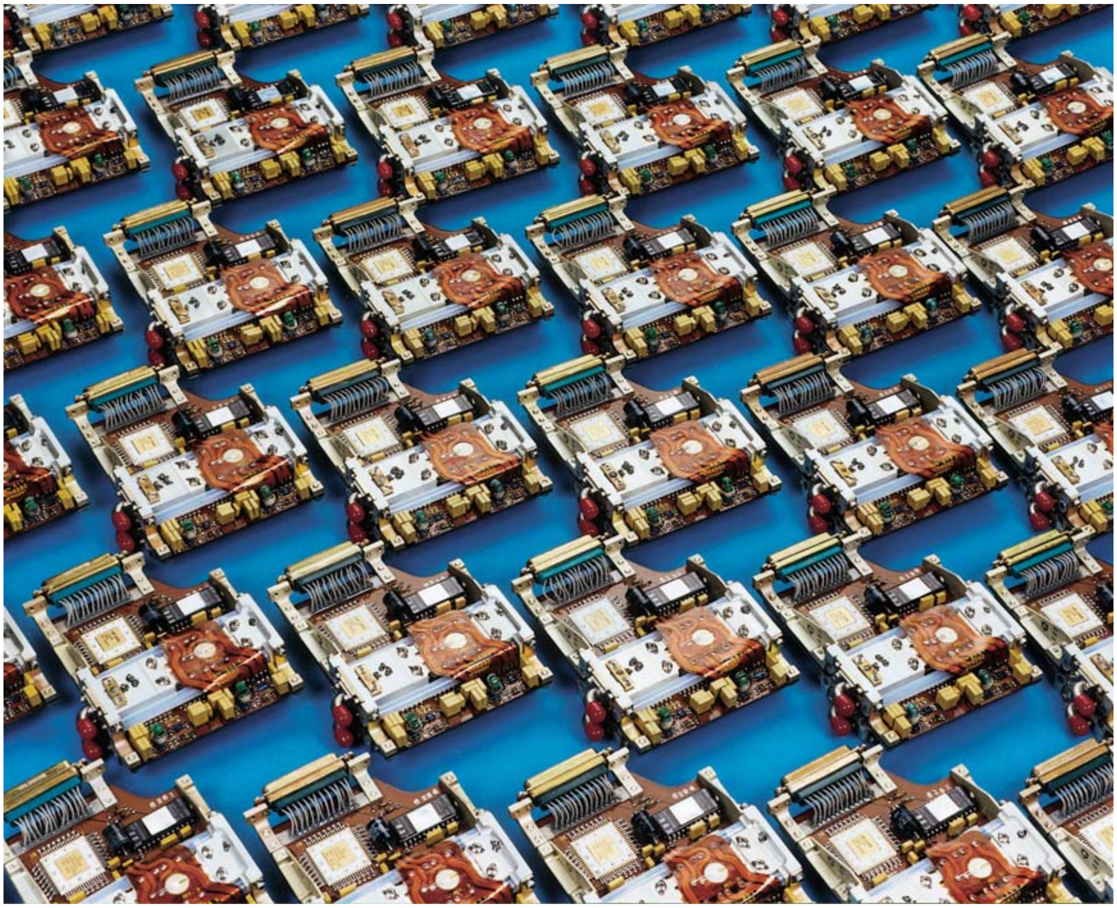

White Paper

Ferrite Device Reliability

A METHOD FOR PREDICTING FERRITE DEVICE RELIABILITY USING INTERFERENCE THEORY

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1 Abstract

A generic model is developed to determine the reliability of ferrite devices used in radar antennas and microwave switching networks. An analytical approach based on interference theory, a stress vs. strength analysis used to determine mechanical component reliability, is used to develop the model. The paper discusses the rational for derivation of the model, relevant failure mechanisms, and includes the calculation of reliability for two typical ferrite devices.

2 Introduction

Most of the essential performance characteristics of circulators, phase shifters, and other ferrite devices have been, and continue to be, investigated and quantified (e.g., phase shift accuracy and resolution, insertion loss, switching speed, etc.). However, the reliability aspects of these devices have been neglected. The question of a suitable failure rate model continues to be discussed at design reviews for antennas and switching networks using these devices. A search of the literature for existing reliability/failure data proved to be unproductive. No data dealing specifically with ferrite device failure mechanisms were found. The reason there is a lack of data on the reliability of these devices, and microwave components in general, is simply because they are very reliable. Since there are few if any reported field failures (many of these components are used in military satellites and weapons systems and failures are not routinely reported), very little relevant reliability data has accumulated. Also, in actual switching or phase shifting operations, the application of electrical stress has a very low duty cycle. A typical duty cycle is less than 1%. Also, because these are rather simple electromagnetic devices in which inherent mechanical and electrical strength far exceeds the applied stress in most applications, the extremes of vibration, temperature, and latch wire current, required to produce measurable degradation or failure are unrealistic. To be valid, an accelerated test must not alter the basic mode and/or mechanism of failure as these extreme values would.

For these reasons, an analytical approach using interference theory (stress vs. strength analysis, used to determine mechanical and electromechanical component reliability) was decided on as the most practical and effective method of determining a realistic reliability value for these devices. Once developed, the model can be used for different applications by substituting the proper stress/strength parameters.

This interference theory stress-strength concept is appropriate only when no significant changes occur in the device over the specified time period. These devices do not demonstrate aging or wear-out characteristic as evidenced by a long history of failure-free service in space and other environments. As an example, waveguide switching assemblies have been in continuous service on the NIMBUS-7 satellite since launch in 1978 and on the TIROS-N satellite launched in 1983.

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3 Device Charcteristics

The ferrite circulator or phase shifter is classified as an electromagnetic device. From a mechanical standpoint, it has no moving parts but in its application is subjected to stresses of vibration, thermal expansion and contraction, the impingement of RF power, etc. In actual use it is subjected to equal or greater electrical stress than most passive electrical components due to the relatively high current level pulses applied to the latch wire. Thus, there are two characteristics that must be analyzed: the mechanical durability and the electrical integrity. These characteristics' can be analyzed independently since in most cases these stresses are not applied simultaneously nor are they accumulative.

The physical configuration of a typical latching circulator and phase shifter are shown in the section views of Figure 1 and Figure 2.

The circulator housing is machined from aluminum and encloses the Y-shaped ferrite toroid. The ferrite is supported at the junction of the Y by spacers on top and bottom. These spacers are bonded to the ferrite on one side and to the housing on the other side. The dielectric transformers are bonded to each leg of the ferrite while the top and bottom edges are bonded to the housing. Thus, the ferrite is supported by and mechanically bonded to the housing at a total of eight points.

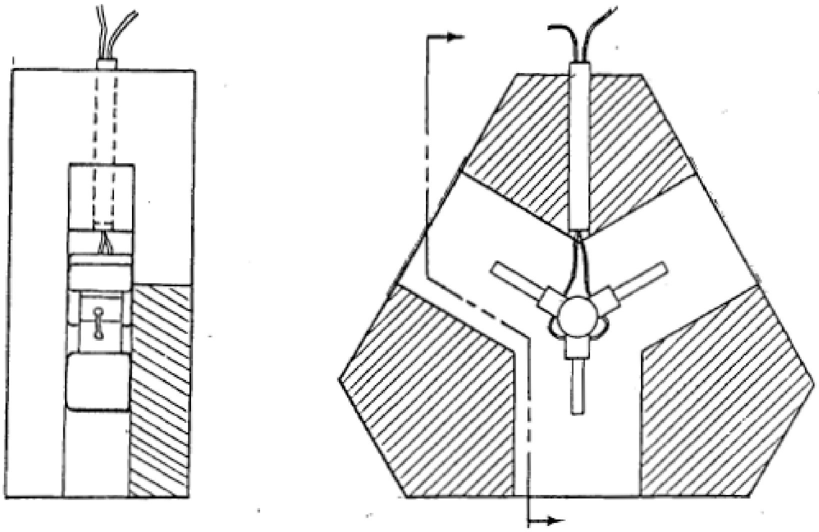

Figure 1. Latching Circulator Configuration 1

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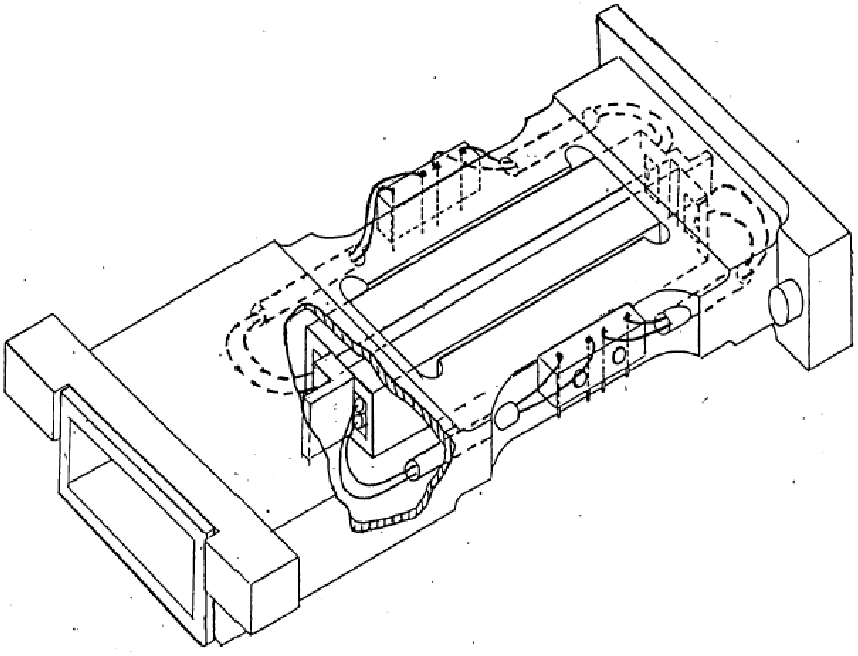

Figure 2. Dual Toroid Phase Shifter

The magnetizing winding (latch wire) passes through an insulated feed-through into the waveguide cavity and through each leg of the ferrite toroid. The dimensions of each element are proportional to the frequency of the intended application. Typically, a circulator designed for operation at 20 GHz would use a single #36 AWG latch wire.

The phase shifter has similar characteristics albeit a different physical configuration as shown in Figure 2

The configuration used in current phase shifter designs is the metalized dual toroid waveguide phaser. In this design the waveguide, plated directly on the ferrite assembly, is essentially a dielectric-ferrite filled rectangular waveguide. The assembly consists of dual ferrite toroids bonded to a dielectric center spacer with the outer surface plated. Latch wires are threaded through dielectric tubing bonded into each toroid center aperture. Dielectric transformers are bonded to each end and the finished assembly is then bonded into the waveguide section.

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4 Method of Analysis

In evaluating electronic component reliability, the concept of constant failure rate is used. This concept is derived from the "bath tub" hazard rate distribution and the belief that electrical component failure rate remains constant during the useful life of the component and failure is dependent only on usage time. However, in applying interference theory to determine the reliability of a simple device such as a phase shifter, the nature of the stress and strength random variables must be known.

It is evident that when the inherent strength of a material or component is less than the stress imposed upon it, a failure occurs. Stress and strength are defined as follows:

> Stress. The stress is defined as a load which might produce a failure of a component, device or material. In the case of these ferrite devices, the term load may be defined as vibration, shock, temperature, or current in the latch wire.
> Strength. The strength is defined as the ability of a component, device or material to operate satisfactorily without failure when subjected to these stresses.

The variability of both stress and strength can be defined by probability distributions. In the case of strength, material property variations (e.g. dimensions, fabrication and assembly processes, etc) might cause the strength of nominally identical ferrite devices subjected to the same stress to vary. All the important variations of the device must be considered when estimating the expected strength distribution function. Similarly, the stress distribution also changes under different applications and environments. These ferrite devices however, are individually designed for a specific application and applied stresses (current pulse characteristics, temperature, vibration) are relatively constant over operating life.

A plot of the distribution about the mean for applied stress, s, and inherent strength, S, shows an area of overlap no matter how great the distance between means. This overlap is where inherent strength has the probability of being smaller than applied stress and, thus, is the area of potential failure. Because areas under normal distribution curves represent probability, the overlap represents the probability of failure, P_f. Reliability, the probability of no failure is simply $1-P_f$. To develop this relationship formally, a new variable is defined as $Z = S - s$. If $Z > 0$ the part will not fail; failure will occur when $Z \le 0$. It is known that if S and s are normally distributed independent variables (which is the case here) with mean values μ_S and μ_s and variances σ_S^2 and σ_s^2 then $Z = S - s$ is normally distributed with mean value $\mu_Z = \mu_S - \mu_s$ and variance σ_Z^2 is given by $\sigma_Z^2 = \sigma_S^2 + \sigma_s^2$. Consequently, the

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probability of failure, P_f, will be given by the area under the normal curve whose mean and variance are μ_Z and σ_Z^2.

Normalizing Z by subtracting the mean and dividing by the standard deviation defines a new variable X_Z as,

$$X_Z = \frac{(S-s)-(\mu_S-\mu_s)}{\left(\sigma_S^2+\sigma_s^2\right)^{1/2}} \tag{4-1}$$

This variable has a mean value of 0 and a standard deviation of 1.
For $Z = 0$ or $S = s$,

$$X_{Z=0} = \frac{-(\mu_S-\mu_s)}{\left(\sigma_S^2+\sigma_s^2\right)^{1/2}} \tag{4-2}$$

Thus, any value of X_Z less than $X_{Z=0}$ represents failure. The probability of failure P_f (probability that $X_Z < X_{Z=0}$) can be found directly from a normal distribution table. Finally, reliability is given by $R = 1 - P_f$.

Some values showing the relationship between reliability and $X_{Z=0}$ are given in Table 1.

Table 1. Values of Reliability in Relation to $X_{Z=0}$

$X_{Z=0}$	Reliability $(1-P_f)$
0	0.5000
0.50	0.6192
1.00	0.8413
1.50	0.9332
2.00	0.9772
3.00	0.9987
5.00	0.9999+

In addition to determining the stress distribution and parameters, it is also necessary to consider the application of stress from the standpoint of mission phase or duty cycle. It has been the assumption in the derivation above that the mean of both the strength and stress distributions remain constant during the useful life of the device. Since the device materials do not show aging or wear-out characteristics, the strength is constant over life. However, stress may be applied intermittently or be of different values during different mission phases. As an example, in a satellite environment, the application of mechanical stress from vibration occurs only during launch and orbit insertion phases. Once in orbit the device is not subjected to this type of mechanical stress for the remainder of its useful life. Also, in actual switching or phase shifting operations, the application of electrical stress has a very low duty cycle. **A** typical duty cycle is less than 1%. That is, the dwell time between sequential setting and resetting of the device accounts for 99% of the operating time.

Since the various mechanical and electrical stresses are applied during different operational phases and at varying levels, the overall time to failure is a function of the sum of the combined mission times at different stress levels. Thus, a particular device must be assigned a reliability value for each distinct operational phase with specified duration and stress.

5 Failure Mechanisms

Possible failure modes exist in both electrical and mechanical characteristics of these ferrite devices. They exist, however, with widely varying probabilities of occurrence. These failure modes are discussed below.

5.1 *Electrical, Solder Connections*

As shown in Figure 2, the ferrite device latch wires are connected by soldering to a terminal board (stake board) using an approved soldering procedure. The stake board, which is an unclad epoxy laminate, is bonded to the phase shifter housing prior to the soldering operation. The reliability of a solder connection does not lend itself to analysis by applying stress versus strength methods. In this application the connections are made by a carefully controlled process followed by documented test and inspection procedures. Finally, each connection is conformal coated to provide further insulation and mechanical rigidity. The connections are not subjected to mechanical stress at any time, during assembly, test or use. The failure rate of these connections is well documented and realistic values are available from several sources. For this reason, solder connections were not included in this analysis.

5.2 *Electrical, Insulation Breakdown*

Under the stress of voltage transients associated with the applied magnetizing current pulses, the possibility of insulation breakdown or arcing must be considered. The magnet wire used in fabricating the magnetizing winding of these ferrite devices is a class 180 (180°C temperature rating), type A (heavy), poly (amide-imide) coated wire per MIL-W-583. The poly (amide-imide) insulation has a nominal dielectric strength of 6,300 volts/mil. [5] Insulation thickness (#36 AWG size) is 0.5 mils ± 0.1 mil, giving a 3,150 volt nominal dielectric strength for a single wire insulation thickness.

Since the latch wires will be at the same electrical potential, arcing must take place between the wire and the housing to effect a failure. The likelihood of this mode of failure is

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extremely small and is further decreased by conformal coating and bonding at the terminals and feed-through. However, a strength/stress analysis of the dielectric strength is included in the examples to quantify this failure mode.

5.3 *Electrical, Latch Wire*

Latch Wire Fusing. In operation, the latch wire or magnetizing winding carries periodic current pulses of from two to eight amperes in magnitude. If this current were applied on a continuous basis to a 34 to 40 gauge wire, the current carrying capacity of the wire would be exceeded. Fortunately, most materials and components can withstand low duty cycle or transient currents far in excess of their rated continuous-duty levels.

The current, I, in amperes at which a wire will melt can be calculated from $I = Kd^{3/2}$ where d is the wire diameter and K is a constant that depends on the metal used. [3] For copper, K=10,244. Table 2 lists the current carrying capacities and maximum power dissipation for wire sizes used in this application.

Table 2. [3]

Wire Size (AWG)	d (mils)	Ic	R/in	Max P_d (Watts)*
34	6.305	5.128	0.0217	0.571
36	5.000	3.622	0.0346	0.454
38	3.965	2.558	0.0550	0.360
40	3.145	1.807	0.0872	0.285

* Power dissipation is for a one inch length of wire at 20°C.

The maximum power dissipation listed in Table 2 is for continuous duty. Typical latching pulse duration is on the order of a few microseconds (in some applications, less than one microsecond) making it necessary to convert the values given to equivalent power dissipation for very short pulse durations.

This is done by applying electromagnetic pulse (EMP) analysis. This type of analysis, called susceptibility analysis, is generally concerned with semiconductor damage due to transient electromagnetic pulses induced in electronic circuits but is applicable to passive components as well. Models developed for susceptibility analysis, based on thermal considerations and experimental results, give the following expression for the failure threshold level for metallization burnout: $P_F = C_1 t^{-C_2}$ where P_F is the power in watts required in time t in seconds to produce device failure. C_1 is a constant determined by test. The constant C_2 has been determined by analysis to be unity for pulse lengths shorter than 100 nanoseconds, 0.5 for pulse lengths in the 100 nanosecond to 300 microsecond range and zero for pulse lengths longer than 300 microseconds. [4] C_1 is called the Wunch-Bell constant and has the units

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(Watt-sec$^{1/2}$). Since C_2 is zero for the continuous current case, C_1 can be set equal to P_d of Table 2 to determine P_F indicating the inherent strength of the latch wires of different sizes.

The stress on the latch wire is the current (RMS value) flowing through the wire resistance for the pulse duration. Both latch wire strength and stress variables are assumed to be normally distributed. Since latch wire current must be maintained within narrow limits to achieve proper operation, this distribution will have a small variance. Similarly, latch wire strength is directly dependent on wire diameter which is controlled within close tolerance and thus the strength distribution also will have a small variance.

Electromagnetic Force. When a current-carrying conductor lies in a magnetic field, forces are exerted on the conductor. These forces are transmitted to the material (electrons within the wire) of the conductor and hence the conductor experiences a force, or torque, or both. In the case of a single wire of small cross-section and short length, these forces are minute. Also, the maximum magnetic flux is present only during the dwell time when there is no latch wire current. During the switching or phase shifting period when the current is maximum, the magnetic field is reversing and sums to zero over time. The effect of these electromagnetic forces were not included in the analysis.

5.4 *Mechanical, Adhesive Bonds*

As shown in Figure 1, a typical ferrite switch assembly consists of a machined aluminum housing containing a Y-shaped toroid supported by two dielectric spacers in the center and by dielectric transformers at the end of each leg. The ferrite is bonded to spacers and transformers with epoxy adhesive which is also used to bond the entire assembly into the housing. This design requires that the adhesive withstand the shear stresses to hold the ferrite/dielectric assembly in place.

Another ferrite switch assembly currently used is shown in Figure 3. This is a spacerless design in which the ferrite toroid is supported only at the end of each leg by adhesive bonding to the dielectric transformers that are each bonded to the top and bottom surfaces of the housing. This design has the ferrite suspended with all its load transmitted through the adhesive. The ferrite itself experiences a bending stress and requires that the bonds take the full load of the ferrite in shear as well as bending (peel).

In some phase shifter applications, in particular where there is a requirement for high peak power, the ferrite material selected is a member of the garnet family because of its superior temperature characteristics. Unfortunately, these materials exhibit magnetostriction which is detrimental to the bonding due to dimensional changes in the ferrite. For this reason, magnesium manganese (MgMn) ferrites which do not exhibit magnetostrictive characteristics have been developed for these applications.

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As a standard practice, a "thermo-mechanical" stress analysis is completed for each ferrite device configuration. These analyses use worst-case values for all parameters including: maximum dimensions for ferrite, spacers, and housing; minimum adhesive layer thickness; maximum application temperature profile as determined by thermal analysis; and conservative adhesive properties at elevated temperatures.

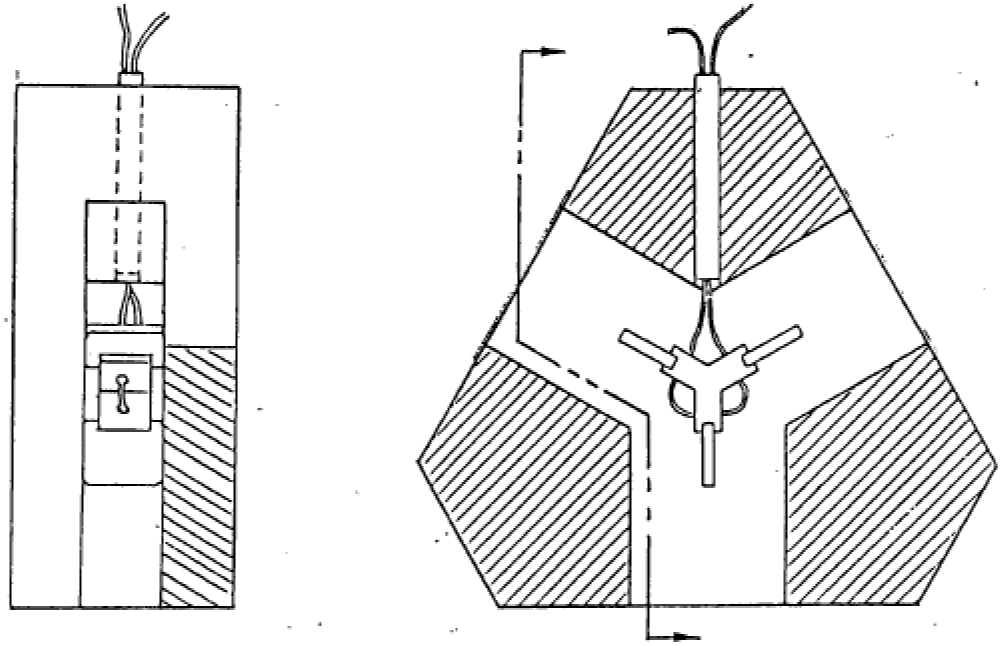

Figure 3. Latching Circulator Configuration 2

Stress values are obtained by finite element analysis and verified by hand calculations using random vibration levels specified for the applicable environment and used in qualification testing of the device. These mechanical stresses, determined by analysis, and the adhesive strength, determined from manufacturer's specifications, are assumed to be normally distributed and were used in the model to determine the reliability of this failure mode.

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5.5 *Mechanical, Ferrite or Dielectric Failure*

The actual fracturing or degradation of the ferrite or dielectric material due to vibration, shock, or high temperature was eliminated from consideration for this analysis. The mechanical and thermal properties of these materials preclude the possibility of failure in the most severe environments expected in actual operation. The possibility of undetected damage occurring during fabrication or assembly is eliminated by testing since any discontinuity (such as a fracture not visible by inspection but which might make the toroid susceptible to damage due to shock during operation) would be readily detected by its effect upon microwave performance of the device.

5.6 *Mechanical, Metal Fatigue*

Another possible failure mode of these ferrite devices is the fatiguing and breaking of the latch wires by vibration. Although the device configurations shown in Figures 1, 2 and 3 are not dimensioned, in all cases the latch wires are unsupported for very short distances. In the case of the latching circulator, typically the length of the unsupported latch wire is from 1/4" to 1/8" depending on the application frequency. In the typical dual toroid phase shifter, as shown in Figure 2, the latch wires are staked with epoxy adhesive at both ends of the ferrite and waveguide feed-throughs leaving only an approximate 5/16" length of unsupported wire. These typically short wire lengths coupled with the very low mass of the small diameter wire make failure by fatiguing of the latch wire improbable. Maximum bending stress in the latch wire in the configuration shown in Figure 1 has been determined analytically and indicates a wide margin of safety. This failure mode was not included in the analysis.

5.7 *Failure Mechanism Summary*

Of the failure mechanisms discussed above only three are believed to present a realistic risk of failure for ferrite devices of this type. These failure mechanisms are latch wire fusing, latch wire insulation breakdown, and structural damage due to adhesive bond failure. The other failure mechanisms discussed, which includes ferrite material failure caused by thermal or electrical stress, or metal fatigue of the latch wire due to vibration, are believed to have inherent strength or demonstrated reliability far in excess of the typically applied stress.

6 Device Reliability

In this section the reliability of the two ferrite devices shown in Figures 1 and 2 is calculated using interference theory techniques.

6.1 *Ferrite Latching Circulator (Figure 1)*

In the first of the two models, the device is a ferrite circulator designed for use in an 18-port beam forming network (BFN). The BFN is used in a geosynchronous orbit space environment, switching a nominal RE frequency of 20 GHz. Physical characteristics were described in Section 3.

Electrical failure modes to be considered include the probability of latch wire fusing and insulation breakdown (arcing).

Latch Wire Fusing. The energy required to fully reverse the magnetization of the ferrite is provided by a current pulse of less than one usec duration with a maximum peak current of 8A. Maximum switching rate is 14 kHz. The current pulse shape is complex due to the characteristics of the ferrite and the inherent impedances of the latch wire and switch driver components. The rms current in the latch wire was calculated using the expression below and an approximation of the waveform as shown by the broken line in Figure 4.

$$I_{\mathrm{rms}} = \left[\frac{1}{T} \int_0^T I^2(t)\,dt \right]^{1/2} \tag{6-1}$$

The actual waveform was approximated by combining two waveforms (0 to t_1 and t_1 to t_2) and the total rms value determined from

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$$
\begin{aligned}
I_{\text{rms}} &= \left[I^2_{\text{rms}(1)} + I^2_{\text{rms}(2)}\right]^{1/2} \\
&= \left\{ \frac{1}{T}\int_{t_0}^{t_1} I_1^2 dt + \frac{1}{T}\int_{t_1}^{t_2}\left[\frac{I_2 - I_1}{t_2 - t_1}(t - t_1) + I_1\right]^2 dt \right\}^{1/2} \qquad (6\text{-}2)
\end{aligned}
$$

where I_1 = 2A, I_2 = 8A, t_1 = 600nsec, and t_2 = 900nsec. This gives an rms current of 3.46A for the pulse duration of 900 nsec for a #36 AWG latch wire of 3” length. Resistance of the latch wire was calculated at the worst case operating temperature of 83°C. Power dissipation is 1.54W. Thus, μ_s = 1.54W.

The waveform and its parameters must be maintained within narrow limits over the life of the device to meet specified microwave requirements. Because of this, there is little variation in the applied peak current. The value was established by worst-case analysis of the circuit to be in the range of +1.36A to -1.17A. Since the possibility of failure of the latch wire due to the stress of high current is to be determined, the worst case peak current of 8.0A+1.36A was used to calculate a power dissipation of 1.88W which represents a 3σ upper bound of the stress distribution. Then $3\sigma_s$ = 1.88W - 1.54W = 0.34W and σ_s = 0.11W.

Using the data from Table 2, the power dissipation of the latch wire (at 83°C) is 1.72W on a continuous duty basis. The mean power dissipation for a 900nsec pulse duration is then 1.81kW calculated using the expression given for the threshold level of metalization burnout, $P_F = Kt^{-1/2}$, with K = 1.72W. Thus, μ_S = 1.81kW.

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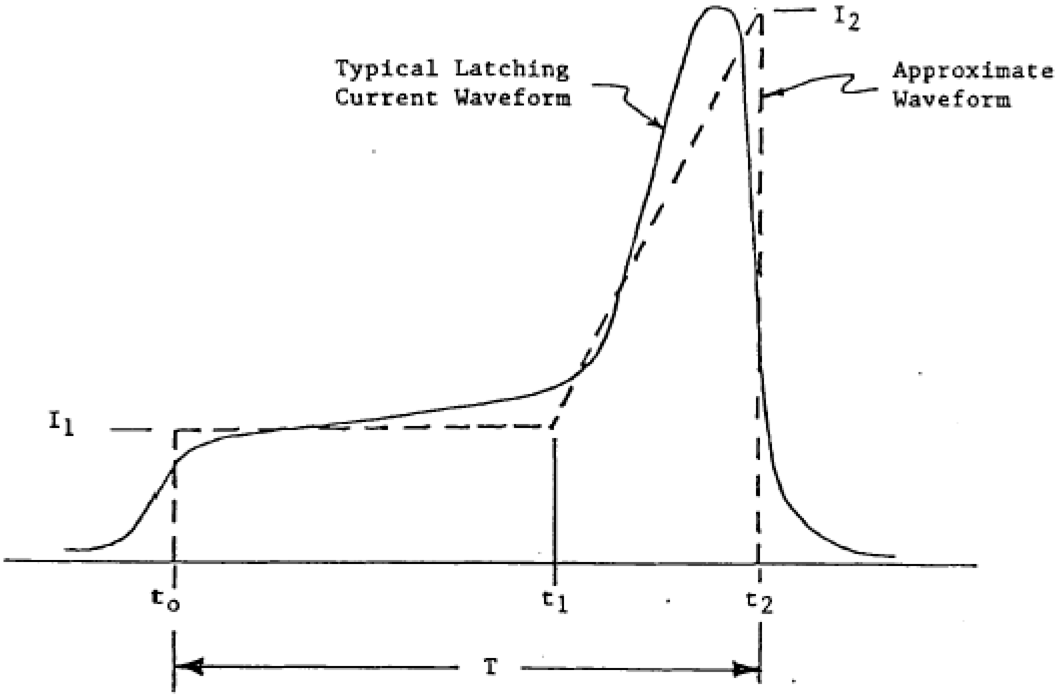

Figure 4. Latching Circulator Current Pulse

The dominating variable in determining maximum P_F of the latch wire is its diameter. The diameter is directly proportional to resistance which is directly proportional to P_F. Federal specification J-W-1177A/Gen (imposed on the wire manufacturer) requires a tolerance of ~0.1 mil on wire diameter. However, to account for all possible wire anomalies (elongation, tool marks, impurities, etc.) the minimum diameter was taken as the nominal diameter of the next smaller wire size, in this case a #37 AWG wire. In this particular application, the P_F for a latch wire of this diameter is 1.57kW and this value was used as a basis for the lower bound, or 3σ limit of the strength distribution. Then, $3\sigma_s$ = 1.81kW - 1.57kW and σ_s = 80.0W.

The reliability of the device for this failure mode can now be calculated using the following values for the parameters of normally distributed stress and strength

Mean stress, μ_s = 1.54W

Stress variance, σ_s^2 = 0.0128W

Mean strength, μ_S = 1.81kW

Strength variance, σ_S^2 = 6.4kW

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then, $Z = (\mu_S - \mu_s)/\left(\sigma_S^2 + \sigma_s^2\right)^{1/2} = 22.6$

From Table 1., reliability of the latch wire $R_{LW} > 0.9999+$. It should be apparent that when $\mu_S >> \mu_s$ and $\sigma_S >> \sigma_s$ that $X_{Z=0} \approx \mu_S / \sigma_S$.

Insulation Breakdown. In applications that require fast switching of an inductive load, such as the ferrite toroid used in the latching circulator, a kickback voltage transient occurs at the time the latching current pulse is turned off. The more rapidly this current is cut off, the higher the amplitude of this voltage spike. In this application, the amplitude of this voltage transient is approximately 120V with a duration of less than 200nsec. Thus, the mean voltage stress (μ_s) is set to 120 volts. Since latch wire current is maintained within close limits, the variance in the amplitude of this transient voltage is small. Based on the variance of the worst-case current, the upper limit was determined to be 144V, or $3\sigma_s = 24V$ and $\sigma_s^2 = 64V^2$.

For a #36 AWG wire, the poly (amide-imide) insulation has a nominal dielectric strength of 6,300 Volts/mil.[5] Specified insulation thickness is 0.52 mils ±0.12 mils. This sets the upper and lower limits on the breakdown voltage at 4.04kV and 2.52kV, respectively. The mean breakdown voltage (μ_S) was taken as 3.28kV and the 3σ value as 757V. Thus, $\mu_S = 3.28kV$ and $\sigma_S^2 = 63.7kV$.

The latch wire leads, where they are in contact, will be at the same electrical potential and arcing must occur between the wire and the housing to effect a failure. Since the latch wire does not come in physical contact with the housing at any point, this is a very unlikely failure mode. However, to quantify the probability of insulation breakdown due to voltage stress, the reliability was calculated using the following parameter values: $\mu_s = 120V$, $\mu_S = 3.28kV$, $\sigma_s^2 = 64V$, $\sigma_S^2 = 63.7kV$. Once again $\mu_S >> \mu_s$ and $\sigma_S >> \sigma_s$ that $X_{z=0} = \mu_S/\sigma_S = 13$. From Table 1, $R_{IB} >> 0.9999+$.

Mechanical Failure Modes. The primary failure mode considered in determining the mechanical reliability for the device shown in Figure 1, was failure of the adhesive bonds due to shear stress.

A formal stress analysis was performed on the program for which the device was designed. Calculations were based on worst-case values for all variables including: maximum thickness for the ferrite, spacer, and housing; minimum adhesive layer thickness; maximum thermal profile as determined by thermal analysis; and conservative adhesive properties at these worst-case temperatures.

A finite element analysis of all material layers was performed and determined that the maximum shear stress was 9.2 psi for the specified vibration levels. The adhesive has a nominal shear strength of 285 psi for this configuration. Thus, $\mu_s = 9.2$ psi and $\mu_S = 285$ psi.

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The lower bound of the strength distribution was not established by testing because of the high vibration levels required and a conservative value of 60% of the mean strength was assumed giving a vale of $\sigma_S = 57$ psi.

Since $\mu_S >> \mu_s$ and $\sigma_S >> \sigma_s$ an approximate value for $X_{\mathbf{z=0}}$ is given by $\mu_S/\sigma_S = 5.0$. From Table 1. it can be seen that $R_M > 0.9999+$. Note that this reliability (probability of success) value applies only to that portion of the operating time when stress due to vibration is actually applied. For this device, used in a geosynchronous satellite application, stress is applied during the launch and orbit insertion phases only.

In summary, the orbital reliability of the latching circulator, when it is performing the function for which was designed, is the product of the electrical failure mode reliabilities, $R_{\mathbf{LW}}\ R_{\mathbf{IB}} > 0.9999+$. Mechanical reliability, applicable only during the launch phase, is $R_M > 0.9999+$.

6.2 *Dual Toroid Phase Shifter (Figure 2)*

The second example of application of the reliability model is for a dual toroid phase shifter used in quantity in an airborne radar application. The physical characteristics are described in paragraph 1.2 and the device configuration is shown in Figure 2.

As in the latching circulator example, the electrical failure modes to be considered for this device include the probability of latch wire fusing and insulation breakdown causing a low impedance short circuit.

Latch Wire Fusing. The phase shifter differs in operation from the latching circulator in that very accurate and repeatable set and reset pulses must be applied to the ferrite toroids. The set current pulse is proportional to an analog input voltage which determines the precise phase shift required. The reset current pulse returns the ferrite to a fully magnetized or zero differential phase state. In all cases, the reset pulse current level is equal to or greater than the set current level. Maximum current stress on the latch wire was, therefore, based on the magnitude of the reset current. The reset pulse shape is similar to that of the latching circulator shown in Figure 4. Pulse duration is approximately 1 psec and nominal peak current is 7A. The RMS current in the latch wire was calculated by the method described for the latching circulator and was found to be 2.8A. The reset latch wire is #36 AWG of approximately 4.5" length with a resistance of 0.187 ohms (at an operating temperature of 71°C). Power dissipation in the latch wire is 1.50W per switching event. Thus, $\mu_s = 1.5$W. Worst-case peak current was determined to be 8.4A and this value was used to calculate a power dissipation of 2.18W which represents the 3σ upper limit of the strength distribution. Then $3\sigma_s = 2.18\text{W} - 1.50\text{W} = 0.68\text{W}$ and $\sigma_s = 0.23$W.

Using the data from Table 2, the maximum power dissipation of the latch wire (at 71°C) is 2.45W on a continuous duty basis. The mean power dissipation for a 1 μsec pulse duration, however, is 2.45kW and thus μ_s = 2.45kW. As in the first example, the maximum power dissipation for a #37 AWG wire was used to establish the 3σ lower limit of the strength distribution. For the phase shifter, the value is 2.18kW. Then $3\sigma_S$ = 2.45kW - 2.18kW = 0.273kW and σ_S = 91W.

The following parameters were then used to calculate the reliability of the latch wire for this failure mode.

Mean strength, μ_S = 2.45kW
Strength variance, σ_S^2 = 8.30kW
Mean stress, μ_s = 1.5W
Stress variance, σ_s^2 = 0.053W

Then $X_{z=0}$ = 26 and R_{LW} > 0.9999+. Since four latch wires are required for successful operation of the phase shifter, the total reliability is $(0.9999+)^4$.

<u>Insulation Breakdown</u>. The probability of insulation breakdown and arcing in the phase shifter latch wires was determined using the same method as was used for the latching circulator example. In this application, the amplitude of the transient voltage peak is approximately 130V with duration of less than 200ns. The upper limit of this transient voltage spike, based on the variance of the worst-case peak current, was determined to be 156V. For the stress distribution then, μ_s = 130V and σ_s^2 = 75V.

The mean and variance of the insulation dielectric strength distribution are the same as for the latching circulator example since the latch wire size is identical. Therefore, μ_S = 3.28kV, σ_S^2 = 63.7kV and R_{IB} > 0.9999+. The possibility of insulation breakdown on any one of the four latch wires must be considered, thus $R_{IB} > (0.9999+)^4$.

<u>Mechanical Failure Modes.</u> The dual toroid phase shifter is used in an airborne environment and is subjected to aircraft vibration levels during all mission phases. However, unlike the latching circulator the phase shifter, incorporated as an integral part of the waveguide, is not subjected to shear stress at the adhesive bonds holding it in place. The dual toroid configuration is a mechanically captive design with maximum surface area for bonding and is further secured by a thermister mounting plate and thermal adhesive. Thermal analysis shows a maximum ferrite temperature of 75°C for worst case operating conditions. For this device, this is far below its thermal capacity. For these reasons, the probability of mechanical or thermal failure is extremely low – approaches zero.

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7 Summary

A realistic model has been developed using interference theory' to quantify the reliability of ferrite devices used in military and commercial microwave antenna applications. Interference theory has been successfully applied to determine the reliability of mechanical and electromechanical devices by analyzing the stress vs. strength probability density functions of defined failure mechanisms. For the devices examined here, the possible electrical failure modes analyzed include latch wire fusing due to high current and insulation breakdown from transient voltage spikes. The primary mechanical failure mode analyzed was the possibility of adhesive bond failure due to vibration and thermal stress.

The reliability of two ferrite devices, a latching circulator and a dual toroid phase shifter, was determined using the model with applicable thermal and structural analysis data. The results show that for the electrical failure modes the probability of successful operation in the intended environment was > 0.9999+**.** Thus, the probability of failure due to electrical stress approaches zero. For the mechanical failure modes considered (latching circulator only), reliability was also found to be greater than 0.9999+**.** This reliability value applies only to that period of device operation when stress due to vibration is applied.

In summary, the analysis procedure developed is a valid approach in quantifying the reliability of microwave ferrite devices, and for the examples analyzed using this method, reliability is shown to be so high as to be considered equal to unity when used in predicting system probability of success.

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