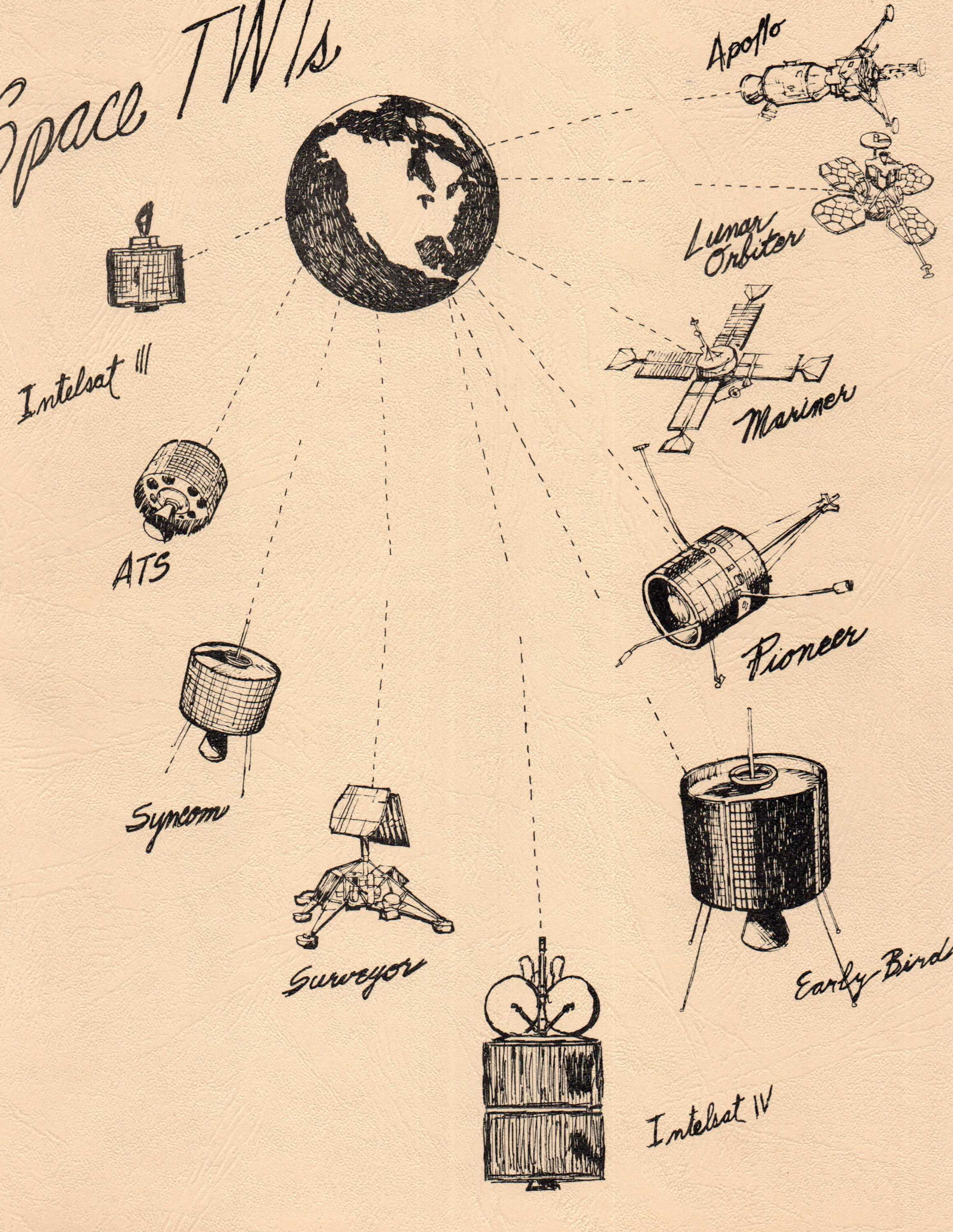
Space TWTs


Apollo
Lunar Orbiter
Intelsat III
Mariner
ATS
Pioneer
Syncom
Surveyor
Early Bird
Intelsat IV

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LATEST ADVANCES IN SPACE TWT'S

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Abstract

With Apollo XI and XII, Mariner VI and VII, Intelsat III, and Advanced Technology Satellites (ATS-E) recently behind us, this paper will present the state of today's art, and indicate developing trends in Low and Medium Power Traveling-wave Tubes for Space Communications. This paper then is divided into three parts. In the first part, the measured life performance of traveling-wave tubes built by the Electron Dynamics Division of the Hughes Aircraft Company for use on Syncom, Surveyor, Advanced Technology Satellite, Lunar Orbiter, Early Bird, Mariner, Apollo, Pioneer, Tacsat, Intelsat II and Intelsat III programs in space and in life test positions in our facility, is presented. Part two covers the electrical characteristics of tubes being built for present space communication applications with particular emphasis on distortion characteristics. The third section covers programs to provide higher power and lower distortion at frequencies from L-band through S, C, X, Ku, K and Ka-bands, at power levels from 100 milliwatts to 10/40 watts.

Introduction

With Apollo XI and XII, Mariner VI and VII, Intelsat III and TACSAT behind us, a new generation of space vehicles and communication satellites are being built for launch early in this decade. As more sophisticated communications are required to fill future space requirements, it is time to take stock of the present-day or near-term capabilities of low and medium power traveling-wave tubes.

In this paper, we shall look at past, present, and future traveling-wave tubes. From past efforts we can obtain data on life, and parameter drift with life, and update reliability assessment figures. From the data taken on tubes we are presently delivering to near-term spacecrafts, we can obtain the electrical characteristics of existing hardware, with particular emphasis placed on the distortion characteristics. Finally, from the electrical characteristics of tubes now in development at the Electron Dynamics Division we can look at the higher efficiency and lower distortion figures we foresee for the next generation of space efforts.

Life Performance

Through December 29, 1969, a total of 1,905,307 hours of operation had been accrued on sixty (60) traveling-wave tubes which are undergoing life tests at our facility. Shown in Table I, these tests began on March 12, 1962 when tube type 314H, Serial No. 12, was placed on the life test rack. Ultimately, eight more of these SYNCOM 2.5 watt L-band tubes were added, and all nine tubes are still in full operation after 555,503 total hours or more than seven years operation per tube. Several other types were added over the years and round out the table.

TABLE I
HUGHES SPACE TRAVELING-WAVE TUBE
LIFE TEST AND SPACE OPERATION SUMMARY

SPACECRAFT	TUBE TYPE	LIFE TESTS NO. OF TUBES	LIFE TESTS TOTAL HOURS*	SPACE OPERATION NO. OF TUBES	SPACE OPERATION TOTAL HOURS**
Syncom	314H	9	555,503	4	71,229
ATS	384H	12	552,286	-	---
ATS	384HA	13	236,612	16	26,168
Early Bird Intelsat II	215H	8	138,640	18	180,634
Apollo	384H	5	55,585	24	1,367***
Surveyor	349H	8	272,060	8	800***
Pioneer	214H	2	37,906	8	75,200
Intelsat II	226H	3	56,715	8	43,900
Mariner	216H	--	--	2	32,500
Surveyor	340H	--	--	2	200***
Lunar Orbiter	220H	--	--	5	1,250***
TACSAT	240H	--	--	2	3,500
TOTALS		60	1,905,307	93	436,748

* as of 12/29/69
** as of 8/1/69
*** Estimated Time

In addition, 436,748 hours of operation in space had been achieved on 93 tubes by August 1, 1969.

From data as comprehensive as this, changes of tube parameters with operating time can be determined, and credible reliability figures can be ascertained.

Power Output and Gain Changes with Life

On the surface, one would think that a value for change in power output with life would be readily available from such a large amount of data, but many complications arise. For example:

1. For 40 dB directional couplers the best calibration we can get is ± .1 dB per 10 dB of decoupling or ± .4 dB uncertainty.

2. With a large number of tubes starting life at different times, a plot of power output versus operating time distorts the calibration error. This suggests plotting versus calendar date.

3. Tubes start life with different power levels suggesting normalization of output power to start-of-life power.

   Figure 1 is a plot in this fashion for eight (8) 4 watt C-band 36 dB gain ATS traveling-wave tubes (384H). The ± .4 dB uncertainty is clearly indicated, and a "best fit" straight line has a slope of -0.1 dB per three years.

Since data is taken at a fixed input power, a change in the power output with life is also a change in the saturated gain with life.

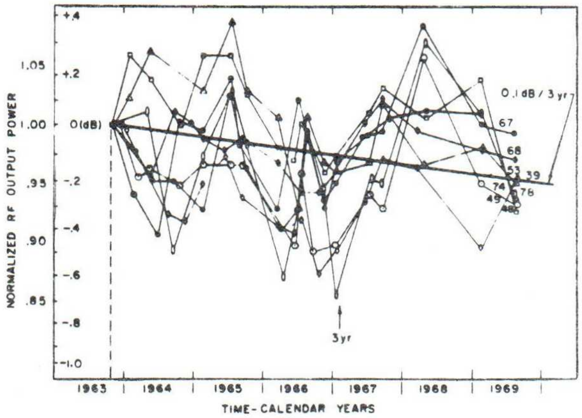

Figure 1. Normalized power output vs time for eight space TWTs on life test.

Other Parameter Changes with Life

Throughout all of the years of this program, data has been recorded on all dc input parameters and on saturated drive and power output. In addition, cathode activity has been measured. No significant or important changes have been recorded.

Life Expectancy

Life is an interesting parameter to define, since in the absence of a catastrophic failure, how shall we define end-of-life? The RF output power decreasing with time may cause the system to deliver too little power to accomplish the mission, if the total system is not designed to accommodate these changes. Let us, at least for the purpose of this paper, define end of life as the time when power output has dropped by 1.0 dB (20%) from start of life, Figure 2. To date, no tubes have failed this requirement, and from Figure 1, we are still in the early portion of the life chart. From data such as this we believe that ten years of life can be reliably achieved.

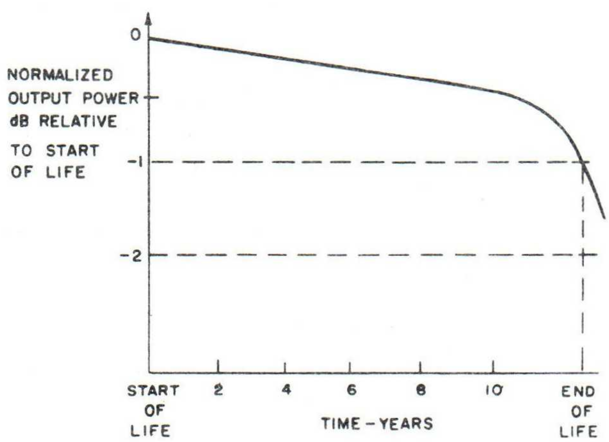

Figure 2. Idealized long life TWT power output vs time.

Reliability (MTBF)

The foregoing data is also useful in predicting reliability levels. Since each tube utilizes the same basic design configuration and is fabricated with common processes and materials in the same controlled environment by the space tube group, it is felt that the data presented in Table I is applicable to all medium powered space tubes built at this facility. Utilization of this data and the X^2 (Chi^2) confidence table yields a mean-time-between-failures (MTBF) greater than one-million hours at the 90% confidence level.

At the present time, deliveries are being made on medium power output and/or driver traveling-wave tubes for communication satellite requirements at C, X, and Ku-band. Telemetry requirements are being filled with presently available S-band TWTs. The generalized performance of these traveling-wave tubes is presented in the following discussion.

Description of TWT Transfer Characteristics and Performance Parameters

Gain, Phase Shift, AM/PM Conversion

A typical power output and relative phase shift characteristic is shown in Figure 3 for a TWT operated as a wide band, low distortion amplifier. Here it is seen that phase shift is relatively insensitive to drive in the small signal ("linear") portion of the RF output power characteristics. As the traveling-wave tube is driven into saturation, the rate of phase change increases and then decreases as the output power saturates. The slope of this line, or AM/PM conversion, is plotted against RF drive in Figure 4. The peak AM/PM generally occurs at a drive level 5 to 10 dB below saturation drive. These data are for the case of a single carrier. For the case of two or more carriers, transfer takes place giving PM at the output on one carrier due to AM at the input on the other. The general trend with drive is similar for this case but the specific values are different and are also a complicated function of the relative carrier amplitudes.

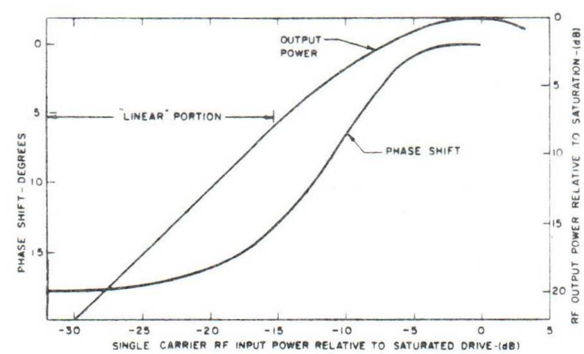

Figure 3. Typical power output and phase shift as a function of RF input power for communication type TWT.

Power, Gain and Efficiency

Efficiency is generally defined as that portion (percentage) of the maximum total primary input power that is realized as saturated RF output power in the case of a single carrier. Efficiency as well as gain and output power vary with the beam voltage. A typical case is shown in Figure 5.

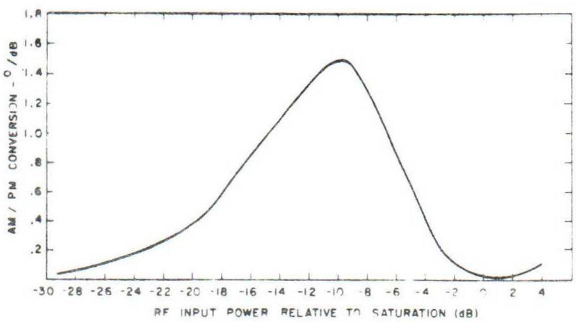

Figure 4. Typical single carrier AM/PM Conversion

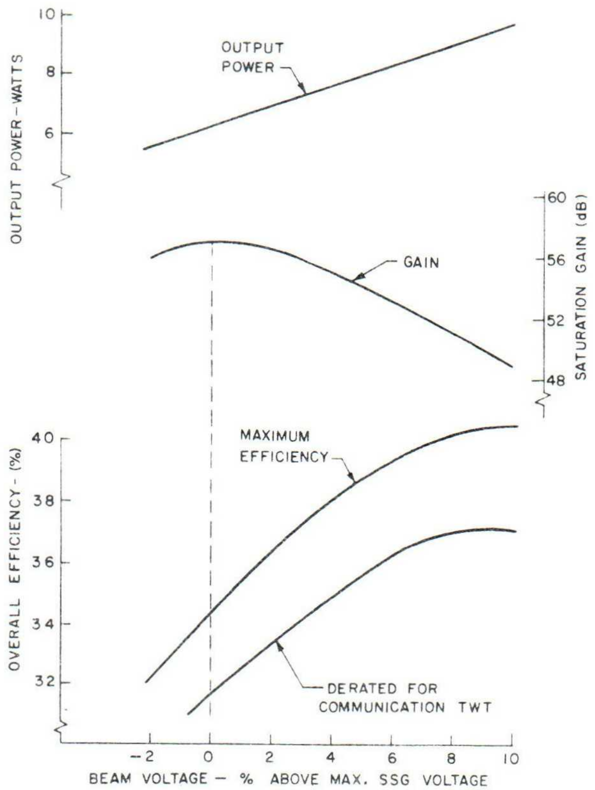

Figure 5. Power, gain, and efficiency vs beam voltage for Intelsat IV type output TWT.

Here it may be seen that power and efficiency increase with voltage up a point while gain decreases with increasing voltage in the typical region of interest.

Noise Figure

The noise figure is a measure of the degradation in signal-to-noise ratio with passage of the signal through the traveling-wave tube. For the medium power satellite traveling-wave tubes under consideration, the noise figures range from 18 to 30 dB. Typically, communications, satellite transponder output traveling-wave tubes have noise figures from 24 to 27 dB, while for driver TWTs the noise figures range from 16 to 23 dB. This parameter increases as the frequency and power level increase.

Intermodulation Distortion

When more than one carrier is introduced at the traveling-wave tube input, a mixing, or intermodulation process, takes place. This results in intermodulation products which are displaced from the carriers at multiples of the difference frequency. The power levels of these intermodulation products are dependent on the relative power levels of the carriers and the efficiency of the TWT. For the case of two balanced carriers, Figure 6 shows the variation of carrier and IM product power level with total drive power. The single carrier power curve is also plotted for comparison. As was the case with AM/PM conversion, the IM distortion is significantly reduced in the small signal (linear) region of the RF drive range.

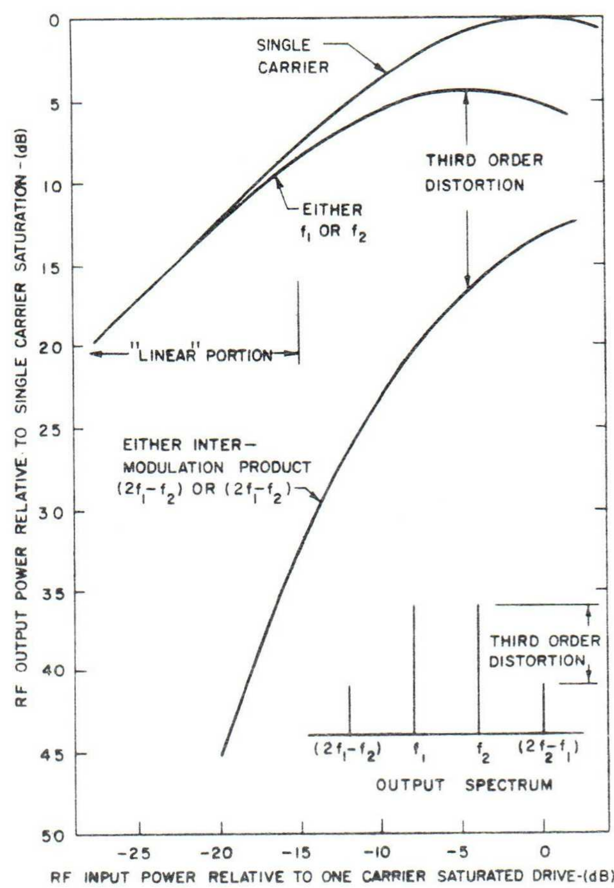

Figure 6. Typical third order intermodulation data for Intelsat IV type TWT.

Distortion Parameter - Beam Voltage

Phase shift and AM/PM conversion are plotted vs beam voltage in Figure 7. These parameters also increase as the overvoltage and efficiency increase.

Harmonic Power

Because of the wide bandwidth of the device, the output spectrum generally contains some harmonic

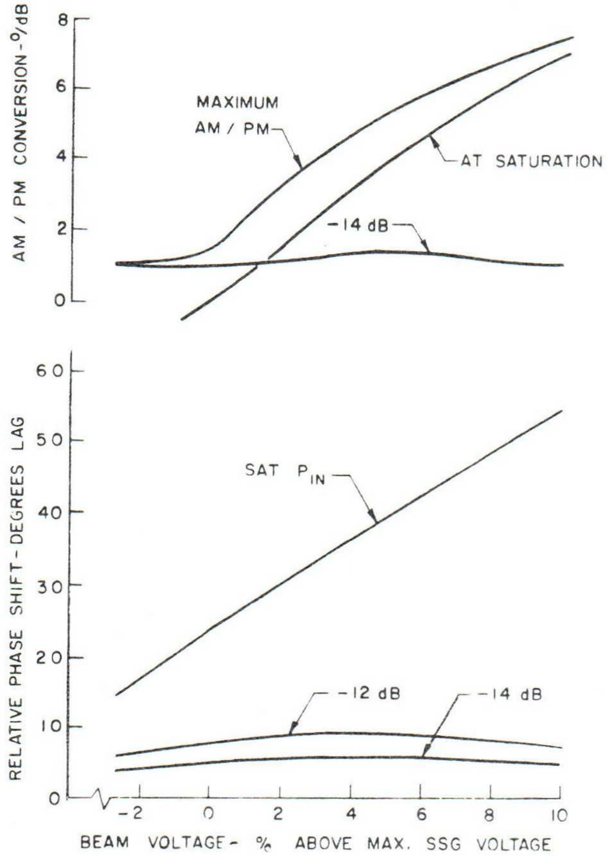

Figure 7. AM/PM conversion and phase shift for Intelsat IV type output TWT.

power. Figure 8 shows the variation of second-harmonic power as a function of beam voltage (efficiency) with RF drive level as a parameter.

This performance varies with the frequency so that the harmonics of the upper-band edge fundamentals are lower than those of lower band edge fundamental drive signals.

VSWR Bandwidth

RF mismatches within the operating band must be minimized as they cause gain variation and time delay distortion. Figure 9 shows excellent cold and operating reflection coefficients versus frequency for a typical satellite traveling-wave tube.

Gain, Power and Efficiency Bandwidth

Figure 10 shows the way in which the smoothed small signal gain, as well as the overall efficiency, varies with frequency for a range of values of the beam voltage. This figure demonstrates that maximum gain flatness and gain bandwidth are not consistent with maximum power output and efficiency.

Time Delay Distortion/Fine Grain-Gain Variation

Time delay distortion is directly related to the RF mismatches present in the traveling-wave tube. A typical example of the time delay variations with frequency is given in Figure 11. Fine grain gain variation is also dependent on the various local RF mismatches and gain in the traveling-wave tube. Typical characteristics are also shown in Figure 11.

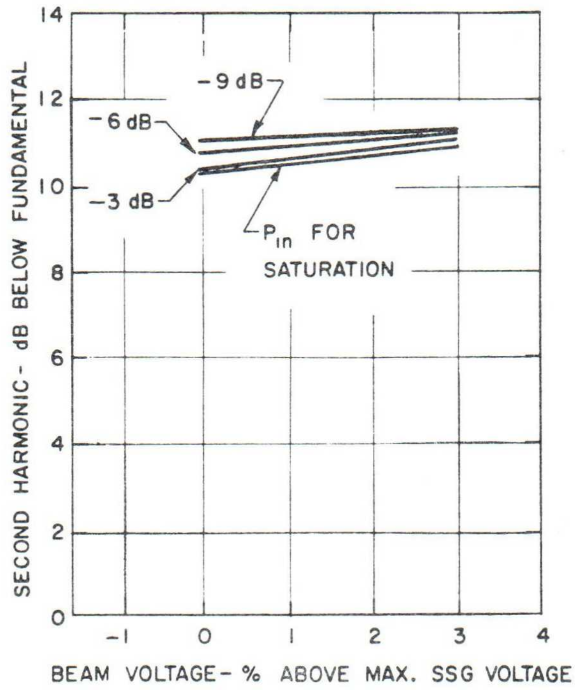

Figure 8. Harmonic power vs overvoltage for X-band space TWT.

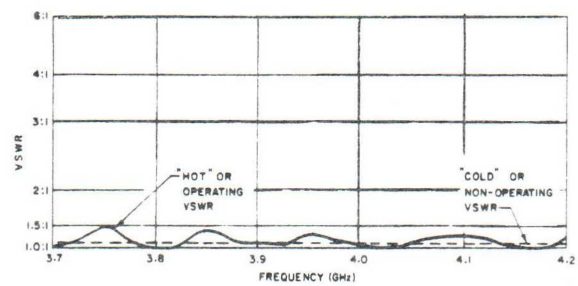

Figure 9. Typical output VSWRs for Intelsat IV driver TWT.

Design Tradeoffs for Best Overall Performance Summary

Several conclusions are drawn from the TWT properties described in the previous section:

1. Optimum efficiency, either in the form of increased dc primary power and/or of reduced RF output power, must be traded for optimum performance in any of the following areas:

   AM/PM conversion
   Phase shift
   Wide band gain flatness

   This is consistent with the requirements of present wide band communication satellites where wide traveling-wave tube bandwidths are utilized. Furthermore, operation in the linear region for minimum distortion performance is common practice. Traveling-wave tubes providing single carrier, saturation RF output power in the range of 0.1 to 22 watts, are used in present applications.

2. In narrow band applications, and/or where modulation schems are such that AM/PM and IM distortion are of little consequence, maximum TWT efficiency can be realized. This has been the case with many of the experimental space probes launched to date as well as some of the earlier communications satellites.

The demonstrated capabilities of TWT design in past and present applications for wide and narrow band applications are given in Table II to provide historical perspective.

Bandwidth is probably the most significant performance characteristic as it sets the TWT apart from other microwave tubes. To take full advantage of the wide bandwidth, the TWT must have acceptably low VSWR across this bandwidth. Also, it must be operated so as to achieve optimum gain and power over this band; optimum being dependent on the system application.

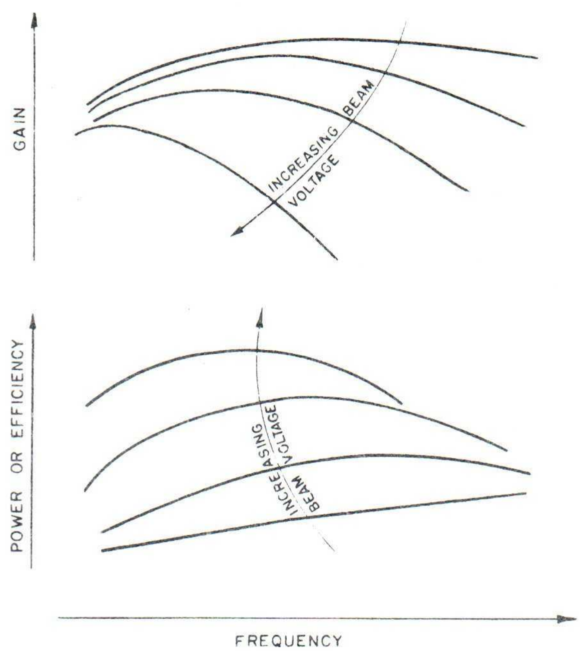

Figure 10. Illustrating the gain-bandwidth, power-efficiency tradoff.

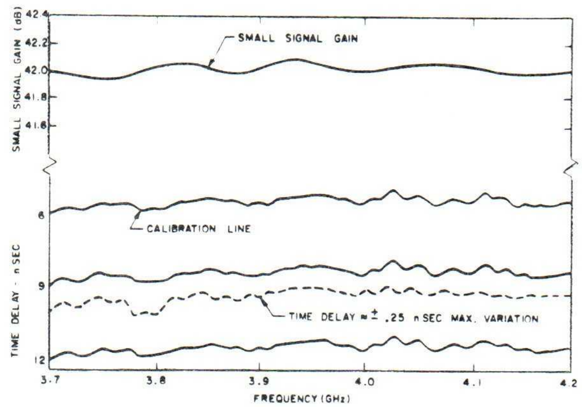

Figure 11. Time delay and small signal gain vs frequency - Intelsat IV type driver TWT.

Developmental Programs

As previously indicated, there are two general types of systems utilizing TWTs as the final RF amplifier. The type of system which has been referred to as narrow band permits one to design the TWT for optimum efficiency operation. The narrow band system is used when the transmitter is at a source of information such as an Apollo or Mariner system. The "broadband" system requires low distortion performance because of communication requirements, and normally the TWT has a lower efficiency than for the narrow band system. While the broadband type is used as a microwave relay link in systems such as the Intelsat series of communication satellites, the latter satellites require that large amounts of information be handled. As time goes on, frequency allocations are being used up and future systems will have to utilize higher and higher frequencies.

This section contains description of some of the current traveling-wave tube development programs at Hughes Electron Dynamics Division. The improvements to performance characteristics are in the area of higher efficiency, lower distortion, or higher frequency. We will first discuss the high efficiency work.

Presently, laboratory models of highly efficient traveling-wave tubes which are suitable for the next generation of deep space probes are being tested. The design for these models was a product of our advanced large signal computer program for traveling-wave tubes. The computer analysis is a very powerful tool in discovering new techniques for efficiency enhancement and for aiding us in

TABLE II

	SYNCOM	SURVEYOR	LUNAR ORBITER	APOLLO	ATS	EARLY BIRD & INTELSAT II	PIONEER	INTELSAT III	TELEMETRY (EXP.)	TACSAT	INTELSAT IV	DEVELOPMENT	DEVELOPMENT	
TUBE	314H	349H	220H	394H	384H	215H	214H	235H	219H	240H	261H	265H	837H	UNITS
POWER	2	10	13	5/20	4	6	8	12	20	20	6	20	1.5	Watts
GAIN	33	27	27	26/20	40	40	27	43	30	43	50	45	42	dB
BANDWIDTH	10	10	10	10	100	120	10	250	10	70	30	500	1400	MHz
FREQUENCY	S	S	S	S	C	C	S	C	X	X	C	X	X	Band
EFFICIENCY	20	25	28	32	33	33	33	34	35	33	31	29	15	%

putting these techniques into practice. By using the computer, we have explored velocity resynchronization methods for efficiency improvement. The methods are designed to overcome a basic limitation of traveling-wave tubes - the loss of synchronism between circuit velocity and the average-beam velocity at large-signal levels. This occurs because the kinetic beam energy serves as the power source for the amplified RF energy. Therefore, at large signal levels, the power is extracted from the electron beam. This slows the beam down, and the required synchronism between circuit wave and the beam is no longer maintained. Then it is possible to improve the efficiency by resynchronizing the beam and the circuit at large signal levels.

There are several ways to do this. They are: velocity taper method, voltage jump method, and combination voltage jump velocity taper. Considering the velocity taper first, the velocity profiles of the circuit wave and the beam velocity are shown schematically in Figure 12. The axial phase velocity of the circuit wave is reduced at approximately the same rate that the average beam velocity reduces toward the output end of the tube. As a result of this resynchronization, a higher power output and better efficiency are obtained.

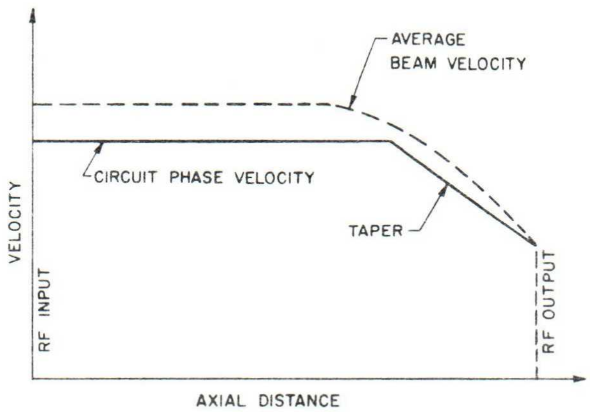

Figure 12. Velocity profiles of velocity taper.

This design approach was verified by constructing several models of a 20 watt S-band type of TWT with results on a typical tube as shown in Figure 13. We see from this type of tube that over 45% efficiency (including heater power) has been measured in the laboratory. By comparison, previous space tubes were at the 35% level. The RF output power versus input power is shown in the next figure (Figure 14) at 2.3 GHz. The gain of the tube was 31 dB and the tube exhibited a fairly flat saturation region. Limited data on distortion measurements have revealed that this tube has a relatively low AM to PM conversion at saturation for a high efficiency type of tube (3.5^o per dB) because this tube is not overvoltaged (i.e., not operated at a voltage above that for maximum small signal gain). This tube is presently being evaluated on a company funded program. The second efficiency improvement method of voltage jump, has also been investigated both theoretically and experimentally. The velocity profile for the voltage jump tube is shown in Figure 15. In the voltage jump method the circuit wave velocity remains unchanged and the beam is reaccelerated at the beginning of the voltage jump section. The beam is then resynchronized with the circuit wave. Again, the output power is increased and the efficiency is higher.

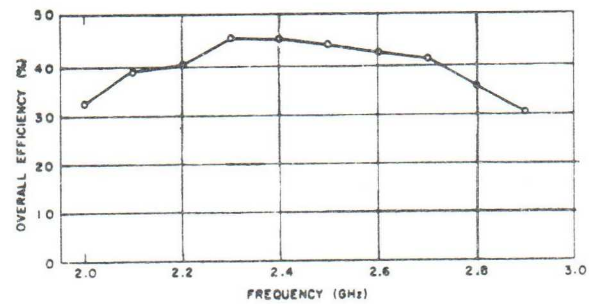

Figure 13. Measured efficiency of 20 watt space type velocity taper TWT.

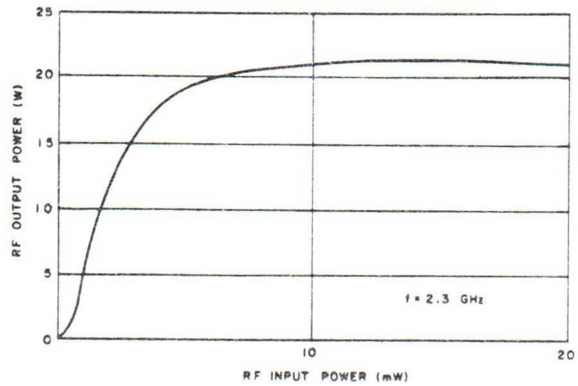

Figure 14. Measured RF power transfer characteristic for velocity taper TWT.

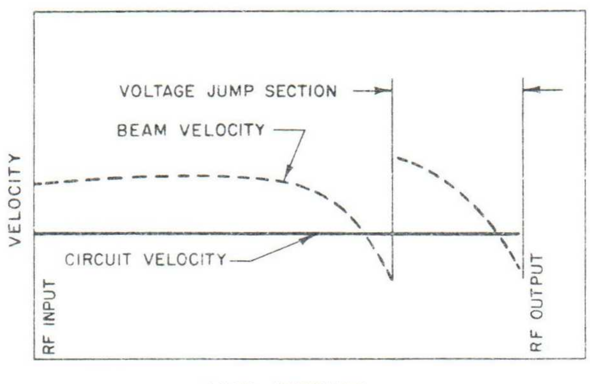

Figure 15. Velocity profile for voltage jump circuit.

Thus, the two methods are equivalent in their function of resynchronizing the beam and the circuit wave at large signal levels. However, in comparing the two methods, one finds that the voltage jump method is somewhat more effective due to the higher beam voltage in the voltage jump section.

A practical drawback of the voltage jump method is that an additional traveling-wave tube electrode is required to supply voltage to the jump section. Also, the helix jump section must be electrically insulated from both the input and helix and the RF output connector by dc blocks, as indicated in Figure 16. A single section, lower gain, voltage jump tube has been tested with results that fully confirm the design and prediction approach. Efficiencies of about 50% have been achieved with power levels up to 33 watts over a considerable range of frequencies, as shown in Figure 17 and 18. This gain was about 11 dB. The power conversion of the tube is shown in Figure 19.

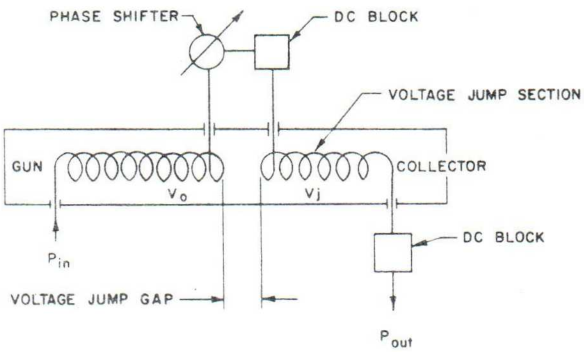

Figure 16. Helix TWT with voltage jump.

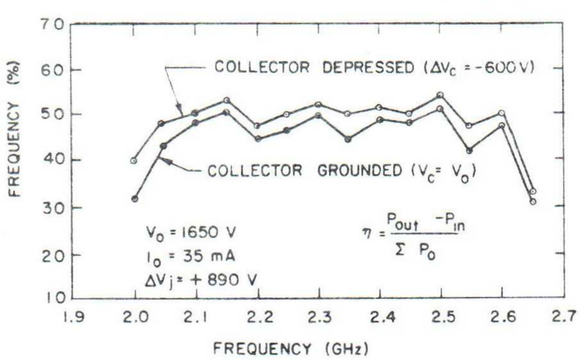

Figure 17. Efficiency of voltage jump tube.

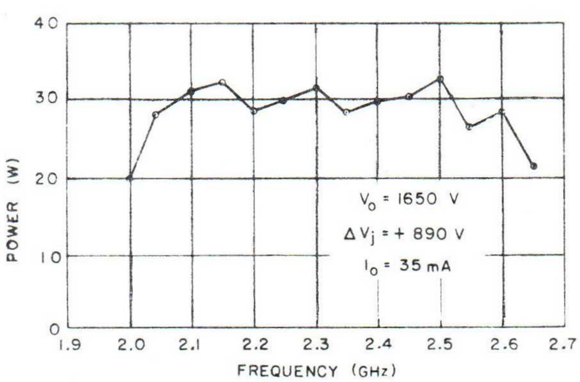

Figure 18. Output power of voltage jump tube.

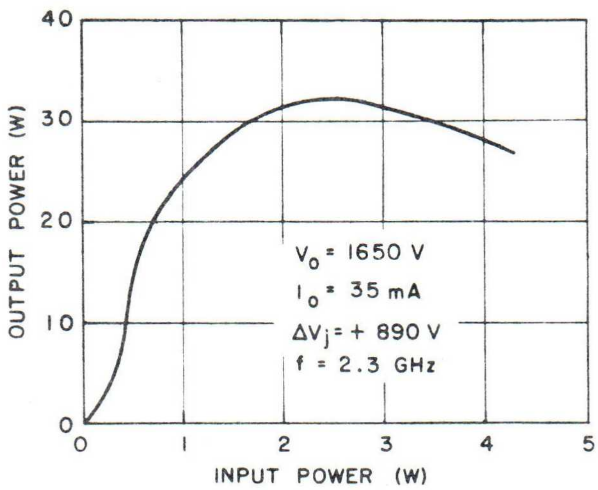

Figure 19. Power characteristics of voltage jump tube.

The combination voltage jump and velocity taper method has not been fully evaluated experimentally, however, it should provide even higher efficiencies. From both a system and a tube standpoint, the velocity taper method is the simplest to implement. Because of this most of our development effort has been concentrated on this method. The present tube has exhibited efficiencies greater than 45% and calculations show that over 50% efficiency can be achieved with this type of approach.

Work on improvement of traveling-wave tube distortion (because it is a more recent requirement) has proceeded at a slower rate than efficiency work. Distortion and efficiency values may be extracted from the large signal computer program previously mentioned. We are still exploring the effect of various tube parameters on distortion performance.

One tube type, the 269H, is being experimentally developed for an improved distortion performance. Preliminary results show that the same tube factors which improve distortion performance may also reduce its length and therefore its weight. This improved distortion performance is indicated in Figure 20 which shows the improvement that has thus far been realized.

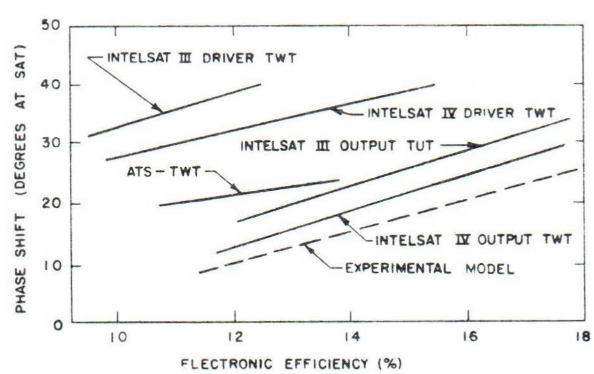

Figure 20. Phase shift at saturation vs electronic efficiency for selected Hughes space TWTs.

Comparing the 269H to a typical medium power "broad band" space tube, we find that for the same gain and power output, the 269H is 11% shorter for the same allowable phase distortion and has a higher basic efficiency. This means that a higher RF power output can be obtained from this tube for the same amount of allowable phase distortion.

The ordinate in Figure 20 is representative of the phase distortion in the traveling-wave tube at levels near saturated power output. The intermodulation distortion for the 269H is quite similar to our other tubes except in the area of "linear" operation. Here where the tube is nearly linear, the intermodulation of the 269H is improved because the phase distortion, or AM to PM conversion, is reduced. The improvement made is indicated in Figure 21. While not a large value, the improvement is significant in that, prior to this tube, it was not known how to design for reduced intermodulation distortion, especially at the low power levels.

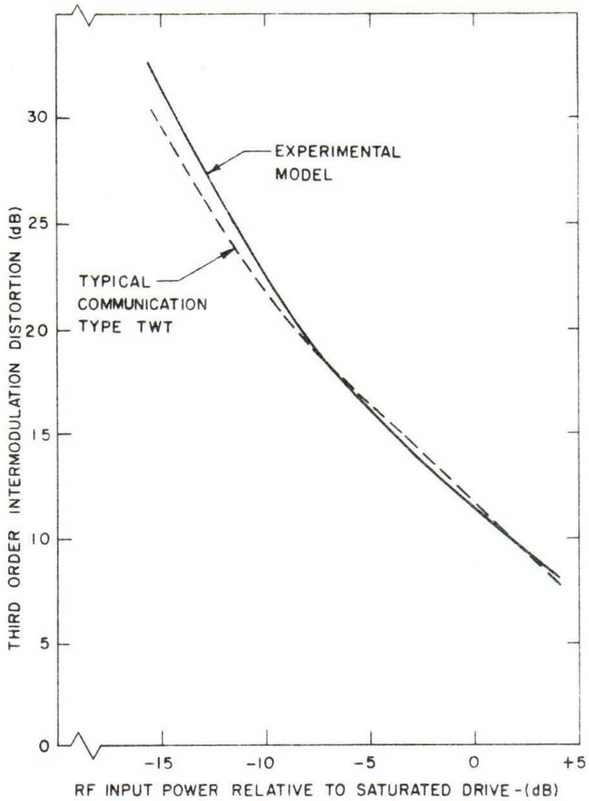

Figure 21. Experimental model intermodulation distortion compared to average of many communication type TWTs.

The requirement for lower distortion performance from a tube is quite evident in the specifications for present communication satellites, and is expected to get even more stringent in the future. We have found that it is possible to improve the distortion performance of the tube without sacrificing too much in the efficiency. Future improvements in the area of distortion will not be dramatic in that the orders of magnitude in improvement is not expected in the near future. At present, these improvements are of an evolutionary or refinement type.

As previously mentioned, the RF spectrum is becoming more crowded as time goes on and the only place to fit a new system into the spectrum is at higher and higher frequencies. We are presently developing TWTs for frequencies ranging from 17 to 30 GHz for use in communication type satellites. As frequency is increased, the dimensions of the tube must decrease. For the same power output level, the thermal loading of the traveling-wave tube circuit is higher. This increased heating becomes a problem at higher power output levels and actually limits the power output capability of the tube as indicated in Figure 22. Higher power output could be obtained safely by using a solenoid focused tube, but this is much too heavy for the present spacecraft capability.

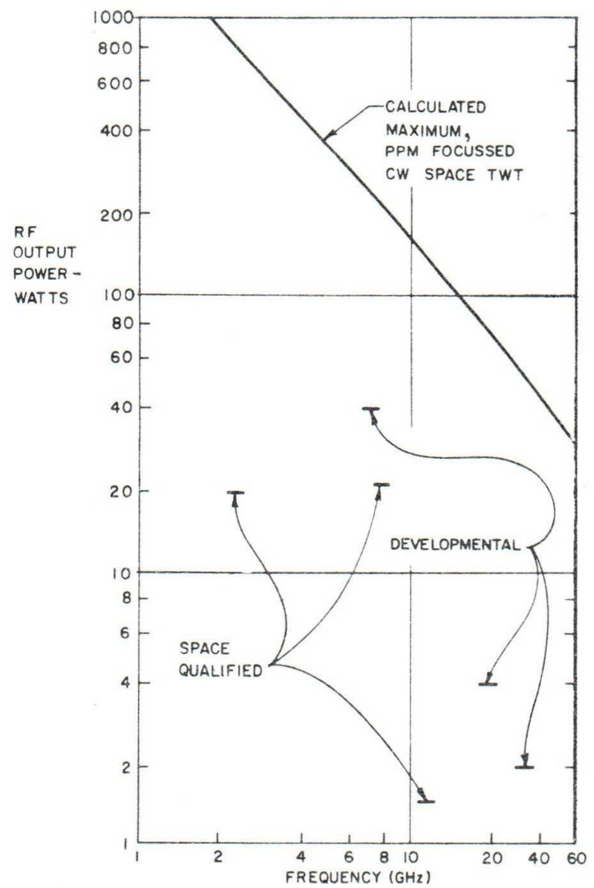

Figure 22. Theoretical limitation of RF power output for space TWTs.

Besides limiting the RF power output, the increased frequency of operation increases mechanical problems in assembling the tubes. As parts become smaller, required tolerances become nearly impossible to hold and parts become so tiny that their strength is inadequate for TWTs which must withstand launch type vibration and environment. An example of the dimensions involved is given in Table III for a tube under development at 30 GHz. The sizes listed for the helix or slow wave structure of the TWT would be even smaller except that the operating voltage of the tube is raised to keep the sizes within reason. This higher operating voltage also makes it possible to use PPM focusing with its consequent weight savings.

TABLE III

TUBE TYPE	254H
OPERATING FREQUENCY	29 to 31 GHz
POWER OUTPUT	2 WATTS
HELIX DIAMETER	.026 INCHES
WIRE DIAMETER	.005 INCHES
OPERATING VOLTAGE	5000 VOLTS

Higher frequency tubes present other problems connected with the small sizes of parts. One is that of providing a low input and output VSWR. Use of waveguide inputs and outputs to the tube instead of coaxial connectors has enabled us to reduce these problems as far as mismatch is concerned. The results of this are shown in Figure 23 for the 837H TWT.

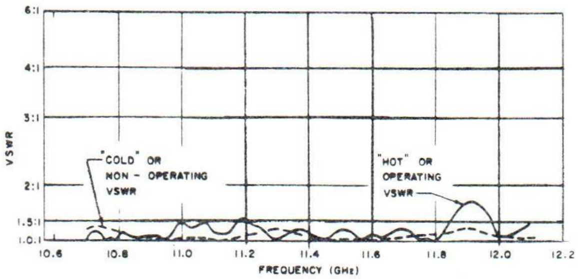

Figure 23. Output VSWRs of X-band communication TWT with waveguide connectors.

For tubes in the one to ten watt power output range, the relatively high voltage of operation required to make the RF circuit a reasonable size produces a low current or low perveance electron beam. The low perveance produces problems such as reduced gain per wavelength and reduced efficiency. The lower gain per wavelength makes the tube longer, thus heavier. The lower efficiency is made even lower because RF losses increase with increasing frequency. Because of the small helix size, the beam diameter is very small. This requires the design of higher area convergence electron guns. Associated with the higher operating voltages we have the concurrent problem of voltage breakdown in both the power supply and the TWT.

All of these problems are amenable to solution by spending the required development time and money. The full capability of traveling-wave tubes for high frequency performance has not yet been reached nor will it be in the near future.

In summary, today's space TWTs are backed by years of life test measurements showing little change in their parameters. Reliability estimates have continually increased and the present estimate has reached to a MTBF of one-million hours at a 90% confidence level. In addition to the ever-improving reliability, these tubes have complied with the more stringent specifications for lower distortion and higher efficiency at the increased frequencies. Our hope is that the data presented herein will provide the system designers with some indication of present and future space tube capabilities.

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