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Final Technical Report
November 1980

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TRAVELING WAVE TUBE FAILURE RATES

Hughes Aircraft Company

J. H. Engleman
J. Kennedy
S. R. Wood

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

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APPROVED: Lester J. Gubbins

LESTER J. GUBBINS
Project Engineer

APPROVED: Quentin J. Porter

QUENTIN J. PORTER, Acting Chief
Reliability & Compatibility Division

FOR THE COMMANDER: John P. Huss

JOHN P. HUSS
Acting Chief, Plans Office

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A traveling wave tube (TWT) failure rate model is derived. The model gives TWT failure rate as a function of power, frequency, and environment. The data base used to derive the model was obtained from military users of TWTs, TWT manufacturers, and manufacturers of systems containing TWTs. The model is applicable to pulsed and continuous wave TWTs, TWTs used in radar, electronic countermeasures, and communications applications, and all military environments.

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EVALUATION

This contractual effort is part of the broad RADC Reliability Program intended to provide reliability prediction, control and demonstration procedures for military electronic systems and equipment. The prediction procedures are contained in MIL-HDBK-217C for which RADC is the preparing activity. The model for predicting traveling wave tube (TWT) failure rates developed in this effort will replace the TWT information presently in MIL-HDBK-217C. This effort is responsive to TPO IV F2, Equipment/System R&M.

LESTER J. GUBBINS
Project Engineer

TWT FAILURE RATES
TECHNICAL REPORT
JULY 1980

1. INTRODUCTION

This study was performed to derive a model to predict the failure rates of traveling wave tubes (TWTs). A model has been derived and is reported on in detail in this report. This model is intended to replace the one in MIL-HDBK-217C (Ref. 1). The 217C model is appropriate only for high power pulsed TWTs used in radar and electronic countermeasure (ECM) transmitters. The new model applies to low power and continuous wave (CW) TWTs as well.

The new model includes the effects of the frequency of a TWT as well as power level and environment. The data base includes a wide range of environments, applications, power levels, frequency levels, and TWT types. The result is a model with wide applicability.

Section 2 shows the data base and discusses the data collection and data screening that went into its formation. Section 3 describes the mathematical modeling applied to the data base. Section 4 describes the new model and its implications. Section 5 compares the new model with the MIL-HDBK-217C model. Section 6 gives some recommendations for future studies. Three appendices are also included.

2. DATA COLLECTION AND DATA BASE

2.1 <u>Data Collection</u>. The bulk of the effort and the most difficult part of the study was the collection of data for the data base. The data collection plan was to solicit TWT information from manufacturers, contractors, and users of TWTs, as well as from data collection centers. As a first step, we asked the Government-Industry Data Exchange Program (GIDEP) Operations Center in Corona, California, to distribute an urgent Data Request (UDR) to all subscribers to the GIDEP service. There are some 600 subscribers to GIDEP in government and industry. Of these, three responsed, one of which was a Hughes Aircraft Company division. The UDR is shown as Figure 2-1.

The next step was to contact military bases and data collection centers by telephone to request the information listed on the UDR. These requests yielded various results: usable data, unusable data, leads as to where to go for additional information, and computer printouts. In many cases, military sources provided failure rates but not the necessary TWT description. For a description it was often necessary to contact the TWT manufacturer. As it happened, the manufacturers had not only the TWT descriptions, but failure rates as well. As time went on, we obtained more and more information from manufacturers and less from military sources. Of course, the military sources provided failure rates associated with actual field operation, where the manufacturer's data usually had to do with test conditions.

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URGENT DATA REQUEST

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1. REQUESTER (Complete Items 1 thru 13)

Joe Engleman
Hughes Aircraft Co.
Bldg. 373 M/S A335
P.O. Box 92919 Los Angeles, CA. 90009

Phone: (213) 648-2849

2. DATE (Day, Month, Year): 28 JUNE 1979

3. UDR NO:

4. SUBJECT CATEGORY

TWT Reliability

5. TYPE OF DATA NEEDED (Check as required)

	TEST	X	FAILURE RATE		FAILURE MODE		METHODOLOGY
	DESIGN	X	FAILURE EXPERIENCE		SPECIFICATION		MAINTENANCE
	METROLOGY		OTHER (Specify)				

6. COMPONENT / PART / MATERIAL / TEST EQUIPMENT / PROCESS DESCRIPTION

Interested in TWT information which can be used to derive a TWT failure rate model. Please include, to the extent possible:

1. Brief TWT description.
2. No. of operating hours.
3. No. of failures.
4. Times of failures.
5. Definition of failure.
6. Failure mode, at least whether sudden or gradual degradation.
7. Frequency.
8. Output power.
9. Operating temp. of heater.
10. Application.

(Continued Below)

7. MANUFACTURER	8. MANUFACTURER PART NUMBER	9. IND/GOVT. DNO.
N/A	N/A	N/A

10. APPLICATION (Aircraft, Missile, Shipboard)	11. SPECIFICATION NO
All	N/A

6.- Continued

11. Manufacturer.
12. Environment (Please select a MIL-HDBK-217 designation).
13. Number of turn-ons.
14. Gain at (1) beginning of life, and (2) time of failure.
15. Duty cycle (pulsed TWTs only)
16. Manufacturing date.
17. No. of TWTs.
18. Duration of operation.

Also, please specify whether the data reflects:

1. Continuous wave or pulsed TWTs.
2. TWT only or TWT & power supply.
3. Test data or field data.
4. Failures or replacements.
5. Oxide or dispenser type cathode.

12. DATA SOURCE SEARCHED

If you can in any way help this GIDEP participant, please contact him directly. Then complete the remainder of this form and return it for report submittal credit to

Officer in Charge, GIDEP Operations Center, Corona, California 91720

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Figure 2-1. Urgent data request.

The UDR requested 23 different data elements. These data elements were meant to be exhaustive, rather than reflecting a realistic expectation of what we would receive. The following is a brief discussion of some of these data elements:

1) Number of operating hours: Total TWT hours, as opposed to hours on each individual TWT.

2) Number of failures: Failures that could with reasonable probability be ascribed to a TWT. This therefore excludes all other transmitter and receiver component failures, and in particular the failures of TWT power supplies sometimes called electrical power converters (EPCs).

3) Times of failures: Knowing the times at which failure occurred enables one to estimate hazard rate, the instantaneous failure rate. These data were obtained on a few TWTs, and the results yielded some very interesting hazard rates. These are discussed in Appendix C.

4) Frequency: This was known to be a reliability parameter based on an earlier study performed by one of the authors (Ref. 2), as well as on the failure rate models for klystrons in MIL-HDBK-217C.

5) Output power: This was also known to be a reliability parameter from Ref. 2.

6) Application: Radar, ECM, or communications.

7) Oxide versus dispenser type cathode: Some of the more recent high frequency CW TWTs have dispenser cathodes, which have desirable properties for high frequency applications. They were anticipated to have lower failure rates than comparable oxide cathode TWTs.

2.2 Data Base. The data base is shown in Table 2-1. The table shows all the information used in deriving the model, but not all the information available to us. The data base from which the model was derived consists of 59 data sets, or points, and was distilled from 144 data sets received. Data sets were screened out for the following reasons:

1) Incomplete information.

2) Duplicate information.

3) Too few hours and failures. In some cases, these were combined with other data sets.

4) Outliers. In a few cases, the failure rates were several times too high or too low compared with those of similar TWTs. One such TWT had never been a production model, but had only been tested as an R&D model.

A total of 30.4 million tube-hours was collected.

TABLE 2-1. DATA BASE

Data Set	Frequency, GHz	Power, watts	Mode*	Environment **	λ 0.60, F/10^6 hours
1	5.64	12000	P	G_B	254
2	5.55	20000	P	G_B	321
3	7.5	3.5	CW	S_F	17
4	2.36	8	CW	S_F	8
5	7.5	3	CW	S_F	9
6	2.3	2.5	CW	S_F	1.0
7	2.3	9	CW	S_F	1.5
8	4	12	CW	S_F	3
9	7.2	20	CW	S_F	13
10	4	6	CW	S_F	2
11	4	5.5	CW	S_F	3
12	11.5	1.5	CW	S_F	5
13	4	5	CW	S_F	1.2
14	7.25	20	CW	S_F	44
15	7.5	20	CW	S_F	26
16	7.5	0.6	CW	S_F	6
17	8.77	3	CW	G_B	44
18	7.07	3.5	CW	G_B	12
19	2.3	22	CW	G_B	7
20	6.32	35	CW	G_B	7
21	14.7	0.06	CW	G_B	553
22	1.7	0.06	CW	G_B	16
23	7.35	400	CW	G_B	135
24	4	5	CW	G_B	4
25	7.5	3	CW	G_B	49
26	7.5	3	CW	G_B	50
27	7.5	3	CW	G_B	29
28	8.15	3000	CW	G_F	118
29	8.15	15	CW	G_F	43
30	8.15	5000	CW	G_F	47
31	8.15	15	CW	G_F	63
32	7.53	3000	P	A_{UF}	538
33	7.53	3000	P	A_{UF}	570
34	8.15	4	CW	G_F	197
35	8.15	3	CW	G_F	87
36	8.15	8000	CW	G_F	76
37	7.5	0.05	CW	G_F	46
38	9.49	8	CW	A_{UF}	596
39	7.5	0.0035	CW	G_F	78
40	4	5	CW	S_F	1.3

*P = pulsed; CW = continuous wave
**Symbols are explained in text

Table 2-1, continued

Data Set	Frequency, GHz	Power, watts	Mode*	Environment **	λ 0.60, F/10[6] hours
41	7.53	5000	P	A_{UF}	3514
42	0.56	5000	P	G_F	89
43	0.29	0.001	CW	G_F	90
44	14	10000	P	N_S	146
45	5	20000	P	N_S	285
46	7.7	35	CW	S_F	32
47	14	40	CW	N_S	55
48	13.89	0.6	CW	G_B	46
49	9.17	0.6	CW	G_B	42
50	1.41	0.06	CW	G_B	23
51	2.83	0.06	CW	G_B	18
52	0.71	0.06	CW	G_B	12
53	5.66	0.06	CW	G_B	64
54	9.8	0.06	CW	G_B	153
55	2.3	10	CW	G_B	5
56	5.6	0.2	CW	G_F	141
57	0.56	250	CW	G_F	155
58	5.6	5000	P	G_F	233
59	0.42	70	CW	G_F	26

*P = pulsed, CW = continuous wave
**Symbols are explained in text

In addition, some data which we anticipated receiving never arrived, even though we impressed on our sources the importance of their data. Deleted data sets are discussed in more detail in Appendix B.

In a few cases, the frequency or frequency band was classified. The values appear in a separate report submitted to RADC.

In Table 2-1, the power level for pulsed TWTs is the peak power, rather than the average power. The environmental symbols are those used in MIL-HDBK-217C. A complete listing of the MIL-HDBK-217C environments is given below.

G_B Ground, Benign

S_F Space, Flight

G_F Ground, Fixed

G_M Ground, Mobile

N_S Naval, Sheltered

N_U Naval, Unsheltered

A_{IT}	Airborne, Inhabited, Transport
A_{IF}	Airborne, Inhabited, Fighter
A_{UT}	Airborne, Uninhabited, Transport
A_{UF}	Airborne, Uninhabited, Fighter
M_L	Missile, Launch

All of the G_B data in the table reflect testing in a laboratory environment.

The failure rates are 60 percent confidence limits, as have always been used in deriving MIL-HDBK-217 failure rates. Such confidence limits can be up to twice that of a best, or point estimate.

The TWT failures used to calculate the failure rates in Table 2-1 include infant mortality failures, random failures, and wearout failures. A few data sets showed actual failure times, rather than just the failure count, so that hazard rates could be and were plotted. The hazard rate curves show evidence of these three main types of failure, with some surprises. These are given in Appendix C.

3. ANALYSIS

The statistical tool used to determine the effect of several factors on a parameter of interest is regression analysis. This is most easily described in the case of a single factor. Figure 3-1 shows a typical plot of statistical data, called a scatterplot, in this case for failure rate (λ) versus frequency. It shows, for example, that although an exact failure rate cannot be predicted from a knowledge of the frequency, there is nevertheless some relationship between the two. This means that knowing the frequency helps in estimating failure rate. This is suggested by the solid line. Regression analysis, so named because it was first applied to a study of successive offspring who regressed back toward the population mean, gives the curve which best fits a given set of data. In most cases "best" is taken to mean that curve that minimizes the sum of the squared deviations from the curve.

The single factor case is represented in two dimensions as in Figure 3-1. In addition, any number of factors can be treated using regression, but the n-factor case is represented in (n + 1) dimensions, and is therefore impossible to graph. This is called multiple regression and is the analytical method used in this study.

Figure 3-1 illustrates another feature of the data encountered, namely, the tendency of the scatter of the points to spread out with increasing values of a factor, as emphasized by the dashed lines. This violates one of the assumptions underlying regression analysis, which is that the amount of variation about the curve, as measured by the standard deviation, remains constant for different values of the factor, or factors.

There is, however, a remedy for this, and that is to use a logarithmic transformation of the parameter of interest, in this case failure rate. This is illustrated in Figure 3-2.

The log transformation, besides making the data amenable to regression analysis, also yields a model with a different functional form. The usual functional form for single factor regression is

$$Y = b_o + b_1 X, \qquad \text{(Eq. 1)}$$

where

Y = the parameter of interest, called the dependent variable,

b_o = a constant, also called the Y-intercept,

b_1 = the coefficient of X,

and

X = the factor, called the independent variable.

Regression analysis has to do with determining the values of b_o and b_1 so as to minimize the sum of squared deviations from the fitted curve. These minimizing values of the coefficients are called estimates. When a log transformation is made, we get the following result:

$$\log Y = b_o + b_1 X. \qquad \text{(Eq. 2)}$$

Taking the antilog (where all logs are to the base e),

$$Y = e^{b_o} \cdot e^{b_1 X}, \qquad \text{(Eq. 3)}$$

which can be written in the form

$$Y = B_o B_1^{X}. \qquad \text{(Eq. 4)}$$

This new model is such that the independent variable X has an exponential effect, as opposed to an additive effect as in Equation 1. This is a desirable result, as it turns out, because nearly all the models in MIL-HDBK-217C have exponential and/or multiplicative effects.

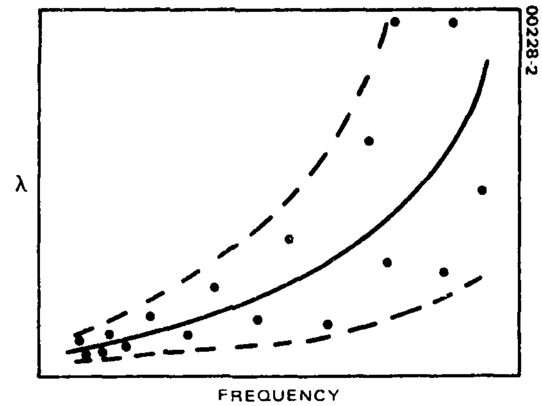

Figure 3-1. Typical scatterplot of failure rate versus frequency, showing increasing variation.

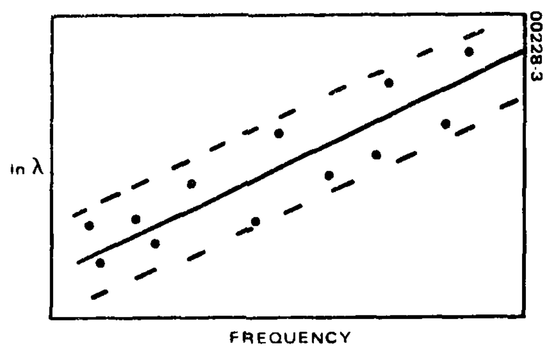

Figure 3-2. Log failure rate versus frequency, showing constant variation.

The log transformation of failure rate was used to derive the model presented in the next section. The two independent variables used in the analysis were frequency (F) and power (P). Two functional forms were used: 1) log λ with log P and log F; and 2) log λ with P and F. That is, the log transformation of failure rate was used with and without the log transformation of P and F.

In order to treat the qualitative variables (mode (pulsed versus CW) and environment), we used indicator variables. These are simply variables that take on the value 1 if an item has a certain characteristic and 0 if it does not. If we let X in Equation 2 be an indicator variable for the S_F environment, for instance, and the estimate of b_1 is -1.6, then $B_1 = e^{-1.6} = 0.2$. This means that if a TWT is to be operated in a space environment, we should apply a factor of 0.2.

The regression analysis was accomplished using the computer program STEPREG, which is included as part of the statistical program package in the Dartmouth Time Sharing System (DTSS), and Program No. 024: Stepwise Regression in the Biomedical (BMD) statistical program package, both available at Hughes Aircraft Company. These programs derive a best-fitting model in a series of steps by determining the statistical significance of each independent variable, selecting the most significant one, determining the significance of each of the remaining independent variables, selecting the most significant one, and so on until there are no longer any independent variables that meet a preselected significance level. Statistical significance is measured by the probability of observing an effect as large as the one actually observed due to chance alone. The critical significance level used for this analysis was 0.05. This means that if an independent variable has associated with it a significance level of 0.05, then, simply stated, there is a 0.05 probability that the variable has no real effect. This was done for the two functional forms mentioned earlier, and the form with the best fit was chosen. The degree of fit of a model to the data is measured by the square of the multiple correlation coefficient, R^2. This measures the fraction of the variance of the dependent variable which is explained by the independent variables in the model.

The following variables were used in the analysis:

1) Power (P)

2) Frequency (F)

3) Power x Frequency (PF)

4) Mode (Pulsed versus CW)

5) Environment:

   a) G_B

   b) G_F

c) S_F

d) N_S

e) A_{UF}

In the course of the regression analysis, it was found that some of the independent variables were correlated among themselves. In particular, P is correlated with PF and also with Mode. This situation is called collinearity. The effect of collinearity is that two highly correlated independent variables will either not appear together in a regression model, or if they do, the result will be unstable; that is, a slight change in the data base can produce large changes in the resulting model.

Another aspect of collinearity is that it may make little difference which of two highly correlated variables appears in the model. With this in mind we tried forcing variables into the model in an attempt to obtain a better model. The results are shown in Table 3-1. Six combinations of cases are shown: models using P, PF, or Mode, each with and without log-transformations of P and F. We see that models 1 and 3 both have the same R^2 values and standard error of the estimate (σ). They each have the same variables, except that model 1 has a power effect and model 3 has a mode effect. Also, since most of the airborne TWTs in the data base are pulsed, there is an interaction effect between these two factors. The A_{UF} factor in model 3 is reduced due to the presence of the mode factor. Based on a comparison of this factor with those in other MIL-HDBK-217C models, the A_{UF} factor in model 1 appears to be the most reasonable. For this reason, model 1 is chosen in preference to model 3. Model 1 is recommended for use in MIL-HDBK-217C, and is discussed in detail in the next section.

Another factor considered was the focusing method. Four TWTs had failure rates much smaller than would be predicted on the basis of their parameter values, and they were all solenoid-focused TWTs. They appear in Table B-1 as data set numbers 19, 20, 75, and 76. Examination of these data suggests that power has no effect on the failure rate of solenoid-focused TWTs. A separate solenoid model would be desirable, but four data sets are not considered adequate to derive a model, and none was derived.

TABLE 3-1. TWT REGRESSION ANALYSIS SUMMARY

		FACTOR*									
Model	Description	Constant Multiplier	P	F	PF	Mode	S_F	A_{UF}	G_F	R^2	σ
1	P forced	10.6	1.00012^P	1.165^F		--	0.22	18	2.7	0.76	0.92
2	PF forced	12.9	-	1.145^F	1.00001^{PF}	--	0.20	13	2.6	0.73	0.98
3	Mode forced	10.5		1.177^F	--	5	0.21	7	2.6	0.76	0.92
4	P forced, logs	45	$P^{.084}$		--	-	0.10	11	--	0.60	1.15
5	PF forced; logs	46		-	$P^{.04 \ln P}$		0.11	11	--	0.60	1.16
6	Mode forced, logs	13.6		$F^{.52}$	--	5	0.18	7	2.6	0.72	0.98

*Interpret Model 1 thusly: $\lambda = 10.6\,(1.00012)^P\,(1.165)^F\,(0.22 \text{ if } S_F)\,(18 \text{ if } A_{UF})\,(2.7 \text{ if } G_F)$

4. RESULTS

4.1 <u>The Model.</u> The best fitting model of the six tested is as follows:

$$\lambda = 11\,(1.00012)^{P}\,(1.16)^{F}\,(3 \text{ if } G_F)\,(0.2 \text{ if } S_F)\,(18 \text{ if } A_{UF}). \qquad \text{(Eq. 5)}$$

This is model J in Table 3-1. Also included in the analysis but not statistically significant were the G_B and N_S environments, pulsed versus CW mode, and the power-frequency interaction term, PF. The R^2 value associated with this model is 0.76. In addition, there are two other measures of how good the model is: the significance level of the model and the standard error of the estimate. The significance level of the model is the probability that a fit as good as the one obtained could have occurred due to chance alone. For this model the significance level is less than 0.0001, or one chance in 10,000. The standard error of the estimate is the standard deviation of the differences between the observed failure rates and the failure rates predicted by the model. For this model the value really pertains to the log of the failure rate, and has the value 0.92. Approximately 95 percent of the differences in logs can be expected to lie within ±2 x 0.92, or ±1.84. This means that 95 percent of the true failure rates will lie within exp (-1.84) and exp (1.84) times the predicted failure rate, or between 1/6 and 6 times the predicted failure rate. These accuracy factors are worse than might be expected, but there are may identifiable reasons for this as discussed in Section 4.4

Besides the all log-transformation models discussed earlier, a third functional form was also tried using the expression log (λ - c), with c = 1 and c - 0.5. The motivation for this was the idea that a TWT has an intrinsic failure rate apart from the effects of power, frequency, and other factors. This failure rate would be denoted by c. However, neither of the resulting models was as good as the log λ model, based on their R^2 values.

Since TWTs are used in environments other than the three that tested significant, it was necessary to estimate the environmental factors (Π_E) for each of the others using judgment. The factors for G_B and N_S turned out to be not significantly different from 1. Judging from MIL-HDBK-217C, this appears to be a good relative value for G_B, but not for N_S. To assign a value to N_S, we consulted MIL-HDBK-217C, which gives a ratio between N_S and G_F tube environmental factors, for instance, of 6.5:1. As a compromise between this value and 1/3:1 as suggested by the results of the analysis, we chose a ratio of 1-1/3:1, yielding a Π_E of 4 for N_S. The factors for A_{IT}, A_{IF}, G_M, N_U, A_{UT}, and M_L were chosen with the estimates in Equation 5 and the corresponding MIL-HDBK-217C factors in mind. We feel that the factors are fairly accurate, and that they are consistent among themselves. The finished form of the model appears on the next page, which shows the model (Equation 6), the Π_E factors (Table 4-1), and a table of values of λ_b (Table 4-2). λ_b is also shown graphically in Figure 4-1.

TWT FAILURE RATE MODEL

$$\lambda = \lambda_b \, \Pi_E, \qquad \text{(Eq. 6)}$$

where $\lambda_b = 11\,(1.00012)^P\,(1.16)^F$,

and

P = power (peak, if pulsed mode) in watts,

F = frequency in GHz.

Notes:

1) If a TWT is operated below its rated power level, use the rated power level.
2) If the frequency is given as a band or as two different values, use the geometric mean of the band endpoints or of the two values. (Geometric mean of two numbers X and Y = $\sqrt{XY}$.)
3) Do not apply a duty factor; the effect of duty cycle is included in the model.
4) Applicable power range: 1 mW - 20 kW
5) Applicable frequency range: 300 MHz - 15 GHz
6) Model does not apply to solenoid focused TWTs

TABLE 4-1. TWT ENVIRONMENTAL FACTORS (Π_E)

Environment:	G_B	S_F	G_F	A_{IT}	A_{IF}	N_S	G_M	N_U	A_{UT}	A_{UF}	M_L
Π_E	1	0.2	3	7	14	4	10	6	9	18	80

TABLE 4-2. λ_b, BASE FAILURE RATES FOR TWTS

Power, watts	Frequency, GHz								
	0.1	1	2	4	6	8	10	12	14
0-10	11	13	15	20	27	36	49	65	88
100	11	13	15	20	27	36	49	66	89
500	12	14	16	21	28	38	52	69	93
1,000	13	14	17	22	30	41	55	74	99
3,000	16	18	21	29	38	52	70	93	126
5,000	20	23	27	36	49	66	88	119	160
8,000	29	33	38	52	70	94	127	170	229
10,000	37	42	49	66	89	119	161	216	291
15,000	67	77	89	120	162	218	293	345	531
20,000	122	141	162	219	295	396	535	719	967

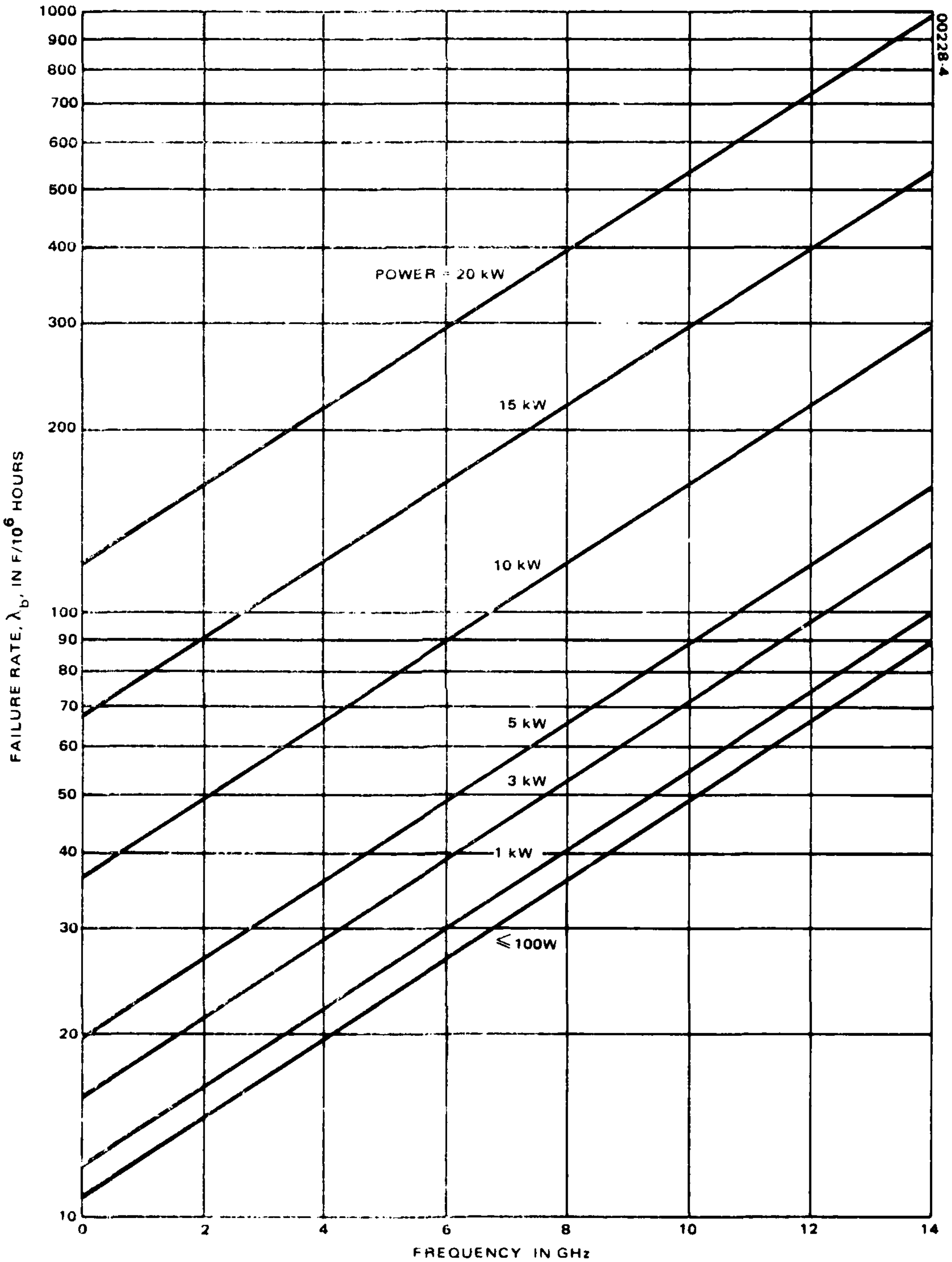

Figure 4-1. λ_b versus frequency and power.

4.2 Space Environment. The Π_E factor for the S_F environment is much lower in relation to the other environments than is typical in MIL-HDBK-217C. Typically the factors for the S_F and G_B environments are equal, for instance, whereas in this model the S_F factor is 1/5 that of the G_B factor. This may be explainable by the fact that the S_F environment is a vacuum, and we would expect a TWT, which is a vacuum tube, to have higher reliability in a vacuum than in the atmosphere. Nature may abhor a vacuum, but TWTs seem to thrive in one.

Furthermore, this suggests that the failure mechanism one would naturally associate with a vacuum tube in the atmosphere (as opposed to a vacuum), leakage, is responsible for a very high percentage of TWT failures. This in turn would imply that the hazard rate is increasing, since leakage is a kind of wearout, and the hazard rate associated with wearout is increasing. This is belied by some of the data, however, as shown in Appendix C. All the hazard rate plots reflect atmospheric (ground) operation, but there is no consistent pattern of increasing hazard rate. The effect of the leakage failure mechanism on TWT failure rate is therefore unclear.

4.3 Other Parameters. In addition to the parameters discussed above, type of cathode was also considered. Data sets 48 and 49 in Table 2-1 are for dispenser cathode TWTs, whereas all the others are for oxide cathode TWTS. The failure rates of these TWTs as predicted from the model were on the average 33 percent lower than the actual, which was well within the accuracy of the model, and not low enough to make them significantly different from the oxide cathode TWT failure rates. As more data become available on dispenser cathode TWTs, they may eventually prove to have lower failure rates, expecially for high frequency, high powered TWTs.

The power/frequency interaction effect was expected to be more significant. It is difficult to design a TWT that yields both high frequency and high power, as explained in Reference 3 and quoted here:

> As frequency is increased, the dimensions of the tube must decrease. For the same power output level, the thermal loading of the traveling wave tube circuit is higher. This increased heating becomes a problem at higher power output levels and actually limits the power output capability of the tube. Higher power output could be obtained safely by using a solenoid focused tube, but this is much too heavy for the present spacecraft capability.
>
> Besides limiting the RF power output, the increased frequency of operation increases mechanical problems in assembling the tubes. As parts become smaller, required tolerances become nearly impossible to hold and parts become so tiny that their strength is inadequate for TWTs which must withstand launch type vibration and environment.

This would explain the effects of power, frequency, and their interaction effect on TWT reliability.

The suspected reason that the power-frequency (PF) interaction effect did not show up as significant is that the factor PF is highly correlated with power (P). As discussed earlier, it is the nature of regression that if two independent variables are themselves highly correlated and one of them is included in a model, the model is not greatly improved by including the other.

A similar problem exists between power and mode (pulsed versus CW). As a rule, the pulsed TWTs have much higher (peak) power levels than CW TWTs, so in that sense, power and mode are correlated.

4.4 Limitations of Data Base and Analysis. The accuracy factors of 1/6 and 6 mentioned earlier were a matter of some concern to the authors. At the same time, we realized that such factors are seldom reported in studies of this kind, and that a factor of 6 may in fact be good. We did think of several contributing causes, and these are discussed below.

1) Limited hours and failures: Many of the data sets had zero, one, and two failures. The failure rate estimates for such cases can be off by as much as an order of magnitude (from the true failure rate). Eliminating or combining these data sets would have improved the fit of the model to the data, but the resulting accuracy factors would not reflect the model's true ability to predict failure rates which one is likely to observe in real life.

2) Removal rates versus failure rates: In general, field data reflect removal rates and test data reflect failure rates. Removals can result not only from TWT failures, but also from failures which are erroneously thought to be TWT failures, secondary failures, failures which cannot be corroborated by the repair facility, and system failures. Some of the failure rates in the data base are actually removal rates.

3) Definition of failure: Some TWTs in the data base may have had much more stringent success requirements than others, thus accounting for more reported failures.

4) Absent parameters: Many possible parameters or factors were omitted, either because the data were not readily available, or the parameter was used in the analysis but found to be non-significant. Some of these are listed below:

   a) Mode (pulsed versus CW)

   b) Some environments

   c) Duty cycle of pulsed TWTs

   d) Quality level, level of screening, amount of burn-in, etc.

   e) Maturity, learning factor, etc.

f) Cathode design

g) Focusing method

h) Gain

i) Efficiency

j) Physical size

k) Other design considerations: coupled cavity, depressed collector, multistaged collectors, etc.

5) Limited size of the data base: Some parameters might have become significant had there been more data sets.

6) Model not optimal: After more than 20 years of TWT technology, it is still not clear what the functional relationships are between TWT failure rate and various other parameters. It could be that functional forms other than the ones considered would yield better fits, even though many good candidate models were investigated.

7) Nonconstant failure rates: In the few cases where we could calculate hazard rates (instantaneous failure rates), we found increasing, decreasing, and constant functions, and various combinations of these. Average failure rates were used in these cases, even though they did not reflect the extremes of the hazard rate functions. These cases made us realize that there could be other cases where a constant failure rate estimate was a poor measure of how the TWT actually behaves. Nonconstant hazard rates are discussed further in Appendix C.

8) Sixty percent confidence limits: These have always been popular in reliability because of most people's desire for conservatism regarding engineering numbers. However, there is really no justification for using confidence limits in regression analysis. The effect of using 60 percent confidence limits is indicated below. The table shows the factor which is multiplied by the best, or point estimate to obtain the 60 percent confidence limit.

Number of Failures	Factor
0*	0.9
1	2.0
2	1.6
3	1.4
⋮	⋮
10	1.2

*Note: In this case use one failure and apply the factor.

5. COMPARISON TO MIL-HDBK-217C MODEL

The model presented here yields typically much lower failure rates than the TWT model given in MIL-HDBK-217C, as shown in Table 5-1. In addition, there are several qualitative differences:

1) The new model includes the effect of frequency.

2) The new model does not account for a learning factor (Π_L).

3) MIL-HDBK-217C really only applies to high power, pulsed TWTs, whereas the new model applies to low power, CW TWTs as well.

These differences should be kept in mind when reading the table.

The table compares failure rates for selected powers, frequencies, and environments. Two values of Π_L were used for the 217C failure rates.

Three possible reasons for the large differences between the old and new failure rates are discussed below.

1) Newer data: The data base in this study contains data on TWT operation through 1979. It is the authors' understanding that the 217C model is based on Ref. 4, which is dated August 1976, so that presumably it reflects data roughly through that date. Failure rates of components and assemblies typically improve with calendar time, as quality measures and technology improve.

TABLE 5-1. COMPARISON OF NEW AND MIL-HDBK-217C TWT FAILURE RATES

Power, watts	Frequency, GHz	Environment	Failure Rate in Failures/10^6 Hours: MIL-HDBK-217C, $\Pi_L = 1$	MIL-HDBK-217C, $\Pi_L = 2$	New
5	4	S_F	10	20	4
20	7.5	S_F	25	50	7
1,000	1	G_F	150	300	43
1,000	10	G_F	150	300	164
10,000	1	N_S	2,600	5,200	169
10,000	10	N_S	2,600	5,200	644
1,000	1	A_{UF}	1,700	3,400	259
1,000	10	A_{UF}	1,700	3,400	985

2) Failure rate screening: The data in this study were screened for any failure rates that appeared much too high based on the level of the associated parameters. In particular, a few very high failure rates were deleted from the data base. If this was not done in the earlier study, its failure rates would be higher on the average.

3) Failure screening: Most of the field failure rates in the data base are in fact failure rates and not removal rates. Ref. 1 specifically states that its failure rates are actually removal rates. Removal rates can be several times higher than failure rates.

6. RECOMMENDATIONS

We recommend the use of the model given in Equation 6 for TWT reliability prediction purposes. We feel that it is a significant improvement over the model which now appears in MIL-HDBK-217C.

Also, further studies are warranted as discussed below.

1) A follow-on study to enlarge the data base would be desirable. In particular, a study of this kind would ideally have each MIL-HDBK-217C environment represented by a large number of data sets.

2) A method should be derived to handle nonconstant failure rates. There is much evidence that TWT failure rates are decreasing, increasing, or a combination of both.

3) New developments in TWT technology should be accounted for, such as dispenser cathodes and K band TWTs.

4) Solid state GaAs FET amplifiers need a treatment similar to the one in this study.

5) In general, methods are needed for predicting the reliability of new technology devices not yet fully tested and used. These include GaAs FET amplifiers, laser devices, integrated circuit/discrete part hybrids, charge coupled devices, nickel hydrogen batteries, and so on. This could be based on a combination of physics of failure considerations, engineering judgment, and Bayesian statistics. A study to develop such a method could be very valuable.

6) Finally, we recommend that RADC consider the use of best, or point estimates instead of 60 percent limits for deriving failure rate models. The appropriate use of confidence limits (also called interval estimates) is for reliability demonstration. If confidence is desired in relation to a failure rate model, that confidence should come from the standard error of the estimate.

REFERENCES

1. MIL-HDBK-217C, Reliability Prediction of Electronic Equipment, 9 April 1979.

2. Engleman, J.H., TWTA Failure Rate Model Revision, Hughes Technical Internal Correspondence No. 4600.1/2792, 3 October 1977.

3. Benton, J., H. Smith, and P. Wolcott, Latest Advances in Space TWT's, presented at AIAA 3rd Communications Satellite System Conference, April 1970.

4. Zimmer, R.P., F.H. Vogler, F.E. Gramling, and H.M. Wadsworth, High Power Microwave Tube Reliability Study, FAA Report No. FAA-RD-76-172 (also designated as RADC Report No. RADC-TR-76-256), Georgia Institute of Technology, August 1976, A032697.

APPENDIX A. DATA SOURCES

Tables A-1 through A-3 show the sources available for TWT failure data. Many of these data sources provided the data sets from which the data base in Table 2-1 was obtained. We have deliberately dissociated each data set in Table 2-1 from its source as was requested by many of the sources.

The Defense Logistics Services Center provided a comprehensive computer printout, together with a set of templates for quick identification of desired information. By use of the templates, the following information was easily obtained from the printout: TWT national stock number, TWT manufacturer's name and part number, end item identification (system), and user or manager of the system using TWTs and/or TWTAs.

The lists of TWT part and component manufacturers (Table A-1) and system manufacturers (Table A-2) were provided mainly by the Defense Logistics Services Center. In some cases, a manufacturer was not contacted for TWT failure data, due principally to time constraints for completion of this report. In other cases, data were not available from, or supplied by, a contacted manufacturer. In all cases, data supplied by a manufacturer were used in the data base (Table 2-1). Tables A-1 and A-2 include summaries of manufacturer contact and data utilization.

TABLE A-1. TWT PART AND COMPONENT MANUFACTURERS

	Manufacturer Contacted?	Data Available?	Data Supplied?	Data Used?
Hughes Aircraft Company Electron Dynamics Division Torrance, California	Yes	Yes	Yes	Yes
ITT Electron Tube Division Easton, Pennsylvania	Yes	No	–	–
Litton Systems, Inc. Electron Tube Division San Carlos, California	Yes	No	–	–
Sperry Microwave Electronics St. Petersberg, Florida	Yes	No	–	–
Teledyne MEC Palo Alto, California	No	–	–	–
Thomson-CSF Electron Tube Division France	Yes	No	–	–
Varian Associates, Inc. Palo Alto, California	Yes	Yes	No	–
Watkins-Johnson Company Palo Alto, California	Yes	Yes	Yes	Yes

TABLE A-2. SYSTEM MANUFACTURERS

	Mfgr Contacted?	Data Available?	Data Supplied?	Data Used?
Antekna, Inc. Mountain View, California	No	–	–	–
Ford Aerospace and Communication Corporation Western Development Laboratories Division Palo Alto, California	Yes	Yes	Yes	Yes
Goodyear Aerospace Corporation Arizona Division Litchfield Park, Arizona	Yes	Yes	Yes	Yes
Harris Corporation Government Systems Group Operations Melbourne, Florida	Yes	Yes	Yes	Yes
Hewlett-Packard Company Palo Alto, California	Yes	No	–	–
Hughes Aircraft Company Ground Systems Division Fullerton, California	Yes	Yes	Yes	Yes
Hughes Aircraft Company Space and Communications Group El Segundo, California	Yes	Yes	Yes	Yes
ITEK Corporation Applied Technology Division Sunnyvale, California	No	–	–	–
ITT Avionics Division Nutley, New Jersey	Yes	No	–	–
McDonnell Douglas Corporation McDonnell Aircraft Company St. Louis, Missouri	No	–	–	–
Raytheon Company Electromagnetic Systems Division Goleta, California	Yes	Yes	Yes	Yes
Sanders Associates, Inc. Nashua, New Hampshire	No	–	–	–
Sperry Gyroscope Great Neck, New York	Yes	No	–	–
Sperry Univac Defense Systems Salt Lake City, Utah	Yes	No	–	–
U.S. Army Missile Command Redstone Arsenal, Alabama	No	–	–	–
Westinghouse Electric Corporation Defense Systems and Technology Division Baltimore, Maryland	Yes	Yes	No	–

The list of users or managers of systems using TWTs and/or TWTAs (see Table A-3) was provided primarily by the Defense Logistics Services Center. Again, time constraints did not permit us to contact and obtain data from all of the users and managers. Some who were contacted had no available data. In two cases, submitted data were not used in the data base (Table 2-1). A summary of user/manager contact and data utilization is shown in Table A-3.

TABLE A-3. TWT USERS*, MANAGERS*, AND DATA COLLECTION CENTERS

	Source Contacted?	Data Available?	Data Supplied?	Data Used?
Air Force Logistics Command Wright-Patterson AFB, Ohio	Yes	Yes	Yes	No
Chief of Defence Denmark	No	–	–	–
Codification Bureau Director Materiel for the Armed Forces of the Netherlands Netherlands	No	–	–	–
Defense Electronics Supply Center Dayton, Ohio	No	–	–	–
Defense Industrial Plant, Equipment Center Memphis, Tennessee	No	–	–	–
Forces Armées Belgium	No	–	–	–
Government-Industry Data Exchange Program (GIDEP) Operations Center Corona, California	Yes	Yes	Yes	Yes
Materielamt der Bundeswehr Germany	No	–	–	–
Ministry of Defence England	No	–	–	–
NATO Supply Center Grand Duchy of Luxembourg	No	–	–	–
Navy Aviation Supply Office Philadelphia, Pennsylvania	Yes	No	–	–
Sacramento Air Logistics Center McClellan AFB, California	Yes	Yes	Yes	No
San Antonio Air Logistics Center Kelly AFB, Texas	Yes	No	–	–
U.S. Army Communications and Electronics Materiel Readiness Command Ft. Monmouth, New Jersey	Yes	Yes	Yes	Yes
U.S. Army Missile Materiel Readiness Command Redstone Arsenal, Alabama	No	–	–	–
Warner-Robins Air Logistics Center Robins AFB, Georgia	Yes	Yes	Yes	No

*Users or managers of systems using TWTs and/or TWTAs.

APPENDIX B. DELETED DATA

A number of data sets gathered during the study were not included in the data base, and these are shown in Table B-1. Listed are some of the reasons why the sets were deleted:

1) Missing information: Some data sets did not include frequency, power, or both. Others did not specify the environment in which the TWT was used. These were all major factors on which the analysis was based; consequently, these points were deleted. A few of the data sets did not include failure rates, which also resulted in exclusion from the data base.

2) Zero failures: In a few instances the TWT had no failures during a very short operating time. The resulting high failure rates were outliers in the analysis, and these points were also excluded.

3) Duplication: Some data sets were found to be duplications. In particular, there were cases where both TWTA and TWT data were submitted for the same part number. It was shown that the failures of the TWTA were, in fact, failures of the TWT, and already recorded. These data were also deleted.

4) Developmental units: In one instance, it was learned that a TWT was a developmental model put through developmental tests which accounted for an unusually high failure rate in view of its parameter values. These data were deleted.

5) Wrong type of information: some data sets were found to be maintenance data rather than failure data, and could not be used.

TABLE B-1. DATA SETS DELETED FROM DATA BASE

Original Data Set	Frequency, GHz	Power, watts	Mode	$\lambda_{.60}$	Reason for Deletion
1	–	–	–	246	Missing data
2	5.6	5,000	Pulsed	149	Duplication
4	0.56	250	CW	177	Duplication
5	0.42	70	CW	57	Duplication
7	–	–	–	2,000	Missing data
8	–	–	–	2,174	Missing data
9	–	–	–	500	Missing data
10	I-band	–	–	400	Missing data
18	–	50,000	Pulsed	–	Missing data
19	0.45	200,000	Pulsed	103	Missing environment
20	0.45	200,000	Pulsed	34	Missing environment
21	0.45	200,000	Pulsed	71	Missing environment
22	–	150,000	Pulsed	8	Missing data
31	8.15	1,500	–	42	Klystron
44	1.84	2.5	CW	29	0 failures; $\lambda_{.60}$ too high
50	10.08	26	CW	68	0 failures; $\lambda_{.60}$ too high
51	2.3	28	CW	40	0 failures; $\lambda_{.60}$ too high
53	2.25	100	CW	119	Developmental model and developmental test
56	–	0.06	CW	222	Missing data
57	–	0.06	CW	146	Missing data
64	–	0.6	CW	114	Missing data
66	–	0.6	CW	457	Missing data
67	–	0.6	CW	241	Missing data
68 to 70	–	–	–	–	Missing data
75	1.27	175,000	Pulsed	79	Solenoid focusing; very low λ
76	0.45	250,000	Pulsed	38	Solenoid focusing; very low λ
84	2.3	8	CW	8	0 failures; $\lambda_{.60}$ too high
85 to 88	2.3	20	CW	44	0 failures; $\lambda_{.60}$ too high
89	2.25	23	CW	102	0 failures; $\lambda_{.60}$ too high
90	2.25	28	CW	84	0 failures; $\lambda_{.60}$ too high
91	10.08	26	CW	58	0 failures; $\lambda_{.60}$ too high
92	2.3	20	CW	–	Missing data
93	2.25	35	CW	–	Missing data
123	9.8	0.6	CW	267	TWTA data already considered in TWT data
124	14.7	0.6	CW	135	
126	9.8	0.6	CW	313	
131	–	50 kW	–	265	Missing data; environment missing
144	4	5	CW	21	Abnormally high failure rate for TWT

APPENDIX C. HAZARD RATES

Some of the data sets included failure times of the TWTS, so that hazard rate (instantaneous failure rate) could be calculated and plotted. The results are shown in Figures C-1 through C-6. These hazard rate plots show patterns of decreasing, increasing, and constant functions, plus various combinations of these. They are all decreasing initially, which is a common phenomenon in field operation. This can be due to the reduction of operator error associated with becoming familiar with the equipment, and can also be a result of the early elimination of those TWTs with initial defects. This is referred to as "infant mortality".

The hazard rates in Figures C-2, C-4, and C-5 are suggestive of the bathtub curve so commonly referred to in reliability literature, but rarely substantiated with actual data (see Figure C-7). The bathtub curves shown here differ from the curves usually seen in the literature in that there is no long period of constant hazard rate. The increasing hazard rate period, which is associated with wearout, seems to begin during the decreasing hazard rate period, so that the constant hazard rate period is either obscured or nonexistent. This means that the failures which have been reported are either infant mortality failures or wearout failures, but no so-called "random failures". Random failures are those associated with a constant failure rate, and are characterized as being sudden and unpredictable rather than gradual and predictable. Only the curve in Figure C-1, and to some extent, Figure C-3, shows any evidence of a constant hazard rate.

The hazard rates in Figures C-4 and C-5 are similar in shape, and the associated TWTs are similar as well. The TWTs are both manufactured by the same manufacturer, are pulsed, low frequency, and high powered.

The TWT associated with Figure C-6 is made by a different manufacturer, pulsed, and medium powered, and has a decreasing hazard rate as far as the data goes, but a comparison to Figures C-4 and C-5 is not conclusive.

The authors attempted to include the six hazard rates in the data base by computing the average failure rate for each. This was based on the formula:

$$\lambda_{avg} = 1/M,$$

where

$$M = \text{the mean life}$$

$$= \int_0^{\infty} R(t)\, dt .$$

R(t) was computed by numerically integrating the hazard rate, and M was computed also by numerical integration.

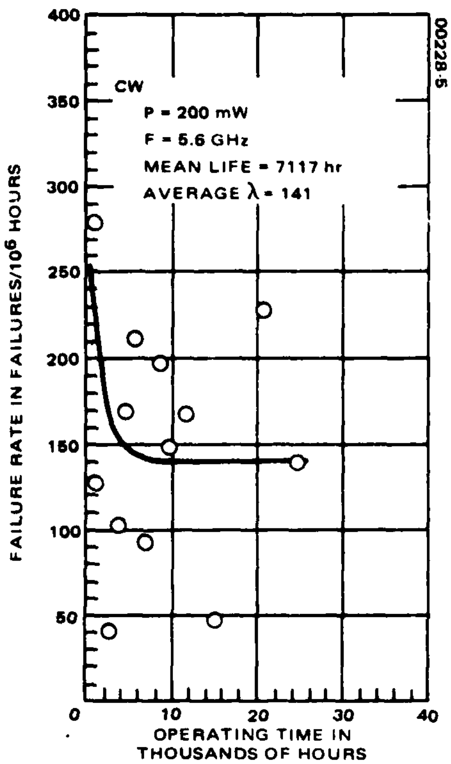

Figure C-1. Hazard rate no. 1

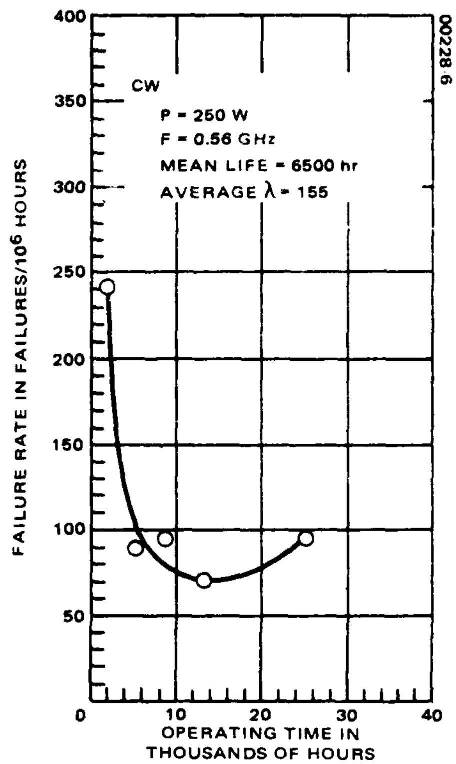

Figure C-2. Hazard rate no. 2.

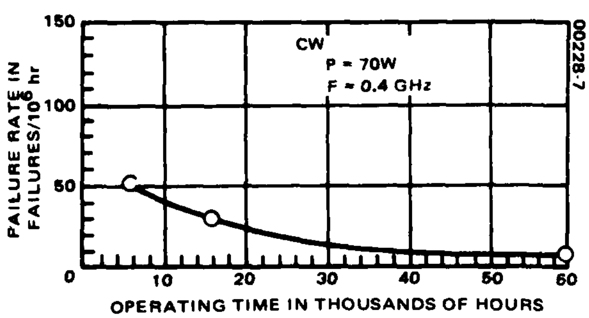

Figure C-3. Hazard rate no. 3

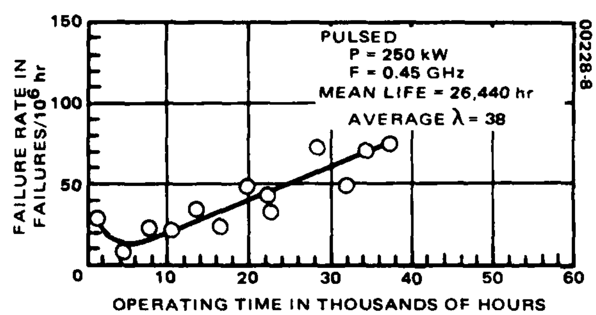

Figure C-4. Hazard rate no. 4.

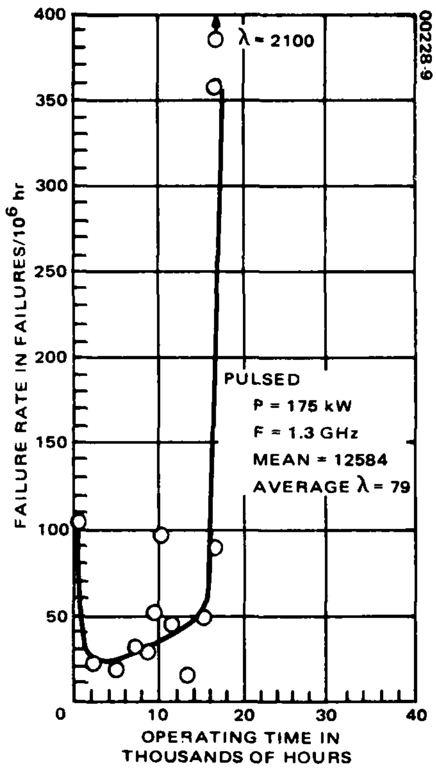

Figure C-5. Hazard rate no. 5.

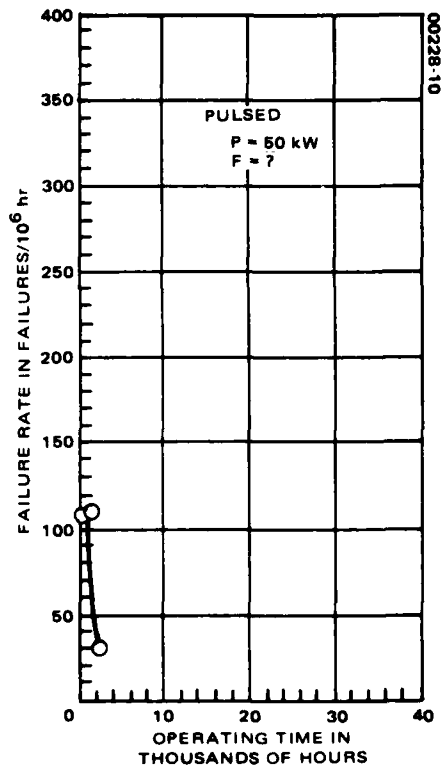

Figure C-6. Hazard rate no. 6.

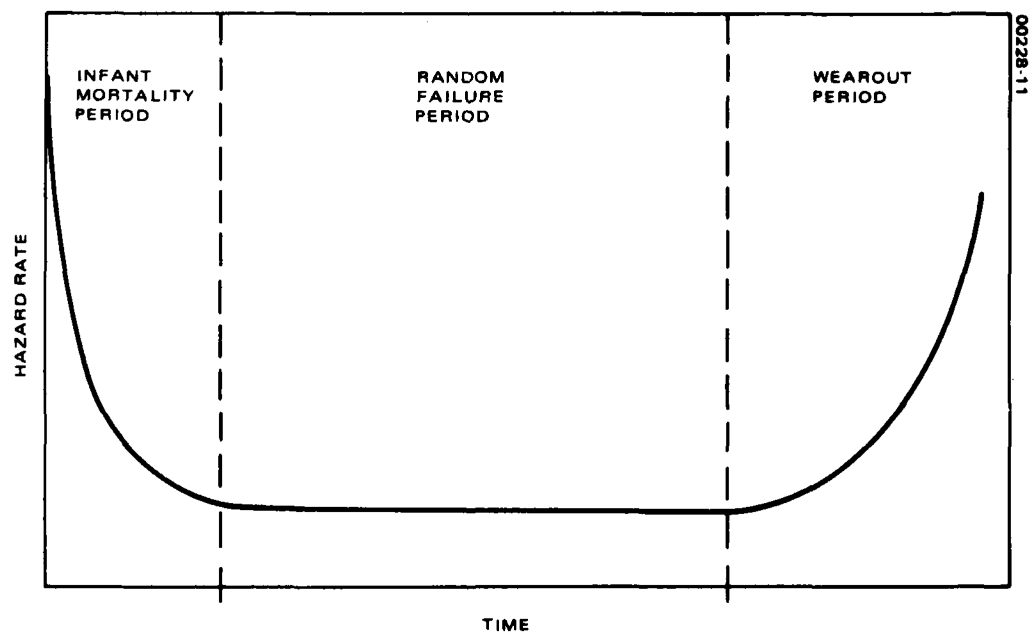

Figure C-7. Typical bathtub curve referred to in reliability literature

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RADC plans and executes research, development, test and selected acquisition programs in support of Command, Control Communications and Intelligence (C^3I) activities. Technical and engineering support within areas of technical competence is provided to ESD Program Offices (POs) and other ESD elements. The principal technical mission areas are communications, electromagnetic guidance and control, surveillance of ground and aerospace objects, intelligence data collection and handling, information system technology, ionospheric propagation, solid state sciences, microwave physics and electronic reliability, maintainability and compatibility.