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High Efficiency, Long Life Traveling Wave Tubes for Future Communications Satellites

J.A. Dayton, Jr.
Lewis Research Center
Cleveland, Ohio

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High Efficiency, Long Life
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J.A. Dayton, Jr.
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Abstract

Electron beam devices, primarily traveling wave tubes (TWT's), have been used as the power amplifiers in almost all space communications and data transmission systems. Based on the technology that is presently available and the expected success of current research efforts, it is reasonable to predict the development of a new class of microwave TWT's with efficiencies in excess of 60% and lifetimes of at least ten years. Because of this rapid advance of technology, the TWT is expected to remain the dominant device for power amplifiers in space.

Introduction

NASA, particularly through the Office of Aeronautics and Space Technology, has been in the forefront of research to develop the TWT technologies that will enable future communications missions. The NASA program develops devices for future agency missions and has two main generic research thrusts, to increase TWT efficiency and operating life. This research program is managed by Lewis Research Center and is conducted in house and through contractors.

This paper will survey research on efficiency enhancement and reliability improvement, concentrating primarily on NASA contributions.

Reliability

Performance in Space

The reliability of the TWT in space has been a continual subject of dispute. When TWT failures occur, the results can be of great significance to the satellite operator. For this reason, an expensive documentation procedure must be completed before a TWT is "qualified" for space. Also, because of the commercial significance of TWT failures, satellite operators and tube manufacturers may be unwilling publicly to document failures. For similar reasons, the TWT reliability data for military communications satellite systems is usually not readily available.

NASA's experience in deep space communications has been quite successful, although it represents too small a sample to be statistically significant. The TWT's on board the Pioneer and Voyager spacecraft, all manufactured by Watkins-Johnson, have accumulated approximately 500,000 hours of operation and, until the last few months, had suffered no failures. This fall one of the X-Band TWT's on Voyager 2 suffered cathode failure after more than ten years of operation in space. However, the backup TWT was turned on and is performing satisfactorily to support the encounter of Voyager 2 with Neptune in August 1989.[1]

One of the difficulties of presenting reliability data for performance in orbit is that the available telemetry frequently does not provide sufficient information to distinguish definitively between failures of the TWT and failures of the high voltage power processor. For this reason, orbital data are customarily presented for the traveling wave tube amplifier (TWTA), not the TWT and power processor separately. A further complication in making comparisons is that operation at different power levels and frequencies imposes different requirements of voltage, dimensional tolerances and cathode current density. The largest body of data available in the open literature was presented in 1986 by Illokken[2] for TWTA's in commercial service, equipped with Hughes TWT's. Illokken reported 18 random failures for C-Band TWTA's at a variety of power levels in more than 45 million hours of operation for a mean time between failure (MTBF) of 1.8453×10^6 hours at a 90% confidence level. At Ku-Band, again for a variety of power levels, Illokken reported one random failure in over one million hours of operation in orbit for an MTBF of 305.2×10^3 hours at a 90% confidence level.

The lower MTBF for Ku-Band TWTA's is based on a small statistical sample and may not represent a meaningful trend to reduced reliability at higher frequencies. However, the possibility of reduced reliability is inherent as frequency is increased. For example, Ku-Band TWT's generally require higher cathode current densities than can be reliably supplied by the oxide cathodes used in most of the C-Band tubes that have been flown in space, necessitating the use of dispenser cathodes. There is a limited amount of life test data available on a variety of dispenser cathodes that indicate that they can be used to achieve the operating lifetimes required, but these lifetimes have yet to be demonstrated in space. Other potential reductions in reliability at higher frequencies may be due to generally higher voltages and smaller dimensions, both of which increase electrical and thermal stress.

Cathode Life Test Data

The requirement for higher cathode current densities in higher power, higher frequency tubes has led to the development of a variety of barium dispenser cathodes. The Type M dispenser cathode[3] is most commonly used for high current density applications at the present time. This cathode consists of a porous tungsten matrix coated with a layer of osmium/ruthenium and filled with an impregnant of BaO, CaO and Al_2O_3 in a variety of proportions. In order to establish nonproprietary reliability statistics for dispenser cathodes, NASA initiated a cathode life test program[4] 15 years ago. In this facility, located at Watkins-Johnson, up to 12 cathodes may be under test at one time in simulated tubes. Data for Type M cathodes operated in this facility are shown in Table 1. Type M cathodes continue to operate at a current density of 2A/cm^2 for up to 9 years and at 4A/cm^2 for 5 years. Cathodes to be used in the Advanced Communications Technology Satellite (ACTS) program will be tested in this facility.

A much larger facility is now operating at the Rome Air Development Center where 75 cathodes of various types have undergone testing.[5] Under joint agreement with NASA, RADC is testing NASA-owned Siemens Type MK reservoir cathodes and later this year will begin testing an improved reservoir cathode developed by NASA.[6] As described below, reservoir cathodes offer the potential of extremely long operating life.

While most cathode manufacturers maintain life test facilities, there is no substitute for the nonproprietary facilities maintained by RADC and NASA. In particular, the size of the RADC facility permits testing of a wide variety of cathode types under identical conditions.

Table 1

NASA LIFE TEST DATA FOR TYPE M CATHODES
OCTOBER 1987

S/N	LOADING (A/cm^2)	EMISSION (%FROM INITIAL)	OPERATING HOURS TOTAL
M1	2	-7.1	78,961
M3	2	-6.0	56,629
M4	2	-1.0	61,548
M6	2	-6.2	51,083
SP-2	4	-6.7	*38,781
SP-3	4	-6.2	43,508
SP-4	4	-6.0	35,116
SM-1	4	-4.1	42,704
SM-2	4	-5.8	40,616
SM-3	4	-3.9	23,636

*REMOVED FROM TEST DUE TO NON-CATHODE FAILURE

Novel Cathode Types

A variety of novel cathode types have been introduced in the last few years in an attempt to obtain the high current densities and long life needed for future applications.[7] NASA's principal contribution to this effort is the improved reservoir cathode[6] shown in Figure 1. This cathode features a tungsten-osmium alloy surface for enhanced electron emission at lower operating temperatures, a porous tungsten plug for regulating barium flow to the cathode surface and a novel barium oxide encapsulation system to simplify handling and storage. The operating life of this cathode is determined by the size of the reservoir and may, therefore, be tailored to the needs of a specific application. The emitting surface of this cathode has been demonstrated to produce space charge limited emission of up to 100 A/cm^2. It is projected that this cathode may achieve emission current densities of 10 A/cm^2 with operating life of 100,000 hours. In tests conducted to date, the improved reservoir cathode has bemonstrated an emission of 16 A/cm^2 for more than 15,000 hours without degradation.

Power Processors

The question of TWT reliability cannot be addressed fully without discussing the reliability of the power processor that converts the low voltage DC typically available on a spacecraft to the high voltages required to drive the tube. Approximately half of the TWTA failures that occur in space are due to the power processor, although an exact figure is not available due either to inadequate telemetry or proprietary restrictions. As the higher frequency bands are utilized for space communications, voltages between 10 and 20 kV will generally be required, placing an added burden on power processor technology. The potted power supplies now used do not appear to be suitable for this voltage range. Any bubble, crack or fault in the potting when subjected to high electric field potentials and repeated temperature cycling in orbit can eventually provide a conductive path that will short out and disable the amplifier. Generic research is needed on open construction power processors that rely upon the vacuum of space for electrical insulation. This technology was pioneered by NASA in the power processor flown on the Communications Technology Satellite (CTS) in 1976[8] and is being employed again on ACTS. The CTS power processor operated without fault in space at voltages up to 13 kV. The only potting in the CTS power processor was used to maintain the thermal integrity of the inductors and transformers.

Efficiency Enhancement

Multistage Depressed Collector

The invention of the multistage depressed collector (MDC) by H. Kosmahl[9] has resulted in approximately doubling the saturated efficiency of microwave tubes, providing the technology that has enabled high power transmitters for space and airborne applications. Figure 2 illustrates the efficiency enhancement possible for a tube as a function of its basic electronic efficiency and the collector efficiency. The improvement in efficiency is most striking for devices with low electronic efficiencies; for this reason the MDC is extremely effective when used with millimeter wave devices that are inherently inefficient. Figure 2 neglects the effects of beam interception and RF circuit losses. At the other end of the RF spectrum, the MDC was recently successfully demonstrated by Varian Associates with a klystron of the type used as transmitters for terrestrial UHF television.[10]

A major advance in MDC technology has been the development of computer aided design techniques[11] that accurately predict collector efficiency. An example of this computation is shown in Figure 3. Illustrated here are the trajectories of primary and secondary electrons, equipotential lines and the cross section of a typical collector geometry. These computational techniques have generally predicted MDC efficiency within two percentage points of measured values.

The principal area of research in MDC technology at the present time is the suppression of secondary emission by using low atomic number materials as electrodes, by microscopically roughening the electrode surface or by applying a low secondary yield coating to an electrode.[12,13] Improvements of approximately 12% in overall efficiency are typically achieved in tests of tubes with MDC's with secondary suppression. A typical low secondary yield surface is shown in Figure 4.

Computer Aided Design for Specific TWT Characteristics

Modern computer techniques have enabled the design of slow wave circuits for TWT's that produce specific characteristics needed for particular applications without requiring changes in most of the tube's external features. An example of this technique as presented recently by Curren et al[14] is shown in Figure 5. This work employs the dynamic velocity taper first reported by Kosmahl and Petersen at this conference in 1984.[15] Two circuits are designed to fit within identical vacuum envelopes. Circuit A is designed for maximum gain and efficiency for single channel operation at saturation, conditions that are tailored for transmission of data from deep space. Circuit B is designed to minimize phase distortion. The two circuits are of identical length, and are designed to operate with the same electron gun and vacuum envelope. As can be seen from Table 2, Circuit B exhibited reduced phase distortion at no sacrifice in efficiency, but with reduced gain. Both circuits have produced a saturated power output approximately 30% greater than obtained with a conventional helical circuit. With modern multistage depressed collectors, these 20-watt tubes are expected to achieve overall efficiencies in excess of 55%.

Diamond as a Dielectric Circuit Support

A number of slow wave circuit types require dielectric materials for mechanical support, electrical isolation and thermal conductivity. Diamond is ideally suited for this application because of its high strength, extremely low dielectric losses and very high thermal conductivity. Circuit losses are reduced both by reduced losses in the dielectric supports and by permitting the circuit to operate at a lower temperature and, therefore, a lower resistivity. Two experimental tube types in which NASA has employed diamond as a dielectric are the 29 GHz TunneLadder[16] and a 20 GHz helical TWT.[17] In the TunneLadder, diamond chips are braised into a ridged waveguide structure to support a ladder-type slow wave circuit. In the helical TWT, Figure 6, mechanical compression is used to maintain contact between the helix, the diamond supports and the barrel. With a multistage depressed collector this tube is expected to achieve an overall efficiency in excess of 60%. Both devices have exhibited remarkable power handling capabilities, but further development is necessary before this technology is ready for production devices.

Conclusions

Because of its efficiency and reliability, the TWT has been the amplifier chosen for almost all microwave space communications systems. The research programs described in this paper will provide the technology to produce a new generation of space communications TWT's with lifetimes in excess of ten years. Current research is demonstrating startling improvements in tube efficiency by using dynamic velocity taper circuit designs to maximize electronic efficiency, diamond support structures to reduce RF circuit losses, and multistage depressed collectors with secondary emission suppression to increase collector efficiency. To achieve very high efficiency, it is also necessary to virtually eliminate electron beam interception. The exact values of efficiency that can be achieved depend on the operating frequency and power level of the tube, but efficiencies of 60% or more are available at K-Band for moderate power levels. The TWT has been the backbone of space communications systems, and there is every reason to expect it to continue to be.

Table 2
TEST RESULTS FOR WJ-3716 TWT's AT 8.4 GHz

PARAMETER	TWT TYPE A	TWT TYPE B
Helix voltage, volts	3150	3235
Beam current, mA	32	27.5
Saturated gain, dB	51.71	41.0
Beam efficiency, %	23.7	25.2
Saturated RF output power, dB_m	43.91	43.5
Helix current, mA	1.5	1.25
Beam transmission efficiency, %	95.3	95.5
Phase shift at saturation, °/dB	4.84	3.13

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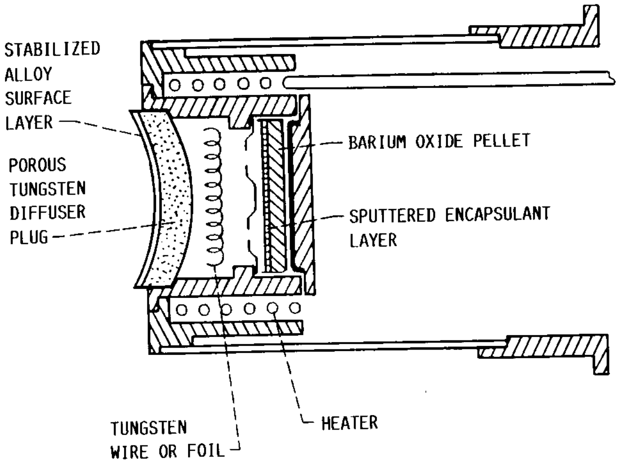


FIGURE 1. - IMPROVED RESERVOIR CATHODE UNDER DEVELOPMENT BY NASA AT VARIAN ASSOCIATES.

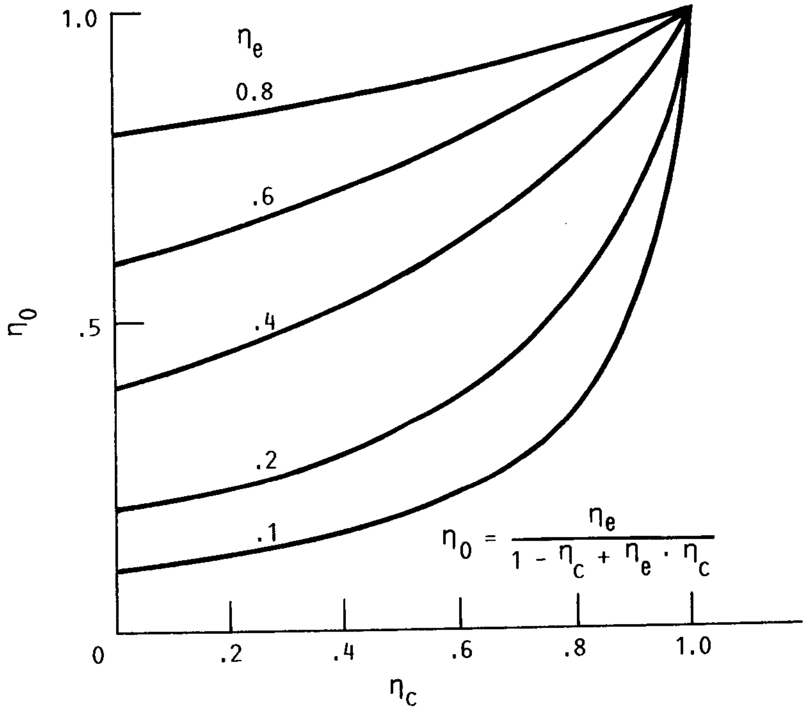


FIGURE 2. - OVERALL EFFICIENCY VERSUS COLLECTOR EFFICIENCY.

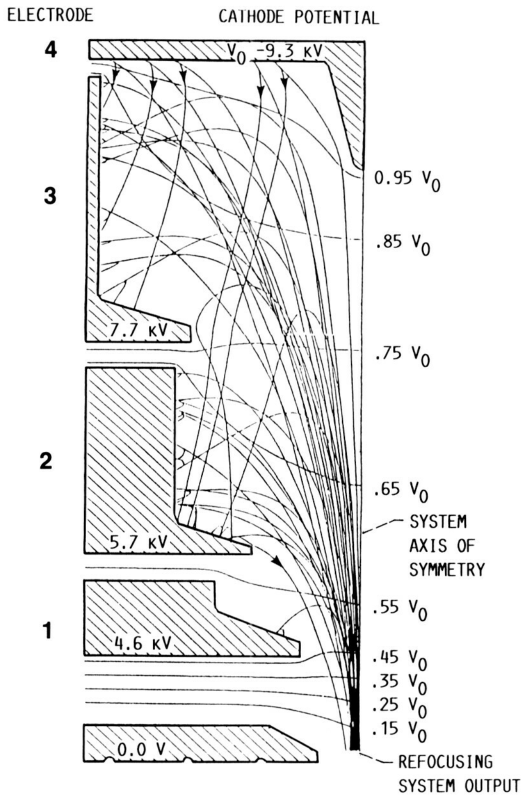


FIGURE 3. - A TYPICAL COMPUTER-GENERATED PLOT OF ELECTRON BEAM TRAJECTORIES IN A FOUR-STAGE DEPRESSED COLLECTOR IS SHOWN. THE CIRCULARLY SYMMETRIC COLLECTOR ELECTRODES ARE SHOWN IN A SECTION VIEW WITH THE RIGHT VERTICAL EDGE BEING THE COLLECTOR CENTER LINE. BOTH PRIMARY AND LOW ENERGY SECONDARY ELECTRON TRAJECTORIES ARE SHOWN; THOSE SECONDARY TRAJECTORIES THAT IMPACT LESS DEPRESSED ELEMENTS HAVE BEEN LABELED WITH ARROWS. EQUIPOTENTIAL LINES ARE SHOWN AND ARE LABELED AT THE RIGHT.

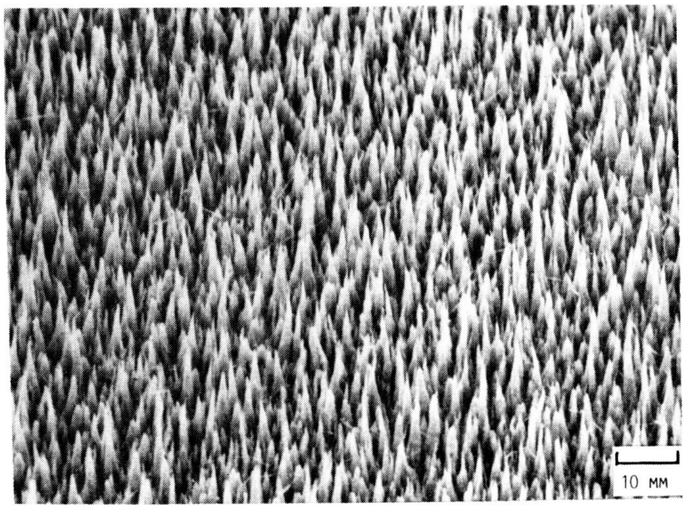
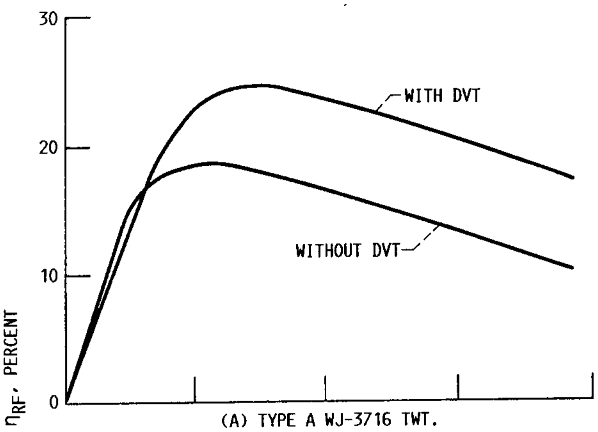
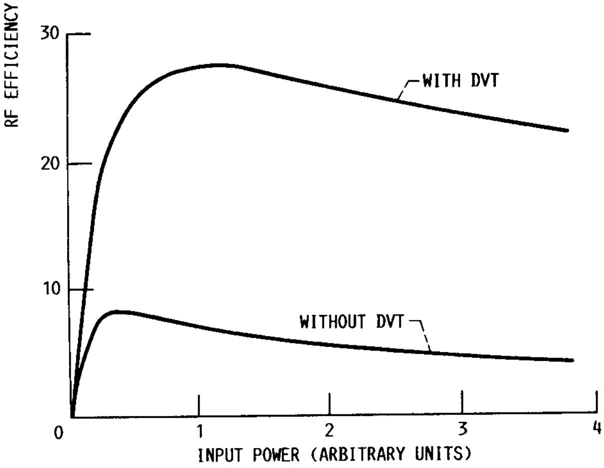


FIGURE 4. - ELECTRON MICROGRAPH OF ION-TEXTURED GRAPHITE SURFACE HAVING SECONDARY ELECTRON YIELD OF 0.2. GRAPHITE SPIRES ARE 7 TO 10 MICROMETERS HIGH AND SPACED 2 TO 4 MICROMETERS APART.



(A) TYPE A WJ-3716 TWT.



(B) TYPE B WJ-3716 TWT.

FIGURE 5. - PREDICTED RF EFFICIENCY AS A FUNCTION OF INPUT POWER FOR TYPES A AND B WJ-3716 TWT'S WITH AND WITHOUT DVT'S.

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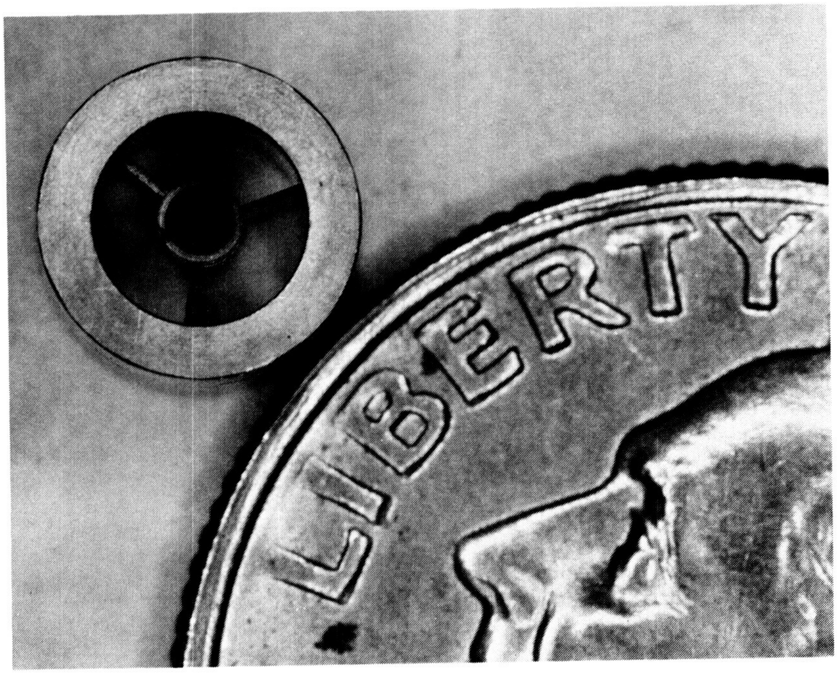

FIGURE 6. - END VIEW OF A DIAMOND SUPPORTED 20 GHz HELICAL SLOW WAVE CIRCUIT AS FABRICATED BY HUGHES ON A NASA CONTRACT.

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