Thermal Stress-Induced Breakdown in an *S*-Band Isolator

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***Abstract*—In increasing the average power capability of a high peak power *S*-band isolator, severe RF breakdown was repeatedly encountered, which always led to extensive destruction of the ferrite material. Through careful study of the microwave and thermal test data, it was ascertained that breakdown was preceded by thermally induced stress and fracture in the ferrite, which was a consequence of a thermally induced adhesive failure. It is shown that the adhesive parameters of importance include the tensile strength and the thermal elongation of the adhesive layer. Also, restrictions on the range of dielectric loss tangents of the ferrite consistent with the proposed breakdown mechanism are given.**

I. Introduction

In HIGH-POWER radar transmitters, the power tube output window must be protected from damage caused by power reflected from antenna mismatch. This protection is usually provided by a ferrite isolator, which transmits power to the antenna with minimum transmission loss, and diverts reflected power to a matched termination capable of safely dissipating that power.

Typically, isolators used for high-power vacuum tube protection comprise a four-port differential phase shift circulator [1] with a fluid-cooled load to absorb power reflected from the antenna. The 90° nonreciprocal phase shift sections in conventional high-power circulators consist of two waveguides connected on a common narrow wall, each of which has four strips of transversely magnetized ferrite material, located symmetrically on the broad walls, such that each strip is halfway between the broad-wall centerline and the narrow wall of the guide. These ferrite strips are thin enough that RF power absorbed in them can be removed by conduction to the guide broad wall, which is then fluid cooled. This design requires many heavy permanent magnets located on the outside of the fluid-cooled phase shift sections.

In order to reduce weight for airborne applications, the circulator in question was designed with only two ferrite strips per waveguide as shown in Fig. 1, thus halving the magnet weight. This calls for thicker ferrites (about 0.5 cm) to maintain the same phase shift for a given length of the guide. In this case, it is 0.56 cm and therefore raises the possibility of overheated ferrites, and calls for tighter tolerances in the insertion loss of the ferrite.

When these units were first high-power tested, we experienced repeated RF breakdown events which cracked and vaporized the ferrite material to such an extent that any detailed evidence of the origin of breakdown was destroyed. The ferrite slabs were fastened with a high-temperature hard epoxy adhesive[1], which has a relatively high thermal conductivity. After reducing the adhesive thickness to 0.05 mm and still observing the RF breakdown, a more flexible silicone adhesive[2] was successfully tried. This was somewhat surprising because the silicone had about 1/10 the strength of the epoxy, based on lap shear test data, and also because the silicone had a lower thermal conductivity.

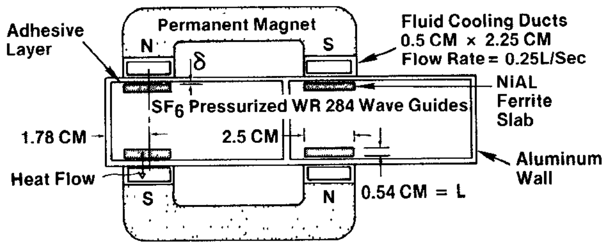

Fig. 1. Cross section of phase shift section.

The object of this paper is to show how the use of the more flexible silicone adhesive solved the RF breakdown problem, and more generally, how the parameters of the adhesives and the ferrites can affect the safe operating range of such high-power nonreciprocal components.

The proposed isolator breakdown mechanism is based on RF heating of the ferrite rather than a spark-induced arc discharge. This has been substantiated by tests performed at 40–50-kW average power, and duty factors up to 0.03. Only the high-duty (0.03) tests produced breakdown, once the adhesive thickness was reduced to the order of 0.025 mm. Analytical estimates of the peak RF field also indicate that at the highest peak power considered, and the approximately 1 ATM SF_6 pressurization used, the peak RF field is 4–5 times below the SF_6 breakdown value.

The proposed model starts with adhesive failure due to excessive stretching beyond its elastic limit. This arises from the temperature gradient across the adhesive film due to ferrite RF heating. Once the adhesive breaks, the

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[1]"Bondmaster" 688, Hardener CH 1, manufactured by the National Starch Chemical Corporation, Bridgewater, NJ.
[2]Dow Corning Part #RTV-DL-2144, Dow Corning Corporation, Midland, MI.

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portion of the ferrite slab no longer joined to the waveguide will heat up to the point that thermal stress cracking occurs. When pieces of ferrite are broken off, they continue to heat up and chemically react with the SF_6 gas giving off H_2S gas and a white powder, which has been spectrochemically analyzed as aluminum flouride. This H_2S gas reduces the spark breakdown resistance of the SF_6 gas.

The details of the final passage to arc discharge formation are not known. Rapid thermal decomposition of SF_6 in the presence of various metals, silicon compounds, and organic insulators has been observed to occur for temperatures at or greater than 500°C. Visual observation of the arc damage in the circulators tested indicates that the damage is restricted to the ferrites and the adhesive. Thus the aluminum flouride must come from the aluminum content of the ferrite, and the H_2S was formed from a reaction of the adhesive and SF_6 and/or its decomposition products at high temperatures.

II. Model of the Adhesive Fracture

The adhesive fracture can be modeled by considering Fig. 2, which shows the waveguide-ferrite adhesive interface. We assume that the stress system is at equilibrium at the centerline of the ferrite. The adhesive is modeled as an array of elastic fibers joining the guide to the ferrite. Microwave-absorbed power causes the ferrite to thermally expand in the $\pm Z$ direction from the ferrite centerline, due to the temperature gradient ΔT established across the adhesive layer. The cumulative ferrite expansion $\alpha Z \Delta T$ is given in terms of the relative fiber elongation $S/\delta = (l/\delta) - 1$ by

$$Z(\alpha \Delta T) = \delta \sqrt{(S/\delta)^2 + 2(S/\delta)} \qquad (1)$$

where α is the ferrite thermal expansion coefficient (8.2×10^{-6} for NiAl ferrite). Equation (1) can be used to calculate the distance Z_B along the ferrite from its centerline at which the adhesive layer will rupture, in terms of the percent elongation S/δ at which rupture occurs in the particular adhesive material. For hard epoxies, S/δ is typically 0.01. For $\Delta T = 5$°C over a 0.025-mm thick adhesive layer, Z_B is of the order of 6 cm. This indicates that if the individual ferrite slabs are more than about 12 cm long, adhesive fracture would occur. Similar calculations with silicone parameters indicate Z_B values in excess of 50 cm.

ΔT used in (1) is determined by the insertion loss, the incident average microwave power, the adhesive thickness of 0.025 mm, and the adhesive thermal conductivity, which is nominally 0.001 cal/cm − °C for the epoxy and the dimensions of the adhesive slab. Calculated values of ΔT are tabulated in Table I. From the table we see that the assumed value of 5°C for ΔT is valid. Measured adhesive thickness was between 0.025 and 0.050 mm.

III. Stress Cracking the Ferrite

The next step in the RF breakdown model is thermally induced stress cracking of the ferrite slabs. The proposed

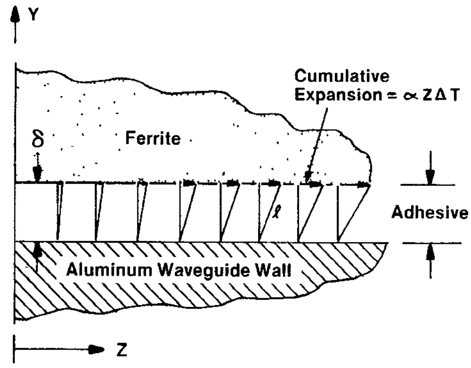

Fig. 2. Cumulative thermal stretching of the adhesive.

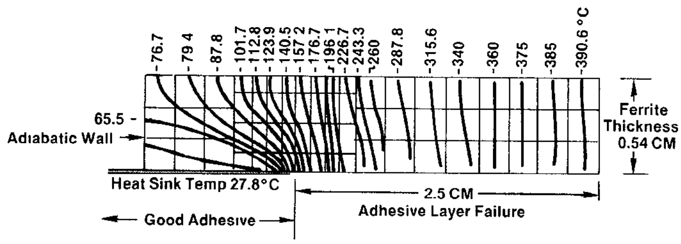

Fig. 3. Temperature distribution in ferrite slab end after adhesive failure.

TABLE I
CALCULATED FERRITE TEMPERATURE RISE AS A FUNCTION OF INCIDENT POWER AND INSERTION LOSS

	INSERTION LOSS (dB)		
	0 2	0 25	0.30
AVERAGE INCIDENT POWER (kW)	TEMPERATURE RISE °C		
40	2.55	3.18	3.80
50	–	3.97	4.74

mechanism assumes that the adhesive fails near the end of a ferrite slab. Then the slab end heats up due to RF losses, until a point is reached where the shear force due to a gradient in thermal expansion normal to an isothermal surface exceeds the Young's modulus of the ferrite. This model was investigated using a two-dimensional heat flow calculation assuming an unperturbed TE_{10}-mode RF power dissipation density distribution as the source term in the heat flow equation. Fig. 3 shows the computed temperature distribution in the ferrite slab assuming an adhesive failure occurring at 2.5 cm from the end. The source power density was 46.3 W/cm^3. This corresponds to the typical measured insertion loss of 0.3 dB at 50-kW average incident RF power. In the vicinity of the adhesive break, one can find a roughly square cross section of ferrite with a thermal gradient of about 100°C. This gives rise to shear forces which can exceed the ferrite tensile strength, which is typically less than 10 percent of its compressive strength of about 50 000 psi.

The temperature distribution is given by Poisson's equation

$$\nabla^2 T = q/K \qquad (2)$$

with T the Kelvin temperature, q the source function in W/cm^3, and K the ferrite thermal conductivity in W/°C cm. Equation (2) was solved using a two-dimensional difference approach of the form

$$T_i=\frac{\Sigma}{4}+\frac{q_h 2}{K} \tag{3}$$

where T_i is the temperature of the ith mesh cell location in a square mesh, Σ denotes the sum of the four nearest neighbor temperatures, and h is the linear dimension of the mesh cell. Fig. 3 shows a solution assuming an adhesive fracture occurring at 2.5 cm from the ferrite slab end, with a source power density of 46.3 W/cm^3, determined from the typical measured insertion loss (0.3 dB), and a 50-kW average RF incident power to the circulator.

The computational mesh size was made finer in the region where stress gradients were expected to be maximum. The isotherms are drawn over the mesh. One notices the region around the adhesive break where there are roughly square portions experiencing the order of 50–100°C thermal gradients. These give rise to shear forces which can exceed the tensile strength of the ferrite, typically less than 10 percent of the compressive strength of about 50 000 psi. These shear forces can be estimated by assuming that the force is given by the product of the modulus (2.1×10^7 psi), the thermal expansion coefficient (5.0×10^{-6}/°C), and the temperature gradient (100°C). Using these values, one obtains 17 200 psi, which far exceeds the approximately tensile strength of 5000 psi.

It is worthy to note that when a breakdown event was stopped instantly, we discovered cracked off end pieces of ferrite with fracture contours corresponding in shape to the isotherms shown in Fig. 3, typically in the region of the highest gradient. The break points were about 2 cm from the end of the slabs, consistent with the predicted location of the adhesive rupture. It is only after this stress-induced rupture that the ferrite can become hot enough to react with the SF_6 gas, creating new constituents including H_2S, which can readily break down at reduced peak power levels.

IV. Thermal Analysis

The temperature drop over the adhesive layer was estimated at about 5°C, based on measured insertion loss, incident average power, adhesive thickness, and thermal conductivity. An empirical check has been made in the following way. Low-power level insertion loss and isolation data were taken on a phase shift section, operated over a temperature range of 25–90°C by adjusting the cooling fluid temperature. During a high-power test, we also obtained isolation data over a range of average RF power values. The result of comparing these two sets of data is shown in Figs. 4 and 5. Fig. 4 shows isolation versus coolant temperature for five frequencies in S band at 50-MHz intervals. It also shows measured average RF input power values taken at the center frequency, corresponding to the isolation values associated with the center frequency isolation versus temperature curve. For example, at 40-kW average power, the test unit showed about 31-dB isolation. The design was reasonably conservative

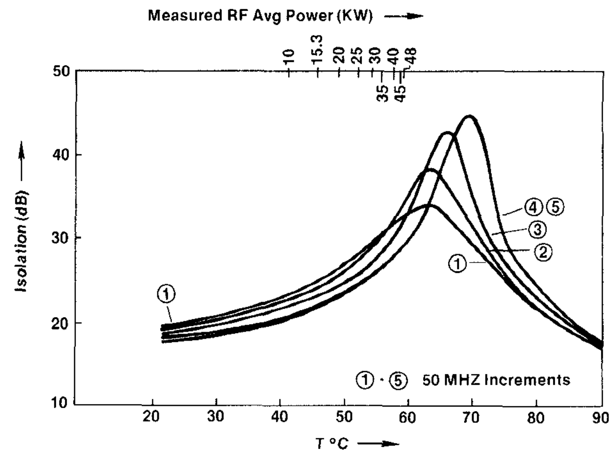

Fig. 4. Isolation versus average ferrite temperature.

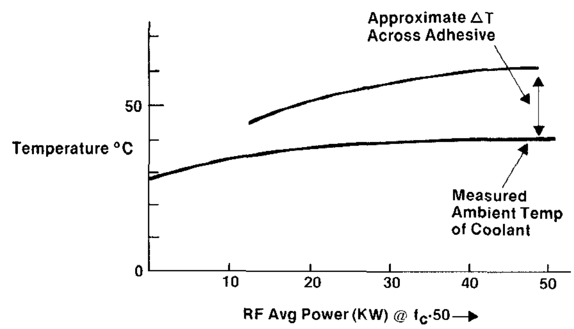

Fig. 5. Ferrite temperature versus RF power.

in that for maximum RF power, the isolation peak had not yet been reached. From these curves, we plot the ferrite temperature, averaged through its volume, versus the average incident RF power level in Fig. 5. It also shows the coolant temperature. The temperature difference between these curves should give a measure of the temperature drop over the adhesive. At high-power levels, the average ferrite temperature appears to be about 20°C above that of the coolant. 3.3°C of this can be accounted for by heat transfer from the cooling duct surface to the coolant [2], assuming the dimensions shown in Fig. 1, 50-kW average incident RF power, 0.25-dB insertion loss, and 0.27-l/s volume flow rate, in a single coolant duct. For these parameters, the conditions for turbulent flow were satisfied [2].

If we assume that the ferrite experiences uniform RF dissipation density q throughout its volume, the mean temperature rise T_L will be given by

$$T_L=\frac{qL^2}{3K}, \quad \text{where } K \text{ is the ferrite thermal conductivity.} \tag{4}$$

It yields 9.3°C for the assumed parameters above. Allowing for these two effects, we get about 7°C across the adhesive. We have two independent experimentally based estimates of the temperature gradient over the adhesive which formed the basis by which we calculated the position of adhesive rupture, using (1).

The 0.25-dB insertion loss value is typical of the isolator under high average-power conditions. This depends on the parameters of the ferrite. The range of ferrite material

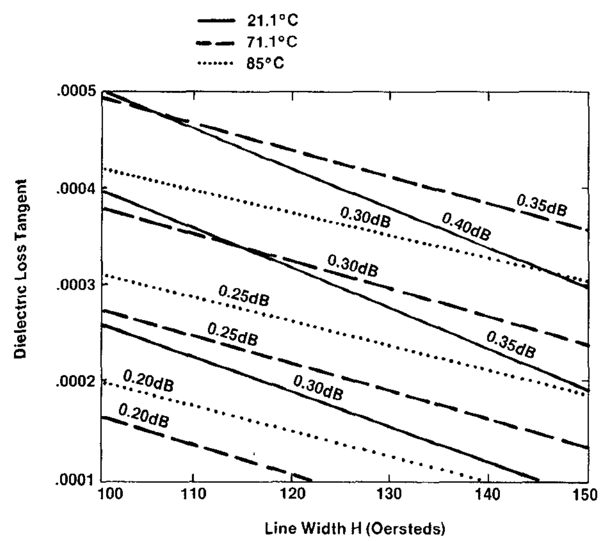

Fig. 6. Insertion loss versus linewidth and loss tangent.

parameters consistent with high average-power capability in such isolators has been calculated by using the perturbation approach to ferrite-loaded waveguides [1]. The ferrite in question is a NiAl ferrite selected for low loss. Typical values of dielectric loss tangent (tan δ) and line width (ΔH) are 0.0005 and 120 Oe, respectively. Fig. 6 shows insertion loss as a function of line width ΔH and loss tangent for three temperatures. It is clear that keeping insertion loss below 0.25 dB in high-power conditions in which the ferrite slabs heat up due to RF absorbed power, requires a dielectric loss tangent below about 0.0003 and line widths of 120 Oe. The ferrite used in these circulators had line widths of 120 Oe and loss tangent values less than 0.0004.

V. Conclusion

We have proposed and substantiated a mechanism by which high-power ferrite circulators and isolators suffer apparent "arc destruction." The failure mechanism, which is initiated with hard epoxy adhesive layer rupture, can be eliminated by using a highly flexible silicone adhesive. A range of ferrite material parameters consistent with high average-power S-band operation is computed.

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A 50-kW CW Ferrite Circulator in *S* Band

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***Abstract*—A 50-kW CW differential phase-shift circulator at 2450 MHz has been developed. Its insertion loss and isolation are 0.18 dB and 20 dB, respectively, over a bandwidth of 25 MHz at 2450 MHz. It is useful for protecting the microwave source of a high-power system from reflected power. The design and experimental results of the circulator are presented.**

I. Introduction

Microwave power has been successfully used for industrial applications. In France, we tend to use higher and higher power sources at 2450 MHz, and, in particular, a 50-kW CW Thomson CSF klystron. In such a system, an isolator or a circulator is indispensable to protect the high-power source from reflected power.

At this frequency range, a Y-junction circulator is still inferior in power handling capability although this capability is increasing recently. At these power levels, the approach commonly used consists of a four-port differential phase-shift circulator. To reduce the power level received by the ferrite material, we can use either 3-dB couplers or 8.34-dB couplers in tandem [1]–[3].

In our research on a 2450-MHz 50-kW CW circulator, we have taken into account the two above mentioned approaches. This paper presents the realized structures and the design and performance of a 50-kW CW ferrite circulator at 2450 MHz.

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II. Design of a High-Power Ferrite Circulator

The classical differential phase-shift circulator [4] uses a folded magic tee and a 3-dB coupler. Between those two

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