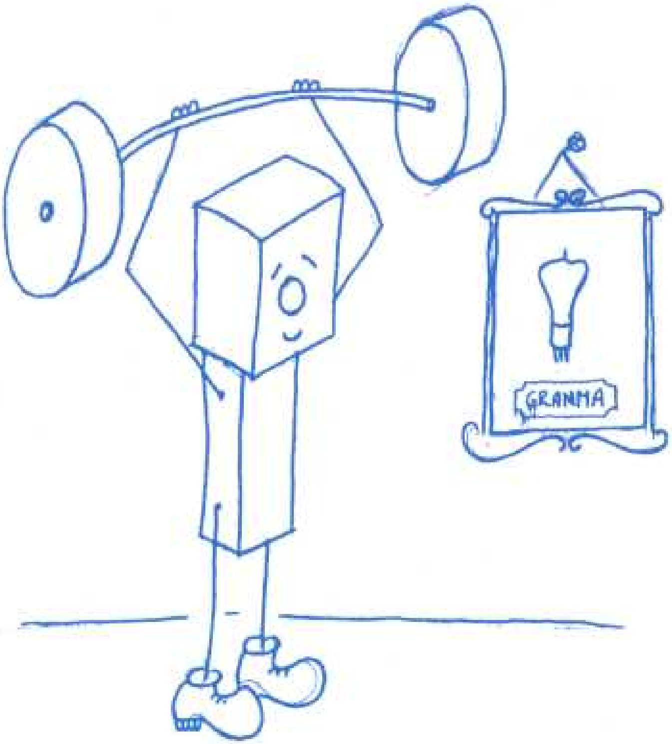
TWT Performance Fundamentals

Traveling Wave Tubes remain the best source for efficient generation of microwave power over broad frequency bandwidths. When compared to solid state technology, today's metal-ceramic traveling wave tube amplifiers combine low acquisition price with affordable maintenance and support. TWTA systems are smaller, lighter, and much more efficient than their SSA counterparts. TWT amplifiers do behave somewhat differently than SSAs. Following is a discussion of some of the more important TWT performance features and design attributes.



➢ Power and Bandwidth

TWT power output is determined by the efficiency with which energy in the electron beam is converted to microwave energy (sometimes called "interaction efficiency" or "beam efficiency").

$$P_{out} = I_{beam} V_{beam} \eta_{interaction}$$

Current emitted from a thermionic cathode obeys a 3/2 power law with respect to applied voltage:

$$I_{beam} = K V_{beam}^{3/2}$$

where the constant K is called perveance. Perveance is an important design parameter since it is totally determined by electron gun dimensions. Using this expression, power output often is given by:

$$P_{out} = K V_{beam}^{5/2} \eta_{interaction}$$

CW (continuous wave) TWTs generally use electron guns which operate in the 0.2 to 1.0 x 10^{-6} perveance range while pulse TWTs push the limits imposed by practical electron gun design and magnetic focusing materials which is not much greater than 2.0 x 10^{-6}. Interaction efficiency is determined by beam size, the uniformity of beam electron trajectories (often called beam laminarity), and helix circuit parameters such as helix and backwall diameter, helix pitch, dielectric support material and shape, helix loss, etc. It varies with frequency because the interaction of helix parameters in a given circuit change as frequency is varied. For example, backwall diameter predominantly affects low band edge performance while the shape of the dielectric rods predominantly affect the high band edge. Practical helix designs have band center interaction efficiencies which range from 10% to 25% and band edge to the center efficiency variations of 50% or more. Practical bandwidths range from hundreds of Mhz to double octave ($F_{hi} = 4\ F_{lo}$). Teledyne specifies "rated output power" which typically is several tenths of a dB or more below saturation.

➢ Efficiency

As the beam gives up energy to the amplified signal, it slows down. By tapering or stepping helix pitch to maintain synchronism between the RF wave and the slowing beam, interaction efficiency often can be enhanced. Determining a satisfactory pitch configuration that works well over the entire frequency band and which preserves other important performance parameters requires computer simulation of the non-linear beam-helix interaction and involves numerous compromises which often trade one desirable effect for another.

A second means of enhancing TWT efficiency is to depress the beam collector voltage(s) below ground so that the unused energy can be recovered from the spent electron beam. The power consumed by a TWT with n stages of collector depression is calculated as follows where collector voltages are referenced to cathode:

$$P_{prime} = V_{filament}\, I_{filament} + V_{beam}\, I_{helix} + \sum_{n} V_{collector}\, I_{collector}$$

$$\eta_{overall} = P_{out} / P_{prime}$$

Since both output power and prime power vary with signal frequency, RF input drive, etc., it is best to state the maximum allowable prime power consumption rather than efficiency when specifying a TWT.

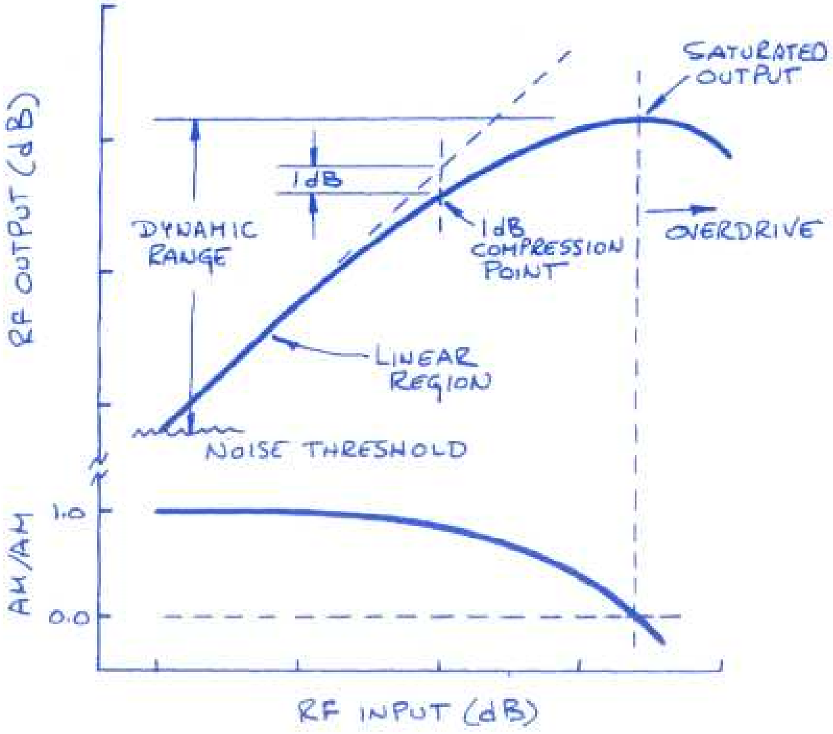
Waste heat dissipation is given by:

$$P_{diss} = P_{prime} - P_{out}$$

The electro optics of a multi-stage depressed collector are quite complicated and depend not only on the geometry and relative voltages of the collector segments but also upon the degree of RF modulation, the magnetic field used to focus the beam, the yield of secondary electrons at the collecting surfaces, etc. The higher the interaction efficiency, the greater the difficulty in collecting the spent beam since strong RF modulation causes the electron velocity distribution to spread. In wide band TWTs, the low band edge harmonic interaction causes a similar effect. Pulse TWTs with high interaction efficiency often cannot practically utilize more than a single stage collector while CW TWTs with lower interaction efficiency successfully utilize two or three stages. In a TWT having a well designed multi-stage depressed collector, the waste heat dissipated by the TWT is nearly constant as RF input drive is varied.

➢ Gain

The dynamic range of a TWT is the region between the point at which the RF output signal just breaks through the noise threshold to the point at which the output power saturates. The linear or small signal region is most often defined as ending when increasing RF drive causes gain to drop 1 dB from it's small signal level (1 dB compression point). Saturation generally occurs at an input drive level 6 to 8 dB above the 1 dB compression point and with 2 to 3 dB higher output power.



AM / AM conversion is a measure of the change in RF output power that results from a change in the RF input drive, i.e. the slope of the transfer curve. In the linear region, AM / AM conversion is 1.0 dB / dB. At saturation, AM / AM conversion is 0 dB /dB. TWTs with high interaction efficiency often exhibit gain expansion near the high band edge (AM / AM > 1.0). This is caused by the inability of the helix velocity tapers to equally match beam slow-down at all frequencies within the band. It generally is undesirable to operate the TWT too far into overdrive as severe beam defocusing can occur in this region.

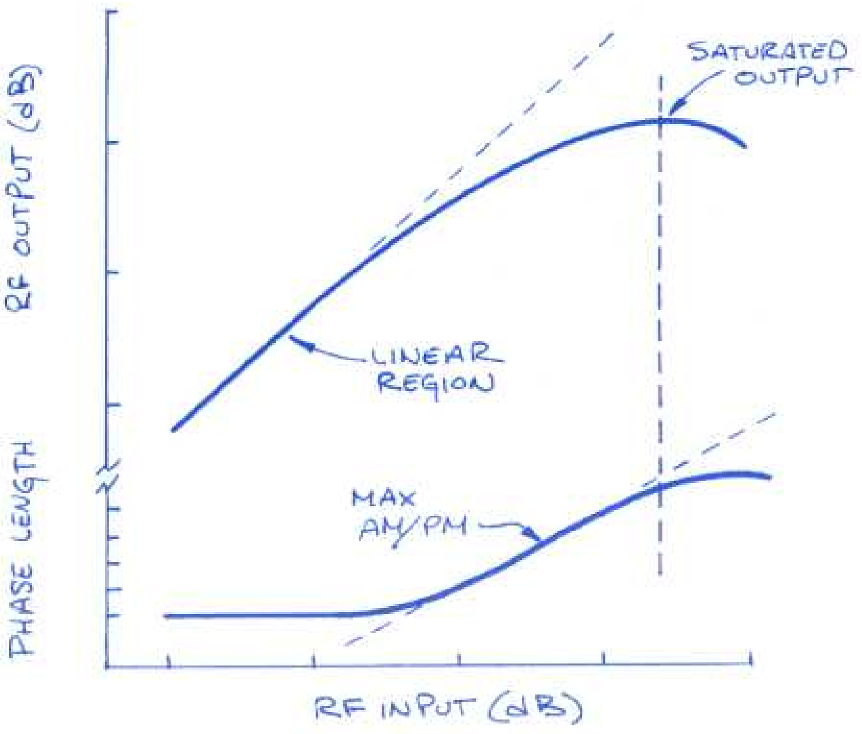
Gain variations over the frequency band result from the frequency dependence of helix velocity and impedance. Additionally, gain varies with the electrical length of the circuit, which, in turn, varies with frequency. A two octave TWT can exhibit as much as 25dB gain variation. This typically can be reduced to ±2.0 dB with the use of an external gain equalizer.

Gain ripple results from signal reflections either internal or external to the tube. Since TWT is electrically "long" (a typical TWT has a phase length of about 10,000 degrees), a relatively small change in frequency (typically 100 to 300 Mhz) shifts phase 360°. Most TWTs exhibit an approximate ±0.2 dB gain ripple at this frequency.

➢ Phase

Any factor which affects the velocity of the electron beam produces phase changes in the RF output signal. As the RF drive level is increased into the non-linear region, the phase length of the tube increases as beam velocity is slowed by transfer of energy to the RF wave. This effect, called AM / PM conversion, is relatively insensitive to RF drive in the linear region. As the TWT is driven toward saturation, the rate of phase change increases. The peak value of AM / PM generally occurs at or several dB below saturation and is frequency dependent (typically increasing with increasing frequency for a given helix design).

If the factor that changes beam velocity varies with time, the result is phase modulation of the RF output signal. The primary factor affecting the velocity of the beam is the cathode voltage. Other voltages or external effects (such as voltages induced by placement of a blower motor too close to the tube) have secondary affects.



Typical phase pushing values for TWTs are:

- 100° / 1% change in Cathode Voltage
- 10° / 1% change in Grid "on" Voltage
- .0005° / 1% change in Collector Voltage

These numbers are approximate. The actual values of phase pushing for any specific TWT are determined by gun perveance, gain, efficiency, etc. Any periodic voltage modulation produces signal side bands, separated from the main signal by the modulation frequency. The depression below carrier of these spurious signals (δ in dB) for sinusoidal ripple can roughly be approximated by the following expression:

$$\delta \cong 10 \text{ Log} \left(\frac{1.13 \times 10^3 \times L^2 \times F^2 \times \nu^2}{V^3} \right)$$

L = TWT RF input-to-RF output length (in)
F = RF Signal Frequency (Ghz)
ν = peak-to-peak Cathode ripple (Volts)
V = Cathode Voltage (Volts)

A ±0.5 volt sinusoidal ripple on a 10 kV TWT with 10" input-to-output length produces –49.5 dBc sidebands at 10 Ghz. Peak-to-peak phase ripple ($\Delta\phi$ in degrees) is directly related to small signal gain ripple (dG—peak-to-peak in dB) by the following expression:

$$\Delta\phi \cong 57.3 \left(10^{(dG/20)} - 1\right)$$

A small signal gain ripple of ±0.2 dB produces phase ripple of ±1.35°. Time delay is the total time it takes for a signal to pass through the tube (typically 3 to 5 nsec) and is the derivative of phase delay. Thus, the same mechanisms that cause phase non-linearity are responsible for time delay distortion. The maximum rate of change of time delay ($\Delta\gamma$ in nsec / Mhz) due to gain and phase ripple is calculated by:

$$\Delta\gamma \cong \frac{\pi \times (10^{(dG/20)} - 1)}{dF^2} \times 10^{15}$$

where dF is the frequency periodicity of the small signal gain ripple (in Hz). A 200 Mhz gain ripple with ±0.2 dB amplitude causes 3.7 psec / Mhz time delay distortion.

➢ Power Combining

With the tube-to-tube performance consistency that is achieved with modern TWT manufacturing technology, power combining is a practical and relatively inexpensive means of achieving high power levels. Typical tracking of a TWT to a phase standard over an octave or greater frequency band when the absolute phase difference between the tubes is zeroed with an input phase shifter is ±20° (40° maximum imbalance between any two randomly selected tubes). When combined in a standard 4-port hybrid junction, such as a waveguide Magic Tee, the resultant combined power in Watts of two tubes with output powers P1 and P2 due to phase (ϕ) and amplitude imbalance at the input ports is:

$$P_{\text{combined}} = (P1+P2) \times \left\{ \frac{1+2X\cos\phi + X^2}{2+2X^2} \right\}$$

$$X = \left(\frac{P2}{P1} \right)^{1/2} \quad \text{for } P2 \le P1$$

Ignoring combining losses (which are on the order of tenths of dB), two 300W TWTs with equal power output and 40° maximum phase imbalance combine to produce 530W (0.54 dB phase imbalance loss). If it were desired to combine a 400W TWT with a 200W TWT with the same maximum phase imbalance, the result would be 517W (0.65 dB phase and amplitude imbalance loss). Because of the relative insensitivity to amplitude imbalance, odd numbers of TWTs combine reasonably well. Power combining neither reduces the amplifier's tolerance to output mismatch nor its' modulation fidelity. With the use of 180° hybrids, harmonic content can be reduced by at least 10dB relative to the tube's stand-alone performance since in this case, harmonic is directed to the "lost-power" rather than to the "combined-power" port of the hybrid. Likewise, since TWT noise output is non-coherent and thus splits evenly between the two output ports of the hybrid, noise is reduced 3 dB per combination.

➢ Harmonics

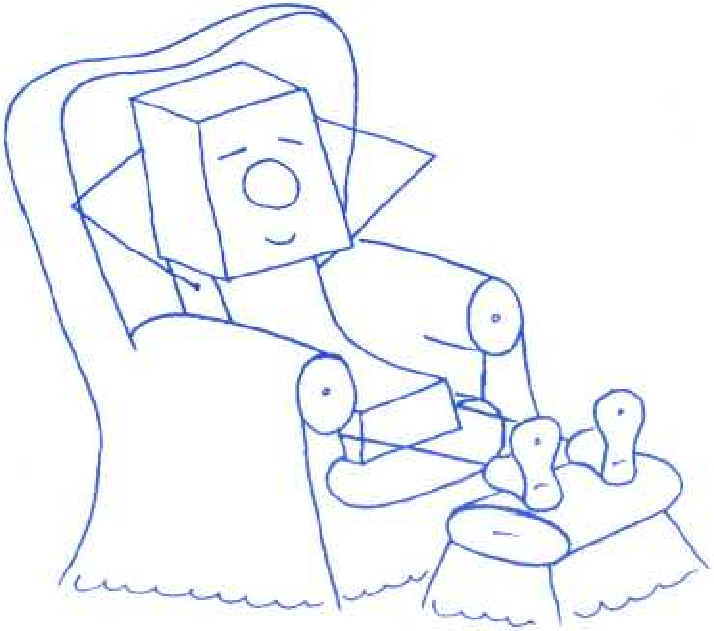
Due to the wide bandwidth and high gain of the TWT, harmonics of the fundamental RF drive signal will appear in the output spectrum as the tube is driven into the non-linear region. Single octave TWTs typically have 3 dB or more low band edge harmonic separation while dual octave TWTs may exhibit harmonics equal to or greater than the fundamental. Higher harmonics also will be present, but to a lesser degree. Broadband TWTs may react to harmonics in the RF drive which, if sufficiently strong, can either enhance or degrade output power depending upon the relative phase angle between the harmonic and fundamental input signals.

- **Noise**

Noise in the output spectrum of a TWT results from the fact that electron emission from the cathode is a random process. Furthermore, the velocities of the electrons emitted by the hot cathode have a Maxwellian distribution. TWT noise figure (in dB) is given by the following expression:

$$NF = 114 + NPO - 10 \,\mathrm{Log}(BW) - G_{ss}$$

-114 dBm / Mhz is the reference thermal noise caused by a room temperature termination at the TWT input. BW is the bandwidth relative to 1 Mhz over which the noise power output (NPO in dBm) is measured. Gss is the small signal gain in dB averaged over the bandwidth BW. Typically noise figures for medium power TWTs are 25 to 35 dB.



Noise can be reduced by gating off the beam when signal transmission is not required either with a grid or focus electrode (FE). A grid cuts off noise to the thermal level. A focus electrode typically cuts gain to zero dB which generally results in noise output 25 to 35 dB above thermal. Most Teledyne CW TWTs are offered in both gridded and focus electrode gated versions. With modern design and fabrication techniques, the reliability of shadow grid versions is equal to or greater than their FE counterparts.

Spurious outputs not correlated to the fundamental signal frequency are minimized by oscillation suppression techniques such as special helix attenuation patterns and pitch changes . Operation of the TWT into highly mismatched loads may increase spurious output since these suppression techniques are sometimes less effective in the presence of strong reflected signals.

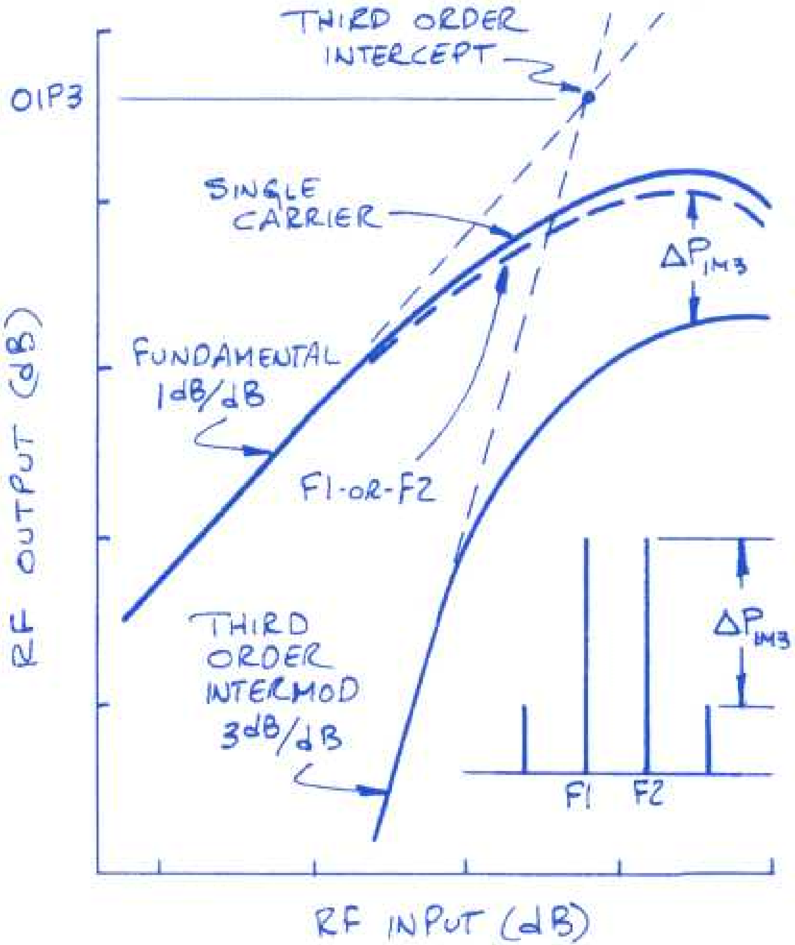
Intermodulation Distortion

When the RF input signal contains two or more discrete carrier frequencies, a mixing process occurs which results in intermodulation products displaced from the carriers at multiples of the difference frequencies. The power levels of these intermodulation products are dependent upon the relative power levels of the carriers and the linearity of the TWT. The two-tone third order intermodulation products (at 2F1 – F2 and 2F2 – F1) are the most important because they are closest to the signal frequencies and largest in amplitude. At saturation, the separation of IM products from the fundamental is typically 10 dB. The amplitude of these products decrease 2 dB for every dB the power is backed down from saturation.

$$\Delta P_{IM3} \cong 2 \times \text{Back-off} + 10\ \text{dB}$$

The third order intercept point OIP3 is a figure of merit and is equal to the output power of each of the two tones when the third order IM separation is 0 dBc. Obviously, the TWT saturates before this point is reached but it can be calculated by projecting the single carrier and IM3 linear gain slopes to their intersection. The separation in dB of the intermod from the carrier (at power P_o) is more accurately given by:

$$\Delta P_{IM3} = 2\,(\text{OIP3} - P_o)$$



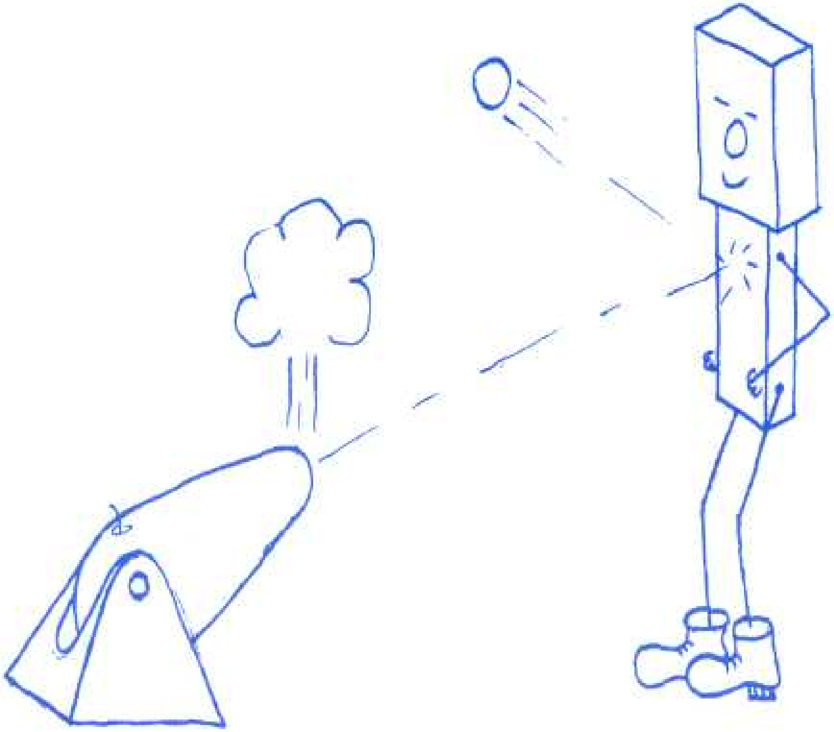
An effect related to IM distortion is spectral regrowth. The name comes from the observation that band limited signals, after passing through a non-linear amplifier, often have components outside of the original band that the signal occupied at the input. This phenomenon is often encountered with a digitally modulated carrier. For example, with Quadrature Phase-Shift Keying (QPSK) modulation, the amplitude of the signal is theoretically constant. However, in the frequency domain, the signal occupies a relatively wide bandwidth. When a QPSK signal is filtered to limit its bandwidth, the sidebands furthest from the carrier are removed. The result is that in the time domain, the signal is no longer constant in amplitude, and AM / AM and AM / PM processes within the amplifier generate new sidebands. Typically, these "regrowth skirts" are separated 8 dB further from carrier than the two-tone IM3 products that would result with the same average carrier power , i.e., -18 dBc IM3 (4 dB back-off) roughly corresponds to -26 dBc spectral regrowth. Use of a predistortion linearizer with the TWT can allow comparable operation to within 2 dB of saturation.

TWTs traditionally have been used for FM applications where they're operated to saturation and are typically so specified. SSAs, on the other hand, traditionally have been specified at their one dB compression point. As a result, the two cannot be compared at a given output back-off level. When specifying a power requirement it is best to specify the absolute output power required for a given level of IM3 distortion, spectral regrowth, or the OIP3. At this point, a SSA will operate closer to saturation but will not have the approximate 3 dB reserve "burn-through" capability of a TWT.

➢ TWT Reliability

If a large number of TWTs were simultaneously put into service, their survival rate history would be characterized by three distinct periods:

- Infant Mortality
- Random Failures
- Wear-out



Infant mortality failures due to workmanship defects are effectively screened-out by "burn-in" before delivery. Random failures during the long middle period are characterized by the time constant MTBF (mean time between failure) which is a measure of the time to which about 35% (e^{-1}) of the tubes will have failed. Cathode exhaustion triggers the point at which tubes wear-out and failure rates increase substantially. MTBF and life clearly are two different measures of a tubes history. Ideally, MTFB exceeds life by a substantial amount. In some cases, cathode life may be so long or the environment may be so severe that random failures account for the majority of tube removals. The best currently available measure of TWT MTBF is MIL-HDBK-217F Notice 2[1] which provides the following estimates:

$$\mathrm{MTBF} = \frac{10^6}{5.5 \times (1.00001)^P \times (1.1)^F} \quad \text{Air Conditioned Fixed Site}$$

$$\mathrm{MTBF} = \frac{10^6}{16.5 \times (1.00001)^P \times (1.1)^F} \quad \text{Fixed Site with Unconditioned Air}$$

$$\mathrm{MTBF} = \frac{10^6}{77 \times (1.00001)^P \times (1.1)^F} \quad \text{Ground Mobile}$$

where P is the rated power in watts (peak, if pulsed) and F is the operating Frequency in Ghz (the geometric mean of the end points is used if the operating frequency ranges over a band).

As an example, the 250W 0.8 to 2.0 Ghz M5670NO is predicted by this model to have MTBFs of 160,764 hrs for Air Conditioned sites, 53,588 hrs for unconditioned sites, and 11,483 hrs for ground mobile operation. This model is very simplistic and does not address failure drivers such as thermal and voltage stress gradients within the TWT, system VSWR, heater on – off cycling, power supply energy discharge during fault conditions, etc. Despite these concerns, experience with modern TWTs used on switching power supplies indicates that the MIL-HDBK typically under predicts MTBF by a factor of 2[2].

A Safety and Set-up instruction booklet is provided with each Teledyne TWT. It contains good advice on set-up procedures to prevent infant mortality problems. The high voltage power supply should be designed to limit energy dissipation to substantially less than 10J with at least several ohms of series resistance in the TWT cathode connection. The tube also should be provided with adequate cooling so that temperatures are maintained within the recommended ranges under all operating conditions. Unlike SSAs, however, TWTs can operate for short periods at

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[1] *Military Handbook, Reliability Prediction of Electronic Equipment,* MIL-HDBK-217F Notice 2, 28 February, 1995.

[2] A. S. Gilmour, Jr., *Principles of Traveling Wave Tubes,* Artech House, Inc., See especially p.523.

chill plate temperatures above their recommended level. TWTs are equipped with thermal interlocks to prevent permanent damage. Any TWT in this catalog can be special ordered for prolonged operation at temperatures reasonably beyond the recommended limits.

➢ TWT Life

Modern TWTs are designed with low temperature cathodes capable of from 20,000 to 50,000 hours of continuous operation. Many Teledyne TWTs have accumulated several times this life. A key to achieving long cathode life is to maintain heater voltage within it's recommended range. If the tube is to spend a substantial portion of its' life in standby, cathode life can be extended by reducing heater voltage 10% during standby. The majority of Teledyne TWTs employ shadow grids to turn the electron beam on and off. For most applications the life and reliability of shadow grid versions is equal to or greater than their ungridded counterparts. However, for those situations where the TWT is expected to be turned on and off infrequently and to operate uninterrupted for thousands of hours, ungridded versions will offer maximum life.

Current process and fabrication technologies have eliminated the need to periodically "refresh" tube vacuum during prolonged storage. If there is concern about turning-on a tube after storage, an extended heater warm-up of from 8 to 24 hours prior to the application of cathode voltage should be adequate. The primary enemies of TWTs are foreign material in HV and RF connectors and corrosion-causing moisture. Keeping stored tubes clean and dry is the best means of insuring high vacuum integrity and long life.

The current generation of TWTs is amassing an excellent life and reliability record. This is being illustrated by experience in space where the failure rate of TWTs on Intelsat satellites has been 15% lower than for SSAs.