AIAA 80-0486R

Past and Present INTELSAT TWTA Life Performance

R. Strauss*
COMSAT Laboratories, Clarksburg, Md.
and
J. R. Owens†
INTELSAT, Washington, D.C.

The traveling-wave tube amplifier (TWTA) is a key element of microwave transponders used in communications satellites. In-orbit performance requirements demand stringent transmission characteristics and high efficiency as well as long and uninterrupted lifetimes. The primary performance limiting element is the cathode of the traveling-wave tube (TWT). Considerable experience related to long-life performance of tubes, power supplies, and cathodes has been accumulated. This paper reviews the TWTA life performance of the INTELSAT IV satellite series, the expected life performance and design concept incorporated into INTELSAT V, redundancy aspects, and the important considerations associated with the candidate cathodes (e.g., oxide and matrix types), particularly with regard to future communication-satellite applications.

Introduction

An earlier paper by the authors[1] described the pertinent life design factors of commercial communication satellites. As indicated, TWTs are among the few major components which, by virtue of a degradation or "wear-out" mechanism, limit the useful life of these satellites. In TWTs, the primary fundamental life-limiting subelement is the cathode. The electron-emission capability of the cathode is controlled by physiochemical processes that proceed inexorably at a prescribed rate. The emission-electron work function increases gradually. The initial cathode current, which is space-charge limited, progresses toward a temperature-limited condition and then noticeably decreases.

Since the TWT gain is directly related to the cathode current, it also decreases in time, followed eventually by a noticeable reduction in rf output power. This type of fundamental degradation mechanism occurs in all current TWTs regardless of cathode type. However, both the mechanisms and specific rates differ greatly depending on the cathode type, the materials used, the tube environment, the operating temperature, the initial setting of the operating space-charge-limited current, and the emission-activation procedures applied. Satellite TWTs have used both oxide and impregnated matrix dispenser-type cathodes. With few exceptions, average cathode-limited TWT lifetimes ranging from 50,000 to 80,000 h either have been space demonstrated or are anticipated on the basis of ground-life test data.

This paper will review the current expectations of TWT life performance in terms of space applications. The review will be based primarily on TWT life performance in operational INTELSAT IV satellites, the life expectancies of TWTs being designed into current satellite programs, and future TWT life expectations utilizing a newer class of cathodes. In addition, some aspects of TWT, or preferably TWTA (TWT + power supply), operating redundancy strategy will be discussed, since this strategy directly depends on the TWTA failure patterns.

Presented as Paper 80-0486 at the AIAA 8th Communications Satellite Systems Conference, Orlando, Fla., April 20-24, 1980; submitted April 23, 1980; revision received Feb. 27, 1981.

*Director, Power Systems Laboratory.

†Manager, Satellite Operations Department.

Commercial Satellite TWT Applications

More than 1000 TWTs are now in space.[2] The majority of these tubes operate at 4 GHz, and without exception have used oxide cathodes (see Fig. 1). Oxide cathodes are typically set to operate at temperatures ranging from 650 to 750°C with space-charge-limited cathode current densities (J_0) usually between 120 and 300 mA/cm^2. The saturation of fully temperature-limited cathode current density is typically more than a factor of 10 greater than J_0 at normal operating temperatures. Furthermore, an increase of 25°C in the actual cathode operating temperature generally will reduce the life of the oxide cathode by a factor of 2 (Ref. 3).

At output-power levels above 10 W and at frequencies of 11 GHz or higher, all current or projected TWT applications utilize the impregnated-matrix-dispenser cathode. This cathode type can provide long life if its operating temperature

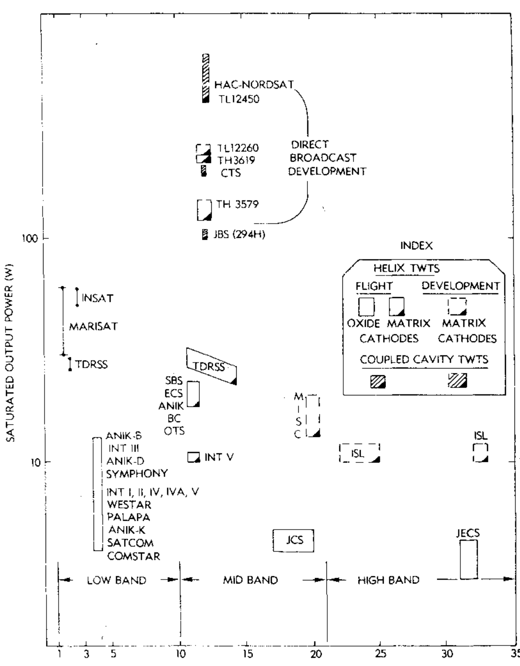

Fig. 1 Active areas of commercial communication-satellite TWT usage and development.

is well controlled and near 1000°C (brightness temperature). At this temperature, the normal space-charge-limited cathode current density typically ranges from $J_0 = 650$ to 700 mA/cm^2. The saturation current density is a factor of 5 to 6 times greater than J_0. Thus, compared with an oxide cathode, the matrix cathode operates significantly closer to its temperature-limited condition and is therefore more temperature sensitive in the normal space-charge-limited region of operation.

To attain a constant cathode current during long-term life, the cathode temperature must be carefully controlled and maintained. However, as will be shown later, the matrix cathode unfortunately does not maintain a constant cathode current, although cathode temperatures are held to within $\sim \pm 10$°C of the preselected initial-life temperature. In addition, experimental data indicate, for example, that an increase of 30 to 40°C in the cathode operating temperature will increase the cathode current by about 1-2% at the start of life and possibly 4-5% toward end of life (~7 yr). Furthermore, such a temperature increase will also accelerate the physiochemical process and reduce the life of the matrix cathode by a factor of 2.

Comparison of Oxide- and Matrix-Cathode Characteristics

Both oxide and matrix cathodes have been used commercially for many years.[4-7] Continuing interest exists in analyzing their characteristics and developing not only improved understanding but also improved performance.[8-11] Figure 2 shows the basic start-of-life and end-of-life cathode current (I_k) as a function of relative cathode temperature and with fixed electron-gun anode voltages. These curves are sometimes referred to as underheating curves.

The well-activated oxide cathode, particularly at the start of life, has a relatively sharp "knee." A knee temperature (T_{kn0}) can be clearly defined by the intersection of the two extrapolated linear portions of the curve. As shown in Fig. 2, the knee of the curve distinguishes between the space-charge-limited region of operation and the temperature-limited region. These two regions are separated in a well-activated cathode by a relatively narrow temperature-transition region. As the cathode's physiochemistry proceeds, the knee temperature (T_{knx}) progresses toward the cathode operating temperature. For this example, $\Delta T_{kno} = T_k - T_{kno} = 60$°C. In some cases, ΔT_{kno} may be as high as ~100°C or as low as ~50°C; however, the progression based on empirical results is between 0.5 to 1.0°C/1000 h of life. End of life occurs when the TWT gain or output power decreases below some level set by system considerations. A typical number is a 4-dB loss of small signal gain. The relationship between the loss of cathode current and small signal gain to a first approximation is as follows:

$$\Delta G_{ss}(\text{dB}) \sim K(G_{ss} + A)\Delta I_k / I_k$$

where G_{ss} is the start of life TWT small-signal gain (dB), A is the wave start-up loss in the TWT, which is typically ~15 dB for a 2-gain-section tube; $\Delta I / I_k = 0.08$ in Fig. 2 for normal and constant cathode temperature; and $K = 0.33$ (theoretical) to 0.65 (actual)—values of K can be determined for each tube type by plotting cathode underheating gain curves.

The matrix cathode has a broad knee without a clear transition region. This is further substantiated by a greater current sensitivity as a function of cathode temperature in the space-charge-limited region. In addition, the impregnated matrix cathode, which is a surface metal-film emitter cathode, depends on a bulk reaction, "Knudsen flow" transport-feed mechanism within the matrix, and surface-area coverage by migration that requires significant time (minutes to several hours) to achieve complete operational equilibrium at a given temperature. These factors lead to an interpretation that the matrix cathode has a small but persistent component of

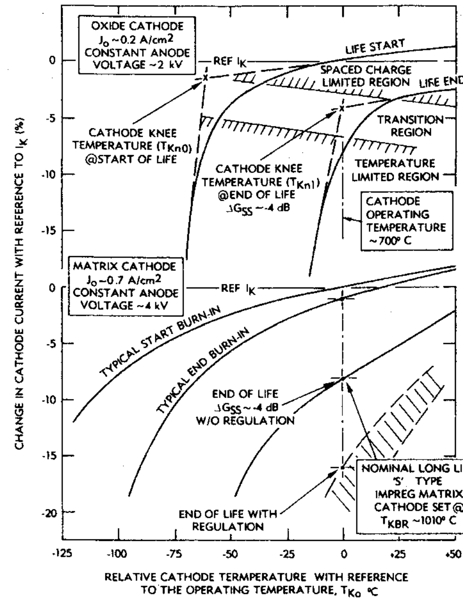

Fig. 2 Comparison of oxide- and matrix-cathode characteristics as a function of cathode temperature.

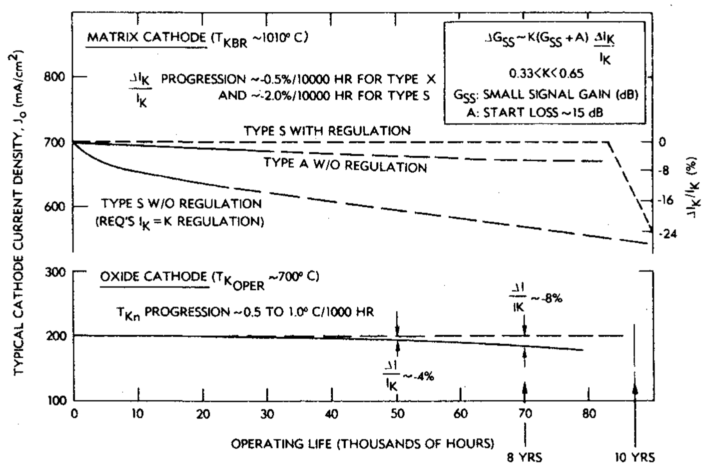

Fig. 3 Comparison of oxide- and matrix-cathode characteristics as a function of life.

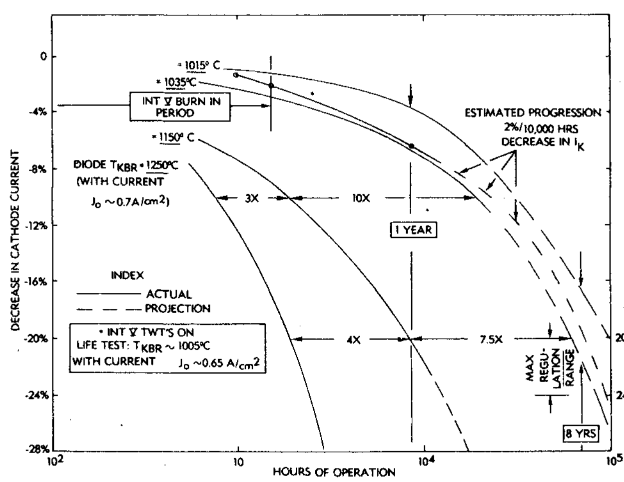

Fig. 4 Nominal INTELSAT IV 11-GHz TWT diode-life comparison.

emission current which is always temperature limited. Therefore, the cathode operating temperature is chosen to be as low as possible, consistent with an essentially (but not completely) space-charge-limited mode of emission. As shown

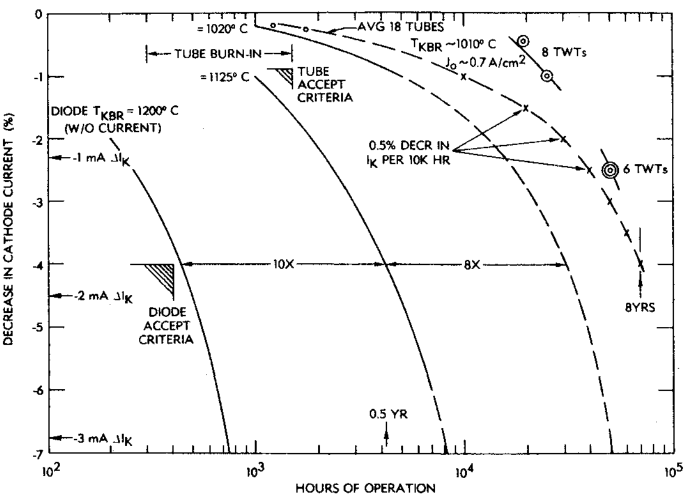

Fig. 5 Nominal SBS 12-GHz 20-W TWT and diode-life comparison (type X impregnated dispenser cathode with custom impregnant ratio).

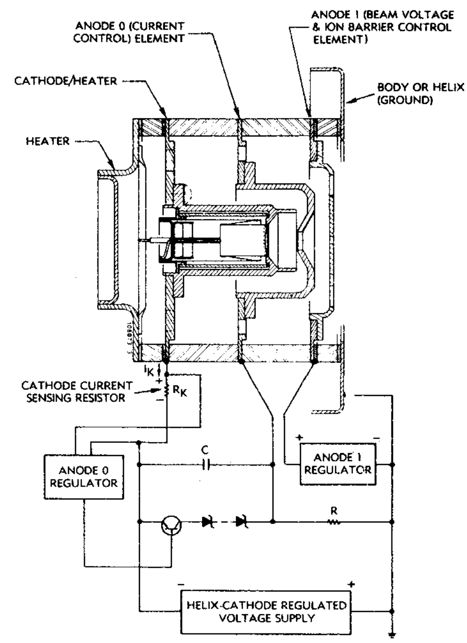

Fig. 6 Conceptual illustration of the dual-anode electron gun and a feedback sensing network which regulates and controls the anode O voltage for maintenance of constant cathode current.

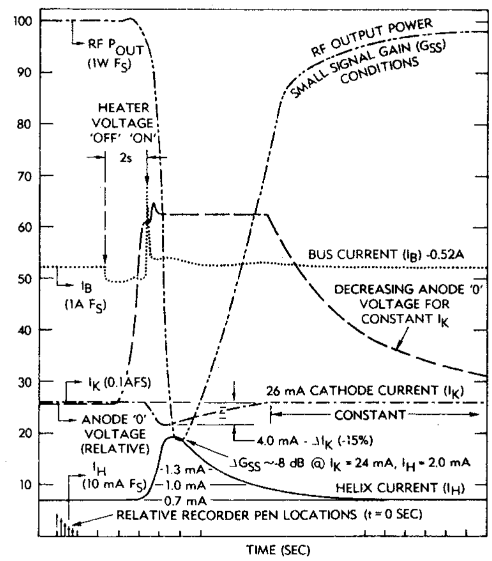

Fig. 7 Dip test of INTELSAT V 11-GHz TWTA engineering model No. 17 (Dec. 1979).

in Fig. 2, a well-activated impregnated-matrix (S type)-dispenser cathode, when set at its operating temperature (e.g., 1010°C brightness), will change its I_k by approximately $\pm 2.5\%$ for a $\pm 50°C$ ΔT_{BR} at emission densities near 0.7 A/cm^2.

As the matrix cathode ages, significant changes are observed. Even after a typical space TWT burn-in period of 1500 or 2000 h, in which the cathode is kept at the normal operating temperature, an observable decay trend is usually noted (see Fig. 3). Depending on factors such as the activation and the cathode, this "initial" decay may require 1000 to several thousand hours until a steady-state decay rate is obtained. The discovery of a "space-charge-limited" emission current decay, strongly dependent on the cathode operating temperature,[8,9,11] was initially reported a few years ago. The complete theoretical explanation for the decay is still lacking, although experimentally, all matrix-type impregnated-dispenser cathodes experience some characteristic decay. As indicated in Fig. 3, some cathodes appear to stabilize at rates as low as -0.5% $\Delta I_k/10{,}000$ h (type X), while others decay more rapidly at rates of $\sim 2\%$ $\Delta I_k/10{,}000$ h (type S) when operated at comparable temperatures such as $1010 \pm 10°C$ brightness without Joule cooling. A current decay concept is disconcerting to the TWT user who has been accustomed to the relatively constant current experienced with the oxide cathodes. As shown in Fig. 3, the usual oxide cathode does not exhibit a decay characteristic until the latter stages of its life. Furthermore, there are other cathode types called reservoir-dispenser cathodes (e.g., MK or L types) which have shown no gradual current decay until the reservoir (e.g., BaO) is depleted; then the current decreases rapidly, again toward the end of life (e.g., 50,000-100,000 h).[12]

During the past few years, extensive tests have been performed on TWTs and cathode testers (usually diodes) to determine the basic emission-current-life characteristics. Dispenser-type cathodes in suitable test diodes can be used to establish cathode-life-acceleration factors,[13] since they are capable of being operated at elevated temperatures. Figures 4 and 5 illustrate this for two types of dispenser cathodes tested. Both appear to be capable of reaching 8 yr of emission life but with dramatically differing end-of-life current degradation. For the S-type (4:1:1 impregnant) cathode, a 20% cathode-current degradation would result in an unacceptable TWT gain reduction.

Thomson/CSF, manufacturer of the INTELSAT V 11-GHz TWT, proposed the use of a double-anode electron gun with the first anode (approximately at half cathode potential) serving as a beam-current-control element.[14] This anode (A_0) intercepts essentially no current, and its voltage can be increased approximately 20% while constant cathode-current conditions are maintained without deleterious defocusing effects; therefore, it is the ideal control element in a constant cathode-current sensing-feedback loop-control network. Such a network was incorporated into the INTELSAT V power supply. Figure 6 illustrates this concept with an electron gun. Figure 7, which shows the responses recorded in a recent dip test (removal of filament power for a prescribed period, which in this case was 2 s), indicates the effectiveness of the constant current-control network as the cathode temperature cools and reheats. The estimated end-of-life current compensator capability allows an uncompensated current decrease of about 25%. Figure 3 illustrates the projected life characteristic for the S-type matrix cathode, with and without regulation.

Performance of Oxide-Cathode TWTs in INTELSAT IV

The largest and oldest "homogeneous" TWTA population in space is aboard the INTELSAT IV series.[15] There are seven satellites, each with four receivers and 24 transmitters arranged in 12 output channels (2 for 1 redundancy). Each receiver contains one driver TWT. The total population is therefore 28 driver TWTs (twenty-six 262H and two 272H) and 168 transmitter TWTs (261H).[16] Every TWT has its own dedicated power supply. Three commands per transmitter TWTA are possible: filament on, high voltage on, and all voltages off. As will be shown later, this permits both the usual "hot" and the occasional "cold" start. The usual start allows 4 min of filament warmup before high voltage is applied to the TWT. The driver TWTAs, on the other hand, could only be given a cold start, in which all voltages are commanded on at the same time. Telemetry is not available except for the changes in bus current ($\Delta I_{\rm BUS}$) after the execution of commands, and temperatures from several judiciously located thermocouples on the despin platform near TWT collectors. Approximately 5 million TWT operating hours have now been accumulated on INTELSAT IV satellites.

Driver TWTA

The receivers are arranged in a quadruple redundancy configuration so that only one driver TWTA is operational at any time. The tube has a saturated output power capability of 1.5 W, but typically operates in the small-signal-gain (linear) region with an output of several hundred milliwatts. Of the seven INTELSAT IV satellites in orbit, four have all receivers stored in an "off" condition to conserve the remaining cathode life. These are contingency or spare satellites. Table 1 shows the estimated remaining receiver life for each satellite, along with the life history of the driver TWTAs.

The oldest satellite (F-2) has approximately 3 months of remaining receiver life. Unfortunatly, the average 262H lifetime was slightly less than 2 yr. The gain degradation patterns were consistent (e.g., loss of cathode current emission and a reduction in linear gain), as shown in Fig. 8. There were never any EPC (power supply) related problems with these tubes. 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 exceptionally high ratio of anode-aperture diameter to cathode diameter (1.05) required by the shallow angle gun for the attainment of an 18-dB noise figure. All the other TWT features were completely consistent with the typical long-life space-tube technology that existed at that time (e.g., an ion-anode blocking voltage, depressed collector, long-term burn-in, and selection criteria). Since these cathode-deactivation patterns allowed time for receiver replacement, system communication services were never compromised in any spacecraft with quadruple redundancy.

The successor TWT (272H) does not appear to have a similar degradation problem. Two were used in the F-1 satellite (see Table 1) and 12 on the three COMSTAR satellites. Several of these 272H tubes have been operating for more than 4 yr without any sign of deactivation. The 272H was virtually identical to the 262H (1500-V cathode voltage) except that its oxide cathode operated at a lower temperature (~700°C), the cathode-current density was lower (200 mA/cm^2), and the anode aperture-to-cathode diameter was notably lower (0.88). Other driver TWTs such as the 233H (INTELSAT III), 276A (Westar, Anik A), and the 263H (DSCS-III) have performed exceptionally well with many tubes whose lives are beyond the 50,000-h mark, again without any indication of deactivation. In all of these cases, the cathode current density was below 200 mA/cm^2 with cathode temperatures of ~690°C.

Driver TWTAs are now being replaced by solid-state driver amplifiers in the more recent series of communication satellites. Current experience with 4-GHz space-borne medium-power solid-state driver amplifiers has been uniformly excellent.

Table 1 INTELSAT IV driver TWTA life history (as of December 1979)

Satellite	Launch date	Months in orbit	Rx life remaining (months)	No. of TWTAs[a] failed	No. of TWTAs never in service	Average useful life (months) of failures
F-1	May 1975	56	N/A	0	3	–[b]
F-2	Jan. 1971	106	~3[c]	4	0	11
F-3	Dec. 1971	97	~11[c]	3	1	24
F-4	Jan. 1972	96	~24[c]	3	0	15
F-5	June 1972	91	~7	3	0	20
F-7	Aug. 1973	77	21[c]	3	1	23
F-8	Nov. 1974	62	24	2	1	21
				Total 18 of 28		

[a] Failed means that the transponder gain has dropped below specification levels but that some useful performance is still possible. The gain loss has always been the failure indicator, but cathode deactivation is the failure cause.
[b] The F-1 spacecraft was equipped with two-262H and two-272H TWTs. Only one 272H (Rx 4) has been in service. It now has satisfactorily accumulated about 40,000 h.
[c] Receiver currently stored off.

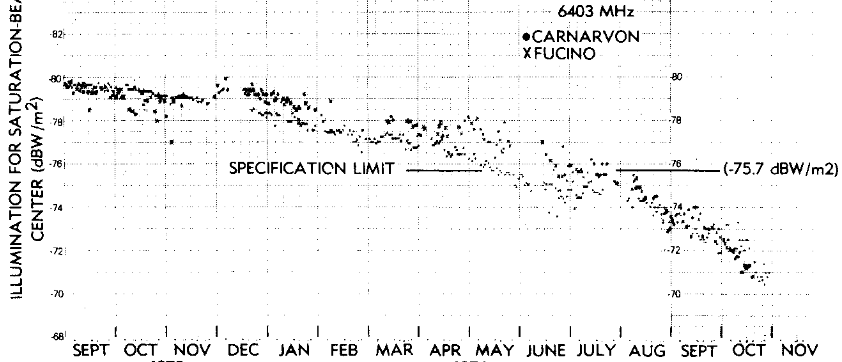

Fig. 8 "Death" of a receiver due to driver-tube-cathode deactivation (INTELSAT IV F5, Rx No. 1).

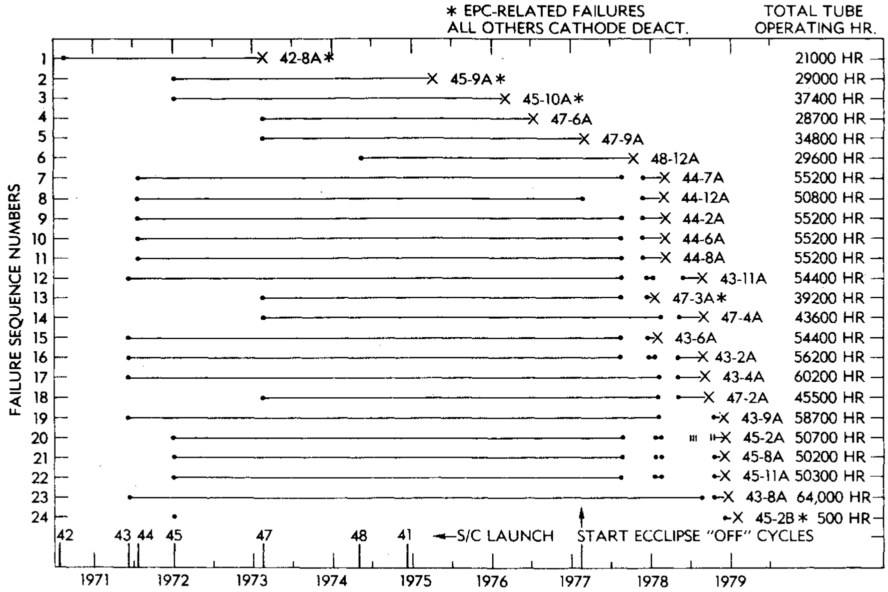

Fig. 9 History of the failed Tx TWTAs on the INTELSAT IV spacecraft [total space population: 168 TWTAs comprising 84A and 84B (redundant) units].

Transmitter TWTA

The seven INTELSAT IV satellites contain 168 transmitter TWTAs; of the initial 84 TWTAs (A units), 61 are still capable of satisfactory performance. The 23 failed A units have been replaced by standby TWTAs (B units) since the spacecraft transmitter is fully redundant (2 for 1). With the exception of one EPC failure (e.g., INTELSAT IV F-5, channel 2-B or as coded: 45-2B), all 24 B units have worked successfully after many years of "off" storage in space. In Fig. 9, which shows the complete history of all 24 failed TWTAs, the relative start times of the B units can be determined from the failure time of the A units.

The total "operated" population (98 TWTAs) may be divided into two classifications: non-eclipse-cycled and eclipse-cycled TWTAs. The non-eclipse-cycled TWTAs were never turned off for an extended period (2-3 months), but they may have occasionally been turned off for testing of the alternate unit. Eclipse "off" cycling on a modest scale did not start until 1977 when the satellite battery performance began degrading. More extensive cycling was started in the spring of 1978. Shortly thereafter, five of eight TWTAs which had been turned off during this eclipse season (2-3 months) failed with fairly rapid (several months) cathode deactivation. Prior to that, only six noncycled TWTAs had failed; three of these failures are believed to be power supply related and three cathode related.

Of the total cycled population ($N_c = 46$) there are now 16 cathode-related failures. The operating life patterns for the uncycled and cycled populations are shown in Fig. 10. Present estimates are for an average TWTA life of 8 yr (non-eclipse-cycled) and 6.9 yr (eclipse-cycled), respectively.

In terms of operating history, the total TWTA population can be divided into four groups. Two groups represent early life failures (e.g., in the 20,000-40,000 h range) comprising about 3% each of the total operated population (e.g., the "early" continuously operated cathode-deactivation group and the EPC-related failure group). The third group, comprising 16% of the operated population, consisted of TWTAs which deactivated after one or more long eclipse "off" periods. The cause for this behavior is still under investigation. The final group (78%) appears to be extremely healthy regardless of the type of operation (e.g., uncycled or cycled). The single EPC-related failure of a backup TWTA is as yet unclassified. Additional life details, including some daily-cycling test results, are reported in Ref. 17.

Since 19 of the failures, excluding the EPC-related failures, were attributed to cathode deactivation, it became necessary to obtain a more fundamental understanding of the detailed

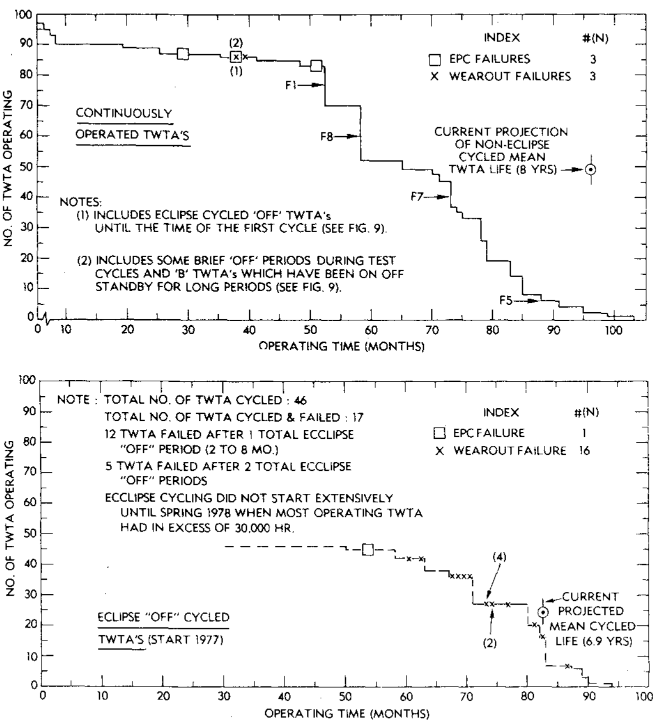

Fig. 10 INTELSAT IV transmitter TWTAs life performance (Sept. 1979).

interrelationships (e.g., gain, cathode current, and bus current). There are basically only three measures available for analysis on each INTELSAT IV transmitter TWTA: change in bus current (ΔI_{BUS}) telemetry, transponder gain, and relative transmitter-saturated output power. Furthermore, each of these measures could be determined with only limited resolution, e.g., 40 mA for ΔI_{BUS} and ~ 2 dB for gain and relative output power. Therefore, simulation tests were conducted at COMSAT Laboratories to analyze the deactivation characteristics. These tests revealed some interesting features of TWTA deactivation. Subsequent in-orbit tests could then be performed with confidence.

INTELSAT IV Transmitted TWTA Deactivation Characteristics

When all TWT supply voltages are kept constant and the cathode current gradually degrades, as in the case of cathode

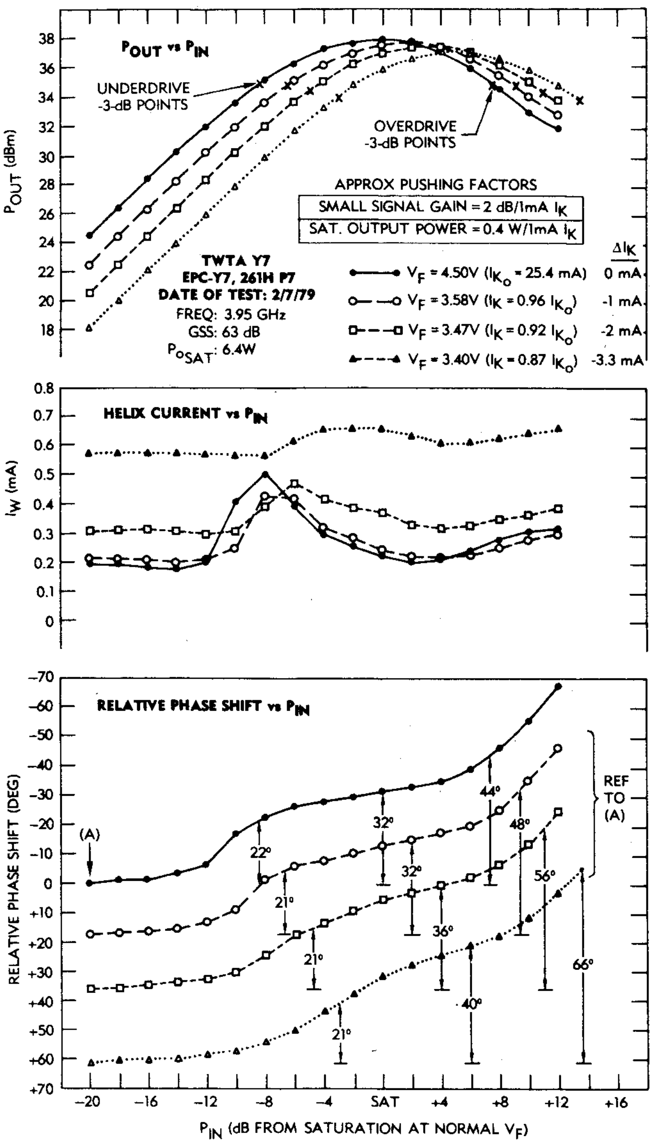

Fig. 11 Effect of reduced I_k by filament underheating (TWT 261H).

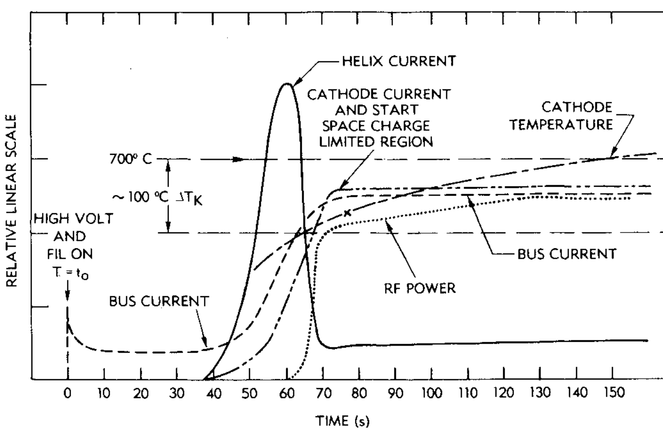

Fig. 12 Cold-start characteristic with normal filament voltage (INTELSAT IV simulator TWTA E5; filament voltage, 4.5 V).

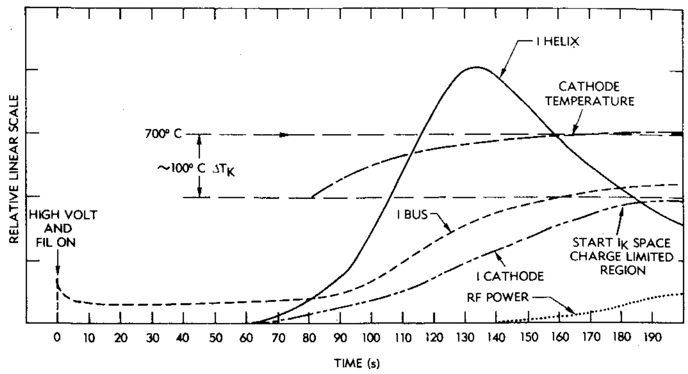

Fig. 13 Cold-start characteristic with cathode degradation simulated by reduced filament voltage (INTELSAT IV simulator TWTA E5; filament voltage, 3.29 V).

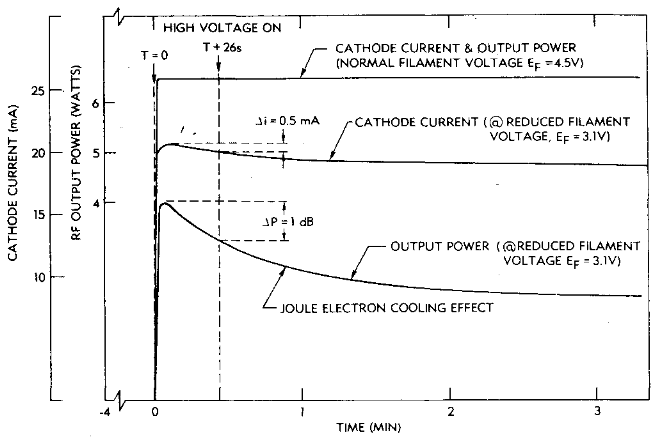

Fig. 14 Cathode current and output-power signature with hot turn on with operation at normal and reduced filament voltage (simulator TWTA E5, $E_f = 3.1$ V, and normal filament voltage, $E_f = 4.5$ V).

deactivation (transition from space-charge-limited to temperature-limited operation), the tube's rf characteristics change. The exact changes can be closely approximated by simulating deactivation through reduction of the cathode temperature. The so-called underheating effects on the rf characteristics and helix interception of the 261H are shown in Fig. 11 as a function of rf drive. Thus, for a reduction in I_k (e.g., $\Delta I_k = -2$ mA), the corresponding changes of gain, saturation drive, output power, helix current, and phase delay can be determined. A family of such curves can be established for most TWTs and life performance assessed if the change in cathode current with time is known. Although other performance factors such as noise figure, VSWR, and gain slope could also have been measured as a function of ΔI_k, this was not considered necessary.

In the INTELSAT IV satellite, the power supply was series regulated so that as a first-order approximation, the bus current (I_{BUS}) was directly proportional to I_k. Figure 12 shows the relative rise of helix, cathode, and bus currents and their correspondence to rf output power for a cold start (all voltages including normal 4.5-V heater voltage applied to the TWT simultaneously). The transient temperature rise of the cathode is superimposed on this figure. It should be noted that the cathode current becomes space charge limited when the cathode temperature reaches more than ~625°C. Figure 13 shows the effect of cathode deactivation. In that case, the filament voltage has been reduced to 3.3 V and the cathode must reach ~700°C before the cathode current becomes space charge limited. Moreover, approximately 180 s are required as shown to reach 700°C. In an actual space TWT-deactivation case, where the filament voltage remains constant (e.g., $E_f = 4.5$ V), the same temperature is reached in less time (~150 s), but the phenomenon is the same: a more-extended starting or stretched transient due to the increased knee temperature, T_{kn} (see Fig. 1), for the aged TWT. This stretching effect has frequently been clearly observed and measured in space TWTs by monitoring ΔI_{BUS} and rf output after a cold-start turn on. Therefore, T_{kn} progression can be measured from the ground provided that the TWT can tolerate cold starts. Since some TWTs cannot survive a cold start due to excessive body-current interception during the extended turn-on transient, this type of procedure cannot be universally applied.

A second method for determining deactivation progression is to observe the bus current and rf transient with a normal "hot" start (typically 4-min filament/cathode warm-up prior to applications of high voltages). A simulated case is given in Fig. 14, which shows the normal start with $E_f = 4.5$ V and the underheated value ($E_f = 3.1$ V). The unexpected $\sim$2-min transient decay in I_k and output power for the latter case is due to the Joule cooling effect, which occurs with electron emission. That is, at the instant at which I_k is drawn, the cathode cools ($\sim 10°$C in this case); since the emission is now temperature limited, the cooling results in a decrease of emission until the cathode reaches its new equilibrium temperature. Obviously, under space-charge-limited emission conditions, this effect is never observed. Therefore, in a seriously degraded TWT, the Joule cooling effect may easily be recorded on the ground, and plans for switching on a redundant TWTA made. A typical trace on a degraded space tube is shown in Fig. 15. The techniques developed by ground simulation have permitted a much better assessment of the start of the TWTs in space.

Redundancy

Several TWTA transmitter-channel-redundancy concepts have been used in communications transponders. As previously mentioned, INTELSAT IV satellites used a 2 for 1 transmitter redundancy. Both INTELSAT IV-A and V have a considerable number of channels with 3 for 2 redundancy. More recent configurations use the concept conceived at COMSAT Laboratories[18] and currently designed into such spacecraft as SBS (two circuits, each with 8 for 5 redundancy) or Anik C (approximated by two circuits, each with 12 for 8 redundancy). There is also the zero-redundancy concept (e.g., SATCOM and COMSTAR) in which a channel is allowed to die when a TWTA fails. Since failure is usually gradual, this allows time (weeks) to reconfigure the ground systems.

Until recently, the choice of a specific concept has perhaps been more subjective than objective. Now that the TWT life patterns are better understood (at least at 4 GHz) and the channel loading as a function of satellite lifetime is also firmer, a more objective TWT redundancy strategy may be chosen. One example of interest was the INTELSAT IV-A 3 for 2 redundancy case.

There are two basic TWTA utilization strategies: minimum switching or equal aging. The minimum-switching strategy minimizes the number of on-off switching cycles, since units are left on until a failure occurs and then the redundant unit is turned on. This obviously is the best choice for channels with 2 for 1 redundancy. For channels with 3 for 2 redundancy, this same minimum-switching strategy can lead to nonoptimum channel availability when wearout failure is strictly due to the length of time that a unit remains on. If both on-line units failed, there would only be one backup unit available when two are needed, and channel capacity would decrease.

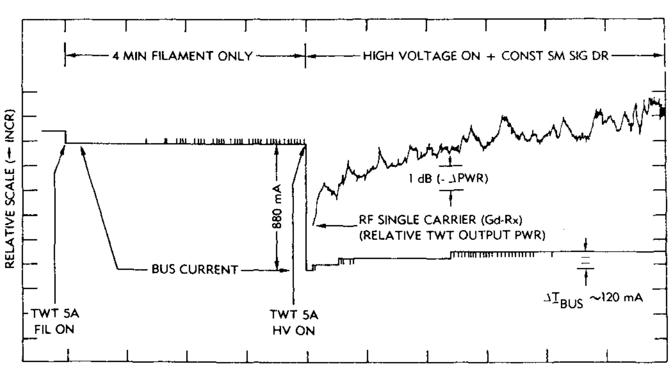

Fig. 15 INTELSAT IV F2 TWTA 5A turn-on sequence (Feb. 1979, Andover, Me.).

For the equal-aging strategy, this problem is overcome by rotating the on-line assignment of the three units to equalize the accumulated life. This strategy does require switching and associated long-term storage of the units after they have accumulated substantial life. Based on the evidence gained on the INTELSAT IV program and the significantly higher failure rate of cycled TWTAs as compared to uncycled TWTAs, it has been decided to use the minimum switching strategy on all channels of the INTELSAT IV-A satellite. Furthermore, current INTELSAT IV-A satellite-transmitter TWTA experience with over 2 million hours of operation on five satellites (20 transmitter channels per satellite) confirms the general early-life pattern established on the INTELSAT IV series of satellites.

Future Life Expectations

Several significant developments have occurred during the past year. In terms of oxide cathodes, the most recent satellite TWTs have used a cathode-current density of 130 mA/cm^2 and cathode temperatures 20 to 30°C lower than normally used for a current density of $\sim$200 mA/cm^2. In principle, this should increase the TWT lifetime by perhaps a factor of 2. That is, if all failures on INTELSAT IV, for example, were due to classic cathode deactivation (as in the case of uncycled population), the mean estimated life would be 16 yr. This trend has been substantiated by 94,000 h of successful transponder operation of the INTELSAT III F-3 satellite prior to its decommissioning during the fall of 1979. The two types of TWTs used (233H and 235H, two each per satellite) were both operated with a cathode current density of $\sim$140 mA/cm^2.

The same order of lifetime could be estimated for matrix-type cathodes operated with a constant-cathode-current regulator providing $J_0 \sim 300$ mA/cm^2 at a brightness temperature near 980°C. Since matrix cathodes are more resistant to residual-gas effects and can be evaluated with accelerated temperature tests prior to flight, they may be preferable to oxide cathodes. Furthermore, development of improved matrix-type cathodes is continuing, with the expectation that 100,000-h cathodes with a capability of 2 A/cm^2 will evolve. This same cathode could, conversely, be operated at the present 0.7-A/cm^2 level with temperatures 60 to 80°C below those currently in use. The expected result would be cathode, and in turn TWT, lifetimes of the order of 200,000 h. These candidate cathode types utilize either osmium or indium, properly incorporated with the tungsten matrix, in impregnated or storage matrix-dispenser-type cathodes.[12]

Conclusions

This paper has documented the past and present status of TWTA lifetimes, primarily in the INTELSAT satellite system. The characteristics of cathode degradation, both for oxide- and matrix-type cathodes, have been presented. Reliable and long-lived TWTA performance has been demonstrated which meets or even exceeds the expectations of the late 1960s. Furthermore, current work on newer types of matrix cathodes indicates that a factor of 2 improvement in lifetimes may be possible. Although space-field-effect transistor amplifiers (FETAs) are strong contenders for displacing space TWTAs at the low power levels ($\sim$1 W or less), they have not yet proven their ability at higher-power microwave levels ($\sim$4 W or greater). Further proof must be established before system designers can with complete confidence elect to use power FETAs rather than TWTAs for long-term ($>$10-yr) satellite applications.

Acknowledgment

This paper is based upon work performed at COMSAT Laboratories under the sponsorship of the International Telecommunications Satellite Organization (INTELSAT).

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