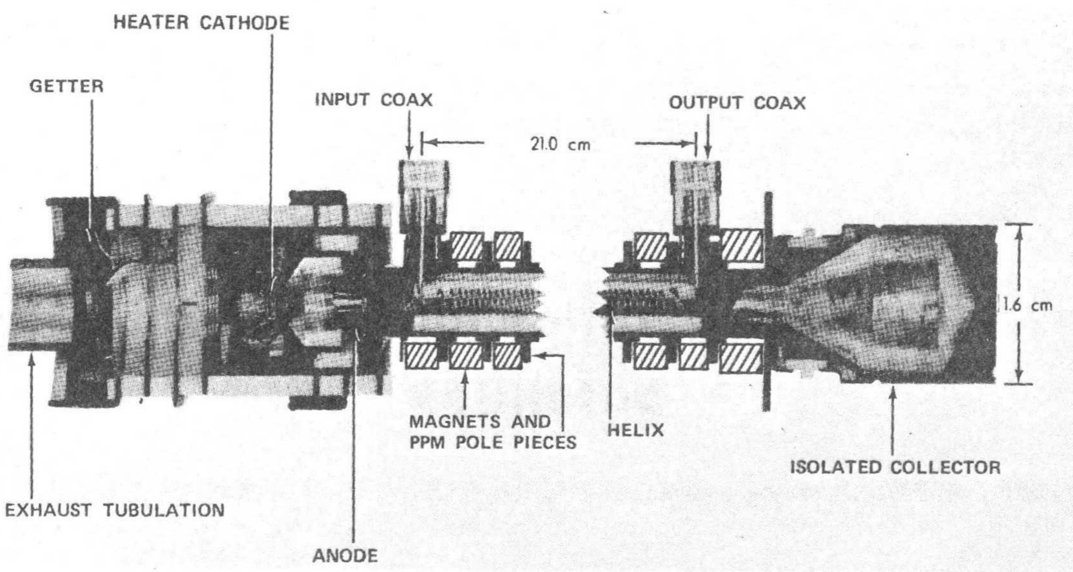


Fig. 1. Section model of 261H INTELSAT IV transmitter TWT single-isolated-collector design (courtesy of the Hughes Aircraft Electron Dynamics Division, Torrance, CA).

TABLE I
SUMMARY OF *C*-BAND TWT SPACE EXPERIENCE (THROUGH MARCH 1976)

Spacecraft and Launch Period	Tube Type[a]	Band-width (MHz)	Saturated Output Power (W)	Saturated Output Gain (dB)	Nominal Overall Efficiency[b] (%)	Cathode Loading[c] (mA/cm^2)	Space Operation No.[d]	Space Operation Total (~hr)
Early Bird (1965)	215H	35	6.0	41	36	180	2	56,000
INTELSAT II (1966-67)	226H 215H	130 130	0.06[e] 6.0	40 41	3 36	110 180	8 16[f]	200,000 200,000
INTELSAT III (1968-69)	233H 235	225 225	0.15[e] 12.0	47 42	10 33	130 140	10 10	416,000 416,000
INTELSAT IV (1971-75)	262H 272H 261H	500 500 36	1.5[e] 1.5[e] 6.0	36 36 58	15 15 30	280 200 190	26 2 168	180,000 8,000 2,300,000
TELESAT/WESTAR (1972-75)	276H 275H	500 36	0.4[e] 5.0	30 55	12 36	150 180	10 60	95,000 1,100,000
ATS-6 (1974)	233HC 235HD	30 700/400	0.2[e] 12.0	52 42	10 33	140 140	2 2[f]	15,000 15,000
SYMPHONY	TL 4003	90	13.0	46	34	120	4	15,000
INTELSAT IV-A (1975-)	276H 271H 275HA	500 36 36	0.4[e,g] 6.0 5.0	30 58 55	12 30 36	150 190 180	12 20 44	7,000 32,000 128,000
SATCOM (1975-)	296H	36	5.0	55	36	180	48	60,000
MARISAT (1976 -)	275H	1	5.0	55	36	180	2	1,000
						TOTAL:	446	5,240,000

[a]H = Hughes Aircraft Co., Electron Dynamics Div., Torrance, CA; TL = AEG/Telefunken, Ulm, West Germany.
[b]Single-collector TWTs.
[c]Oxide cathode.
[d]Most spacecraft use 2-for-1 redundancy.
[e]Driver TWTs.
[f]Phase combined.
[g]Solid state amplifier back up

Significant technology improvements continued to be made. The major developments included weight and power saving electron beam-focusing techniques such as periodic permanent-magnet (PPM) structures [5] and the bundling of precision helix slow-wave structures with ceramic support rods selectively coated with a virtually reflectionless, high-attenuation, and stable pyrolytically deposited carbon attenuator. High-temperature processing, made possible by the adaption of metal/ceramic vacuum seals, contributed to a "cleaner" and better controlled vacuum within the tube envelope. This pro-

TABLE II
CHARACTERISTICS OF THE 291H HELIX TWT

Characteristics at 1.5 GHz	Mode (anode controlled) 1	2	3
Saturated Power Output: P_2 (W)	9	30	65
Saturated Gain: G (dB)	25	37	54
Nominal Overall Efficiency: η_{ov} (%)	35	52	48
Cathode Loading: (mA/cm^2)	70	130	250

vided a more conducive environment for elevating the oxide-cathode current-density levels by a factor of 20 (from approximately 10 to 200 mA/cm^2) relative to those of the necessarily ultraconservative submarine cable tubes [6] having projected lives of more than 25 years. TWT's utilizing these features were fabricated in the early sixties in time for the first communications satellites [7]–[10].

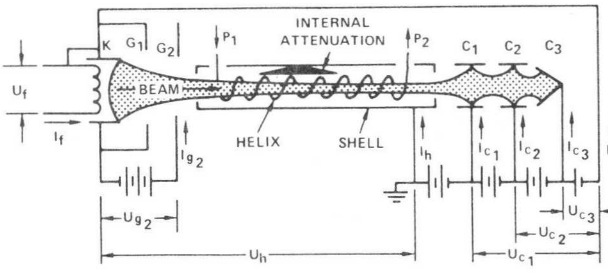
The basic aspect and design of TWT's have, by intent, remained virtually unchanged during the past decade. For example, at *C*-band over 500 tubes are now in space and several hundred more are scheduled for launch during the next few years. Total communications TWT space operating hours are well in excess of 6 million with at least an additional 3 million hours of "burn-in" screening and ground life testing. The basic tube parameters are listed in Table I. A representative design is the 261H (Fig. 1), which, as the 6.0-W INTELSAT IV output amplifier [11], has now logged in excess of 40 000 h each on 11 of 12 channels in the F2 spacecraft launched in January 1971.

In addition, during the past decade considerable tube development has occurred at frequencies other than *C*-band. A noteworthy development is a narrowband helix TWT at 1.5 GHz for the MARISAT program; this tube (291H) is a 3-mode device whose characteristics are given in Table II. Its high efficiency is made possible by a high-interaction-impedance helix design, helix resynchronization, and a 2-depressed-electrode, 3-stage collector [12].

At 12 GHz unusual improvements have also occurred. Two tube types, the Th 3535 and the TL 12022, have been developed in Europe for use on the OTS satellite. Both tubes achieve efficiencies in excess of 40 percent with double depressed-collector designs at power-output levels of approximately 20 W. Variations of these tubes will be described later in this paper to illustrate developments which represent advanced approaches.

III. TWT EFFICIENCY

Efficiency is the ratio of the RF power at the fundamental frequency (or frequencies) into a matched load and the electrical power absorbed by the TWT. The following will refer to TWT's utilizing an electron gun with a thermionic cathode that requires filament power ($U_f I_f$). The cathode current (I_k) is controlled by a voltage (U_{g2}) applied to the nonintercepting electrode grid-2 in the gun. As shown in Fig. 2, the grid is followed by a helix delay line for medium-power TWT's operated at voltage U_h, a collector assembly using one to three different stages operated at $U_{c1} \cdots {}_3$, and a periodic permanent magnet beam-focusing system. There are six different voltages which may be varied independently. Each set of voltages together with the RF drive (P_1) applied to the TWT input determines the distribution of current I_k on the delay line and the collector stages.



NOTE: $U_{g2} \sim U_h$, $U_{c3} \sim 0$ VOLTS
$I_k \sim I_h + I_{c1} + I_{c2} + I_{c3}$

Fig. 2. Three-electrode collector TWT schematic.

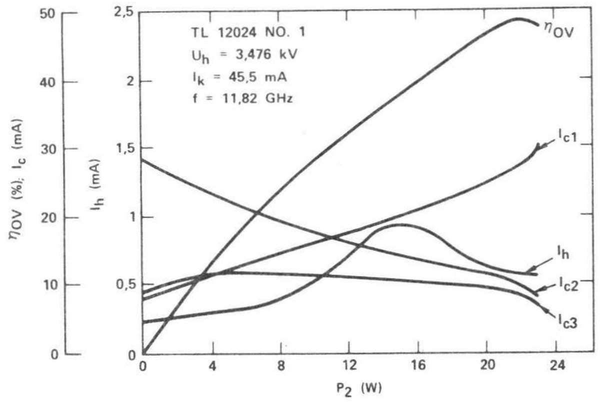


Fig. 3. Overall efficiency of the 3-electrode collector satellite TWT TL 12024 versus output power (uniform helix) showing level-dependent distribution of the beam current on the three collectors and the helix.

As an example, Fig. 3 shows for a 3-electrode collector, the output power and current distribution versus RF input power P_1 at fixed helix and collector voltages. The voltages applied to the TWT are generated by a power supply; by design, each terminal of this supply is characterized by a specific voltage and internal resistance. As a result of varying currents, TWT voltages also depend on RF drive (P_1). The overall efficiency η_{ov} for any value P_1 at a frequency (f) is

$$\eta_{ov} = \frac{G P_1(f)}{U_f I_f + U_h I_h + \sum_{1}^{3} U_{cv} I_{cv}}. \tag{1}$$

[$U_{g2} I_{g2}$ does not appear in the denominator since it is usually negligible relative to the remaining terms, and G is the amplifier power gain at $P_1(f)$.] The largest value of η_{ov} is obtained at saturation drive. Of all possible values of U_{cv} there exists a maximum efficiency, η_{max}, for a fixed helix voltage. Further, as a function of helix voltage there is a maximum value of η_{max}, i.e., the optimum efficiency (η_{opt}) of the TWT.

The TWT efficiency depends on two separate processes.

a) During the interaction processes, part of the kinetic electron energy is converted to RF energy at the fundamental frequency (or frequencies), at its harmonics, and at frequencies corresponding to intermodulation products in the case of multicarrier operation. Part of the RF energy is transformed into heat as a result of RF losses on the delay line, in the internal attenuator, and in the RF matching section. The electronic efficiency (η_{el}) is the ratio of the total generated RF power to the beam power $U_h I_k$, whereas the beam efficiency

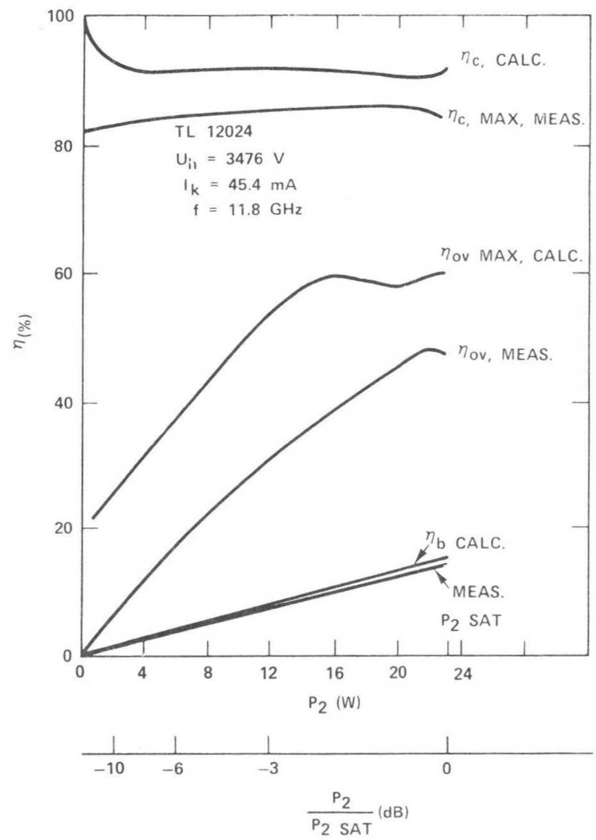


Fig. 4. Measured and calculated values of beam efficiency, overall efficiency, and collector efficiency versus output power for the 3-collector TWT TL 12024.

(η_b) is the ratio of the output power P_2 at the fundamental frequency (or frequencies) to the beam power.

b) Efficiency is improved by means of a multistage collector configuration. In this process, electrons are decelerated to reduce the heat generated by the electrons landing on the collector, sometimes referred to as "soft landing" electrons. The extent to which this deceleration is achieved is measured by the collector efficiency (η_c)

$$\eta_c = \frac{P_{\text{spent beam}} - P_{\text{dissipated}}}{P_{\text{spent beam}}}.$$

It can be shown that

$$P_{\text{spent beam}} = U_h I_k (1 - \eta_{el})$$

$$P_{\text{dissipated}} = \sum U_{cv} I_{cv} - [U_h I_k \eta_{el}]$$

and

$$\eta_c = \frac{1 - (1/U_h I_k)\left[\sum U_{cv} I_{cv}\right]}{1 - \eta_{el}}. \tag{2}$$

It is possible to calculate η_c from the electron-velocity spectrum of the spent beam and the applicable collector configuration. Difficulties arise when η_c must be evaluated from measurements. In this case, direct thermal measurement of collector loss and spent-beam power or a reasonable estimate of η_{el} from the measurement of η_b is required. Calculated values from a computer program derived by Bobisch [13] are shown in Fig. 4 as an example of the variation of these efficiencies for a specific TWT design.

A. Nonlinearities

Since TWT's are used as power amplifiers, it is desirable that they be operated at or close to saturation. In the transmission of broadband information-carrying signals at or near saturation, limitations for acceptable distortion are imposed. These limitations result from systems considerations such as the kind of modulation utilized, e.g., single-carrier FM, multicarrier FM, FDMA, or TDMA. Hence, system requirements are transformed into tube requirements for phase nonlinearities and carrier intermodulation product ratios.

Phase nonlinearities are measured by the total nonlinear phase shift between zero drive and TWT saturation or its derivatives, such as AM/PM conversion and AM/PM transfer coefficients [14]. The actual efficiency, limited by nonlinearities, is defined as the operating efficiency (η_{op})

$$\eta_{\text{op}} = \frac{GP_1\ (f, \text{nonlinearities} \leqq \text{limit})}{U_f I_f + U_h I_h + \sum U_{cv} I_{cv}}. \tag{3}$$

This operating efficiency is obtained by varying the operating parameters (U_h, P_1, U_{cv}) of the TWT while simultaneously requiring that nonlinearities do not exceed the established limits. It is obtained by plotting efficiency and the required nonlinearity bound as two sets of curves versus power (output or input) and eliminating power to obtain one set of curves relating efficiency to nonlinearity. The envelope of this set of curves relates the operating efficiency (η_{op}) to the desired values of the nonlinearities.

Fig. 5 shows the envelope curve for a typical sample of a single-collector TWT developed in 1968 and the equivalent curve for a triple-collector TWT recently developed. Reasonable values of AM/PM conversion coefficient (Kp) are indicated. The comparative benefit of multicollector tubes is significant. Similar curves can be obtained for η_{op} versus total phase shift or 2-carrier intermodulation.

IV. TWT Design

The question now arises as to how to design a TWT for the best operating efficiency. As indicated, this problem may be separated into two parts, namely, the beam/slow-wave interaction process (beam efficiency) and the energy-recovery process (collector efficiency). Depending on the operating frequency, the bandwidth required, and the output-power generating point, a choice of electron-gun design, helix/barrel, PPM structure, and collector(s) is made.

For space TWT's, the helix has been by far the most suitable slow-wave interaction structure. In practice, the helix radial propagation constant

$$\gamma a = \frac{2\pi f}{v_p} a \tag{4}$$

where a is helix radius (in m), f is midband operating frequency (in Hz), v_p is circuit phase velocity (in m/s) $= 6 \times 10^5 (U_h)^{1/2}$ (in V), is typically selected between 1.0 and 1.7 rad at midband with γa of ~1.35 nearly optimum [15]. For fixed-beam characteristics, a lower γa choice will result in a higher interaction impedance [12] and beam efficiency with a more nearly constant RF field across the enclosed beam. A higher γa choice is more suitable for broadband uniform operation with less harmonic content and a lower beam efficiency. Beam efficiencies may range from circa 10 to 25 percent. Computer calculations [16] show that there is generally a

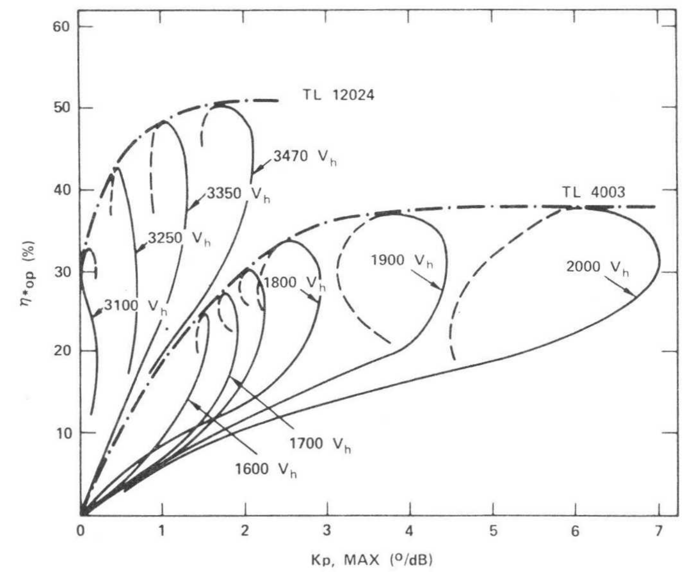


Fig. 5. Operating efficiency versus maximum tolerable AM/PM Conversion coefficient (Kp) for TL 4003 (single collector) and TL 12024 (three collectors) with helix voltage as a parameter [(η_{op}^*)] excludes filament power for comparative purposes. The 4-GHz TL 4003 uses an oxide cathode which requires slightly less power than the dispenser cathode used in the 12-GHz TL 12024).

TABLE III
BEAM EFFICIENCY, OVERALL EFFICIENCY, AND COLLECTOR EFFICIENCY FOR THREE COLLECTOR TWT'S

Efficiency	TL 12023[a]	TL 4012[b]	TL 12023[c]
η_b (at saturation)	13	15	21
η_{ov} (at saturation)	45	45	44
η_c	85	82	71

[a]11 GHz, 20 W, three collectors, uniform helix.
[b]4 GHz, 12 W, three collectors, uniform helix.
[c]11GHz, 20W, three collectors, tapered helix.

slight reduction of theoretical operating efficiency with increasing beam efficiency. Higher beam efficiencies result in a greater electron-velocity spectrum in the spent beam and make the attainment of higher collector efficiencies more difficult. In other words, additional multicollector stages are necessary to capitalize on high beam efficiency so that optimum overall efficiency, as defined in (3), can be attained. This trend is indicated in Table III for 12- to 20-W helix TWT's.

V. HELIX/GUN DESIGN TECHNIQUES

The choice of helix dimensions is fundamental and, as will be shown, represents a compromise between conflicting requirements. It is generally accepted that the interaction efficiency of a uniform helix TWT is proportional to Pierce's parameter C [2] as follows:

$$\eta_b \sim C = \left[\frac{I K}{4 U_h}\right]^{1/3} \tag{5}$$

where I is the beam current, U_h the helix voltage, and K the beam-to-helix coupling impedance. Hence, the tube should be operated at high beam current and low voltage for greater efficiency and high gain per unit length. Also, the coupling impedance must obviously be as high as possible.

A fundamental consideration in the choice of the operating voltage and in turn the current is the ability to adequately focus the electron beam. The current intercepted by the helix, disregarding thermal and reliability considerations for the moment, heavily penalizes the overall efficiency. For example, an increase of 1 mA in a TWT delivering 20 W at 11 GHz, with a cathode current of 40 mA and an efficiency of 40 percent, will raise the power use by 2.2 W and drop the overall efficiency by 1.7 percentage points.

There is an approximate limit to the maximum value of the perveance of a PPM focused electron beam

$$P_{\mu\max} \sim 0.15 \left(\frac{B}{1.8}\right)^2 (\gamma b)^2 \lambda^2 \tag{6}$$

where P_μ is beam perveance = $(I/U_h^{3/2})$, I is cathode (beam) current (in A), U_h is helix voltage (in V), B is peak PPM axial magnetic field (in T), b is mean beam radius (in m), λ is wavelength in vacuum (m), and

$$\gamma b \sim \frac{\gamma a}{2}.$$

This limiting equation is derived from the Brillouin field beam focusing condition, modified for PPM focusing and combined with (4).

Efficiency considerations lead to a value of γb of the order of 0.5 to 0.6 rad. For B = 0.2 T, corresponding to the maximum field obtainable from Alnico 8 (permanent magnet) material, the following result is obtained at 11 GHz:

$$0.3 \times 10^{-6} \lesssim P_{\mu\max} \lesssim 0.5 \times 10^{-6}.$$

With an interaction efficiency of 15 percent, a 20-W tube, for example, would operate at 2900 V and 46 mA of beam current. The winding diameter of the helix would be about 0.9 mm (0.035 in). This limiting perveance value can now be extended by using cobalt/rare-earth magnets. Peak magnetic field values of 0.3 T are attainable. It should be noted that in the case chosen, the magnetic focusing field does not depend on the power, but only on the frequency and the perveance at a given γb.

The choice of the helix diameter, and thus (as will be shown later) the TWT helix voltage, is mainly governed by the quality of the electron gun, as measured by the cathode current, the emission homogeneity, the beam convergence, and the laminarity. For a potential operating life of over 100 000 h, the cathode current density should probably not exceed ~200 mA/cm² with an oxide cathode, or ~0.8 A/cm² with an impregnated cathode ("dispenser" type). A high-interaction-efficiency 20-W 11-GHz TWT requires a beam of about 40 mA, which would in turn require a beam convergence greater than 100 for an oxide cathode. Such a gun would be difficult to produce in a controlled and reproducible manner. The dispenser cathode therefore becomes the logical choice at this frequency and power level. The necessary convergence is reduced to about 25 for a cathode load of 800 mA/cm² and a beam diameter (b) of 0.5 mm (0.020 in).

This combination makes it possible to design a gun having good laminarity at the "crossover" (transition from electrostatic to magnetic focusing) and a constant emission density (to within 10 percent) over the cathode surface. The electron gun is designed with the aid of a computer program that solves Poisson's equation in the presence of a magnetic field. An important point is the effect of the radial velocities of the elec-

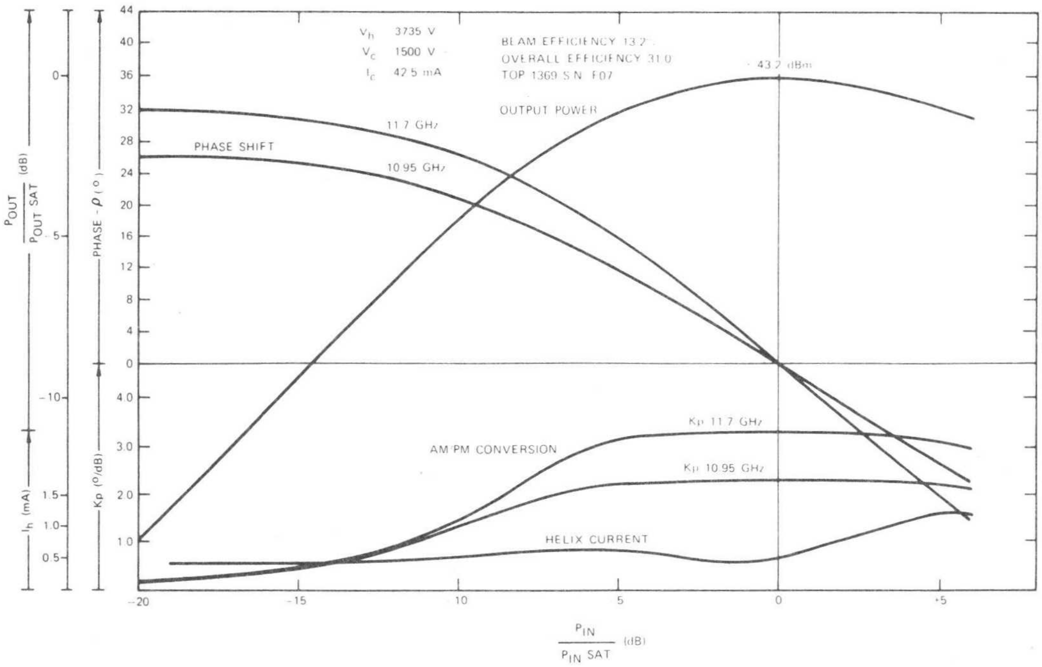


Fig. 6. 20-W, 11-GHz constant pitch helix, single-collector TWT (TOP 1369).

trons emitted by the "hot" cathode [17]. The electrons are emitted from the ~1300-K temperature cathode surface with velocity components in all directions, following Lambert's law and with a statistical averaged energy given by

$$U = kT/e = 0.113 \text{ eV}$$

where T is the absolute cathode temperature, e the electron charge (1.60×10^{-19} C), k is Boltzmann's constant (1.38×10^{-23} J/K), and U is the accelerating potential expressed in volts.

Statistical analysis shows that several percent of the electrons can be emitted with a radial velocity equal to or greater than $\frac{1}{2}$ V. An idea of the effect of such a velocity component on the beam diameter at crossover (where the beam comes under the control of the magnetic field) can be obtained. Assume that, during the time when the electrons travel from the cathode to the crossover point, they are moving radially with an energy of 0.5 eV. Computation gives a deflection of 0.25 mm for a cathode-to-crossover distance of 1 cm and an accelerating potential of 3700 V. Hence, to obtain better than 99-percent beam transmission, the helix diameter must be at least 0.5 mm more than the computed beam diameter. Nevertheless, the homogenous theoretical beam diameter, taken into consideration when computing the interaction with the helix, remains near that originally computed; i.e., it is increased by only about 10 percent, due to electron spreading and PPM beam ripple.

Pierce's theory holds that flat TWT gain is obtained when the radial propagation constant γa (as indicated previously) has a value of approximately 1.5 rad. For tubes with relatively narrow instantaneous bandwidths (about 10 percent or less), as used in communications satellites, this value is too high for optimum bean efficiency. Experience, confirming the computations, has shown that it is possible to obtain a flat gain in a 1-GHz band centered on 11 GHz, with a slow-wave structure consisting of a uniform pitch helix and $\gamma a = 1.2$. The increase in the coupling impedance (K) from this decreased diameter with respect to Pierce's optimum value is of the order of 50 percent, for a constant ratio of beam diameter to helix diameter. The result is a substantial increase in the interaction efficiency.

The specific operating (helix) voltage remains to be chosen. The helix voltage of a TWT delivering, for example, 20W at 11 GHz should be between 3 and 4 kV, which corresponds to a 15-percent helix/diameter variation, whereas the perveance varies by 50 percent, from 0.27 to 0.13×10^{-6}. The variation in Pierce's parameter C and in turn beam efficiency corresponding to this large change in perveance is only 20 percent. However, the final operating voltage within this range will be conditioned by the quality of the electron gun that can be fabricated so that the excellent beam transmission through the smallest possible helix diameter is reliably achievable.

Fig. 6 shows an example of a 20-W TWT at 11 GHz. This tube uses a constant-pitch helix (pitch approximately 450 μm). The inner-helix diameter is 1.1 mm (0.043 in) for an operating voltage of 3.75 kV ($\gamma a \simeq 1.2$). The helix is a tungsten tape of 0.1- $\times$ 0.2-mm (0.004-in $\times$ 0.009-in) cross section. The overall efficiency is typically 31 percent with a single-stage depressed collector, and the beam efficiency is near 13 percent with a maximum small signal to saturation phase shift of less than 35°.

Improvements in coupling impedance (K) were obtained by confining more of the electrical field within the cylindrical space inside the helix. For example, with the same inner helix diameter, the use of a "flat" wire (tape) instead of a "round" wire increases the coupling impedance by 15 to 20 percent, and at the same time improves the thermal contact with the dielectric helix supports. Winding a tape tungsten helix with good accuracy and reproducibility is mechanically more difficult than with round wire.

The helix is supported by three ceramic rods, usually in a triangulated thin-wall metallic shell. The effect of this bundling is to "load" the helix, causing a reduction in phase velocity and interaction impedance due to the effective dielectric constant plus circuit losses from the dielectric losses. In addition, high rod thermal conductivity and contact pressure are necessary to provide a suitable heat path for the heat generated on the helix. The choice of rod materials which have suitable mechanical, thermal, and dielectric properties is limited. They are as follows.

a) *Alumina* (Al_2O_3) has a high dielectric constant, about 9.3, and a fair thermal conductivity, about 0.3 W/cm/°C.

b) *Beryllia* (BeO) has a lower dielectric constant, about 6.3, but excellent thermal conductivity, 2 W/cm/°C.

c) *Boron nitride* (BN), in the anisotropic form, has a plane dielectric constant of 5.3 and good thermal conductivity, 0.7 W/cm/°C.

d) *Isotropic boron nitride* (IBN) has the lowest dielectric constant (3.0) and a fair thermal conductivity of 0.21 W/cm/°C.

As an example, the tube shown in Fig. 6 utilizes IBN support rods and a relatively high midband impedance (70 ohms) is retained. Simultaneously, a good thermal transfer characteristic is confirmed by the temperature gradient between the helix and the envelope, which is less than 30°C/dissipated W/cm of helix length. Under these conditions, the tungsten helix temperature is controlled during operation, and the RF losses are minimized.

It would, of course, be possible to reduce these losses even more by making the helix from a metal having better electrical conductivity than tungsten (copper, for example), or by coating the output section tape with tungsten and ground shell with copper (using sputtering or sintered electrolytic deposition). These two techniques are usable, but the resulting efficiency gain of one to two percentage points must be carefully evaluated against the chance of vaporizing copper due to local transient beam interception.

The influence of the gain of the last helix section on the efficiency was studied. It was found that the efficiency is nearly independent of this gain as long as it exceeds 30 dB. Below that gain figure, the beam efficiency falls off very sharply at the same time that the phase characteristics become degraded. Two percentage points are lost from the beam efficiency at a gain of 25 dB and four points at 23 dB. Simultaneously, the phase shift increases by 6° and 12°, respectively.

VI. The "Tapered" Helix

The energy conservation law indicates that, in a TWT delivering 20 W with a 40-mA electron beam current, the electrons have lost an average of 500 eV of their energy. This means that near the RF output, where the electrons have begun to give up a considerable fraction of their energy and velocity, the RF wave and the beam are no longer well synchronized.

A recognized method for increasing the efficiency consists of progressively changing (tapering) the helix pitch toward the RF output so that the best possible synchronism is maintained between the RF wave and the electron beam. The reduction in the helix pitch must be concentrated in a short section of helix because the beam decelerates over a distance corresponding to only the last few wavelengths of the slow wave. As an example of this technique, a tube with a 1-cm-long "taper" (linear pitch reduction) helix in the output section was developed. The interaction efficiency was increased to 15 percent, for an increase of about two percentage points with a maximum pitch reduction of only 8 percent. The small signal to saturation phase shift increases with frequency, from 29° at 10.9 GHz to 36° at 11.8 GHz. The AM/PM conversion coefficient did not exceed 3.2°/dB.

TABLE IV
Performance Characteristics of Single-Collector Th 3512
[S/N 29, f = 11.35 GHz, Ik = 37 mA (constant)]

U_h (V)	Saturation Phase Shift Delay (degrees)	Beam Efficiency, η_b (percent)	Overall Efficiency, η_{ov} (percent)
3930	46	16.4	38
3830	39	15.7	36.5
3730	32	14.8	34.5
3630	25	13.7	32.6
3530	19	12.3	31.5

An important TWT characteristic is the "overvoltage effect" which relates efficiency to phase delay. If the helix voltage is varied while the beam current is held constant, the output power increases with the beam power (and thus with the helix voltage), but the efficiency also increases. Unfortunately, the small signal to saturation phase shift, and thus the AM/PM conversion coefficient, increases also. Under these conditions, the helix voltage operating point must be chosen as a function of the phase shift specification, as shown in Table IV.

A corresponding effect is observed when the helix pitch is reduced. This occurs because a helix pitch reduction amounts to an effective increase in the difference between the beam velocity and the RF wave phase velocity. This increase is the equivalent of an increase in the helix voltage in the "large signal" region of the tube. Therefore, the effects of increased nonlinearity with increased beam efficiency due to "overvoltage" and "phase helix tapering" are analogous [18].

VII. The Double-Taper Helix

A new procedure has been developed to at least partially overcome the problem of increased nonlinearity with increased beam efficiency. The initial idea came from observing the operation of a TWT with low helix voltage (undervoltage). For example, the TH 3512 normally operates with 3730 V on the helix, but if that value is lowered to 3330 V, an interesting result is obtained. The interaction efficiency is obviously reduced somewhat (to about 8 percent for an output power of 10 W at saturation), but the overall phase shift from small signal operation to saturation is zero, and actually takes on positive values below saturation. This is explained by the fact that under these conditions the slow-wave structure is coupled to the fast space charge wave of the beam, whereas in normal operation coupling is only to the slow space-charge wave [19].

Thus a helix section of increased pitch would have the same effect on the phase as a reduction of the helix voltage and the result could be made to partially compensate for the phase shift caused by the deceleration of the beam as it surrenders energy to the RF field. The "increased pitch" section would have to be removed from the output to avoid detracting from the efficiency, but it would also have to be placed where the signal is already large, since the phase shift results from nonlinearity effects. The section of increased phase velocity would, in turn, be followed by a reduced velocity section, nearer the output, to retain the efficiency. Of course, for acceptance this "double-taper" concept would have to produce an overall increase in the efficiency and linearity.

The concept of the double-taper, as shown in Fig. 7, divides the helix into five distinct sections.

a) In the first section, the fixed helix pitch corresponds to

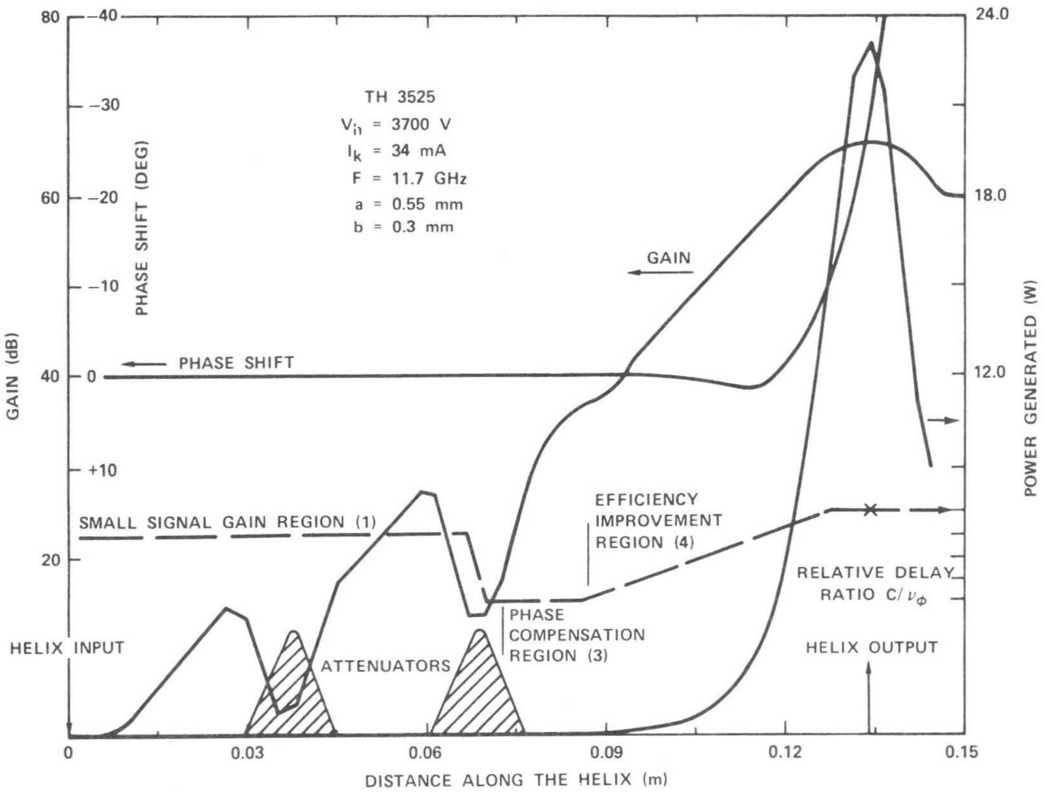


Fig. 7. Double-taper helix profile and computation sample, large signal analysis.

the maximum small signal gain for the selected operating voltage.

b) The next section is the transition zone (under the attenuator) with a fast change in the delay ratio (C/V_p), where C is the speed of light and v_p is the circuit phase velocity.

c) The third section is the zone of positive phase compensation whose depth and length ("hole") define the greater or lesser coupling to the fast space-charge wave, and thus the amount of phase compensation introduced.

d) In the fourth section, the delay-ratio slope is constant. In other words, the helix pitch decreases linearly versus distance from the zone of phase compensation to nearly the end of the helix. At the beginning of this section the wave carried by the helix and the slow space-charge wave carried by the electron beam are relatively far from synchronism, resulting in a weaker interaction. Interaction becomes stronger when moving farther along the helix. As a result, the beam bunching (RF component of the beam current) is progressively greater for a smaller velocity spread within the electron beam. Consequently, both interaction and depressed collector efficiencies are considerably enhanced. The bunching or "phase focusing" is optimized when the slope of the taper chosen provides a constant phase difference between RF beam current and helix RF voltage all along the variable-pitch helix region.

e) Finally, the very short fifth section of constant delay ratio makes it possible to attain maximum taper effectiveness (2-3 wavelengths). The choice of the pitch for this last section is conditioned by the usual efficiency versus phase shift compromise.

The main performance characteristics of the TWT using this helix are given in Fig. 8. Comparison of Figs. 6 and 8 indicates that the beam efficiency of the double-taper TWT is 17.2 percent versus 13.2 percent for the constant-pitch helix tube, despite nearly the same helix voltage and band edge phase shifts. The overall efficiency has been raised from 31 to 43 percent. The two results are not directly comparable because the double-taper TWT has been operated with a 2-stage depressed collector. Nevertheless for comparison if the second collector stage is operated at the same potential as the first, the efficiency still exceeds 36 percent.

In addition, since the helix pitch up to the second attenuator is chosen for constant maximum gain, the gain variation in the 1-GHz band is extremely small (less than 1 dB for a saturated gain of 55 dB). The peak-to-peak group-delay distortion introduced by the double-taper tube is less than 0.1 ns in 100 MHz.

What are limitations of the double-taper? First, determination of the helix profile becomes a costly operation, necessitating the use of a proven computer program, followed by numerous trial and error steps to properly mate the helix to the attenuators and output. Winding a complex helix with great precision is a difficult mechanical problem. In addition, certain operating characteristics, such as the output hot VSWR, become more critical. The double-taper technique is also not applicable to tubes with large instantaneous bandwidth. The weak interaction mechanism, with a constant phase difference between the RF wave and the beam current, provides optimum efficiency for a relatively critical helix length.

The above results do not constitute the ultimate performance. To further improve the performance characteristics, it became necessary to have a longer helix to compensate for the gain lost in the output section. For instance, the TH 3535 delivers 20 W with 60 dB gain at an efficiency of better than 44 percent and a maximum phase shift of only 28°, in the same 10.95- to 11.7-GHz band utilizing a longer helix. A third col-

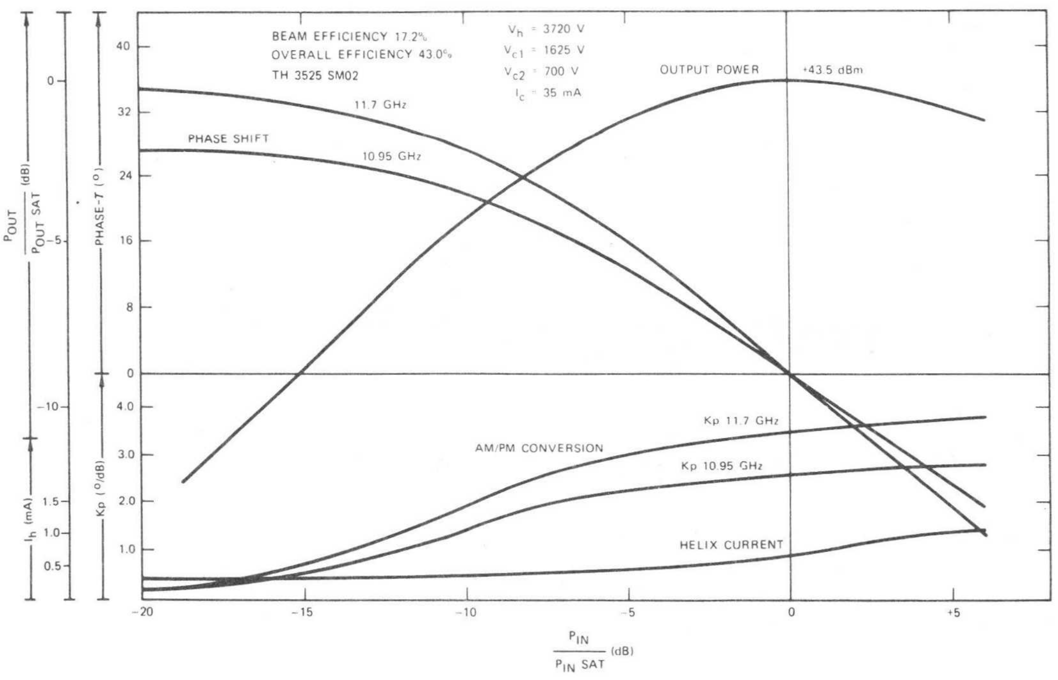


Fig. 8. 20-W, 11-GHz, double-taper, double-collector TWT (Th 3525).

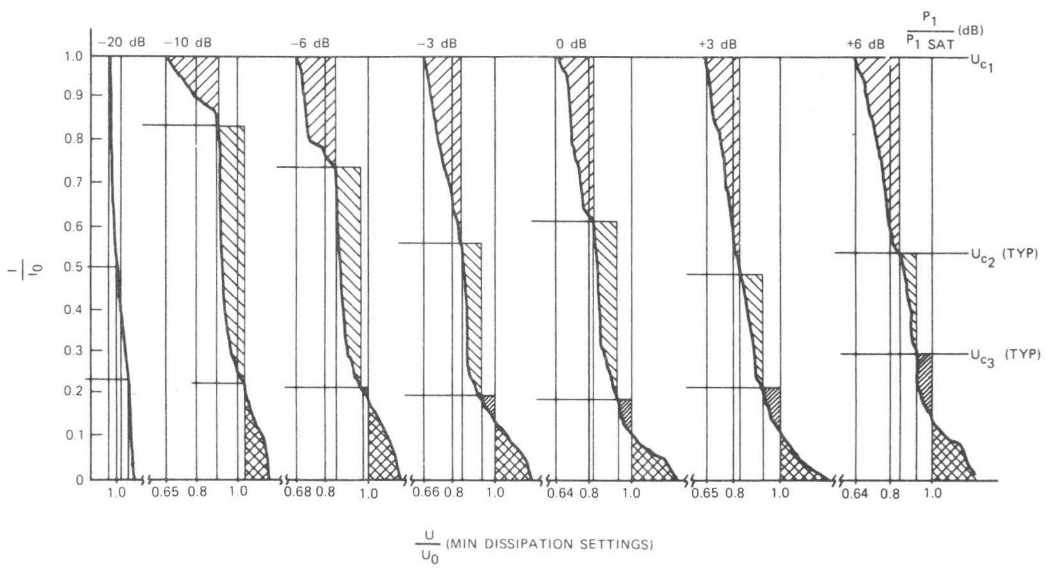


Fig. 9. Calculated velocity spectra of the TWT TL 12024 at different drive levels (U_0 = accelerating voltage of undisturbed beam, I_0 = cathode current of electron beam).

lector added to this tube did not, as expected, provide a significant efficiency improvement at saturation (0.5-1.0 percent) but made overall efficiency at backoff more effective.

VIII. Nature of Spent Beam, Multicollector Principles

Due to the interaction process in a TWT, electrons are subjected to retarding or accelerating forces from the traveling RF fields. Electron bunches are formed which change their position relative to the RF wave as a result of phase slippage and interacting forces. After the RF output of the TWT has been passed by the electrons, the spent or decoupled beam contains a wide and differing velocity spectrum as shown in Fig. 9 for different levels of drive (P_1).

Theoretically, the collector dissipation for a 3-stage collector is

$$P_{\text{dissipation}} = U_{c1}I_{c1} + U_{c2}I_{c2} + U_{c3}I_{c3} - P_{RF}. \tag{7}$$

This loss is represented by the shaded area of Fig. 9. U_{c1}, U_{c2}, and U_{c3} must be chosen so that $P_{\text{dissipation}}$ becomes a minimum. Analog considerations apply for different numbers of collectors. The design of a multistage collector requires an arrangement for velocity sorting which approaches as nearly as possible the above mentioned conditions. The electron optical device must be designed so that fast electrons are not collected at a collector stage with a higher voltage (with respect to the cathode) than necessary. There are a variety of concepts for multistage collectors.

The tilted electric-field collector (TEFC) investigated by Okoshi [20] uses an axial magnetic field for focusing the

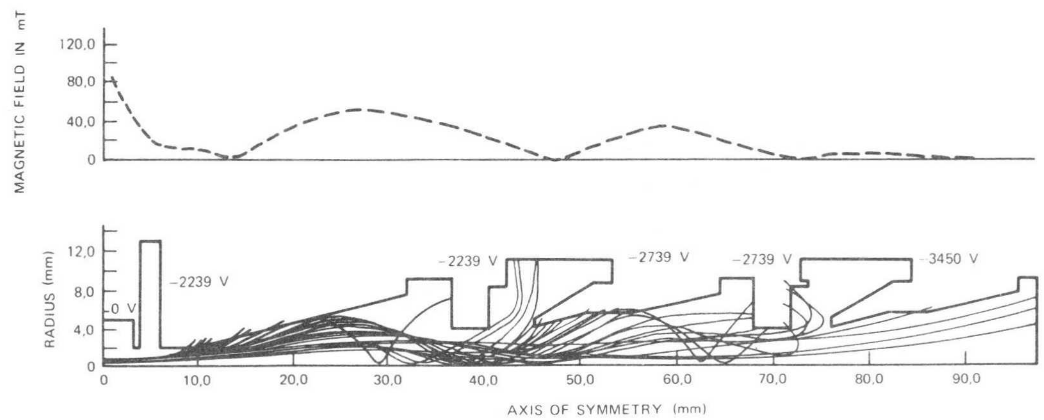


Fig. 10. Calculated electron trajectories in a magnetic lens collector (MLC) at saturation drive used in the TL 12024 together with rotationally symmetric electrode configurations and axial magnetic field (T = Tesla, $P_2 = P_{2\,SAT}, I_{c1}$ = 18.0 mA, I_{c2} = 22.5 mA, I_{c3} = 4.5 mA, and η_c = 90.3 percent).

beam and an electrical transverse component for velocity-dependent deflection of the electrons, so that fastest electrons are least deflected. Other concepts use rotationally symmetric devices with purely electrostatic fields [electrostatic collectors (ECs)]. In this case, velocity sorting is achieved by space charge forces deflecting the slowest electrons away from the axis first. Finally, a magnetic lens collector (MLC) is used with superimposed field RF magnetic lenses and a rotationally symmetric electrostatic field.

IX. Collector Designs and Collector Efficiency

The TEFC configuration results in considerable technological complications, while the more frequently used ECs require a large volume for high efficiency. The MLC configuration combines small size with high collector efficiency. Therefore, it is useful for medium-power TWT's. The design follows an iterative process starting with an electron-velocity spectrum determined from large signal computations and a reasonable geometrical collector configuration. The results of these computations are used to change the shape of collector electrodes in an empirical manner for improved collector performance. Fig. 10 shows computed electron trajectories for an MLC with three stages and the electron-beam spectra from Fig. 9. Collector efficiencies and experimental results are shown in Fig. 3 and 4. The results fall between the theoretical optimum and the measured data. Measured collector efficiencies are lower than calculated values because of several factors.

a) The parameters used in the calculations are simplified. The interaction process neglects, for instance, radial variations of space charge density and the RF electrical field and radial components of the RF field. In addition, it does not include the influence of rotational energy resulting from PPM beam focusing.

b) Due to transverse magnetic field components, the currents intercepted by the helix and first collector stage without RF drive are not zero (see Fig. 3). These unwanted currents contribute to increased dc loss.

c) Computations do not allow for reflected or secondary electrons. Although care has generally been exercised to "catch" electrons only on metallic surfaces which provide a decelerating electric field, the disturbance to the proper current distribution on the collector stages caused by secondary or isolated reflected electrons cannot be avoided.

Variation of RF drive changes the composition of the velocity spectrum as shown in Fig. 9. Maintaining constant collector voltages when varying the RF input does not provide the highest possible efficiency for a specific drive level. For example collector 1 voltage does not require very much change with RF drive down to −10 dB below saturation drive. However, the required U_{c1} is largest at ~− 9-dB drive. Collector 2 voltage for optimum efficiency increases with increasing drive up to saturation (Fig. 11).

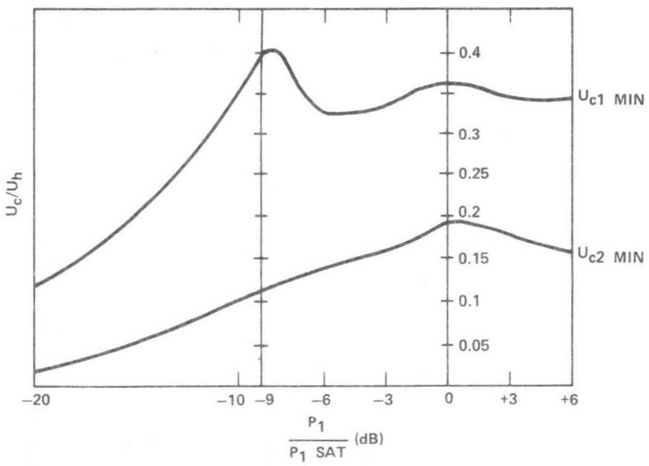


Fig. 11. Calculated values for U_{c1} and U_{c2} resulting in maximum efficiency at various drive levels (see Fig. 12 for MLC conditions).

Selecting collector voltages for variable drive requires adjustment of U_{c1} to the value required for maximum efficiency at −9-dB drive and U_{c2} for saturation drive. Efficiency may be improved for any RF power level by designing the power supply so that U_{c1} and U_{c2} sources have a properly designed internal resistance. In this case, U_{c1} increases with decreasing RF drive because I_{c1} is also decreasing; U_{c2}, however, decreases while I_{c2} increases with decreasing drive.

X. Operating Efficiency

For combined beam and collector efficiencies the overall optimum efficiency as a function of collectors is shown in Fig. 12. These values are for 11-GHz 20-W helix space TWT's with a saturated phase shift delay of ~30° (max $K_p \sim 3°$/dB) [21]. As can be seen, additional collectors beyond three can improve the overall tube saturation efficiency but at a diminishing slope. Thus the change from the single-collector space TWT of the past decade to the present multiple-collector TWT represents a significant increase in communications capacity with all other factors being equal.

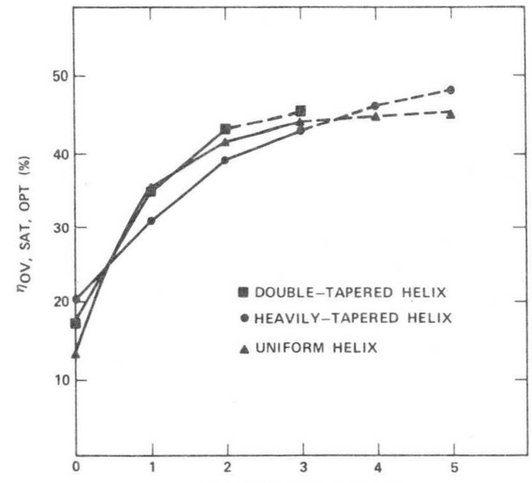


Fig. 12. Typical overall efficiency versus number of collectors.

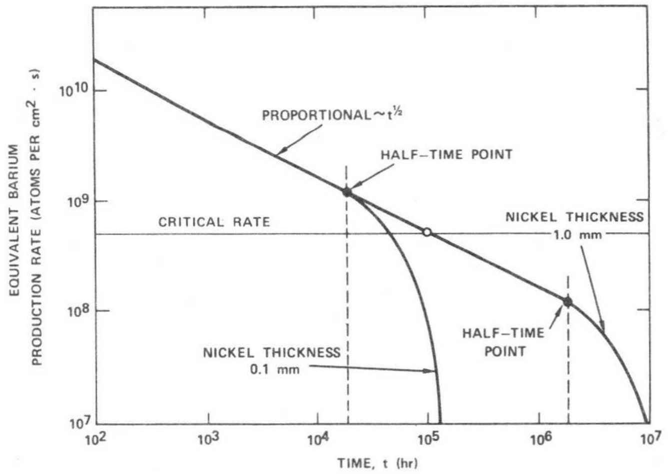


Fig. 13. Calculation of cathode life from the production rate of free Ba (j_k = 120 mA/cm², T_K = 650°C).

XI. Cathode Design

Cathode life essentially determines the actual TWT lifetime. It depends on the cathode itself and the cathode environment during tube processing and operation. The cathode must deliver the necessary current for the TWT. The two following types of thermionic cathodes are presently used in long-life satellite TWT's, depending on the required current density:

a) oxide cathodes (0.1 to 0.2 A/cm²);

b) dispenser-type cathodes (0.4 to 0.8 A/cm²).

A. Oxide Cathodes

Oxide cathodes consist of a heater, a nickel base, and an alkaline oxide coating (BaO/SrO or BaO/SrO/CaO). The base nickel is usually doped with a small fraction of Zr, W/Zr, or Mg. These activators diffuse to the Ni surface and undergo a chemical reaction with the alkaline oxide [22]. Hence, for instance, BaO is partially reduced and excess free Ba exists within the oxide coating. This combination lowers the work function to provide "space-charge-limited" electron emission above 520°C (T_{Kn}, the cathode transition or "knee" temperature) for a well-activated cathode. The cathode emits uniformly as long as the work function is consistently maintained. The actual cathode operating temperature is set higher (650°C to 750°C) for a given level of emission-current density to ensure a uniform work function plus sufficient protection against poisoning, but not so high that excessive depletion of the Ba or other cathode constituents results. Theoretically, a decrease of 25°C will generally double the life of a cathode [8].

Free Ba on the cathode evaporates due to cathode temperature and reacts primarily with residual oxygen in the environment. Therefore, a continuing production of free Ba is required. Early in life the activation content of the base nickel is high enough to produce a large amount of excess Ba. Due to diffusion and reaction of activators, their content in the base material decreases. Simultaneously the alkaline oxide is consumed. A sufficient amount of activators and oxide coating must be available. This requires an adequate thickness of the base material ($\gtrsim$1 mm) and the coating ($\gtrsim$50 μm). For a given "doped" nickel base material, Ba production is calculated as a function of time [23], [24]. The end of the theoretical cathode life is approached when Ba production falls below the required value. Fig. 13 shows this calculation for the cathode used in the TL 4003 at 10^5 h [j_k = 120 mA/cm², T_k = 650°C > 1-mm base Ni (A) thickness, 0.03-percent Mg content].

The actual life of a cathode is much more difficult to evaluate. The required Ba production is in a state of dynamic equilibrium determined by the residual gas pressure, temperature, and cathode current density. The tube's residual gas pressure (essentially oxygen partial pressure) depends on several factors: leaks, gas sources in the material used within the vacuum envelope, cathode gas release, and getter action. During operation the cathode both absorbs gas molecules and delivers gas due to the outgassing of the base material. Therefore, gas cycling occurs in the tube with an equilibrium pressure dependent on and increasing with cathode temperature. Part of the gas molecules are ionized in the electron beam and, by means of the operating voltages of the TWT, accelerated toward the cathode along the beam axis. Ion bombardment occurs in the center of the cathode, where the ions impinge. Bombardment may damage the active surface and in extreme cases evaporate cathode Ni after localized wear-out of the active surface. This sputtering occurs only in a relatively poor vacuum. An essential contribution to TWT life occurs when the residual gas pressure during processing and operation is minimized. Improvements obtained during recent years have resulted in an internal tube working pressure of 10^{-11} to 10^{-10} torr, which is a crucial factor for long-life oxide cathodes.

Thus the gas cycling process limits the life of the cathode. When the cathode is operated at a sufficiently low temperature (~650°C), the gas cycling process exerts little influence on life and may be much less than that determined by the activators in the nickel base. At more elevated temperatures (~750°C), a more active dynamic equilibrium exists and this process becomes more significant. The effects on cathode life are greater with higher gun electrode voltages due to greater ion impact energy. Finally, a qualitative limit (combining cathode operating temperature, residual gas, and beam voltage settings) is reached where a lifetime consistent with satellite requirements (~5-10 years) is no longer achievable. In this case, use of a dispenser-type cathode becomes necessary.

B. Dispenser-Type Cathodes

Dispenser-type cathodes consist of a matrix of porous tungsten impregnated with alkaline-earth (Ba, Ca) aluminates [25]. Free Ba, in this case, is obtained by chemical reaction and subsequent migration through the pores to the surface. Such cathodes, however, had never been used in the space TWT's and it was necessary to determine their optimum operating

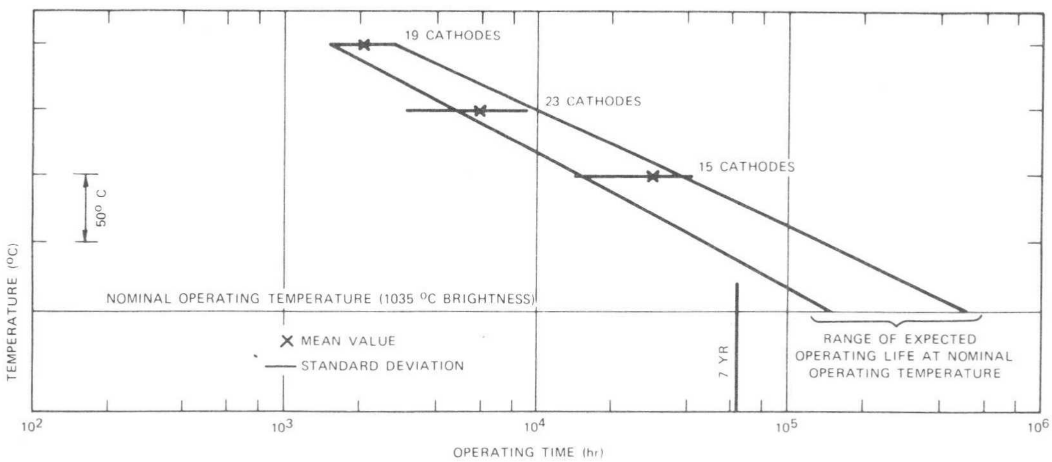


Fig. 14. Results of accelerated life test of space tube cathodes in diode mountings (nominal operating temperature = 1035°C brightness).

temperature and probable useful emission life although virtually all high-power ground station TWT's use these cathodes.

It is well-known that, if the cathode's temperature is too low, the cathode is susceptible to poisoning by the residual gases in the tube, while if the temperature is too high, the active cathode emitter (Ba) will evaporate too rapidly. During operation, the active barium rich (BaO) layer on the cathode surface is continually replenished by Ba + BaO migrating from the interior of the impregnated tungsten cathode to replace evaporated barium. Also, the combination of easily replenishable barium on a tungsten matrix surface makes dispenser-type cathodes much more resistant to high-energy ion bombardment than oxide cathodes (i.e., higher helix voltages, as well as the effects of the residual gas cycling process).

There are, of course, numerous parameters in the design of a reliable impregnated cathode, such as the size of the tungsten particles, the porous tungsten density, and the mole ratio of the impregnant's constituents. Typically the porous matrix is made from tungsten particles whose average size is six microns, sintered to a theoretical tungsten density of 82 percent with an impregnated mole ratio of BaO:4, CaO:1, and Al_2O_3 : 1.

Dispenser-type cathodes are usually operated at temperatures higher than 1000°C. Due to the higher current density the cathodes are smaller, but the power per unit square of heater wire surface is considerably increased relative to that of the oxide cathode. It has been shown that heat transfer by radiation from the heater to the cathode results in insufficient heater life. Therefore, the heater is potted with Al_2O_3 into a cavity on the bottom of the cathode. With this kind of heater construction a total of 3.2×10^6 operating switching hours have been accumulated without one failure.

To determine the optimum cathode operating temperature, a large number of diodes with identical cathode/filament structures were fabricated and placed in life test at elevated temperatures. A plot of the experimentally determined end of life for the different test temperatures was then made (Fig. 14). Extrapolation of the results to lower temperatures yielded the optimum operating temperature for a cathode life of at least 150 000 h, and the range of expected operating life at that temperature.

C. Cathode Testing

Cathodes and their heater exert a stronger influence on life and reliability than any other subassembly in the TWT. Therefore, careful tests must be performed to select cathodes to be used in a TWT and to select flight model TWT's from production. Since the investigations of satellite TWT's by Bodmer *et al.* [8], "dip" testing is widely used. Variation of cathode current versus cathode temperature is observed when the cathode cools down and heats up. The transition or "knee" temperature (T_{Kn}) from saturated to space-charge-limited temperature and the shape of the transition curve are used as selection criteria.

A hybrid "dip" test and a dual-pulse activity test has been investigated for TWT's (INTELSAT Contract 676). Two pulse programs are involved. The first superimposes short rectangular anode voltage pulses (10-μs, 0.1 percent duty cycle) on the normal operating voltage, leading to cathode current pulses four to five times the normal operating current. At this elevated current, transition between space-charge-limited and saturated current occurs at higher temperatures while the rms helix interception is kept sufficiently low. This provides greater potential selection discrimination.

Fig. 15 shows two examples of the first pulse program: dc dip test, pulse dip test, and helix interception are shown versus time after heater power switch off for two samples of the TL 4003. Fig. 15 (a) shows the result of a tube selected as a flight model operated at a cathode temperature of 620°C. The transition point for the pulse current at 560°C, while the dc transition occurs at 515°C. Fig. 15 (b) shows the result of a tube whose cathode has been poisoned by increasing the residual gas pressure to 10^{-7} torr. This cathode must be operated at 750°C to give full emission and has a transition temperature of 735°C where little difference between dc and pulse transition is observed.

Results of the dual-pulse second program after Tischer [26] are shown in Fig. 16. Fig. 16 (a) shows a cathode operating at 650°C in an environmental pressure of 3.5×10^{-10} torr. During the long impulse (50 ms, 1-percent duty cycle) a slight increase of I_K occurs first, most probably due to heating in the interface layer resistance, followed by a slight decrease due to cathode poisoning. When subsequent short pulses (10 μs every 10 ms) are applied, the initial current value of the cathode is immediately reached. Increasing the residual gas pressure to 10^{-8} torr [Fig. 16 (b)] results in a much stronger effect of cathode poisoning followed by a more extended recreation period. Further evaluation of these two pulse test programs is necessary, but it has been demonstrated that they provide

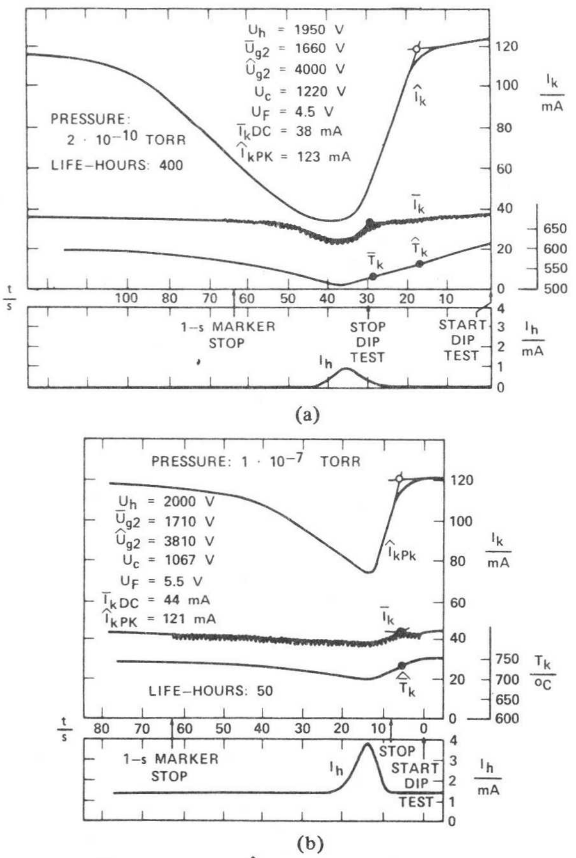


Fig. 15. Dc ($\bar{I}_k$) and pulsed ($\hat{I}_k$) on different cathodes showing cathode current, temperature, and helix interception current versus time (○ = $\hat{T}_{kn}$, pulse transition temperature, ● = T_{kn}, dc transition temperature. (a) Properly activated cathode for a flight model TWT. (b) Partially poisoned cathode by residual gas pressure of 10^{-7} torr.

better insight into cathode performance while preserving cathode operating characteristics during the test.

XII. TWT Life Test Results (Ground Tests)

As an example, fifty oxide-cathode TWT's (TL 4003) out of a production lot have been operated in a life test program. During a 2000 h burn-in period, two tubes were eliminated due to the drift of intercepted helix current. In the subsequent life test period, 50 tubes accumulated approximately 0.5×10^6 h. The test program was continued with 20 tubes having the longest individual life (presently approximately 30 000 h). Cathode activity was tested by dc dip test. A total of 960 000 h have now been accumulated without any failure or variation of characteristics outside the specified range. The transition temperature (T_{Kn}) has been slowly increasing in a quasi-linear manner from ~525°C to ~570°C in more than three years of operation. An average margin of above 20°C is projected for a seven year mission.

Results of dispenser cathode activity tests for 46 20-W 11-GHz, TWT's on continuous life test (Fig. 17) show a regular increase of the cathode knee temperature (T_{Kn}) during the tube's operating life. Cooling down to T_{Kn} during filament switch off dip test is a linear function of time with a slope of 20°C per second. The temperature margin at beginning of life is about 100°C and falls to 50°C after 20 000 hours of operation, following a constant slope on a semilogarithmic scale. Extrapolating to the end of the seven year mission projects a margin of more than 20°C.

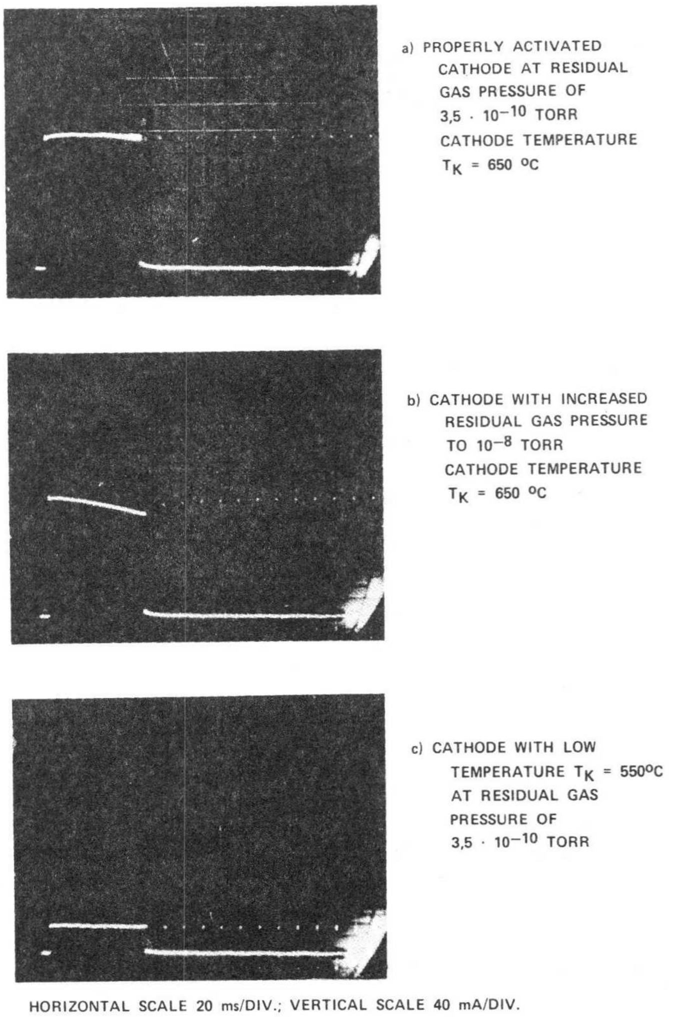


Fig. 16. TWT (TL 4003) testing of oxide cathodes with long/short cathode current pulses.

XIII. TWT Life Test Results (Space)

For the most part, life-test results in space have been extremely satisfactory. Some TWT's have now exceeded 100 000 h of operation. The INTELSAT I through INTELSAT IV spacecraft series have not been life limited by transmitter TWT's and there are indications of average lives in excess of 40 000 h for tube types such as the 261H and 275H (both utilizing oxide cathodes). At this writing only one 261H out of a population of 168 (approximately three to six years in space) has deactivated after two years of operation. Telemetry information is inconclusive regarding the failure source (i.e., tube or supply).

Unfortunately, in spite of the extensive processing and selection precautions applied, one tube type did not live up to projected expectations. This tube, the 262H, is used as a driver TWT in the INTELSAT IV spacecraft. Present deactivation lifetime estimates for this device are of the order of two years. The spacecraft objective lifetime (7 years) was, however, not compromised, since quadruple redundancy had been specified. The major factors pertinent to the limited life of this device are a higher than usual cathode current density (280 mA/cm^2), an associated elevated cathode temperature (740°C), and an as yet unexplained possible correlation factor, a high ratio of anode aperture diameter to cathode diameter (1.05). This latter characteristic originates with the shallow-angle gun re-

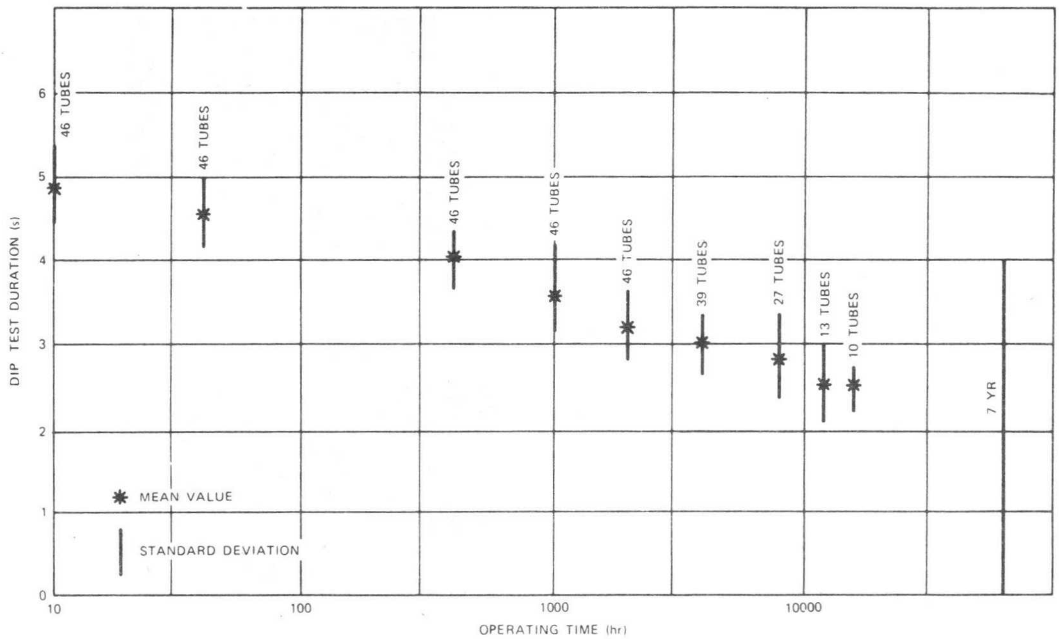


Fig. 17. Th 3525 (η = 4) and TOP 1369 (η = 42) life tests (as of January 1976).

quired for a low-noise driver TWT (approximately 18-dB NF). The implication is that a larger than usual percentage of the oxide cathode area is exposed to "ion" bombardment from the ions generated in the cathode/anode region with a possible resultant gradual "poisoning" as discussed earlier. Examination of failed life test devices has not as yet revealed any obvious ion-sputtering damage. Testing is continuing.

XIV. Conclusion

Methodical advances in efficiency and linearization of the characteristics continue to be made. These advances have been reviewed in terms of the double-tapered helix and triple-collector designs utilizing magnetic lenses for electron-velocity sorting. Overall efficiencies in the 45- to 48-percent region for a 10- to 20-W device are now achievable with phase delays of less than 30°.

Current TWT's are representative of a mature device technology yielding exceptional microwave and efficiency characteristics. This makes them unique for communications satellite transmitters. Not withstanding certain limiting causes, actual lifetime and reliability have increased and the acceptance of TWT's in satellites is a matter of record. Hundreds of TWT's are now in space and hundreds more are expected in the next few years.

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DESIGN CONSIDERATIONS, DESIGN LIMITS AND INTERFACE PROBLEMS FOR HIGH FREQUENCY SATELLITE TWT'S

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1. INTRODUCTION

In the 4 and 12 GHz band helix TWT's are available with up to 30 Watt output power with efficiencies as high as 46 and 48% at low non-linear distortions as 3 degree per dB am-pm-conversion.

As an example the 4 GHz tube TL 4010 is to be seen in Figure 1. The tube was developed under a Comsat contract and will be used in the Anik B satellite.

Main parameters:

Output power:	10-14 W
Efficiency:	> 44%
Frequency:	3,7-4.2 GHz
K_T:	< 4 °/dB
Gain:	> 56 dB
Collector	3 stages
Weight:	< 580 g
Cathode:	oxide
Life data:	1,1 Mio hours

In Figure 2 the 12 GHz tube TL 12024 is shown. This tube was developed under a DFVLR-contract and is foreseen for the Anik C and SBS satellite.

Main parameters:

Output power:	20-23 W
Efficiency:	> 45%
Frequency	11,7-12,2 GHz
K_T:	< 3,5 °/dB
Gain:	> 55 dB
Collector:	3 stages
Weight:	< 590 g
Cathode:	Tungsten-matrix
Life data:	1 Mio hours

Starting from "state of the art" tubes design criteria, limits and interfaces for helix tubes in the 20, 30 and 60 GHz regions will be worked out and presented. Furthermore an outlook what can be achieved with coupled cavity tubes is given.

The parameters of particular interest which have to be regarded are:

- cathode loading and beam area conversion ratio
- magnetic field
- minimum beam diameter or thermal and mechanical properties of the helix
- max. operating voltages.

2. DESIGN CONSIDERATIONS

2.1. Output power versus frequency

Before one can start to took in more detail into the specific tube design the overall output power capability that can be acheived with helix tubes has to be established.

For terrestrial applications helix tubes are developed with up to 400 W output power in the 14 GHz region. For satellite applications we normally back off 3 dB from those values because of reliability considerations.

For finding the frequency dependancy of the output power we have to stick to the following rules. The output power of a TWT is:

$$P_2 = \eta_s \cdot I_0 \cdot V_0 \qquad (1)$$

η_s = beam efficiency
I_0 = beam current
U_0 = beam voltage

The beam efficiency is according to TWT theory:

$$\eta_s = A.C = A \left(\frac{K.I_0}{4\ V_0} \right)^{1/3} \qquad (2)$$

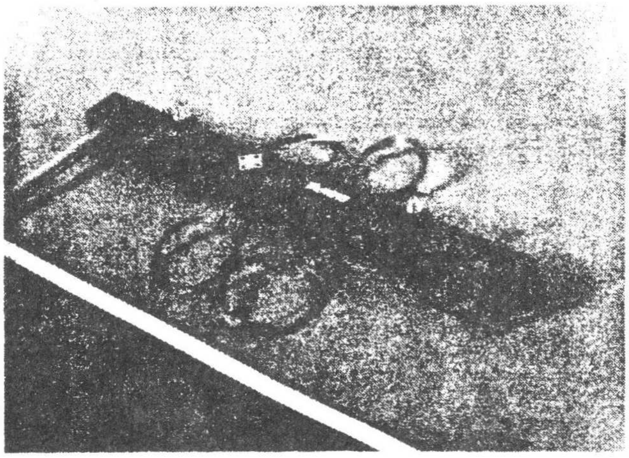


Figure 1.

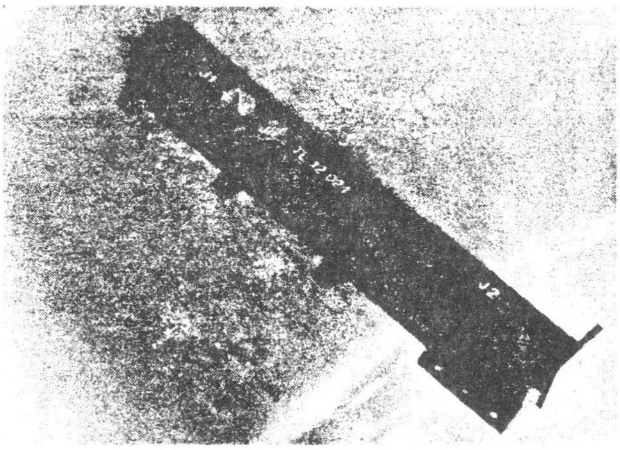
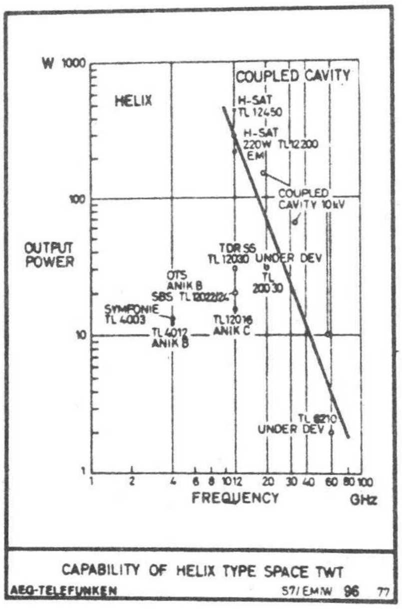
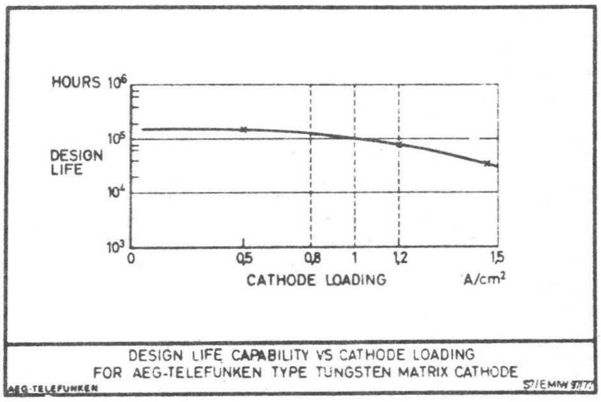


Figure 2.



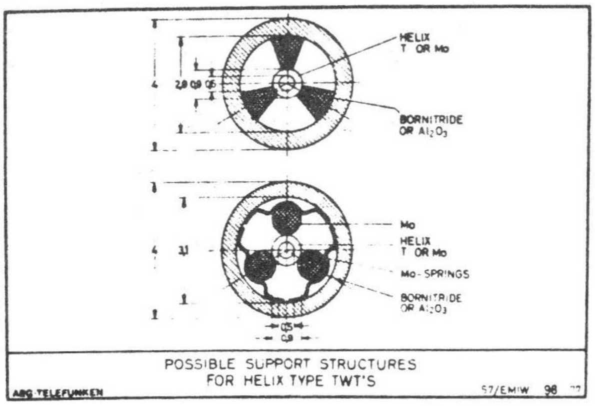
CAPABILITY OF HELIX TYPE SPACE TWT

Figure 3.



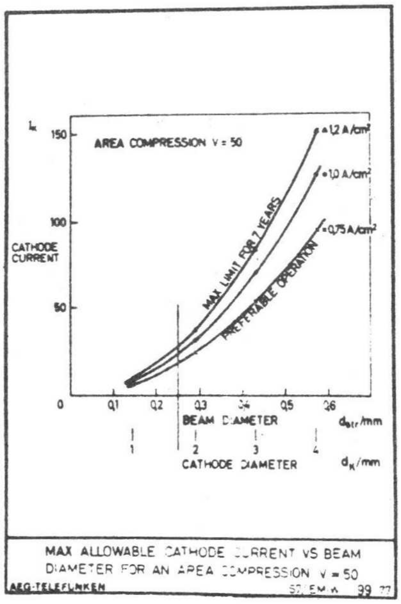
DESIGN LIFE CAPABILITY VS CATHODE LOADING
FOR AEG-TELEFUNKEN TYPE TUNGSTEN MATRIX CATHODE

Figure 4.



POSSIBLE SUPPORT STRUCTURES
FOR HELIX TYPE TWT'S

Figure 5.



MAX ALLOWABLE CATHODE CURRENT VS BEAM
DIAMETER FOR AN AREA COMPRESSION V = 50

Figure 6.

A is a factor of proportionality and is itself a function of space charge parameters (QC and γb) and delay line attenuation parameter. K is the coupling impedance of the delay line. Beam focussing requires a peak field B of about 2 times Brillouin flux density, which can be calculated according to beam focussing theory to:

$$B = 2.830 \; \frac{I^{1/2}}{U^{1/4} . 2b} \qquad (3)$$

b = beam radius

Furthermore optimum TWT performance is obtained under the following condition for the second space charge parameter.

$$\gamma b = \frac{2 \pi f}{6.107 . U_0^{1/2}} \approx 0,6 \qquad (4)$$

f = frequency

By combining all these equations we obtain:

$$P_{2\ max} \approx A . K^{1/3} . \left(\frac{U_{0\ max}}{f} \right)^{8/3} \qquad (5)$$

From this it can be concluded that the exponent is 8/3 under the assumption of constant voltage. At higher frequencies however the frequency dependance of output power is increased because of the following reasons:

a) increasing delay line attenuation
b) decreasing beam transmission

In fig. 3 the output power versus frequency is plotted. We find that at 20 GHz up to 80 W can be achieved with helix tubes while at 60 GHz the capability drops to 3,5 W.

2.2. Cathode loading and gun design

Two main aspects have to be considered:

a) the area conversion ratio and
b) the cathode loading

In order to guarantee good focussing quality throughout life the entrance conditions of the beam into the magnetic system have to be such, that small changes of the beam in diameter and location of the minimum diameter do not lead to dramatic changes of the beam transmission. A compromise between cathode loading, gun perveance and beam shape leads to an area compression of:

$$\frac{\text{cathode area}}{\text{beam area}} = V \leqq 50 \qquad (6)$$

This value has to be regarded as a maximum. For example:

AEG-Telefunken Symphonie tube	V = 36
AEG-Telefunken OTS tube	V = 25
Hughes Intelsat tubes	V $\approx$ 30

The second important parameter is cathode loading. For the tubes considered only tungsten matrix cathodes can be used. With this kind of cathode extended life test programmes are under way. So far 1 Mio hours are accumulated with diodes and tubes. The longest sample runs are:

80.000 hours for diodes and
32.000 hours for tubes

so far. Most of the testing is carried out at a cathode loading of 0,75 - 0,8 A/cm^2. Going to higher frequency demands going to higher cathode loading because of the max. area conversion of V $\leqq$ 50. At AEG-Telefunken tests were performed operating the cathode up to 1,5 A/cm^2. The result is to be seen from fig. 4. It can be seen that the design life drops with increasing cathode loading. In order to be safe in respect to the normally required 7 years life we feel that one should not go higher than 0,8 A/cm^2. As an absolute maximum, where the design margin is equal to zero a loading of 1,2 A/cm^2 can be considered.

For this investigation we set the following limits:

$$V \leqq 50$$
$$J_K \leqq 0.8 \text{ A/cm}^2 \qquad (7)$$

2.3. Delay line system

The design parameters of the delay line system are influenced by mechanical, thermal, rf and gun design considerations.

a) Mechanical, thermal

At AEG-Telefunken two basic systems were investigated for high frequency use. In fig. 5 the tow systems are to be seen. The thermal contact for system 1 is given by heat shrinking. By system 2 the thermal contact is given by Mo-springs which makes it constant throughout the required temperature range. System 2 was finally chosen. The thermal conductivity of the system is 0,08 W/^{o}K cm, which means that 8 W/cm can be handled at a temperature difference of 100^{o}C between envelope and the helix. These results were achieved with a minimum diameter of 0,5 mm. Below that value problems arise with respect to alignment tolerances and mechanical strength of the helix itself (for example the helix may deform).
As the first limit therefore we get for the minimum helix diameter $\geqq$ 0.5 mm.

$$d_{helix} \geqq 0.5 \text{ mm.}$$

b) Gun design influence

Under 2.2. the max. area compression of the beam was determined to be:

$$V \leqq 50.$$

For a given beam diameter the max. cathode current can therefore be calculated for different cathode loadings. This is shown in fig. 6.

For any required cathode current we get the value of cathode loading when the beam diameter is known. The latter is defined by the choosen propagation factor γb. On the other hand we can determine with this graph what γb we have to select in order to meet the required cathode loading.

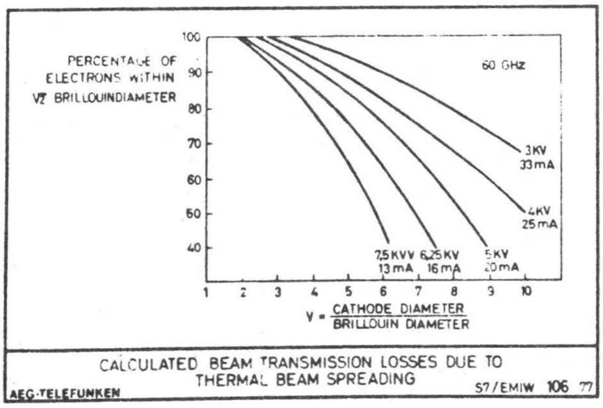


Figure 7.

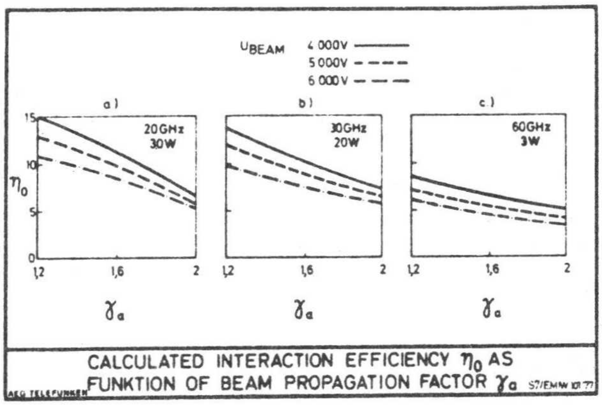


Figure 8.

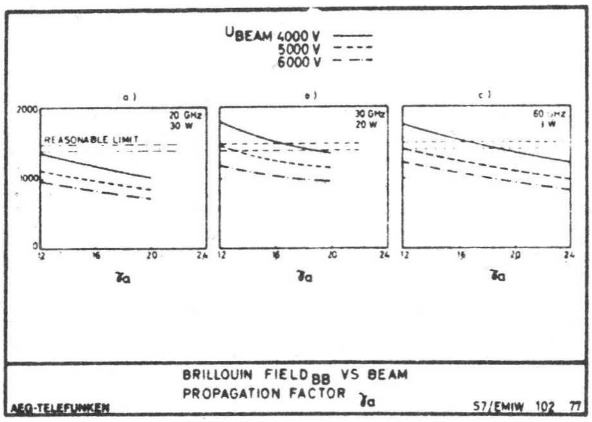


Figure 9.

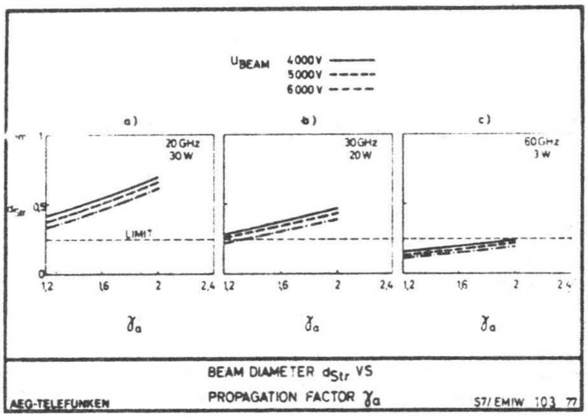


Figure 10.

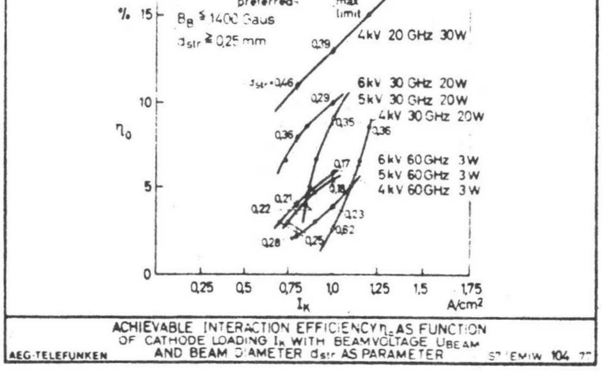


Figure 11.

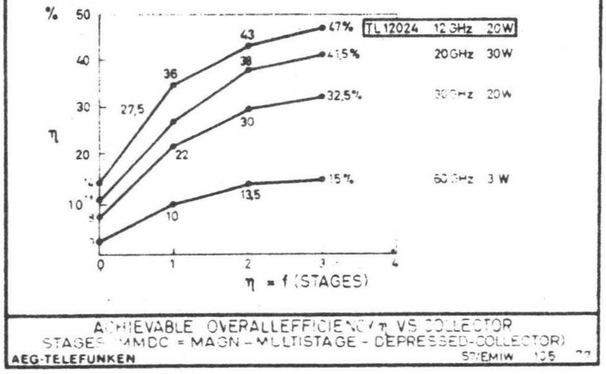


Figure 12.

c) Magnetic

Under para. 2.1. it was explained that the required magnetic flux density is a direct inverse function of the beam radius. As the operating frequency gets higher the beam diameter decreases due to:

$$\gamma . b = \frac{2\pi}{\lambda} . b \quad \text{constant} \qquad (8)$$

λ = wavelength

This means that the magnetic flux density required to focus the beam increases with frequency. As a compromise between field shape, pole piece size, aging factors and required thermal compensations we find that a peak field of

$B \approx 2.800$ Gauss

should not be exceeded with $SmCo_5$ used as magnetic material.
Another factor we have to consider at decreasing beam diameters is the focussing quality due to thermal beam spreading. This effect was calculated for a 60 GHz tube with 100 W beam power. From fig. 7 we see that only 65% of the electrons will be in the $\sqrt{2}$. Brillouin-radius for a beam voltage of 5 kV and an area compression of V=50. This is not tolerable. The only way to solve this problem is to design a semi confined flow gun optic. This however requires a higher peak field to focus the beam. We therefore have to back off from the max. achievable peak field according to the following factors F

20 GHz	F = 1,05
30 GHz	F = 1,2
60 GHz	F = 1,4

2.4. Operating voltages

The operating voltage has to be

a) as high as possible in order to lower the required beam current and improve the focussing.

b) as low as possible in order to improve
- EPC reliability
- HV-voltage corona problems
- To lower the stored energy in the EPC
- Margin against backward wave oscillation.

As a compromise between all tube influencing parameters and available EPC-HV-technology we allow as upper limit a voltage of

$U \leq 6\ 000$ V

3. OPERATING DATA FOR HIGH FREQUENCY HELIX TUBES

3.1. Power levels

In order to limit the complexity we restrict ourselves to certain output power levels. The power levels chosen for more detailed investigations are

20 GHz	30 W
30 GHz	20 W
60 GHz	3 W

These are power levels discussed at different organisations which will be required for future systems. This may not quite hold for the 60 GHz tube but there we hit the capability limit for a helix tube.

3.2. Base tube efficiency, Brillouin flux density and beam diameter.

In fig. 8 the base tube efficiency is to be seen plotted versus propagation parameter γa. (a = 2b). We can see that the efficiency will increase for all frequencies with lower a and lower beam voltage. By fixing those parameters we therefore have to look for the lowest possible values.

Fig. 9 shows the required peak field for focussing the beam versus γ a. From this graph we can find, that certain combinations of peak field and γa lead to forbidden regions. The forbidden regions increase with frequency. Under para 2.3 c) we determined the design peak field for semi confined flow.

Those design values are

20 GHz	2 670 Gauss
30 GHz	2 330 Gauss
60 GHz	2 000 Gauss

In fig. 10 the required beam diameter is plotted versus γa. It can be seen very clearly that in order to meet the allowed min. beam diameter of 0.5 mm the propagation parameter γa has to be increased which lowers the achievable basetube efficiency. Selecting a higher beam voltage however will lead to a lower γa which is desirable for achieving a high base tube efficiency.

3.3 Tube design parameters

Taking into account all design aspects presented in fig. 4 through 10 leads to fig. 11 where the achievable base tube efficiency is plotted versus cathode loading. Parameters on these curves are the operating voltage and the beam diameter.

For the max. allowed cathode loading of 0,8 A/cm^2 we find that max. beam efficiency is achieved with the following voltages:

20 GHz / 30 W	4 kV
30 GHz / 20 W	6 kV
60 GHz / 3 W	6 kV 0,42 mm helix Ø
60 GHz / 3 W	5 kV 0,5 mm helix Ø

For the 60 GHz tube however we find that the cathode loading is not the limiting factor. Here the design is earlier limited by the min. beam diameter of 0.25 mm (helix diameter = 2 x beam diameter). We find, that there is no efficiency benefit by designing the tube for 6 or 5 kV. Because of EPC-reliability and corona problems the 5 kV operating voltage is preferred.

In table 1 the final design values are summarized.

	20 GHz 30 W		30 GHz 20 W		60 GHz 3 W	
beam voltage kV	4	4	6	6	5	4
beam current mA	66	58	40	32	18	22
beam efficiency %	11	13	8,0	9,8	3	3
cathode loading A/cm^2	0,8	1,0	0,8	1,0	0,75	0.9
propagation para γa	1,6	1,4	1,5	1,2	2,25	2,5
Brillouin flux density G	1240	1330	1270	1440	1442	1650
helix diameter mm	0,92	0,7	0,7	0,58	0,5	0,5

Table 1 Tube operating data

From this table it can be seen that no design limit is violated by selecting the proper tube parameters. For comparison the tube data are given in table 1 for a cathode loading of 1 A/cm^2. We see that, except for the 60 GHz tube, this can be done without violating another limit. At 60 GHz we would far exceed the allowed limit for the focussing field. Summarizing all aspects we find that the design parameters which limit the design change their priority with frequency. This is shown in table 2.

	20 GHz 4 kV / 20 W	30 GHz 6 kV / 20 W	60 GHz 5 kV / 3 W
magnetic field	2	2	1
cathode loading	1	1	2
beam diameter	3	2	1

Table 2 Design limits priority

3.4. Collector design and overall efficiency

The overall efficiency of all 3 tubes was calculated for a 3-stage collector. This type of collector where the 3rd stage is at cathode potential is already space qualified from AEG-Telefunken in the Anik B program. The overall efficiency versus collector stages is plotted in fig. 12. In general we can notice that efficiency improvement going from 2 to 3 stages decreases with lower base tube efficiency. The reason for this is, that the velocity spectrum for a low base tube efficiency is so small that energy can be recovered already with 2 stages very efficiently. The graph shows that the overall efficiency drops quite drastically from 41.5% at 20 GHz over 32.5% at 30 GHz to 15% at 60 GHz.

For comparison the curve is shown for the 12 GHz / 20 W TWT where 47% overall efficiency is achieved. The collector depression in general follows the following rule:

collector 1 voltage	1/3 of the beam voltage
collector 2 voltage	1/5 of the beam voltage
collector 3 voltage	equal to beam voltage

3.5. Gain and dimensions

For the three different tubes considered the following saturated gain can be achieved:

frequency GHz	20	30	60
gain sat. dB	50	45	35

The weight which can be realized for all tubes is less than 600 g and the mechanical length is below 280 mm.

4. COUPLED CAVITY TUBES

For coupled cavity tubes in general the same design aspects apply. The choice of the beam voltage is a compromise between coupling impedance or beam efficiency, EPC-HV-technology and mechanical tolerances of the delay line resonators.

A workable figure is:

$U_{beam} = 10$ kV

Taking into account cathode loading of $I_K = 0,8$ A/cm^2 and a magnetic field of approx. 3000 Gauss one can calculate the achievable output power for an area compression V = 50. In the following the results are summarized.

Frequency GHz	20	30	60
Output power W	150	65	10
Overall efficiency %	33	25	18

Table 3 Output power for coupled cavity tubes with a max. beam voltage of 10 kV and a 2/3 stage collector

Repeating the same steps for coupled cavity tubes as demonstrated for helix tubes under para 2 and para 3 we find that here for all frequencies the cathode loading is the limiting factor for achieving higher output power for a given beam voltage.

In fig. 3 the circles indicate the output power that can be realized with coupled cavity tubes of 10 kV beam voltage.

5. SUMMARY

Designing satellite tubes for 20, 30 and 60 GHz cannot be done by simply scaling from available 12 GHz / 20 W tubes. Cathode loading, magnetic field and the minimum beam diameter which can be realized taking thermal and mechanical properties of the helix into account have to be carefully investigated.

A compromise of these three main parameters leads finally to the tube design parameters. As a result we find that with helix tube voltages between 4 and 6 kV an output power of 30 W at 20 GHz, 20 W at 30 GHz and 3 W at 60 GHz can be generated. The design life for those helix tubes is approx. 100 000 hours from the cathode point of view. Looking at coupled cavity tubes the max. voltage is restricted due to EPC-HV-technology to 10 kV_{max}. With this beam voltage an output power can be achieved which is about a factor of 2.5 - 3 higher than achievable with helix tubes for the same cathode design life of 100 000 hours.

DEVELOPMENT OF A 5 WATT TRAVELLING WAVE TUBE FOR 60 GHz

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SUMMARY

For data transmission between geostationary communication satellites the frequency range from 54 GHz ... 64 GHz will be used.

The communication system design demands a transmitter output power of some watts. This can be achieved with a travelling wave tube amplifier.

This paper shows, how frequency, output power, bandwidth, high efficiency and extremely long tube life determine the following main design parameters for such a travelling wave tube,

- perveance of the electron gun
- beam compression
- slow wave structure
- dimensions of the slow wave structure
- collector.

Due to the required electrical parameters, distortion effects must be considered which are negligible for the design of lower frequency TWT's.

These effects are:

- thermal velocity spread of the beam electrons
- undesired modes of the slow wave structure.

The thermal velocity spread of the beam electrons has great influence on the performance of the electron gun and the beam focusing system. A method to reduce this influence is described.

Undesired modes of the slow wave sturcture impair the gain characteristics of the tube. Methods of preventing such modes are being further developed.

INTRODUCTION

This paper deals with the development of a ppm-focused double-stage-collector 60 GHz / 5 W helix TWT for space applications with a design goal of an operating efficiency of 10 % and a saturated gain of 30 dB within a frequency range of 54 GHz - 64 GHz. In addition, a general treatment of "mm TWT's" is given.

Firstly, a short review is given of the applications for TWT's in the mm-frequency range. Then, main design problems and considerations based on the development of the 60 GHz / 5 W TWT are outlined and solutions to overcome these problems are shown.

Furthermore, an efficiency improvement technique is described and finally, the state of the art of mm-TWT's is summarised showing upper design limits.

I - APPLICATION OF TWT'S FOR MILLIMETRE WAVES

Millimetre waves, defined as waves with a wavelength from 1 to 10 mm or a frequency range from 300 - 30 GHz, are used in a wide field of applications.

In this frequency range TWT's may act as power amplifiers both for ground and space applications. Main ground applications are for radar, electronic warfare and communication systems.

Frequencies from 54 GHz ... 64 GHz are envisaged for intersatellite communication where TWT's will be used as high-efficiency and high-reliability power amplifiers.

II - DESIGN PROBLEMS AND CONSIDERATIONS

Before going into details a three-stage-collector-TWT schematic is shown in Figure 1:

The tube sections for beam generating and shaping, beam interaction with the delay line structure and beam collecting, together with their associated voltages can be seen. Multistage beam collectors will be described in a later chapter of this paper as an efficiency improvement technique.

The most frequently used delay line system for mm-TWT's are either helix or coupled cavity chain. In general, the choice between these is made by considering the following factors:

- bandwidth
- dispersion, gain and phase fine structure
- heat transfer to the vacuum envelope
- fabrication.

In view of these considerations, the helix with excellent broadband performance and simple fabrication is used for small power tubes. The coupled cavity chain with its better heat transfer to the vacuum envelope than the helix is normally used for high power tubes. Its disadvantages are small bandwidth and complicated machining.

Beam focusing in most mm-TWT's is done with a periodic-permanent magnet stack using $SmCO_5$-magnets. These reduce size and weight of the focusing system.

Design relations for the delay line propagation constant, the beam perveance and the focusing magnetic field are listed in Figure 2 to explain the fundamental design theory.

The propagation constant is one of the most important design parameters. To achieve optimum tube operation in the mm-range the beam voltage must be very high, which means low beam perveance and very small delay line diameter. This fact leads to high density electron beams for the helix and coupled cavity structure and limits the manufacture with respect to frequency. On the other hand some restrictions have to be made to the beam voltage especially for space tubes to achieve good reliability of the tube power supply.

Due to the requirements for long tube life and high reliability the emission density of cathodes used may not exceed certain values. The beam area compression, i.e. the ratio of cathode area to beam area inside the delay line, will be determined by the cathode design.

From these points it can be seen that electron guns for mm-wave TWT's are of the low perveance type, producing high density beams with a high beam area compression.

Under these conditions the commonly used laminar theory for designing electron guns and beam focusing systems is not valid, as the thermal spread of the beam electrons leaving the cathode is no longer negligible. The influence of transverse thermal electron velocities on the design of electron guns and the beam focusing field has been investigated by several authors [1, 2, 3, 4]. Results achieved there have been used for the design of the 60 GHz / 5 W TWT electron gun and beam focusing field. Formula (3) from Figure 2 derived in [1] shows the influence of cathode temperature, cathode field, beam radius and area compression on the beam focusing field.

An estimation of the effect of thermal spread based on considerations described in [4] is shown in Figure 3, calculated for the 60 GHz / 5 W TWT:

The percentage of electrons inside an ideal equilibrium beam diameter, called the Brillouin-diameter, versus beam area compression for a beam power of 250 W can be seen.

From these figures it is evident that in general a low beam area compression will avoid a lot of problems caused by thermal electron beam spread for the electron gun design and also for the beam focusing field design.

The upper limit of emission density of the tungsten matrix cathode used for mm-TWT's is about 1 A/cm^2.

The schematic of the tungsten matrix cathode is shown in Figure 4:

The cathode consists of a porous tungsten body impregnated with Ba-Ca-Aluminate. This body is held by a moly-sleeve. The heater is embedded in alumina.

During the development of the 60 GHz / 5 W TWT, cathodes with very high emission density to reduce the beam area compression were also tested. Figure 5 shows the first accelerated life test results achieved under high emission density conditions for various new cathode designs. The change of current density versus life time beginning with a density of 6 A/cm^2 can be seen by 1 000 h. This is equivalent to a cathode life of 30 000 h minimum under normal operating conditions.

Another problem concerning slow wave structures is seen in the propagation of the electromagnetic waves along the structure. Resulting from an exact analysis, there exists not only the fundamental mode of propagation, commonly used for interaction with the electron beam, but also an infinite number of so-called space harmonics. These harmonics all have the same frequency and the same group velocity but different phase velocities.

These cause undesired effects such as backward wave oscillations and under certain conditions they impair the helix impedance for the fundamental wave.

Two possible configurations of the helix delay line structure of the 60 GHz / 5 W TWT can be ssen in Figure 6:

Figure 6a shows a configuration using heat shrink techniques to fix the helix inside the vacuum envelope, Figure 6b shows the use of moly-springs.

Based on the assumption of a tape helix model [5, 6, 7] a space harmonic analysis of the 60 GHz / 5 W TWT helix delay line system has been made and is shown in Figure 7:

Helix waves of the fundamental order ($m = 0$) and the order $m = \pm 1$ in a frequency-propagation constant plane have been computed for the dimensions of the delay line system of Figure 6b.

It can be seen that waves of the order $m = \pm 1$ have a cutoff frequency of about 30 GHz. These waves may be explained up to about 70 GHz as the dominant transverse electromagnetic or TEM-mode of a coaxial line having an inner conductor with the helix diameter and an outer conductor with the inner diameter of the vacuum envelope.

Hot measurements have shown that this mode seriously impairs the helix impedance and hence the gain of the tube.

Methods are under development to optimize the boundary value conditions for the helix waves in such a manner that the cutoff frequency of undesired modes of propagation will be shifted up.

Similar problems, especially backward wave problems, are to be solved under the development of coupled cavity structures.

A coupled cavity delay line structure is shown in Figure 8. The dimensions in millimetres are typical for a tube with a centre frequency of about 50 GHz. It is evident that machining will be also a serious problem for mm-coupled cavity tube development.

III - EFFICIENCY IMPROVEMENT

Methods frequently used are velocity tapering of the delay line structure, multistage collectors or both together. The multistage collector method will be described here:

Due to the modulation of the electron beam a wide range of electron velocities will occur and it is possible to collect several velocity groups on corresponding collector stages with the lowest possible voltages allowing all electrons of a group to be collected. It is possible to improve the basic efficiency of mm-TWT's by two to four times, using double to five stage collectors.

Figure 9 shows the spent beam energy distribution of the 60 GHz / 5 W TWT computed for saturated output power. For this tube a double stage collector is provided.

To demonstrate a more sophosticated multistage collector design, a five stage self-radiating collector can be seen in Figure 10. This collector has been developed for space application. The collector stages are insulated from the collector envelope, the collector envelope is bolted by a flange to the satellite and radiates the heat, conducted from each stage to it, into deep space.

Results achieved in the development of the 60 GHz / 5 W TWT will be published later with reference to high emission cathodes and mode shifting under development.

The tube is being developed under a contract of the "Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V." (German Aerospace Research Institute).

IV - STATE OF THE ART OF MM-TWT'S

At the end of this paper a general review is given of the state of the art of mm-TWT's developed or under development. It can be seen in Figure 11:

Upper design limits based on tube design and manufacturing techniques are shown for helix and coupled cavity tubes.

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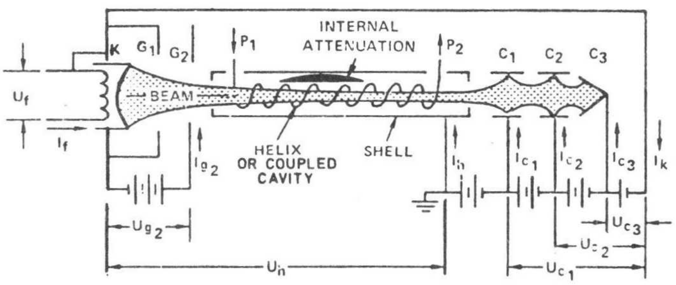

FIG 1 THREE-ELECTRODE COLL. TWT SCHEMATIC

AEG-TELEFUNKEN

(1) PROPAGATION CONSTANT

$$\gamma \cdot B_R \sim \frac{F}{\sqrt{U_0}} \cdot B_R$$

$$(\gamma \cdot B_R)_{OPT} \sim 0,6$$

(2) BEAM PERVEANCE

$$P = \frac{I_0}{U_0^{3/2}}$$

(3) FOCUSING MAGNETIC FIELD

$$B^2 = B_B^2 + A \cdot T_C \cdot \left(\frac{V}{R_0^2}\right) + B_C^2 \cdot V^2$$

F... FREQUENCY

B_R... BEAM RADIUS

U_0... BEAM VOLTAGE

I_0... BEAM CURRENT

B_B... "THERMAL" BRILLOUIN - FIELD

A... CONSTANT

T_C... ABSOLUTE CATHODE TEMPERATURE

V... BEAM AREA COMPRESSION

R_0... "THERMAL" BEAM RADIUS

B_C... CATHODE FIELD

FIG. 2 MAIN DESIGN FORMULAE

AEG-TELEFUNKEN

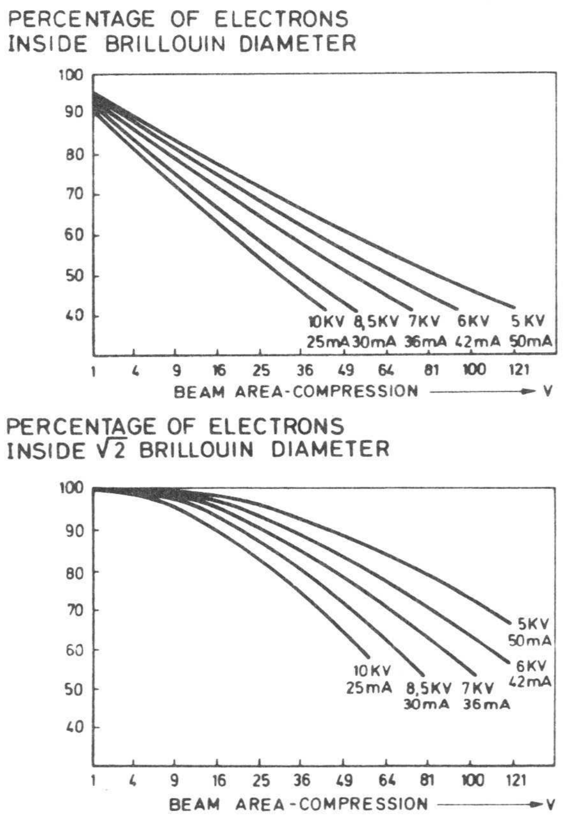

FIG. 3 60 GHZ/5W-TWT FRACTION OF ELECTRON FLOW INSIDE BRILLOUIN DIAMETER FOR 250W BEAM POWER

AEG-TELEFUNKEN

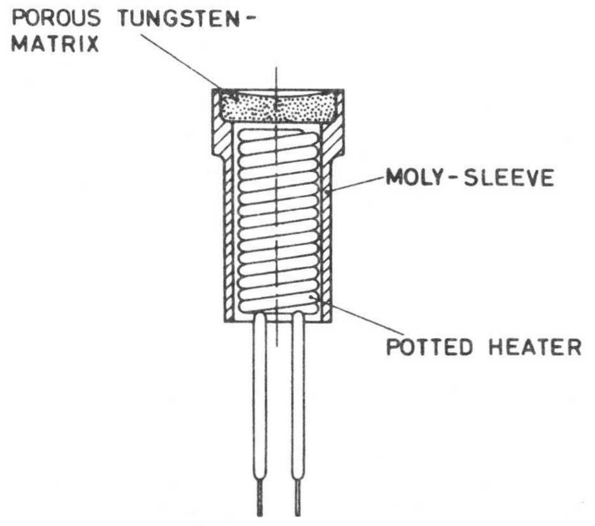

FIG. 4 IMPREGNATED MATRIX-CATHODE SCHEMATIC

AEG-TELEFUNKEN

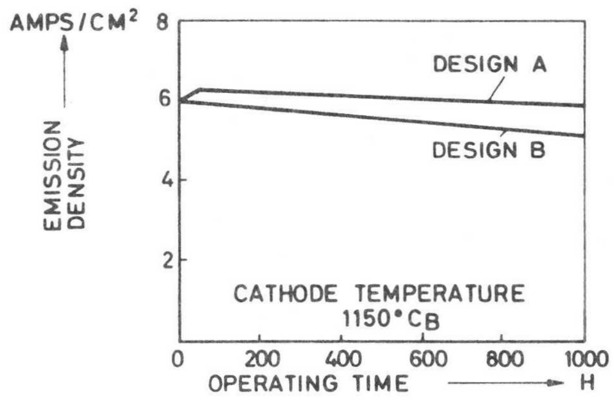

FIG. 5 EMISSION DENSITY DURING ACCELERATED LIFE-TEST

AEG-TELEFUNKEN

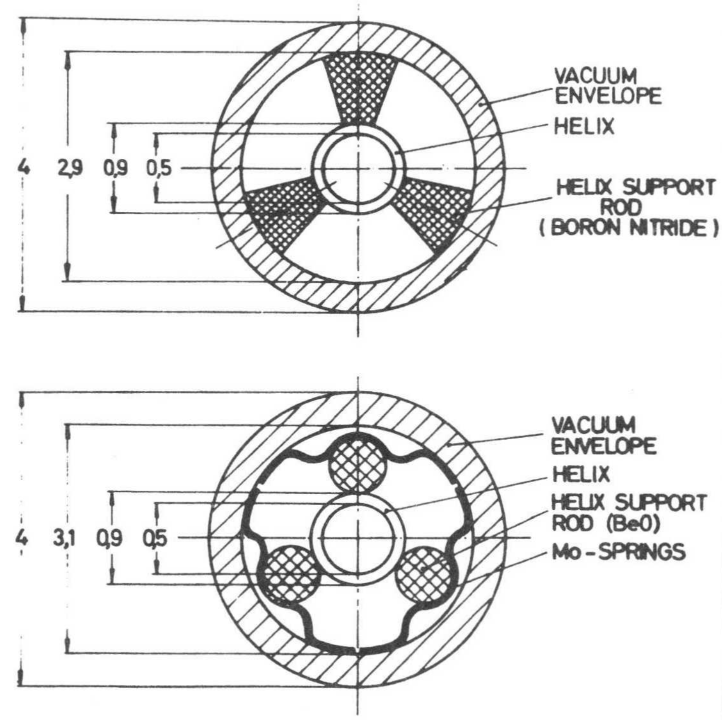

FIG. 6 60 GHZ/5W TWT POSSIBLE HELIX SUPPORT STRUCTURES

AEG-TELEFUNKEN

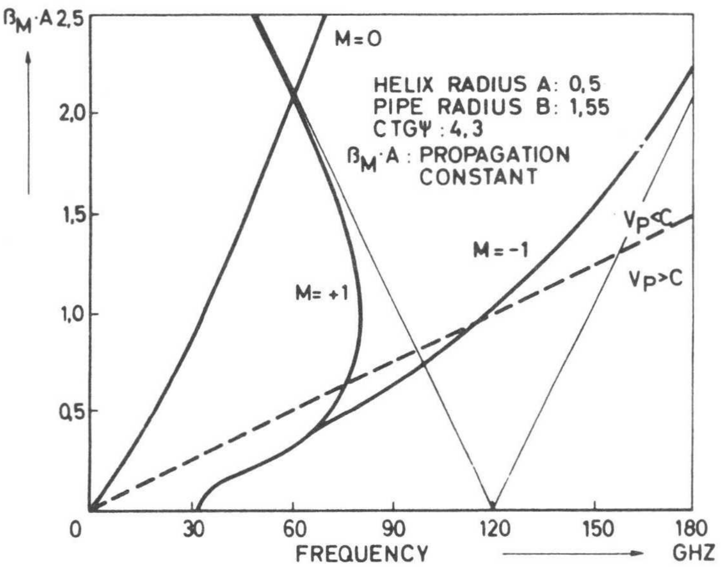

FIG. 7 60 GHZ/5W TWT SPACE HARMONIC ANALYSIS OF DELAY LINE

AEG-TELEFUNKEN

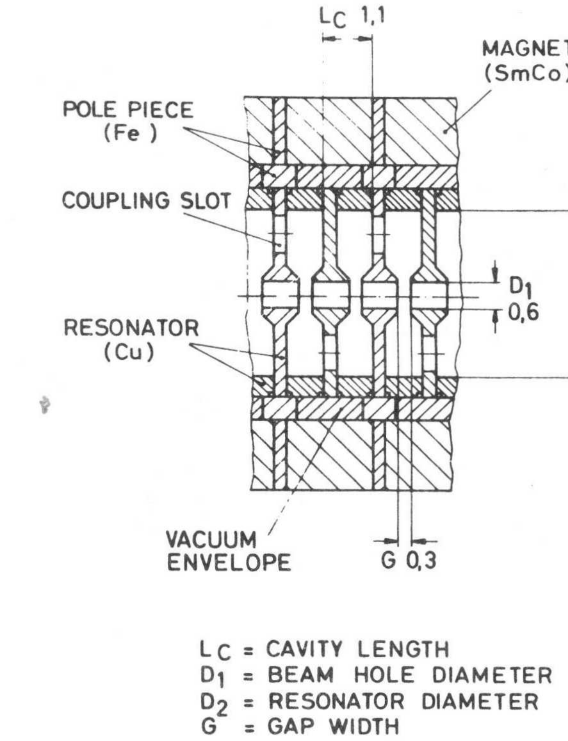

FIG. 8 COUPLED-CAVITY DELAY LINE STRUCTURE FOR MM-TWT

AEG-TELEFUNKEN

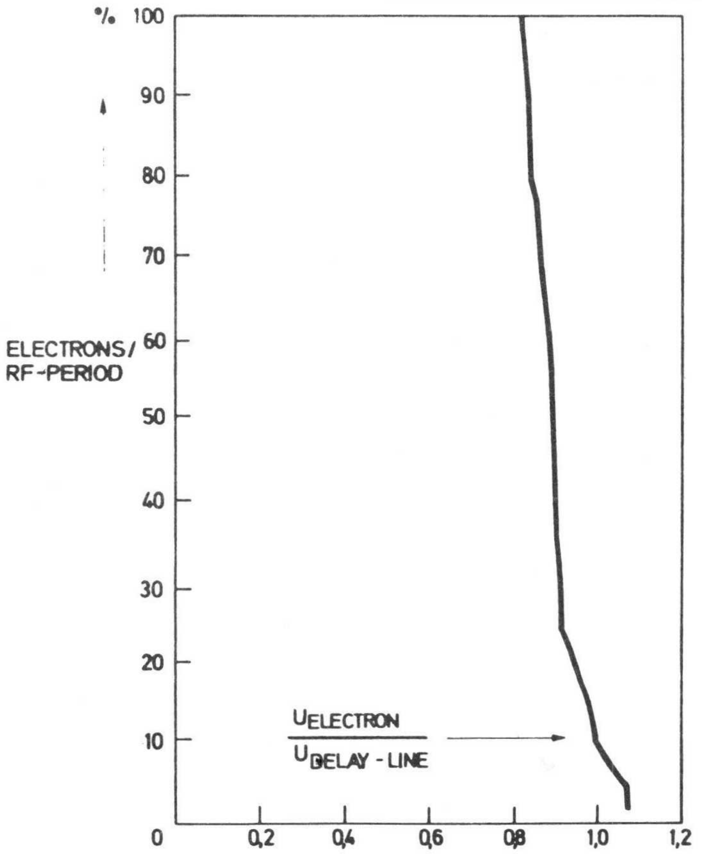

FIG. 9 60 GHZ/5W TWT SPENT BEAM ENERGY DISTRIBUTION FOR SATURATED OUTPUT POWER

AEG-TELEFUNKEN

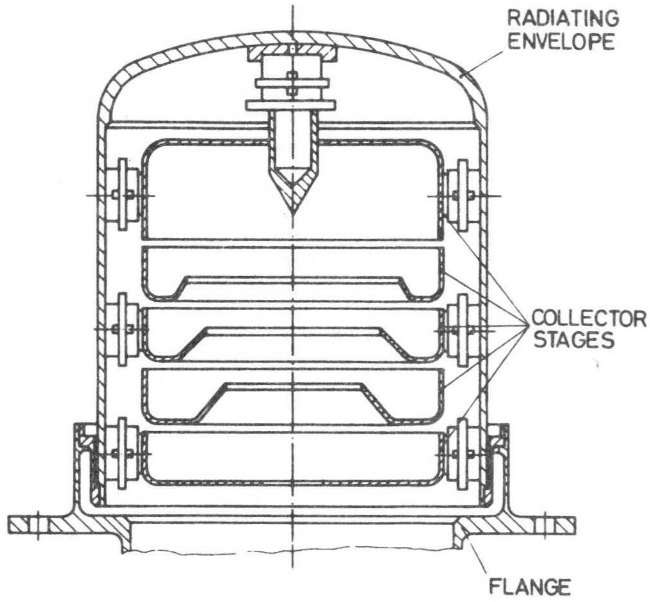

FIG. 10 SELF RADIATING MULTISTAGE DEPRESSED COLLECTOR

AEG-TELEFUNKEN

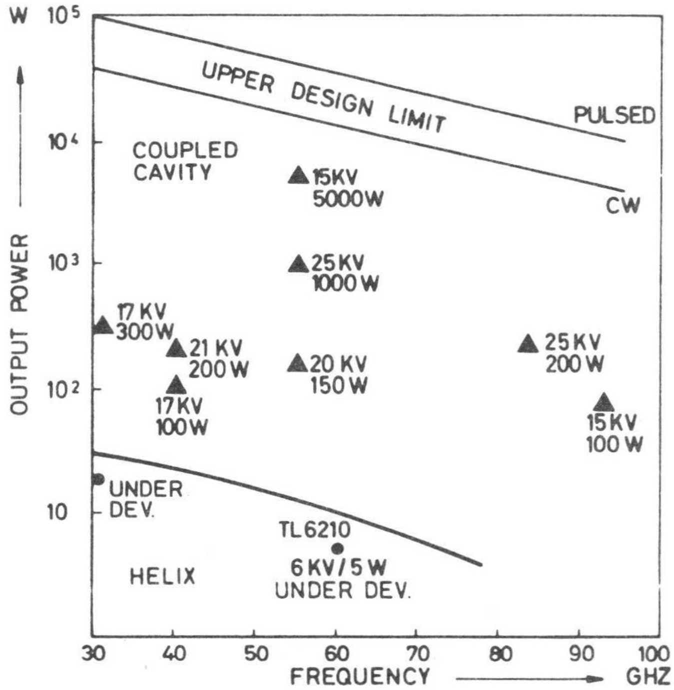

FIG. 11 MM-TWT DESIGN REVIEW

AEG-TELEFUNKEN

HIGH POWER SATELLITE TRAVELLING WAVE TUBES
WITH 200 W AND 450 W OUTPUT POWER

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Abstract

For future TV broadcasting satellites as BS II, German TV-SAT, Nordsat etc., power amplifiers in X-band of a few hundred watts are required. At AEG-TELEFUNKEN helix tubes and coupled cavity tubes were developed for this application. Power levels of 100 W, 200 W and 260 W are covered by broadband helix tubes. Beyond 260 W coupled cavity tubes were developed with 450 W and 800 W output power. All tubes are equipped with multi-stage-self-radiating collectors for weight saving and efficiency improvement. Power weights of less than 15 g/W could be realized for the tubes.

General

Different television-broadcast-satellite- (TVBS) studies in Europe were performed which showed that for this application tubes in the power class of approx. 200 W and approx. 500 W were required. AEG-TELEFUNKEN started the development in 1972 under a feasibility contract of the German Space Agency (DFVLR) where a 800 W breadboard-model tube was built. More detailed studies finally led to power levels of 200/260 W and 450 W. AEG-TELEFUNKEN then started the development aiming for this power level. Engineering-models of the 200 W and the 450 W tube were delivered in 1979. A 260 W contract , awared in 1979, calles for flight-model tubes in late 1981 which will be used in the German TV-SAT. Within this contract a life test program is carried out where seven tubes will be tested under realistic environmental conditions. Besides that fifteen gun testers are included in this program to verify th the predicted cathode performance. The program is such that the results are direct applicable to any power level within the 100 W to 500 W range.

450 W Coupled Cavity Tube TL 12450

Concept

The tube consists of the following three main subassemblies

a) Electron gun with mod-anode and AC-heater

b) Delay line out of three section coupled cavities with direct heat transfer to a baseplate

c) Collector self-radiating with five stages.

Fig. 1 shows the 450 W tube TL 12450. The tube length is 500 mm at a weight of 6,700 g.

Electron Gun. The electron gun uses a modified "Pierce" optic for beam forming. The cathode used is of tungsten matrix type. Extended life tests performed at AEG-TELEFUNKEN show that with this type of cathode more than 100,000 hours can be achieved operating with a cathode loading of 0.75 A/cm^2. In this life test program we have now accumulated 1.3 million hours with tubes and diodes. Six tubes have now operated successfully for 48,000 hours. The longest sample run with diodes is more than 100,000 hours. Twelve samples have now reached 74,000 hours and ten others have passed the 50,000 hour point. Furthermore another life test program with 25 tubes was started. Fourteen tubes are operating between 5,000 and 34,000 hours so far.

Designing the gun for the 450 W led to a cathode loading of 1.1 A/cm^2 because of the beam area compression ratio of 50. We regard this as the upper limit for long life space tubes. Due to this, accelerated life programs were performed with different cathode loadings in order to find the relation between cathode loading and life.

Fig. 2 shows the result. It is seen that with a cathode loading of 1.1 A/cm^2 a cathode life of 90,000 hours is achievable which leaves enough margin for the required 7-year life (62,000 hours).

Delay Line System. The tube uses a coupled cavity circuit as a delay line because of thermal considerations. The delay line is formed by copper resonators and iron pole pieces. The pole pieces are part of the vacuum envelope and extend right down to the electron beam. This integrated technique has two main advantages:

- Best use of the magnetic material $SmCo_5$, which means lowest possible magnet weight and

- Complete compensation of transverse magnetic fields and, therefore, excellent beam transmission.

The delay line itself consists of three sections which are separated by an internal sever. This gives high isolation between input and output beyond 100 dB. The sections are terminated by absorbers which are designed to withstand very high reflected power, for instance 100 W continuously, or total output power for a few seconds.

The system has excellent thermal properties, because each copper resonator is directly screwed to the baseplate which is part of the tube housing. The thermal gradient is such that the maximum temperature drop between baseplate and hottest point of the output resonator is only in the order of 30 °C. For the baseplate to which the tube is mounted the permissible temperature is - 30 °C to + 80 °C which means that the resonator is at 110 °C maximum. This is well below the maximum allowed copper temperature for long life tubes.

Collector. Because of the high overall efficiency required the collector is of 5-stage design. A special feature is that the collector is completely decoupled from the baseplate and radiates its dissipated power directly into space without any additional radiators. The radiator temperature will be at 300 °C to 350 °C. The mechanical design leads to very low collector weight, approx. 2.0 kg at a total tube weight of 6.8 kg because direct heat conduction, rather than radiation is used inside the collector from the electrodes to the outer envelope which is entirely on ground potential. Tests with elevated temperature have been performed which show that no degradation in isolation and heat transfer characteristics will occur within a 10-year life.

RF-Measurements

The tube is designed to operate between 11.7 GHz and 12.5 GHz. In order to cover the band four sets of parameters have to be used. Each set of parameters gives a 1 dB instantaneous bandwidth of 200 MHz.

Fig. 3 shows the saturated output power of the engineering-model for two sets of operating parameters. It can be seen from this figure that the 450 W output power is achieved over the total band.

Fig. 4 shows the measured instantaneous bandwidth of the engineering-model for a typical set of parameters. Optimizing the tube for the required 30 MHz channel leads to less than 10 W output power variation in a channel.

The gain of the tube is beyond 50 dB. Nonlinear phaseshift is typically around 50° and the AM-PM conversion factor measured was below 4.5 °/dB.

The overall efficiency recorded on the engineering-model is to be seen from fig. 5. The tube was optimized for this midband channel and it can be seen that overall efficiency is in excess of 50 %.

200/260 W Helix Tubes TL 12200/TL 12260*

Concept

As described in the section before the tube consists of three main subassemblies as well

a) Electron gun with mod-anode and AC-heater

b) Delay line out of two section tape helix. The output helix has a taper against backward wave oscillation. The envelope has an integral pole piece design which assures excellent focusing by optimum thermal properties

c) Collector self-radiating with three resp. five stages.

Fig. 6 shows the engineering-model 200 W tube TL 12200. The overall length is 400 mm. The weight with three stages is 2.6 kg and with five stages 3.3 kg. The difference is due to the collector which results in an efficiency improvement of approx. 4 % to 5 %.

* For the 200/260 W tubes an EPC is under development at AEG-TELEFUNKEN Backnang.

Electron Gun. The electron gun is of modified "Pierce" type. A tungsten matrix cathode with a 0.7 A/cm^2 current loading is used which operates near 1020 °C. This will result in an expected life of more than 100,000 hours (fig. 2). The mechanical design uses the so-called sandwich-technique where ceramic rings and electrodes stacked on top of each other form the vacuum envelope. The gun design allows final mechanical allignment during focusing for achieving excellent beam transmission. The beam area conversion is less than 50 what assures optimum entrance conditions.

Delay Line System. The delay line used for this tube is a two section tape helix. Both sections are tapered against backward wave oscillations. The output section has an efficiency taper on top. By means of special heat removal design 2.7°K/Wcm are achieved which keeps the helix within safe operating temperature limits. Under worst case conditions the helix of the 260 W tube stays below 200 °C. which is a safe limit for long life tubes. The tube is severed and internally terminated by carbon layers on the BeO-helix supporting rods. The vacuum envelope is formed by pole pieces and spacers out of copper. The inner diameter is honed after bracing what results in

- excellent thermal contact between supporting rods and pole pieces
- exact allignment between magnetic and beam axis what results in excellent and unproblematic focusing.

The pole pieces have two copper extensions which are in direct contact with the baseplate. This technique has a power handling capability for satellite application of up to 280 W rf-power. The power fading after "snap on" is less than 0.05 dB what demonstrates the excellent heat transfer properties. The magnetic material used is $SmCo_5$.

Collector. The collector is of the same basic design as for the 450 W tube. The 200 W tube is equipped with a three stage self-radiating collector while the 260 W tube has to use a five stage design because of efficiency requirements. The interface between three stage and five stage collector with the delay line is identical so that either tube can be equiped with either one of the different collectors. The weight difference of the two collectors is approx. 500 g which is the penalty for gaining 4 % to 5 % overall efficiency. The operating temperature of the collector is between 300 °C and 350 °C depending on drive conditions.

RF-Measurements

The tube is designed for an instantaneous bandwidth of 800 MHz (11.7 to 12.5 GHz).

In fig. 7 the output power for both tubes 200 and 260 W is shown versus frequency for constant conditions. It can be seen that the tubes have an excellent broadband performance. There is less than 0.5 dB power variation across the whole band.

Fig. 8 shows a typical transfer curve. The 200 W tube saturates with an input power of approx. 20 mW which corresponds to 40 dB gain minimum. The 260 W tube has a saturated gain of 42 dB minimum what means that less than 10 mW input power is required to saturate the tube.

The nonlinear phaseshift of the tube is approx. 45°. This is a typical figure across the whole 800 MHz band. Measured intermods give values which are typical for helix tubes (11 dB at saturation and 36 dB at 13 dB below 2 carrier saturation). The measured noise figure is below 35 dB. The second harmonic was measured 30 dB below the fundamental. This is due to the waveguide output which suppresses the coupling efficiency at these frequencies. The AM-PM conversion factor measured was 4 °/dB.

The overall efficiencies measured so far depend on the number of collector stages used. With two stages 40 % to 41 % was achieved under nominal conditions. Using a three stage design 43 % to 44 % could be measured. With the final five stage collector design 46 % to 47 % was achieved so far. These results show that even the three stage collector was not fully optimized. A five stage collector has to be used to guarantee 45 % efficiency minimum under worst case conditions with some design margin.

Fig. 9 shows the overall efficiency versus collector stages for the 200/260 W tubes. It can be seen that a relative good agreement between calculated resp. scaled data with actually measured data is achieved.

Conclusion

Four high power X-band tubes for TV-SAT application were developed at AEG-TELEFUNKEN. The status of these tubes is as follows

- 800 W tube TL 12800: breadboard status
- 450 W tube TL 12450: engineering-models delivered
- 200 W tube TL 12200: engineering-models delivered
- 260 W tube TL 12260: qualification and flight-models production contract awarded with flight model delivery in late 1981.

During the development a power limit for a helix tube in this frequency range could be established which is 280 W. Above this power level coupled cavity tubes have to be considered.

The test results available so far demonstrate that the tubes will meet their main specified parameters for use as power amplifiers in broadcasting satellites:

- Cathode design life of more than seven years
- Specific weight of less than 15 g/W
- Efficiency of 45 % for broadband helix tubes
- Efficiency of 50 % for coupled cavity tubes.

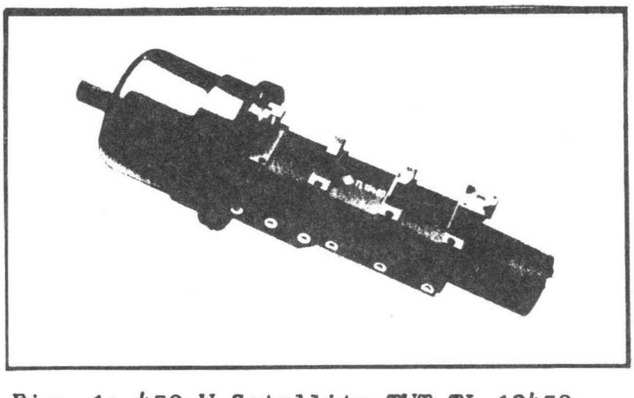

Fig. 1: 450 W Satellite TWT TL 12450

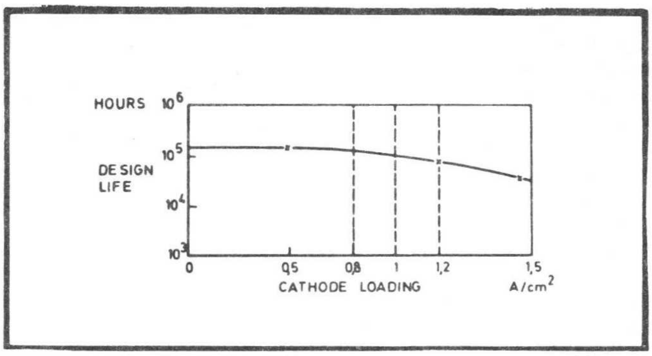

Fig. 2: Design life capability versus cathode loading

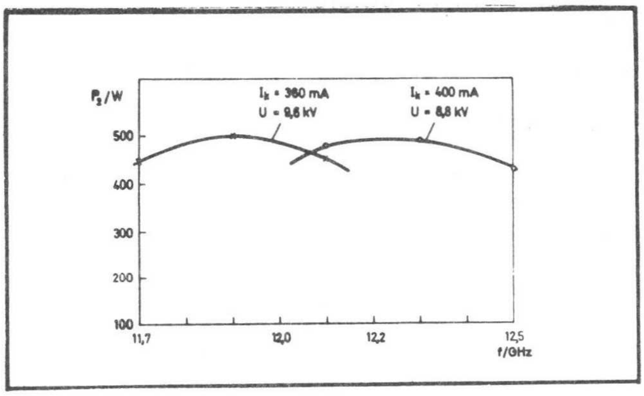

Fig. 3: Saturated output power versus frequency for the 450 W TWT TL 12450

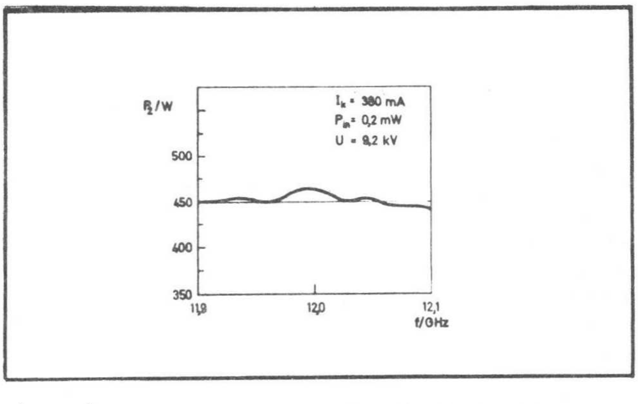

Fig. 4: Instantaneous bandwidth of satellite TWT TL 12450

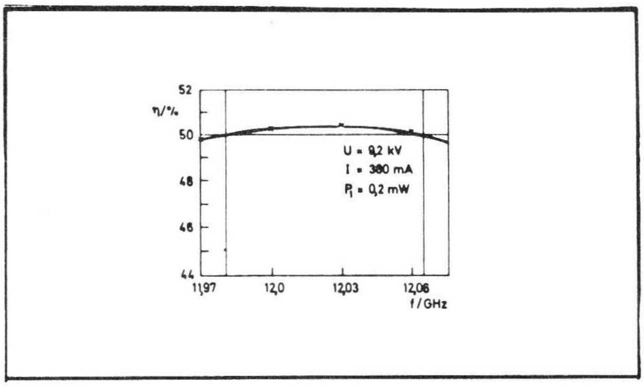

Fig. 5: Overall efficiency measured in a channel bandwidth of 80 MHz for the TWT TL 12450

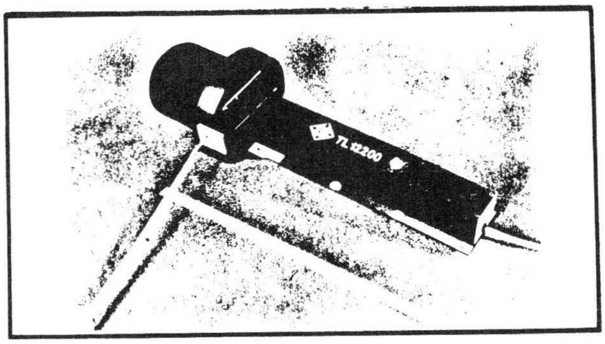

Fig. 6: 200 W Satellite TWT TL 12200

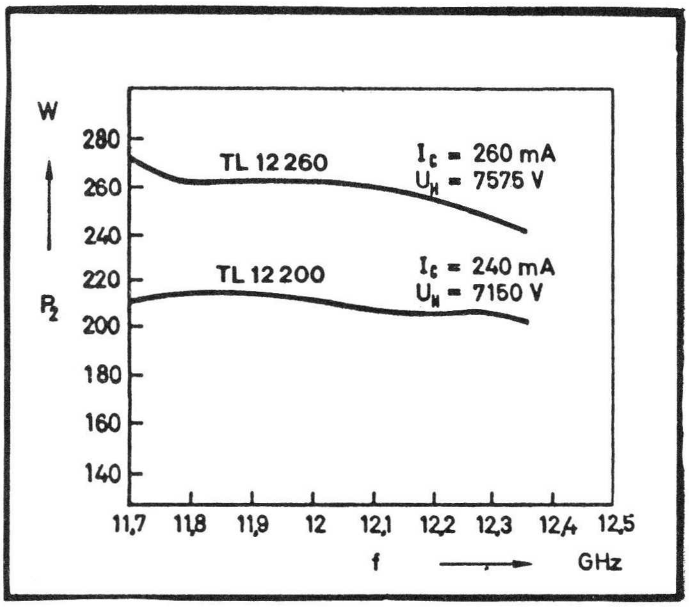

Fig. 7: Output Power P_2 versus frequency for the 200 W TWT TL 12200 and the 260 W TWT TL 12260

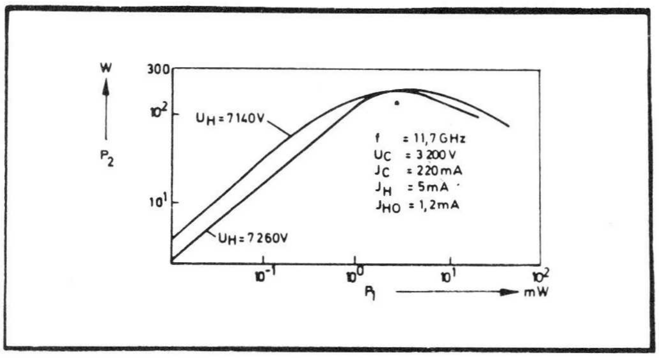

Fig. 8: Output power P_2 versus input power P_1 for the satellite TWT TL 12200

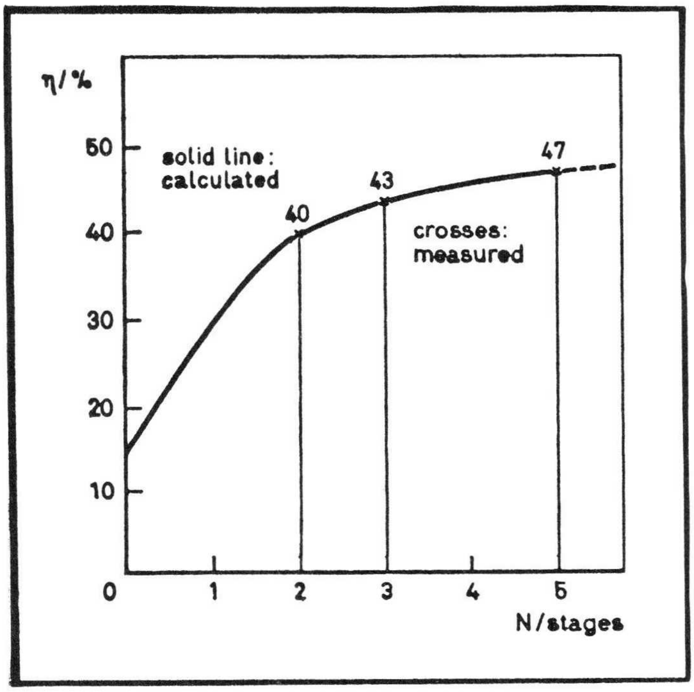

Fig. 9: Overall efficiency η versus collector stages N for the 200 W/260 W TWT

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