STANDARD BASED RELIABILITY PREDICTION OF TRAVELING WAVE TUBE IN COMMUNICATION SATELLITE

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Abstract

A Traveling Wave Tube (TWT) is a vital component of satellite communication transponder. Before launch, it is essential to ensure that TWT meets the life of the satellite in the orbit.. Standard based reliability prediction is fairly accurate, widely used in USA and Europe and specified to the contractors. Part stress and parts count analysis are considered in all the standards. In this paper, part stress analysis based on US Military standard, MIL – HDBK – 217F is considered. Since the standard does not provide the failure rate of individual components used in TWT, Preferred Reliability Practices specified by NASA USA in their documents No PD – ED – 1216 is considered for parts count analysis. The reliability estimated by the above standards does not meet the life of 10 years .In the past five years, tremendous improvements have occurred in the materials, design, fabrication, testing and simulation of TWT. Based on these improvements, reliability is recalculated. The revised reliability estimate meets the life of 10 years and coincides with the reliability claimed by the global suppliers of space TWT.

Keywords: TWT; Reliability; Part stress; Parts count; Redundancy

1. Introduction

A Traveling Wave Tube (TWT) is an electronic device used to amplify Microwave signal. When used along with Electronic Power Conditioner (EPC) , the assembly is called Traveling Wave Tube Amplifier (TWTA).TWT used in communication satellite is placed in Geosynchronous orbit at an altitude of 35,887 KM above the earth. While in orbit, TWT is subjected to temperature cycling, shock, vibration, thermal radiation and nuclear radiation. Key parameters of TWT considered in the reliability analysis are as follows,

- Output power.... 100 watts
- Frequency…….. 4 GHz (C Band) / 12 GHz (Ku Band)
- Gain …………. 60 dB
- Size …………. 375 X 12mm, collector ϕ 110 mm
- Weight ………. 1100 Grams
- Life in the orbit...10 Years

A TWT has the following sub assemblies:

- An Electron Gun to produce high density and high energy electron beam.
- A helix circuit in which the electron beam interacts.
- Collectors that collect spent electrons.
- TWT package which maintains vacuum, cooling for collectors, electrical connectors etc.

A simplified schematic of TWT [1] is shown in Figure 1.

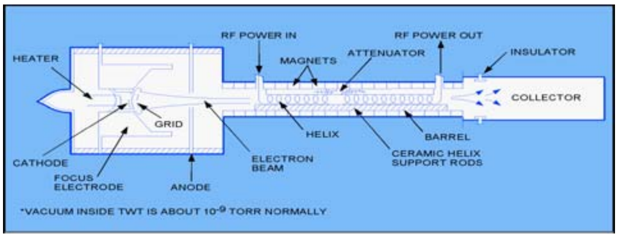

Fig.1 Schematic of TWT

2. Standards Based Reliability Prediction

Failure of a TWT in space is non - repairable. The cost of space TWT with lineariser is more than 100K US $. Failure of TWT means inability to use the respective communication channel unless output-switching matrix is used. Hence TWT is designed to be rugged, reliable and less weight. Cathode exhaustion triggers the point at which TWT tubes wear out and failure rate increases substantially. Parameters such as failure rate, MTBF and reliability explain how long a TWT will function satisfactorily under the environment specified. Reliability can be predicted by the following methods:

- ❖ Based on the failure data and analysis performed over a long period.
- ❖ Accelerated aging test performed in the simulation laboratories.
- ❖ Standards Based Reliability prediction.

Reliability prediction of TWT based on standards is discussed.

Standards Based Reliability Prediction is a methodology for predicting reliability for components and systems based on failure rate estimates published by globally recognized commercial or military standards. Standards based reliability prediction is useful in the initial stages of development when hardware failure data is not available or when manufacturers are obliged contractually by their customers to use published standards for their reliability prediction. Standards based reliability prediction relies on defining failure rates depending on the types of components, the environment and the way components are connected. The component failure rates are then used to obtain an overall system failure rate.

3. Prediction Standards

Governments and Industry organizations introduced several standards. The standards define models for different types based on test data. The models assume a constant failure rate, which describes the life of a component. The popular standards are as follows:

- ❖ USA Militatary Hand book on Reliability Prediction of Electronic Equipments, Standard No:MIL-HDBK-217 F
- ❖ Handbook of Realibility Prediction procedures for Mechanical Equipments from US Navel Surface Center, Standard No: NSWC-98.
- ❖ Bellcore (Telcordia) standard from AT&T Bell labs, standard No: TR-332, Issue 6 and SR-332, Issue1.
- ❖ French Telecommunication standard, standard No: RDF-2000.
- ❖ Chinese Military standard No: 299B.

A brief description is as follows.

3.1 MIL – HDBK -217F standard

The standard supports two methods of reliability prediction [2], parts count and part stress analysis. Parts count requires information such as part quantities, quality levels and the application environments. If the equipment consists of parts operating in more than one environment, the prediction is applied to each portion of the equipment that is operating in distinct environment. The sum of the failure rates of all environments represents the overall equipment failure rate. Part stress analysis requires more detailed information and is usually applicable later in the design phase. The part stress analysis usually results in a lower failure rate or higher system reliability than the parts count method.

3.2 NSWC standards

Naval Surface Warfare Centre of US Navy published the standard. It uses a series of models for various categories of mechanical components to predict failure rates that are affected by stress, flow rates, temperature and other parameters.

3.*3 Bellcore (Telcordia) standard*

The Bellcore standard [3] predicts the reliability of Electronic equipments based on Bellcore (Telcordia) standard, TR -332 Issue 6 and SR – 332 Issue 1 , published by AT& T Bell laboratory. The standard provides prediction at components level, system level or project level. Bellcore utilizes three methods.

- Method I: Parts count
- Method II: combines Method 1 predictions with laboratory data
- Method III: Predictions based on field data.

3.4 RDF 2000 standard

French Telecommunication publishes the standard [3]. Reliability calculation models take into account the influence of the environment.

3.5 Chinese Military standard

The standard [3] uses a series of models for various categories of electronic, electrical and electro –mechanical components to predict failure rates that are affected by environmental conditions, quality levels, stress conditions and other parameters. The standard contains two methods of reliability prediction, parts count and part stress analysis.

Out of the above standards, MIL – HDBK -217F standard address TWT. This standard is widely used in space industries. Hence this standard is considered for reliability prediction of TWT for space in this paper.

4. Reliability prediction of TWT by Part Stress Analysis

4.1 Applicability

Part stress analysis is applicable to TWT, when most of the design is completed and a detailed parts list including parts stress is available. The general procedure is to sum the failure rate at parts level after accounting for parts quality and environment.

4.2 Parts Quality

The quality of a part has a direct effect on the part failure rate and appears in the part model as a factorπ_ϕ. Many parts are covered by specifications that have several quality levels. Hence the part models have values of π_ϕ that are keyed to these quality levels. However in the case of TWT, multilevel quality does not exist and hence is not applicable. Hence π_ϕ is considered as unity for TWT.

4.3 *Environment*

The part reliability model includes the effect of environmental stresses through the environmental factor π_E. The π_E quantified within each part failure rate model. Some equipment will experience more than one environment during its normal use. In such a case, the reliability analysis is segmented. Some environmental symbol and description applicable for space use of TWT are as follows:

Space Flight: S_F

This environmental condition is applicable when the space vehicle carrying TWT is neither under powered flight nor is in atmosphere re- entry. The assigned value for S_F is 0.05

Missile Launch: M_L
This environmental condition is applicable to solid rocket motor propulsion powered flights. Assigned value for ML is 33.

4.4 *Failure Model and Reliability Prediction*

Part failure rate model applicable to TWT used in communication satellite is expressed as follows:
$\lambda p = \lambda_b \pi_E$ Failure / 10^6 hours

Where
λp = Part failure rate
λ_b = Base failure rate
π_E = Environmental factor

4.4.1 Base failure rate λ_b

This is expressed as
$\lambda_{b = 11(1.0001)}{}^{p} (1.1)^{F}$
Where
P = Rated power of TWT in watts, $0.001 \le P \le 40{,}000$
F = operating frequency of TWT in GHz, $0.1 \le F \le 18$

4.4.2 Prediction for 100 watts TWT operating in C band and Ku band are derived as follows:

4.4.2.1 TWT with 100 watts in C band (4 GHz)

$\lambda_{b = 11} (1.00010.)^{100} (1.1)^{4}$
=16 Failures / 10^6 hours
$\lambda p = \lambda_b \pi_E$

For TWT used in communication satellite
π_E = SF M_L
λp = 16 (0.05) (33)
= 26.4 Failures / 10^6 hours

Mean time between failures, MTBF is given by

MTBF = 1 / λp
= 1 / 26.4 X 10^{-6}
= 37, 879 hours (4.32 years)
Reliability R for mission time of 10 years (87,600 hours) is given by
$R = e^{-\lambda p t}$
$= e^{-(26.4 \times 10\text{-}6)(87{,}600)}$
= 0.099

*4.4.2.2 TWT with 100 watts in Ku band (12 GHz)***)**

$\lambda_{b = 11} (1.0001.)^{100} (1.1)^{12}$
=36 Failures / 10^6 hours
$\lambda p = \lambda_b \pi_E$
λp = 36 (0.05) (33)
= 59.4 Failures / 10^6 hours

MTBF = 1 / λp
= 1 / 59.4 X 10^{-6}
= 16,835 hours (1.92 years) \

Reliability R for mission time of 10 years (87,600 hours) is given by
R = $e^{-\lambda p t}$
= e- (9.4 $^{x\ 10\text{-}6)\ (87,600)}$
= 0.006

5. Reliability Prediction of TWT by parts count Analysis

5.1 *Applicability*

The information needed to apply parts count is

- Generic part types and quantities
- Part quality levels
- Equipment environment

The equipment failure is obtained by looking up a generic failure rate in any related document, multiplying it by a quality factor and then summing it with failure rate obtained for other components in the equipment.

5.2 *Reliability Prediction*

The generic failure rate for TWT components is not available in MIL – HDBK – 217 F Notices 2. Hence it is taken from " Preferred Reliability Practices, practice No PD – ED – 1216 ", issued by Lewis Research Centre, NASA, USA [4] . Table 1 shows the reliability for individual components, sub system and overall TWT systems.

Table 1 Reliability calculation based on Parts count

S.No	Sub system	Ni Component	N Quantity	λ_g Failure rate X 10^{-6}	π_Q Application factor	N λ_g π_Q Total failure
01	Electron gun assembly	Heater	1	0.02	4.0	0.08
		Cathode	1	9.20	1.5	13.80
		Electrodes	3	0.03	1.0	0.09
		Heat shield	1	0.02	1.0	0.02
		Electrical Connector	1	0.14	1.0	0.14
02	Helix circuits	Helix	1	2.88	2.5	7.20
		Attenuator	1	0.60	1.0	0.60
		Window	1	0.90	3.0	2.70
		Electrical connector	1	0.14	2.0	0.28
03	Collector Assembly	Collector	3	0.10	2.0	0.60
		Electrical Connector	1	0.14	1.0	0.14
04	TWT package	Isolators	2	0.02	1.0	0.04
		Vacuum Envelope	1	0.04	1.0	0.04
		Structural section	1	0.60	2.5	1.50
$\lambda_{equip} = \sum_{i=1}^{N} Ni\ (\lambda g\ \pi Q)i$ = 27.23 Failures / 10^6 hours MTBF = 36, 724 hours (4.19 years) Reliability, R for mission time of 10 years = 0.092						27.23

6. Summary of Reliability Prediction

Failure rate, MTBF and reliability of TWT based on part stress and parts count are summarized in Table 2.

Table 2 Comparison of Reliability Prediction

S.No	Prediction analysis	Operating frequency	λp Failure rate (hours)	MTBF (Years)	R Reliability
1. a)	Part stress	4 GHz	26.4×10^{-6}	4.32	0.099
b)	Part stress	12 GHz	59.4×10^{-6}	1.92	0.006
2.	Parts count	-	27.23×10^{-6}	4.19	0.092

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7. Reliability Prediction of improved TWT based on parts count method

The reliability prediction based on improved components is given in Table 3.

Table3. Reliability Prediction of improved TWT based on parts count method

S.No	Sub system	Ni Component	N Quantity	λ_g Failure rate X 10^{-6}	π_Q Application factor	$\lambda_g \cdot \pi_Q$ Total failure
01	Heater gun assembly	Heater (2W, potted) Cathode (M-Type) Electrodes Heat shield Electrical connector	1 1 3 1 1	0.005 0.100 0.005 0.010 0.050	2 1 1 1 1	0.010 0.100 0.015 0.010 0.050
02	Helix circuits	Helix coil Attenuator Microwave Window Electrical connector	1 1 1 1	0.100 0.050 0.100 0.050	2 1 1 1	0.200 0.050 0.100 0.050
03	Collector Assembly	Collectors Electrical connector	4 1	0.010 0.050	1 1	0.040 0.050
04	TWT package	Vacuum Envelope Structural section	1 1	0.010 0.010	1 1	0.010 0.010
					$\Sigma \; \lambda g \; \pi Q$ =	0.695

$$\lambda \text{ equip} = 0.695 \text{ Failures} / 10^6 \text{ hours} = 695 \text{ FIITS}$$

$$\text{MTBF} = 1 / \lambda \text{ equip} \quad 10^6 / 0.695 = 14388489 \text{ hours, 1642 years}$$

$$R_{10 \text{ years}} = e^{-\lambda t}$$

$$= e^{-0.06} = 0.942$$

8. Conclusions

Space TWT incorporating the latest developments such as M – type cathode, potted low power heater, digital cathode current control, multi depressed collectors, tapered helix, microwave windows, conduction & radiation cooling and ceramic metal package has reliability in excess of 10 years. The reliability estimates is in par with the claim of space TWT manufacturers (800 FIT). Parts count analysis help in identifying the parts with low reliability and scope for improving it. Also, redundancy technique helps in enhancing the reliability further. Chronology of satellite failures and its analysis also helps in improving reliability.

References

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