STRESS RELIEF OF CERAMIC COMPONENTS
IN HIGH VOLTAGE ASSEMBLIES

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Prepared by R. J. Heinen

Two types of ceramic packages were evaluated to determine the effectiveness of encapsulating the ceramic components in beta eucryptite filled epoxy. The requirements (no high voltage breakdown, no ceramic cracking, and no encapsulant cracking) were met by the spark gap assembly, but the spraytron assembly had cracking in the encapsulant after thermal cycling. The encapsulation of the ceramic component in beta eucryptite filled epoxy with a stress decoupling material selectively applied in the stress concentrated areas was used to prevent cracking in the spraytron encapsulant. This method is proposed as the standard encapsulation process for high voltage ceramic components.

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SUMMARY

Two types of ceramic packages were evaluated to verify the effectiveness of encapsulating the ceramic components in beta eucryptite filled epoxy (BEFE). The effectiveness was determined by the following set of requirements: no ceramic cracking, no encapsulant cracking, and no high voltage breakdown. In previous assemblies, the process of encapsulating a sprytron included a stress decoupling material to protect the sprytron from excessive induced thermal stresses. The encapsulation process uses no stress decoupling material because the sprytron has a higher expected stress strength than previous sprytrons. A theoretical stress analysis verified the maximum stress in the ceramic to be 60 percent of the expected ceramic strength, leaving a 40 percent safety factor. A sample of each assembly was thermal cycled at temperatures in excess of product specifications to encourage potential electrical failures or cracking to occur. No electrical failures and no cracking in the ceramic components occurred. No cracks were found in the spark gap encapsulant, but cracks in the sprytron encapsulant were found after the thermal cycling was completed. The spark gap assembly was proved to be an effective encapsulation process, but the sprytron assembly must be modified to prevent the encapsulant from cracking.

A follow-up theoretical stress analysis was done on a cross-sectional area of the sprytron assembly, and the maximum stress developed in the encapsulant was 32 percent less than the expected encapsulant tensile strength. A hypothesis that stress concentrations exist at the sprytron egression was proposed to account for the encapsulant cracking. A second set of sprytron samples was temperature cycled to verify the hypothesis. All six samples had cracks in the encapsulant at the interface where the sprytron egresses from the encapsulant as was hypothesized.

The encapsulation of ceramic devices in BEFE is an effective encapsulating process when a stress decoupling material is selectively applied to stress concentrated areas. The BEFE provides sufficient dielectric strength to prevent high voltage breakdown and to isolate the high voltage from other components and the mass encapsulant (urethane foam). The decoupling material prevents cracking in the ceramic and encapsulant when the ceramic components are totally or partially encapsulated. When the decoupling material is selectively applied to the stress concentrated areas, the rest of the ceramic component is rigidly held by the BEFE during shock environments. This process is proposed as the standard process for encapsulating high voltage ceramic devices in assemblies. The initial investigations have verified the effectiveness of this process to prevent cracking in the encapsulant.

DISCUSSION

SCOPE AND PURPOSE

Two types of ceramic packages were evaluated to verify the effectiveness of the ceramic stress relief. The evaluation was to determine if the method of encapsulation is sufficient to protect the ceramic components. A set of requirements was established to determine the effectiveness of the ceramic stress relief. The requirements were no high voltage breakdown, no ceramic cracking, and no encapsulant cracking.

PRIOR WORK

The packaging of fragile high voltage components has evolved from a rubber booty around a glass tube to today's approach of direct encapsulation in beta eucryptite filled epoxy.¹⁻³ These prior approaches have not achieved the desired simultaneous characteristics of dielectric strength, shock resistance, and safe thermal inducted stress levels.

ACTIVITY

A theoretical stress analysis was done on the encapsulated ceramic. Constrained thermal expansion formulas were used to calculate the maximum stress expected in a ceramic sphytron tube and the ceramic spark gap when encapsulated in beta eucryptite filled epoxy (BEFE). The highest stress was calculated to be in the flat base of the ceramic sphytron tube. This stress was 60 percent of the expected ceramic strength, leaving a 40 percent safety factor. All stresses for the spark gap were lower than those for the sphytron tube. Since the calculated stresses are expected to be higher than the real life stresses because of the assumptions made, the requirement (no ceramic cracking) will be satisfied. Details of this analysis are in Appendix A.

A sample of each ceramic component, the sphytron and the spark gap, was encapsulated and then thermal cycled. Figure 1 shows the sphytron physical configuration, and Figure 2 shows the spark gap physical configuration. Figure 3 shows the encapsulation level and the final configuration of the sphytron assembly. Figure 4 shows the encapsulation level and the final configuration of the spark gap assembly. Each sample was subjected to 25 temperature cycles. The temperatures used during the thermal cycling are shown in Figure 5. The temperatures used were

Figure 1. Sprytron Assembly

deliberately worse than those required. The extreme temperatures were used to encourage any possible failure to occur.

During the 25 temperature cycles, electrical tests were performed periodically to determine any changes in the performance of each assembly. No handling of the assemblies was done during the thermal cycling. This procedure eliminated any electrical variations caused by a change in component location. Baseline data was established on each assembly prior to cycling. Measurements were made using the following instruments with the indicated resolution. An electrometer with a 0.5 nanoamp per increment resolution measured the sprytron and spark gap leakage current. An oscilloscope with a 125 amperes per increment resolution

Figure 2. Spark Gap Assembly

measured the sprytron output current waveform. A voltmeter with a 1 volt per increment resolution measured the breakdown voltage of the spark gap. Incremental changes and the as-read data were plotted (Tables 1 and 2). The limited data supports the requirement of no high voltage breakdown.

After thermal cycling, a visual inspection revealed cracks in the sprytron encapsulant, but no cracking was observed in the ceramic components themselves or in the spark gap encapsulant. Cracks in the sprytron BEFE were observed along the sides of the sprytron where the encapsulant was the thinnest. The cracks propagated radially outward from the sprytron-encapsulant interface. The encapsulant was etched away, and a thorough visual inspection was made of the two ceramic components. Under magnification, there

DIALLYL PHTHALATE
DAM

CERAMIC

SPRYTRON
EGRESSING
FROM BEFE

BETA-EUCRYPTITE
FILLED EPOXY

Figure 3. Encapsulated Sprytron Assembly

were no visible cracks found in the ceramic components. The samples evaluated support the following conclusions: the spark gap assembly is an effective encapsulating process, but the sprytron assembly is inadequate to prevent the encapsulant from cracking.

**BETA-EUCRYPTITE
FILLED EPOXY**

Figure 4. Encapsulated Spark Gap Assembly

A theoretical stress analysis was conducted on the encapsulant around the sprytron. A cross-sectional area in the middle of a concentric cylindrical sprytron assembly was analyzed (Figure B-1). This analysis neglects the end effects where the sprytron egresses from the BEFE. The computed stresses were 32 percent of the expected BEFE tensile strength. Detailed assumptions and calculations are in Appendix B.

A hypothesis that higher thermal stresses exist in the encapsulant at the interface where the sprytron egresses from the BEFE compared with the stresses calculated for a cross-sectional area was proposed as the reason why the BEFE cracks during thermal cycling. These hypothesized high stresses exceed the BEFE low temperature tensile strength resulting in cracks beginning in the BEFE. The

Figure 5. Temperature Cycle

combination of the cross-sectional area stresses and the brittleness of the BEFE at cold temperatures promotes the cracking that starts at the sprytron egression and propagates radially outward along the sides of the sprytron. The quantitative theoretical analysis requiring finite element methods is beyond the scope of this short-term project. However, samples of the sprytron assemblies were thermal cycled to verify this hypothesis.

Six sprytron assemblies were encapsulated and thermal cycled. Three were encapsulated in BEFE to a level below the metal-ring cathode, and the other sprytrons were encapsulated to the level of the flat base. The product specified temperature cycle was used (Figure 5). After seven cycles, the samples were visually inspected. All the samples, regardless of potting level, had cracking. Two sprytron assemblies were sawed in half to determine how far the cracks had propagated down the sides of the tube, but no cracks were found in the sawed surfaces of BEFE. The cracks started at the encapsulant-component interface where the sprytron egresses from the BEFE. This empirical evaluation has verified the hypothesis. Figures 6 and 7 show typical cracks and the two different potting levels.

Observation of another program's sprytron assembly illustrates the effectiveness of a decoupling material around the egressing sprytron. After two sprytron assemblies were recovered from

Table 1. Electrical Testing of Sprytron Assembly

Number of Cycles	Leakage Current (in nanoamperes)		Output Peak Current (in amperes)	
	As-Read Data	Incremental Change	As-Read Data	Incremental Change
0*	0.5		22,025	
2	0.5	0.0	21,900	-125
4	0.5	0.0	21,775	-250
6	0.8	+0.3	21,775	-250
8	0.6	+0.1	21,775	-250
10	0.6	+0.1	21,900	-125
12	0.7	+0.2	22,150	+125
14	0.7	+0.2	22,025	0
16	0.6	+0.1	21,775	-250
18	0.8	+0.3	21,900	-125
20	0.7	+0.2	22,275	+250
22	0.6	+0.1	22,275	+250
24	0.7	+0.2	22,150	+125
25	0.7	+0.2	22,025	0

*The incremental change is based on this data reading.

D-tested assemblies, a thorough visual inspection revealed no cracks in the ceramic sprytron or the BEFE encapsulating the sprytron. This particular sprytron assembly uses a syntactic polysulfide sleeve around the ceramic where the sprytron egresses from the BEFE. The sleeve provides enough decoupling between the ceramic and the BEFE to prevent the BEFE from cracking.

ACCOMPLISHMENTS

The ceramic packages were evaluated to determine the effectiveness of the ceramic stress relief. The requirements (no high voltage breakdown, no ceramic cracking and no encapsulant cracking) were met by the spark gap assembly, but the sprytron assembly had cracking in the encapsulant. The cracking started at the BEFE-sprytron interface where the sprytron egresses from the BEFE.

Table 2. Electrical Testing of Spark Gap Assembly

Number of Cycles	Leakage Current (in nanoamperes)		Breakdown Voltage** (in volts)	
	As-Read Data	Incremental Change	As-Read Data	Incremental Change
0*	0.6		6265	
2	0.7	+0.1	6261	+4
4	0.6	0.0	6268	+3
6	0.6	0.0	6262	-3
8	0.7	+0.1	6256	-9
10	0.7	+0.1	6261	-4
12	0.6	0.0	6265	0
14	0.7	+0.1	6265	0
16	0.7	+0.1	6259	-6
18	0.8	+0.2	6257	-8
20	0.7	+0.1	6264	-1
22	0.8	+0.2	6260	-5
24	0.7	+0.1	6268	+3
25	0.8	+0.2	6267	+2

*The incremental change is based on this data reading.

**Each read is the average of 10 test runs.

The encapsulation of ceramic components in BEFE with a stress decoupling material selectively applied to stress concentrated areas was investigated and proposed. A decoupling material in selected areas allows the rest of the ceramic component to be held rigidly by the BEFE during shock environments. The decoupling material also prevents cracking in the ceramic and the BEFE. When a ceramic component is totally encapsulated, weak areas of the component have to be decoupled from the BEFE to prevent ceramic cracking in these areas. The probe area of a sprytron is a weak area that needs this additional stress relief when encapsulated. In partial component encapsulation, stress concentrations develop at the ceramic-BEFE interface where the sprytron egresses. These stress concentrations exceed the BEFE tensile strength and require decoupling to prevent cracking. The BEFE provides sufficient high voltage isolation of the ceramic component from other components and the mass encapsulant.

Figure 6. Typical Cracking in BEFE at Metal Ring Interface

FUTURE WORK

A future evaluation is planned to assure the elimination of cracks in the sprytron encapsulant. Incorporation of a stress decoupling material around the sprytron where the sprytron egresses from the BEFE will be evaluated. The decoupling material (such as syntactic polysulfide) should relieve the stress concentration in the BEFE and thus stop cracking in the BEFE.

Figure 7. Typical Cracking in BEFE at Ceramic Interface

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Appendix A

STRESSES IN ALUMINA COMPONENTS CAUSED BY ENCAPSULATION IN BETA EUCRYPTITE FILLED EPOXY

SUMMARY

Constrained thermal expansion formulas were used to calculate the maximum stress expected in an alumina spraytron tube and an alumina spark gap when encapsulated in beta eucryptite filled epoxy. The Young's modulus of the encapsulant was also measured at -55°C , 24°C , and 75°C . The highest stress was calculated to be in the flat base of the alumina spraytron tube. This stress was 60 percent of the expected alumina strength, leaving a 40 percent safety factor. Since the calculated stresses are expected to be higher than real life stresses because of the assumptions made, the spraytron tube should be safe. All stresses for the spark gap were lower, so it should also be safe. More refined calculations should be made for the spraytron tube base and diametral compression of the spark gap using the finite element method thermal and stress analysis codes currently available at Bendix Kansas City.

ACTIVITY

The fabrication area was visited to view the actual geometry, component placement, and other details of encapsulating alumina spraytron tubes and spark gaps in beta eucryptite filled epoxy (BEFE). The configuration was such that approximate calculations could be made using constrained thermal expansion formulas already available at Bendix.¹ However, the Young's modulus of the BEFE had to be measured first.

Tensile samples of BEFE were made and tested at -55°C , 24°C , and 75°C . The Young's modulus values for each sample per ASTM D638 are shown in Table A-1. Note that most of the data scatter for the 75°C tests occurs because of the extremely limited portion of each test curve which approximated a straight line. The classical Young's modulus may be of limited value at this temperature for this material.

Constrained thermal expansion calculations were made for the spraytron tube when encapsulated in BEFE in a diallyl phthylate dam and undergoing a temperature change from 75°C to -55°C . Axial and radial stresses were calculated by assuming the materials were arranged as concentric cylinders. The details of top and bottom ends of the spraytron tube were neglected. The most severe stress calculated for the spraytron tube under these simplifying and conservative assumptions was a 144.8 MPa maximum tensile

Table A-1. Young's Modulus for Beta Eucryptite Filled Epoxy

Specimen Number	Young's Modulus (GPa)		
	-55°C	24°C	75°C
1	12.63		
2	10.83		
3	8.42		
4	12.83	7.38*	
5	14.56	9.45*	
6		10.14	
7		10.55	1.26*
8		9.73	0.49*
9			0.42
10			0.48
11			1.03

Averages: 11.87 GPa at -55°C
 9.45 GPa at 24°C
 0.74 GPa at 75°C

*Tested at the lower temperature first.

NOTE: The small straight line portion on the 75°C test curves probably accounts for much of the data scatter.

stress at the inner surface of the bottom at -55°C caused by inward bending. Since the tensile strength of this alumina has been measured at Bendix¹ to be 241.3 MPa and since the calculated stress is expected to be higher than the true stress because of the simplifying assumptions made, the spraytron tube should be safe. In addition, the effective pressure on the tube end was calculated to be 62.0 MPa, which is well below the 16.5 MPa to 32.4 MPa measured for hydraulic pressurization to failure.

The axial stress was also calculated for the spark gap. This resulted in 151.7 MPa maximum tensile stress in the metal end of the spark gap. Even if this is above yield, the metal will not

fail in a brittle fashion as would a ceramic. This would transmit the relatively low tensile stress of 16.5 MPa to the cylindrical alumina shell from bending. Because of the close proximity of the diallyl phthylate dam to the spark gap, the effective diametral compressive stress was calculated. It was 68.9 MPa tensile at the worst location on the alumina wall interior. These worst case stresses predict safety for the spark gap.

The above calculated values are believed to be conservative. However, more reliable values which reflect the detailed part and encapsulation geometry can be calculated using the finite element analysis codes SASL and WILSON for thermal stress analysis. These codes are both available at Bendix, and personnel are trained in their use. The bottom end of the spraytron tube and diametral compression of the spark gap have high enough stresses that they should be further investigated. This analysis could be completed in 300 work hours and three calendar months. Actual spark gap failure data for comparison could be obtained in the same calendar duration at an additional cost of 50 work hours plus the spark gaps for testing. This cost effective preliminary work should be weighed against the potential cost of a production failure due to a marginal design.

Appendix B

BEFE THERMAL STRESS ANALYSIS

Assumptions:

- Zero stress between the BEFE and the ceramic is at 70°C.
- The lowest temperature to which the BEFE is subjected is -40°C. Thus, a temperature change of 110°C is developed.
- The smallest width of BEFE is 2.5 mm.
- The spraytron assembly materials are arranged in concentric cylinders (Figure B-1).
- The analysis computes stresses in a cross-sectional area.
- All end effects are neglected.

Physical Properties:

	<u>BEFE</u>	<u>Ceramic</u>
Thermal Coefficient of Expansion (α)	20 X 10 ⁻⁶	4.5 X 10 ⁻⁶ mm/mm/°C
Modulus of Elasticity (E)	11.87 X 10 ⁶	276 X 10 ⁶ kPa
Tensile Strength	56, 166	kPa
Poisson's Ratio (μ)	0.35	0.2
A = 8.6 mm		
B = 10.2 mm		
C = 12.7 mm

Figure B-1. Sprytron Configuration

The pressure (P) developed between the ceramic and the BEFE during thermal cycling is computed by the following equation.

$$P = \frac{\alpha_2 - \alpha_1 \Delta T}{\frac{1}{E_1} \left(\frac{A^2 + B^2}{B^2 - A^2} - \mu_1 \right) + \left(\frac{1}{E_2} \frac{B^2 + C^2}{C^2 - B^2} + \mu_2 \right)}$$

$$P = \frac{20 \times 10^{-6} - 4.5 \times 10^{-6} \cdot 110}{\frac{1}{276 \times 10^6} \left(\frac{8.6^2 + 10.2^2}{10.2^2 - 8.6^2} - 0.2 \right) + \frac{1}{11.87 \times 10^6} \left(\frac{10.2^2 + 12.7^2}{12.7^2 - 10.2^2} + 0.35 \right)}$$

$$= 3,870 \text{ kPa}$$

After the developed pressure has been computed, the maximum stress in the BEFE is calculated using the following equation.⁴

$$\begin{aligned}\text{Maximum Stress in BEFE} &= P \left(\frac{B^2 + C^2}{C^2 - B^2} \right) \\ &= 569.6 \frac{0.4^2 + 0.5^2}{0.5^2 - 0.4^2} \quad 3,870 \frac{10.2^2 + 12.7^2}{12.7^2 - 10.2^2} \\ &= 17,933 \text{ kPa}\end{aligned}$$

The percentage difference between the expected BEFE tensile strength and the maximum developed stress is computed as follows.

$$\frac{17,933}{56,166} \times 100 = 32\%$$

Therefore, the maximum calculated stress in a cross-sectional area of the BEFE during thermal cycling is 32 percent of the maximum tensile strength of BEFE.

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