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TRAVELING-WAVE TUBE RELIABILITY ESTIMATES, LIFE TESTS, AND SPACE FLIGHT EXPERIENCE

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Traveling-Wave Tube Reliability Estimates, Life Tests, and Space Flight Experience

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Key Words: Reliability estimates, Life tests, Space flight experience, MTBF, Failure modes, Critical ranking, and Sequential testing

Abstract

An assessment of the probable failure modes of high-power traveling wave tubes (TWT's) intended for use in space is presented. The infant mortality, useful life, and wearout phase of the tubes life are considered. The performance of existing developmental tubes, flight experience, and sequential hardware testing are evaluated. The reliability history of TWT's in space applications is documented by considering (1) the generic parts of the tube in light of the manner in which their design and operation affect the ultimate reliability of the device, (2) the flight experience of medium-power tubes, and (3) the available life test data for existing space-qualified TWT's in addition to those of high-power devices.

Based on generic failure rate data from existing literature, an analytical estimate of the MTBF of a specific high-power TWT used for the Communications Technology Satellite (CTS) is calculated. The same procedure is also applied to a tube characteristic of existing space-qualified devices in order that the validity of the analytical predictions may be compared with demonstrated MTBF. A failure effects analysis with criticality ranking is then presented for the CTS tube in order to uncover those components which most strongly affect its reliability, the critical design weaknesses of the tube, and its wearout modes. A sequential test is then described which determined early within the development program whether the tube could demonstrate with reasonable confidence a given MTBF range.

Introduction

In today's communication satellites, and in most other types of existing spacecraft, a traveling-wave tube (TWT) serves as the final output stage of the transmitter. It is generally the only vacuum tube device utilized in the onboard communication system and, in terms of current research and development, it is highly unlikely that it can be replaced by any solid-state device in the foreseeable future.

Most space applications of traveling-wave tubes require long operating times for earth/satellite communications. Therefore, reliability without maintenance is a major design and manufacturing concern. Since TWT's will be employed in space communication systems for some time, it is important to evaluate their present flight experience and demonstrated life data, and to make reliability estimates in order to develop a basis for engineering decisions concerning the kind of performance which can be expected from these tubes in current applications and in the future. Although some existing tube types of up to 20 watts output have demonstrated lives of over 5 years in spacecraft missions, proposed future missions will require new tubes operating at higher power levels, frequencies, and efficiencies. A large number of long duration tests have been conducted to date on traveling-wave tube systems, subsystems, and components. However, these tests have typically been part of a technology development phase which for the most part can not be considered sequential reliability testing since each system tested may be slightly different. Thus, even though space-qualified communications systems have flown, system reliability, particularly in the case of the new high-power devices, can only be inferred from the results of past and present developmental testing and estimated by analytical techniques.

Estimates of Generic Failure Rates

The TWT belongs to a general class of devices designated as beam-type microwave tubes. The name arises because their operation requires a long confined flow (beam) of electrons along the axis of the tube. Figure 1 illustrates a cutaway view of a super high-frequency (12 GHz) TWT which was developed for the CTS program by NASA (Ref. 1). It is the objective of this section to describe the characteristics of this component in some detail with particular emphasis on how their design and structure affects reliability.

The reliability growth predictions that are given in the following discussion, are based largely on engineering judgment. Failure rates are shown as means and extremes. These data were developed from several different sources of failure rates for each type of component (Refs. 2-8). It is expected that a component will exhibit a low (L), mean (M), or upper (U) failure rate depending on the design and application stresses and material strengths. Mean values are used for calculations allowing the confidence interval to define the next estimate range.

Gun Structure

In a properly designed and procsssed TWT, the ultimate life of the tube is determined by depletion of the active cathode material. High-power operation requires two basic changes in the electron gun design. First, the cathode potential is raised to 8.5 kV or more as compared with about 5 kV or less in lower power tubes. Higher voltages impose more stringent insulation requirements on a structure which is basically designed for electron optic characteristics rather than breakdown properties. Second, the cathode loading is usually increased to around 0.5 amp/cm^2 or greater, if reasonable sized guns are to be employed. Oxide-coated cathodes, as employed in the medium power-tubes, are limited to currents on the order of tenths of amp/cm^2 if long lives are to be expected. The high-power tubes must employ impregnated tungsten cathodes (or the so-called dispenser cathodes). This type of cathode is considerably newer than the oxide cathode and, as such, less knowledge and experience is available to document performance. As with the oxide-coated type, expected life is determined ultimately by the amount of reducing impurity added to the basic cathode structure. These high-current cathodes also require higher temperature operation increasing both the prime power requirements for the heater and the complexity of the thermal design of the gun (Ref. 7).

From a reliability point of view we will consider the gun structure to be composed of five parts. A compilation of the estimated generic failure rates for these parts is given below. The failure rates where obtained from existing literature (Refs. 5-10). The table lists the upper (U) and lower (L) values found in

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the literature along with the mean (M) which is normally used in calculations.

Part	Gfr/10^6 Hours		
	U	M	L
Cathode heater	0.04	0.02	0.01
Cathode	20.0	9.2	7.0
Electrodes	0.15	0.09	0.03
Shields	0.04	0.02	0.005
Connectors (4 pin)	0.54	0.14	0.02

Circuit

A number of different types of circuits have been developed to overcome the basic power handling limitations of the helix at high frequency. The coupled-cavity slow wave structure has become the most popular because of its many advantages. The drive tube through which the electron beam passes is defined by a series of gaps at the centers of the cavities. Interaction of the fields in the cavity with the electron beam occurs through the fringing fields at these gaps. Coupling holes placed in the transverse walls of the cavities (the web) allow rf energy to pass from one cavity to the rest. As with the helix, the coupled cavity circuit effectively reduces the speed with which the rf energy can propagate along the structure. In effect, one can imagine that the energy must move back and forth in order to pass through the coupling holes of successive cavities. The result is that the energy travels, at the speed of light, a considerable distance in order to travel a relatively short distance along the tube axis. Most of the basic rf properties of the TWT are determined by this structure. The frequency is determined by the overall size of each cavity. The wave velocity is made synchronous with the electron beam by the appropriate spacing between successive cavities. The bandwidth is determined by the size of the coupling holes. All of these dimensions can be varied over wide ranges in order to perform tradeoffs between electrical and thermal requirements. However, once the design is established, the dimensions must be closely controlled (at 12 GHz dimensions are specified to 0.0005" with ±0.0002" tolerance) in order to avoid serious degradation of the electrical performance of the circuits.

Medium-power tubes that have been used in space have a helix circuit configuration. The estimated generic failure rates for this type of tube are tabulated below (Refs. 5-10):

Part	Gfr/10^6 Hours		
	U	M	L
Helix	5.26	2.88	0.50
Attenuator	1.03	0.60	0.15
Windows	2.43	0.90	0.37
Connectors (2 pin)	0.27	0.14	0.05

High-power tubes using the coupled cavity circuit configuration modifies the estimated generic failure rates as follows (Refs. 5-10):

Part	Gfr/10^6 Hours		
	U	M	L
Coupled cavities	0.08	0.01	0.003
Attenuator	1.03	0.60	0.15
Sever	0.40	0.14	0.04
Waveguides	1.92	1.10	0.59

Magnetic Focusing Configuration

Perhaps one of the most valuable aspects of the coupled cavity structure is that its geometry is ideal for employing periodic permanent magnet (PPM) focusing. The cavity walls are made of iron in order to channel the magnetic field from annular permanet magnets down to the beam drift tube. This allows relatively weak magnets to produce the strong focusing fields required at the gaps. Unfortunately, iron has poor thermal and electrical conductivity. Thus, it is often necessary to copper plate a section of the iron in order to improve the rf properties and to provide integral cooling passages in the structure.

The magnetic focusing structure is composed of the following parts with their respective estimated generic failure rates (Refs. 5-10):

Part	Gfr/10^6 Hours		
	U	M	L
Magnets	7.11	5.65	2.02

Collector

When the spent electron beam leaves the rf circuit region it is terminated on a collector in order to complete the dc electron flow circuit. Considerable kinetic energy remains in the beam, as typically only 10 to 30 percent has been converted to rf signal energy. Hence, the collector must be able to dissipate the remaining energy in the form of heat. This is accomplished by brazing the collector to a ceramic insulator which in turn is brazed to the tube vacuum envelope. A heat path is, therefore, provided while maintaining the necessary electrical insulation of the collector from the tube body. The collector electrode is typically constructed of copper (oxygen free to avoid cathode poisoning) in order to have high electrical and thermal conductivity and low outgassing properties. It is often operated at a potential below the circuit potential in order to slow the beam velocity down before collection, and thereby reduce the impingement energy and improve the tube efficiency. This is called depressed collector operation which offers two practical improvements. First, with less kinetic energy being dissipated in the collector, the collector operates at a lower temperature. Second, in slowing down, the beam actually delivers energy to the power processor supplying the collector potential; energy which would have otherwise been dissipated in the collector as heat. Hence, the overall power requirements of the tube are reduced. High gain TWT's have a wide range of electron velocities in the spent beam. Since the spent beam will actually have a wide electron velocity spread, it is necessary to collect these electrons with several electrodes at different potentials. The use of multiple collectors reduces the energy of different velocity ranges within the spent beam to a minimum, thereby, achieving a much more efficient recovery. Combination of improved circuit efficiency with depressed collection has resulted in tubes with overall efficiency greater than 50 percent (Ref. 9).

The design of these multiple collectors is quite involved due to the complicated trajectories of the electrons in the device (Ref. 9). Reflection of electrons back into the circuit region and secondary emission of electrons from the electrodes are the two main practical difficulties encountered when electron trajectories are not optimum.

Tubes that have been used in space are of the single stage (1S) collector configuration with a one-pin (1P) high-voltage connection. The estimated generic failure rates for these parts are as follows (Refs. 5-10):

Part	Gfr/10^6 Hours		
	U	M	L
Collector (1S)	1.10	0.40	0.12
Connector (1P)	0.14	0.04	0.005

The addition of a multistage depressed collector tends to complicate the design and thus lower reliability; the effect should be no worse than a linear function by stages. A 10-stage (10S) depressed collector would have an estimated generic failure rate as follows (Refs. 5-10):

Part	Gfr/10^6 Hours		
	U	M	L
Collectors (10S)	11.0	4.0	1.2
Connectors (10P)	1.36	0.35	0.05

Remaining TWT Considerations

There are several additional components that are necessary to provide the proper electrical, mechanical, thermal, and environmental conditions for a TWT to operate. The mechanical configuration of the tube is constructed to provide the necessary vacuum envelope. Further protection against vibration may also be obtained by suspending the basic tube in a separate protective metallic body and heat sink. In addition to the components described above, a high-power tube will often be provided with some means of continuous pumping in order to insure a high vacuum.

These remaining parts are listed below, along with their respective estimated generic failure rates (Refs. 5-10):

Part	Gfr/10^6 Hours		
	U	M	L
Vacuum envelope	0.6	0.04	0.02
Ion pump	10.0	1.0	0.10
Structural sections	1.35	0.60	0.03

Flight Experience

One of the design requirements for the CTS spacecraft was a performance goal of 2 years of useful life. Since 1964, four space missions have been documented using TWT communication systems demonstrating useful lives in excess of 2 years (17 520 hr) (Refs. 10, 11). A chronological listing of these long-life space missions using TWT communications is shown in Table I. Of the eight Pioneer tubes considered in Table I, only one tube failed in flight. In particular, after 14 days, Pioneer 7 was forced to switch to its backup tube. This tube subsequently provided continuous operation for over 3 years and was still operating in 1970 when the final flight report was prepared. The tubes in Pioneers 8 and 9 have exhibited failure-free lives of at least 3 and 2 years, respectively, at the time of the report while the tube in Pioneer 6 was still operating continuously after approximately 46 720 hours (about 5 1/3 yr). It is unfortunate that more recent information was not available but these figures do demonstrate qualitatively the long-life capabilities for space used TWT's. A quantitative measure of the tube's overall exhibited mean time between failures ($\overline{t}_e$) can also be made. Comparison of this exhibited ($\overline{t}_e$) with the calculated ($\overline{t}_c$) estimated range at 90 percent confidence gave some validity to this analysis. For the combined Pioneer data shown in Table I, one failure occurred in 119 272 hours; therefore, ($\overline{t}_e$) = 119.3 khr. We could expect the next Pioneer TWT to fail some time in the range from 39.6 to 2310 khr with a 90-percent confidence.

Life Tests

During the past 10 years, a substantial number of TWT long-duration tests exhibiting useful lives in excess of 2 years have been performed (Refs. 6, 10). The majority of these tests were performed as part of a TWT development phase. Care must be exercised in using this data to reflect fully developed, quality controlled, flight ready devices. However, these tests did serve to uncover chance and wearout failure modes. The wearout failure modes through component developments were brought to a minimum which enhanced the confidence in those parts which repeatedly survived. Finally these tests provided data on the fundamental and limiting TWT failure modes. In many cases the test periods approached the operating times required by typical space communication missions. These data allow projection of ultimate life to be made with improving confidence and accuracy. Four typical sets of TWT life test data are shown in Table II. Line 1 of Table II summarizes power life characteristics of nonflight members of the Syncom 314H and the 10-watt Pioneer 349H tubes. Demonstration of a MTBF range from 56.3 to 3280 khr with a 90-percent confidence, without any observed failures, attests to the flight readiness of these tubes. Line 2 of Table II relates to the 5-watt 384H TWT designed for the Advanced Technology Satellite. The 12 tubes noted are the original tubes placed on tests in October of 1963. As of May 3, 1966 they had attained the performance as shown with no significant reduction in cathode activity or power output. Lines 3 and 4 of Table II demonstrates the performance of 1000-watt, s-band reflex klystrons intended for space use. The structure and the design of these beam-type devices is quite similar to that of a traveling-wave tube. This is particularly true for the cathode configuration. The usual test procedure consisted of removing a small sample from each month's production and to operate them at rated specifications for a time slightly greater than the warranty period. The tubes were removed at this time, though operating normally, to avoid wearout bias.

Failure Considerations

Since the CTS Program was functioning with fixed time, dollar, and performance constraints, it was unlikely that the amount of testing required to generate the classical failure rate curve as shown in Fig. 2 could take place before launch for the high-powered transmitter experiment package (TEP). In this section, it is intended to show that different methods are available to demonstrate that the TEP was ready to perform its experimental function when launched. Early and wearout failures can be avoided by careful selection and application of the preflight checkout procedures and by not planning to use the equipment beyond the estimated wearout interval, (t_m) in Fig. 2. The methods by which these various failure rate intervals can be identified are categorized as follows:

1. Early Failures: Identify potential early failure modes; identify checkout procedures required to assure that most early failures have been removed; specify the minimum preflight test period (t_b).
2. Chance Failures: By analysis of the various parts that are used in the CTS TWT, estimate the MTBF range at a 90-percent confidence level.
3. Wearout Failures: Identify life-limiting wearout failure modes and based on existing life test data, estimate the time (t_W) up to which the failure rate can be considered constant and the mean life (t_m).

Chance Failures with Rate Estimates

Reference 12 explains the concept of using the failure rates for the parts of a component to predict the MTBF of a component in a laboratory environment. A reliability analysis of the high-power output stage tube was undertaken using this method. A similar study on medium power tubes was also made so that the results could be compared with available data as a check on the validity of the analysis. These two studies are presented in Table III. Since generic failure rate data for many of the new parts used in the OST did not exist, the part failure rates of similar equipment used in airborne applications was selected. The mean generic failure rates have been tabulated in column 1. An application factor (K_A) is shown in column 2. This factor is an attempt to take into consideration the actual part stresses in an effort to make the total failure rate as accurate as possible. In those cases where the stresses did not seem to make much difference an application factor of one was used. The total failure rate is the product of columns 1 and 2. Under remarks we identify the type of tube to which the data applies. The total generic failure rate for the medium and high-power tubes adds up to be 27.4 F/10^6 and 40.8 F/10^6 hours, respectively. Because parts are subjected to far greater stresses in an airborne environment than in the space environment except for the rather short launching phase, both failure rates were adjusted by an operating mode factor (K_{op}) of 0.33 giving 9.04 F/10^6 and 13.4 F/10^6 hours, respectively. All of the flight programs shown in Table I and the medium power, primary CTS communications system used two tube redundancy to give maximum mission assurance. The estimated MTBF should reflect this redundancy for the medium power tube by a redundancy factor (K_r) equal to 0.204 for $t/\overline{t}$ equal to 0.159 with two switching networks (Ref. 12). Since the high power OST was not redundant, a K_r equal to 1 should be used in this case. Cost, weight, and the experimental nature of the OST ruled out the use of redundancy in this case. Further, many of the spacecraft experiments could function without the TEP. The final modified failure rates are for the medium-power tubes 1.84 F/10^6 hours and the high-power tube 13.4 F/10^6 hours.

The estimated MTBF ($\overline{t}_c$) was calculated by taking the reciprocal of these modified failure rates which come out to be 540 khr for the medium-power tube and 74.6 khr for the high-power tube. The upper and lower 90-percent conficence limits for the estimated $\overline{t}_c$ were calculated using the chi-squared distribution by assuming that one chance failure had occurred. The medium-power estimated MTBF range based on the generic failure rate analysis came out to be 180 to 10 500 khr at a 90-percent confidence level. This can be compared with the data for items 1 and 2 in Table II, the range here at the same confidence level is 56.3 to 4580 khr. This implies that the chance failure rates are somewhat optimistic but suitable for use to identify critical item by ranking. Using comparable numbers for the OST analysis results in a calculated MTBF range of 58.0 to 1450 khr at a 90-percent confidence level. It appears as though the OST does have the inherent design capability to last for the 17 520 hours required by the CTS mission.

Failure Effects Analysis with Criticality Ranking

The output stage tube as applied to the CTS, was an experimental product intended to simplify and reduce the cost of ground-receiving equipment. In this case a failure effects analysis with criticality ranking was undertaken to establish those parts which have a high probability of impacting mission performance. This was a statistical study which requires estimates from experience with similar TWT parts. Not all part failure modes contribute to loss of the OST, nor are all the parts equally susceptible to failure, a ranking according to criticality is shown in Table IV for both medium- and high-power tube parts. This ranking helps to focus attention on those parts where the greatest improvements in reliability can be made within the existing time and money restraints. Part improvement studies are the only means by which these parts changes can be made as it was not practical to use redundancy for the 200-watt OST.

The primary failure modes were classified and listed for each part considering both the type of rf circuit and collector employed. The data was taken from existing literature and the malfunction reports. Only primary failures were considered in the listing of part failures. The method of weighing (W) the TWT loss probability was to assign fixed probabilities to certain events; weighting factor (W) equals 100 for certain total failure, W equals 50 for probable total failure, W equals 10 for possible total failure, and W equals zero for no effect on the tube. By this method of weighing, it is possible to eliminate from consideration, failures that have no effect on the tube and to assign a rating to others for an estimate of loss probabilities. The failure mode frequency ratio was estimated from three case studies by dividing the number of failures of the part in any given mode by the total number of failures of the part in all modes.

These three case studies of beam tube problem areas are summarized in Table V. Two involve the problems encountered in the design and development of high power TWT's while the third is concerned with the problems associated with the OST in production under actual service conditions. The generic failure rates were taken from Table III as the mean values. The criticality number was computed as the numerical product of the TWT loss probability, the failure mode frequency ratio and the generic failure rate. The maximum criticality number was listed and used for ranking in column 6 of Table IV. All high-power tube parts with a maximum criticality number greater than 10 F/10^6 hours were identified as risk items. An intensive development program was conducted to demonstrate that the tube was qualified and ready for flight use.

Reliability Test to Demonstrate Flight Readiness

Reliability and lifetime are two of the most important parameters in TWT design. Demonstration tests performed to verify MTBF and wearout requirments must be compatible with the time phasing of the program and available funds. One of the design requirements for the OST spacecraft was a goal of 2 years of useful life. Three alternatives exist to try and demonstrate this goal:

1. A large number of tubes could be tested to provide meaningful information during the early program phases.

2. A smaller quantity of tubes tested for a longer period, yet within the time span of the program.

3. Demonstration to a lesser requirement, confidence and MTBF, which will provide reasonable assurance in obtaining the spacecraft goal.

The approach described was based upon the second and third alternatives since the time and cost of equipment and tubes to implement the first approach was prohibitive at this power level.

Sequential testing was the optimum approach to reliability demonstration when time is of the essence; i.e., when an accept or reject dicision must be made early in the program or within a specified period of time. Here the test program was based upon the expected time to make a decision, which may be optimized in both tubes and equipment required if the actual tube MTBF exceeds the design objective.

The design of a sequential test to confirm that the 90-percent conficence MTBF range of 2.5 to 145.6 khr can be met using 10-percent consumer and producer risks and applying the Poisson equation (Refs. 13, 14). In this case, the minimum expected time to reach a flight ready decision would be 3.67 khr (about 6 mo) if three tubes were placed on test at the start. The failure history would determine the ready/not ready performance as charted in Fig. 3.

Since the OST development was very hardware limited, it was recommended that one tube be placed on flight readiness demonstration test initially and the test time extended accordingly. If one or more failures occurred, additional tubes would be consecutively tested with an expected time to make the flight readiness decision, no longer than 19.7 unit-khr. Consecutive testing is the optimum approach, since tubes may not be available from production at the same time and, most important, the test time and equipment costs would be prohibitive at this power level. It may be seen in Fig. 3 that if one tube was placed on test, a ready decision would be made as early as 11.0 khr (about 15 mo) accured "on" time without failure.

Reliability demonstration testing based upon the sequential flight readiness test was recommended as follows:

1. One depressed collector TWT was placed on test under full rf drive at room ambient.

2. Test was run continuous wave at room ambient.

3. Test setup, as shown in Fig. 4, included an rf source, a flight type power processor, and monitoring instruments to assure adequate voltage, current, power, and shutdown protective circuits and an rf load.

4. Important parameters were monitored with strip chart recorders to maintain the selected operating conditions and optimize performance.

5. Mean-time-between-failures estimates were based on accumulated test time and the number of relevant failures which occur. This was compared to ready and not ready criterion of Fig. 3.

6. Demonstration test, which are still running, could have been terminated when (1) the 2.5 to 145.6 khr MTBF range design objec ive at a 90-percent confidence level was demonstrated, (2) when the maximum number of allowable failures is reached without decision, or (3 when the accumulated test time is equal to or greater than the maximum number of failures allowed times the slope of the acceptance line 19 7 unit-khr.

The test data obtained from seven tubes indicated a cumulative CW operating time of 21.8 khr with no relevant failures as of October 8, 1976. This test data also demonstrates that the OST was ready for flight as of this review date.

Concluding Remarks

Based on the successes of the Pioneer Satellite Series, both flight qualification and the attainability of long-duration operation in space of TWT communication systems have been established. The extensive developmental, laboratory life, and flight readiness demonstration testing of TWT communications system components and parts have identified the early failure modes which would occur during preflight checkout procedures in the first 100 hours of flight preparations. The CTS Spacecraft was launched on January 17, 1976 and is currently undergoing a period in eclipse of about 6 weeks. The TEP as of August 30, 1976 had accumulated 2839 hours of high voltage on time with 5052 hours of filament on time and was working properly when it entered this eclipse period.

Wearout life-time projections for space used TWT's of 50 to 60 khr are justified in this report. Thus, it appears that the output stage tube can perform for the required operating time of 2 years in the Communications Technology Satellite for this mission.

Because of the lack of statistical testing of the parts used in the output stage tube, other approaches to determining chance failure rates had to be considered in this report. Reasonable estimates of the chance failure rates were obtained by an evaluation of existing similar TWT parts and the use of accepted analytical techniques. This study showed that similar TWT's used in space would have an estimate MTBF in the range from about 56.3 to 4580 khr at a 90-percent confidence level. The CTS output stage tube, because of its high efficiency and power gain requirements would have an estimated MTBF range from 58 to 1450 khr. The maximum criticality numbers were computed for each part and used for ranking. All parts with a maximum criticality number greater than 10 were identified as risk items. An intensive development program was conducted to demonstrate that the OST was qualified and ready for flight use. A reliability test to demonstrate flight readiness was completed. This test confirmed that the 90-percent confidence MTBF range of 2.5 to 140 khr can be met using a 10-percent consumer and producer risks in the Poisson equation. Very tight process controls were also used to manufacture the OST for space use.

Thus, while statistical testing of the OST parts and fully developed, flight qualified, tubes should be undertaken, relatively high output stage tube reliability can be predicted with confidence based on the use of careful design practices, available test data, and accepted analytical techniques.

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TABLE I. - LONG LIFE SPACE MISSIONS USING TWT COMMUNICATIONS

Date	Flight
December 15, 1964	NASA Pioneer 6 - communication system contained redundant TWT's operating at 10 watts in experimental (X) band. This system operated properly for 46 720 hours at the time of the flight report, although there was an upward drift in the helix current but it never did exceed the maximum allowable valve.
August 31, 1966	NASA Pioneer 7 - the communication system was not changed for this flight. This system operated properly for 28 752 hours at the time of the flight report, although one TWT failed due to excessive helix current after 336 hours.
December 13, 1967	NASA Pioneer 8 - the communication system was not changed for this flight. This system operated properly for 26 280 hours. No anomalies have been observed.
September 8, 1969	NASA Pioneer 9 - same redundant communication system. This system operated properly for 17 520 hours. No anomalies reported.

TABLE II. - TYPICAL TWT LIFE TEST DATA

Tube type	Number of tubes	Accumulated hours	Number of failures	MTBF (khr) 90 percent confidence	
				L	U
349 H[a]	7	168 519	0[b]	56.3	3280
384 H	12	236 185	0	78.6	4580
VA - 222	59	438 100	5	47.8	223
VA - 218B	50	204 000	6	19.4	77.9

[a]Tube used in Pioneer communications system.
[b]Since this test was stopped before even one failure occurred, the MTBF range for maximum likelihood was obtained by assuming that one chance failure had occurred.

TABLE III. - TWT MTBF ESTIMATES

Parts	General failure rate M(F/10^6 hr)	K_A	Total (F/10^6 hr)	Remarks
Gun structure				
Cathode heater	0.02	4	0.08	Both
Cathode	9.20	1.5	13.80	<0.2A/cm^2, Med
		2.0	18.40	>0.2A/cm^2, High
Electrodes	0.09	1.0	0.09	Both
Shields	0.02	1.0	0.02	Both
Connectors (4P)	0.14	1.0	0.14	Both
Circuit				
Space used				
Helix	2.88	2.5	7.20	Med
Attenuator	0.60	1.0	0.60	Both
Windows	0.90	2.0	2.80	Med
Connector (2P)	0.14	2.0	0.16	Med
Coupled cavity				
Cavity	0.01	1.0	0.01	High
Sever	0.14	1.0	0.14	High
Waveguides	1.10	2.0	2.20	High
Focusing				
Magnets	5.65	1.0	5.65	High
Collector (1S)	0.40	2.0	0.80	Med
(10S)	4.00	2.0	8.00	High
Connectors (1P)	0.04	2.5	0.10	Med
(10P)	0.35	2.5	0.88	High
Others				
Vacuum envelope	0.04	1.0	0.04	Both
Ion pump (1P)	1.00	2.0	3.00	High
Structural section	0.60	2.5	1.50	Both

TABLE IV. - TWT CRITICALITY RANKING

Part	Primary failure mode	TWT loss probability	Failure mode frequency ratio	Generic failure rate $M(F/10^6\ hr)$	Maximum criticality number $(F/10^6\ hr)$
Collector (10S) Collector (1S)	Melts Opens leads Arcs	100 50 50	0.71	4.00	284 (28.4)
Cathode	Loss of emission	100	0.21	9.20	193
Magnets	Change in magnetic field	50	0.16	5.65	45.2
Helix	Open	100	0.08	2.88	23.0
Ion pump	Flaking Depletion	50 10	0.33	1.00	16.5
Windows	Seal opens	100	0.16	0.90	14.4
Attenuator	Change in pattern or losses	50	0.16	0.60	4.80
Waveguides	Change rf characteristics	10	0.16	1.10	1.76
Vacuum envelope	Leakage	100	0.33	0.04	1.32
Electrodes	Open Mechanical damage Arcing	100 100 100	0.14	0.09	1.26
Cathode heater	Open Internal shorts	100 10	0.50	0.02	1.00
Sever	Change in pattern or losses	50	0.08	0.14	0.56
Structural section	Mechanical damage	10	0.08	0.60	0.48
Connectors (15P),(7P)	Wearout	10	0.08	0.53	0.42 (0.20)
Shields	Mechanical damage	10	0.14	0.02	0.03
Cavity	Thermal deformation	10	0.08	0.01	0.01

TABLE V. - CASE STUDIES OF BEAM-TUBE PROBLEM AREAS

1. OST Development, 200 W, 12 GHz TWT

Electron gun

Broken spot weld-cathode to cathode support ring.
Fractured cathode sleeve at weldment to support ring.
Cathodes in two completed tubes had no impregnant.

Collector assembly

Broken collector insulator.
Leakage between collector elements.
Intermittent high-voltage breakdown.
Excessive outgassing and secondary emission from electrodes.
Electrode support tabs failed under vibration.

Circuit assembly

Vacuum leak at window adapter.
Vacuum leak at input match hole.
Intermittent short in input coupler.
Vacuum leak at output coupler.
Temperature variation of gain equalizer.
Vacuum leak in refocusing section.
Paper left inside tube during assembly.

2. Experimental 4 kW, 12 GHz, TWT

Electron gun

Eccentricity of cathode and focus electrodes leading to poor focus and increased circuit impingements.
Poor magnetic focusing leading to thermal stress of circuit.

Circuit assembly

Cavity web too thin leading to thermal stress.
Circuit nonuniformity arising from careless assembly.
Poor beam-circuit coupling due to poorly held gap spacing tolerances.

3. External Cavity Klystron Amplifier, 20 kW, 0.4 GHz

Electron gun

Open filament (3 tubes).
Shorted filament (4 tubes).
Low beam current (1 tube).

Collector assembly

Melted collector (4 tubes).
Clogged collector (1 tube).

Circuit assembly

Output cavity arc (2 tubes).
High body current (1 tube).

Miscellaneous

Lost cooling (1 tube).
Low-power output (2 tubes).
Cause of failure unknown (3 tubes).

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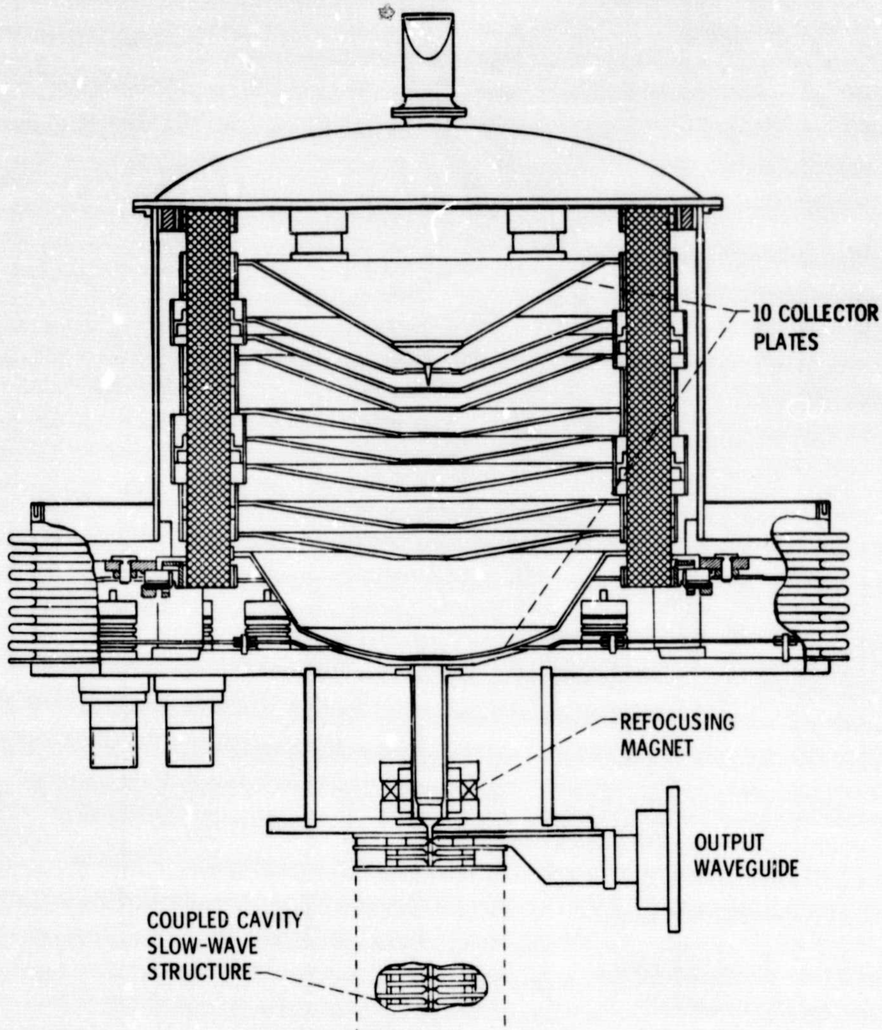

Figure 1. - Cutaway view of coupled cavity traveling wave tube with multistage depressed collector.

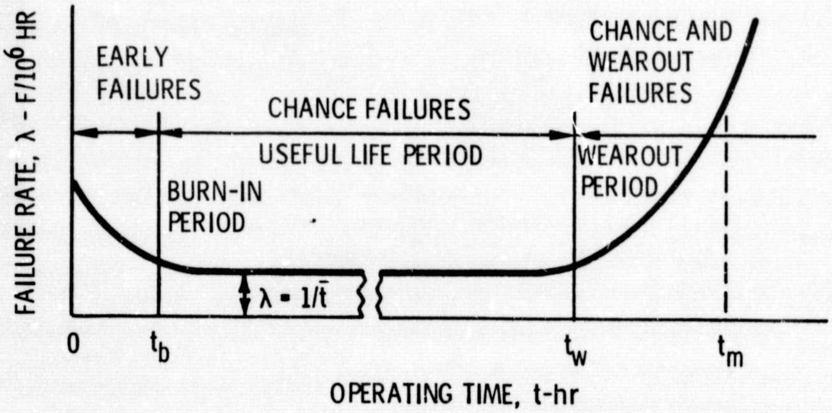

Figure 2. - Typical failure rate as a function of operating time.

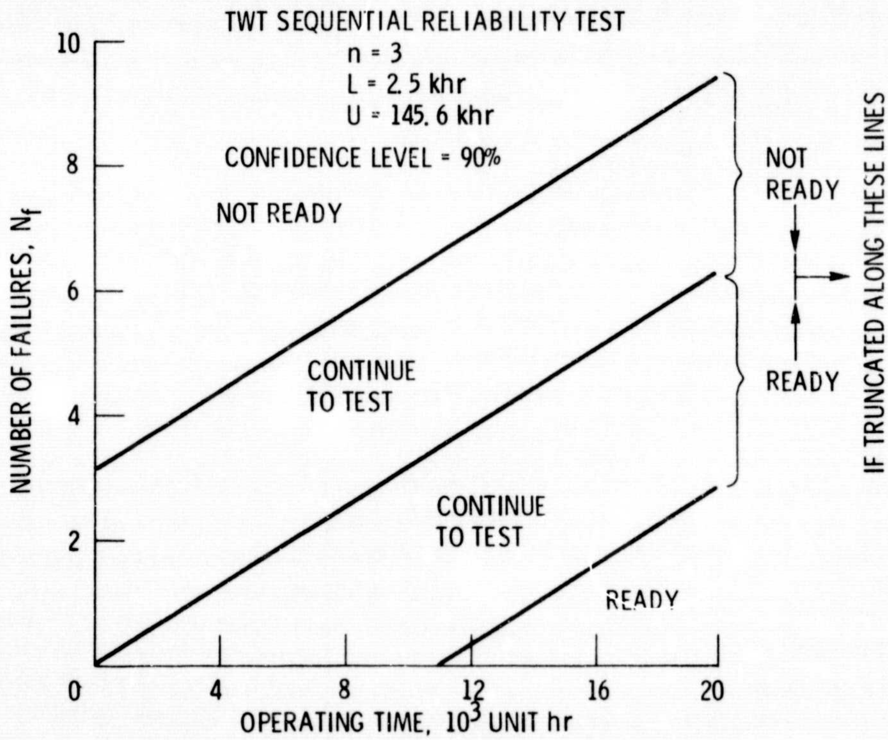

Figure 3. - Flight readiness demonstration test.

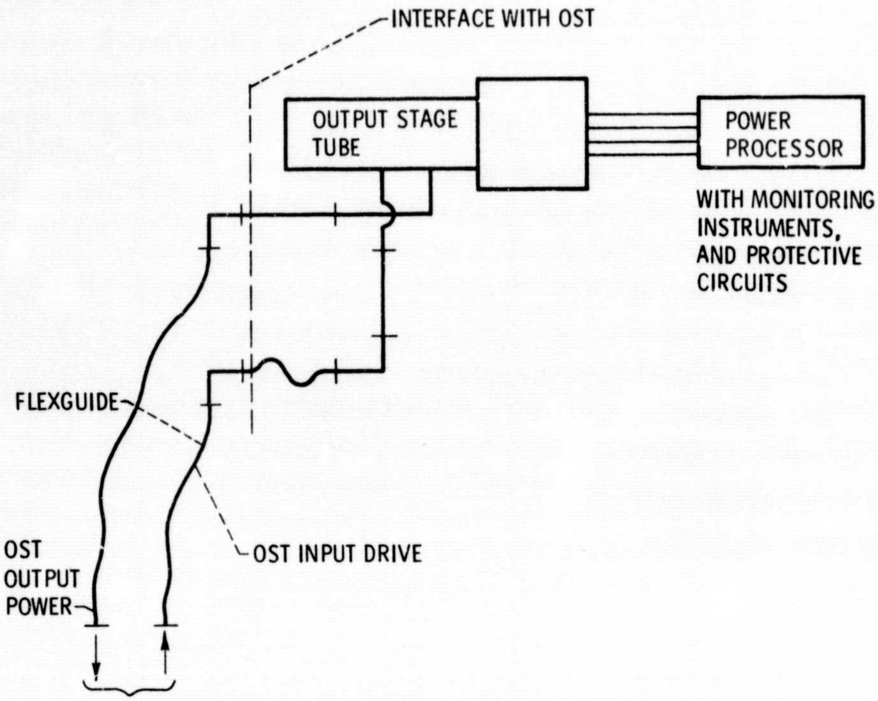

Figure 4. - OST hookup using rf test rack.

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