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UNANTICIPATED EFFECTS OF EPOXY IMPREGNATING TRANSFORMERS

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Abstract: Many Sandia components for military applications are designed for a 20-year life. In order to determine if magnetic components meet that requirement, the parts are subjected to selected destructive tests. This paper reviews the re-design of a power transformer and the tests required to prove-in the re-design. The re-design included replacing the Epon 828/Mica/methylenedianiline (curing agent "Z") epoxy encapsulant with a recent Sandia National Laboratory (SNL) developed epoxy encapsulant. The new encapsulant reduces the Environmental Safety & Health (ES&H) hazards. Life testing of this re-designed transformer generated failures; an open secondary winding. An experimental program to determine the cause of the broken wires and an improved design to eliminate the problem was executed. This design weakness was corrected by reverting to the hazardous epoxy system.

I. INTRODUCTION

This paper describes the process for qualifying a new transformer design and the unanticipated effect a new epoxy formulation has on that design. The design is a 6kV power transformer that utilizes a ferrite pot core. Impregnation of the secondary is essential because of the 6kV. In order to qualify a new component for war reserve (WR) military application, the component must survive severe environmental testing. These tests are considered destructive (D-test), and the D-tested components are marked to prevent use in an actual system. D-Tests includes temperature cycling (TC), mechanical shock, vibration, and repetitive high voltage corona testing.

Sandia has responsibility for the design of magnetic components used on systems developed for the Department of Energy (DOE). Since this responsibility was undertaken in 1949, thousands of magnetic components of more than 100 designs have been built into SNL subassemblies and have been in the DOE war reserve for many years.

A power transformer designed for use in a fireset application was re-designed because of separation between the epoxy encapsulant and the diallyl phthalate (DAP) contact assembly. The new design consisted of eliminating the DAP contact assembly and utilizing a one-piece encapsulation system. Other changes included placement of a stress relief barrier between the epoxy encapsulant and the ferrite pot core, and incorporating a newly formulated epoxy system.

Evaluation of this new design started in 1992 at Martin Marrietta Specialty Components (MMSC) Pinellas plant, prior to the downsizing of the DOE complex that forced the closure of that facility. As a result of that plant closure, Sandia was given mission responsibility for magnetic components. This responsibility means that Sandia is now responsible for the design and manufacturing of magnetic components. Sandia has chosen to have private industry manufacture these components instead of setting up to build in-house; a cost saving to the taxpayer. In late 1996, Vanguard Electronics Co. Inc. was awarded a contract to manufacture this product. Development of this component started in early 1997 and was completed in March of 2000. The reason for the long development time is that schedules kept changing and priorities required Vanguard to work on other Sandia projects. This long development time contributed to the problems that will be discussed.

As mentioned earlier, impregnation is essential. Voids in the secondary winding are a problem that cannot be completely eliminated; therefore, the high-voltage test screening is used to insure product reliability.

II. DISCUSSION

A. Power Transformer Design

Old design:

- Bobbin, Delrin - 2616 size
- Primary 20 turns of 30 AWG with center tap

DISCLAIMER

DISCLAIMER

- Insulation over primary 3 layers of 2mil Kraft paper
- Secondary 645 turns of 42 AWG, 43 turns/layer, 15 layers
- Each layer of secondary separated by 2 layers of 2mil Kraft paper
- Insulation over secondary 7 layers of 2mil Kraft paper, high voltage output lead (solder connection) bedded in Kraft paper
- Core - 2616 size ferrite pot core
- Bond core/coil assembly onto DAP contact assembly
- Solder start & finish primary & start of secondary to appropriate pins on contact assembly
- Solder finish of secondary to red flex lead
- Mold/impregnate with Epon 828/Mica/"Z"

Kraft paper width 0.370"
See molded transformer figure 1.

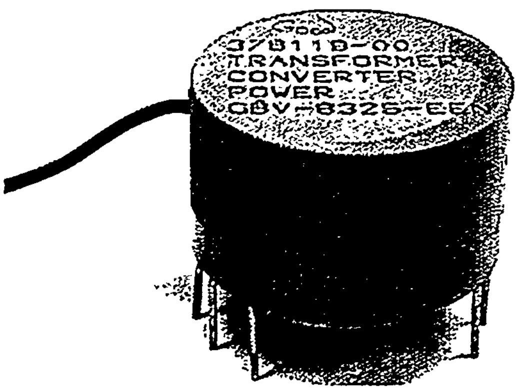
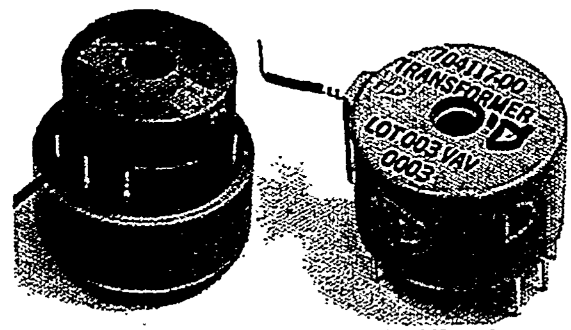


Figure 1. Old Design

New design

- Bobbin, Delrin - 2616 size
- Primary 20 turns of 30 AWG with center tap
- Insulation over primary 3 layers of 2mil Kraft paper
- Skein finish of secondary
- Secondary 645 turns of 42 AWG, 43 turns/layer, 15 layers
- Each layer of secondary separated by 2 layers of 2mil Kraft paper
- Insulation over secondary 7 layers of 2mil Kraft paper, skeined high voltage output lead bedded in Kraft paper
- Core - 2616 size ferrite pot core
- Surround Core/coil assembly with Glass micro-balloon filled Polysulfide
- Solder start & finish primary & start of secondary to appropriate pins on assembly fixture
- Shrink red tubing over skeined secondary finish lead
- Mold/impregnate/encapsulate with formula 456/Mica (Sandia formulation)

Kraft paper width 0.370"
See polysulfide capped core/coil assembly and molded transformer figure 2.



Polysulfide Capped Core/Coil Assembly — Molded Transformer

Figure 2. New Design

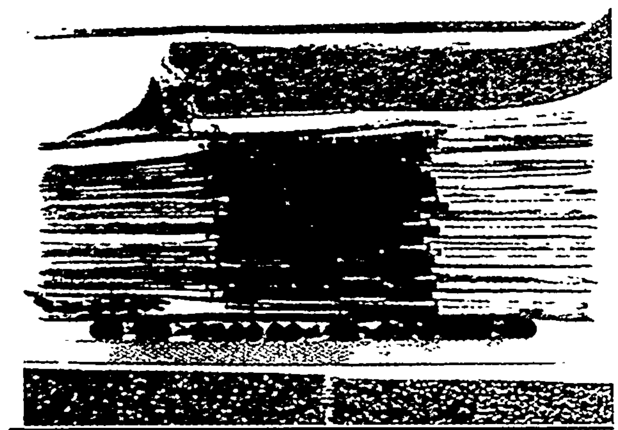


Figure 3. Transformer Winding Crossection

B. Preproduction

Vanguard manufactured a Lot of 35 prototype units and a Lot of 35 process prove-in (PPI) units. The normal developmental process for WR transformers is to build a Lot of prototype transformers followed by a Lot of PPI transformers to prove-in the design and to determine manufacturabilty. This is a new design that had never been produced. We have several innovations. It is the first time we utilized the Sandia developed "Formula 456/Mica" epoxy in a package of this size (1.25-inch diameter). The use of skeining (a process for increasing the external lead diameter from fine wire) and the elimination of the header assembly to utilize a one-piece encapsulation system is also new. Since this part introduced new materials and a new molding process, the Product Realization Team (PRT) added life tests to insure field reliability. Each group of development parts was subjected to 200 temperature cycles, which represents about 40 years of field life. The parts are electrically tested before and after TC. All parts passed all test requirements. Electrical tests consisted of inductance, leakage inductance, capacitance, DC resistance, turns ratio, and insulation resistance.

There was concern for the high voltage capability of the part since sectioning of the parts showed voids in the secondary winding (see figure 3). The encapsulation process consists of pouring the epoxy resin under vacuum and curing under pressure in an effort to eliminate voids. A corona test was developed to screen out potentially bad product. This test can be applied to 100% of the product since it is non-destructive. Since voids are not consistent with good manufacturing processes, improvements in the encapsulation process were incorporated prior to the qualification build. The last two improvements were recommended by Howard Arris and Linda Domeier; encapsulation experts at Sandia. The improvements were as follows:

1. Narrower Kraft paper (0.350") in the secondary winding, allowing better penetration of the epoxy.
2. Higher vacuum - change from 6 torr to 1 torr.
3. Higher vacuum temperature - change from 71°C to 100°C.

C. Qualification Build

The qualification lot consisted of 35 transformers and included the improvements noted above. The qualification lot is manufactured using the same equipment, tooling, and personnel that would be used during production. The results of the qualification build yielded a significant problem not seen before. Eight units developed a break in the secondary winding. These opens were found prior to encapsulation. Seventeen additional failures were generated during TC of the encapsulated units. The units were cycled 100 times from room temperature to -65°C to 93°C back to room temperature. The TC represents accelerated field life with 100 cycles approximating 20 years. The qualification lot was rejected and since time was a concern, an accelerated experimental test program was developed.

D. Experimental Test Program

1. First Experiment

Hoping to find a quick solution, we built two groups of 25 parts. One group had two changes from the qualification lot, and the other group was a control group built like the qualification lot. We replaced the 42AWG secondary magnet wire with 41AWG and reverted to the wide Kraft paper, while retaining the encapsulation changes for the "improved" group. Both groups failed at high rates; however, the improved group was better. The wider Kraft paper decreased failures. Also the pre-potting failures were eliminated. These results and failure analysis (de-potting and analyzing wire break) gave us additional insight into possible failure modes. These are explained in the failure analysis section. We decided that a larger scale experiment would be required to unravel the root cause of the broken wires. With the exception of the change to 41AWG wire, the "improved" design became our new baseline design (see table 2.).

2. Failure Analysis

The failure analysis lab at Allied Signal Federal Manufacturing & Technology division performed the failure analysis. Seven of the open units were de-potted using a chemical solvent. The wire break on four of the units was located at the start of a new layer, typically the first turn of the third, fourth or fifth layer. The wire break on the other three units was located somewhere between the point where the wire exits the coil and the pin. Analysis of the wire break point, in every case, shows a ductile failure. See figure 4. There was no evidence of wire damage in or near the break area.

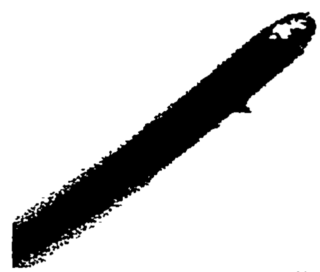


Figure 4. Ductile break

3. Second Experiment

We had Vanguard manufacture eight groups of 10 parts each. These groups were controlled, each with a unique change to aid in determining the cause of the broken wires. The groups are summarized in table 1 & 2.

Table 1. Second Experiment

Group 1. BL + PC + 41AWG.

Group 2. BL + Sandia design engineer observed all processes.

Group 3. BL + PC.

Group 4. Revert to the PPI design.

Group 5. BL + revert to the old encapsulation material (Epon 828/Mica/Z).

Group 6. BL + LWT.

Group 7. BL + LWT + PC + 41 AWG secondary.

Group 8. BL + LWT + replace start lead with skeined lead.

Table 2. Definitions:

- BL = Baseline (Like the qualification parts with HT and HV, except we reverted to WP because of the experimental results on 25 parts which proved that WP was better, i.e., much lower failure rate).
- PC = Precondition (preconditioning the parts before encapsulation with TC sinusoidal, - from room temperature to -20°C in 30min., to 50°C in 1hr., to -40°C in 1hr., to 75°C in 1hr., to -55° in 1 hr., to 93°C in 1 hr., to -55° in 1 hr., to 93°C in 1hr., back to room temperature.).
- HT = High Temperature (100°C Vacuum Temperature).
- HV = High Vacuum (1 torr Vacuum).
- LT = Low Temperature (71°C Vacuum Temperature).
- LV = Low Vacuum (6 torr Vacuum).
- WP = Wide Paper (0.370″ wide Kraft paper).
- LWT = Low Winding Tension (low secondary winding tension ≈23grams.).
- F/C = corona test failures
- F/O = open circuit failures
- SS = Sample Size
- QB = Qualification Build
- TC = Temperature Cycles
- NT = No Test
- T_F = Total Failures
- FR = Failure Rate

We also tested the parts for high voltage corona, a requirement for this product. This was to ensure that we did not create a new problem while eliminating the broken wires.

III. Results

The only acceptable group with no failures was group 5 (see table 3.), in which we replaced the Formula 456/Mica encapsulation material with the Epon 828/Mica/Z encapsulation material. Measurements on the material confirmed significant differences in the physical properties. We had Vanguard manufacture a second qualification lot, 37 transformers, to confirm that the Epon 828/Mica/Z encapsulation material eliminates the broken wires. We had 0 out of 37 fail. Twenty-seven of the 37 transformers were TC 105 times with no failures. Since the second qualification build, Vanguard has maufactured 158 WR transformers. Eleven of the 158 have been D-tested, 105 TC with no failures.

Test Results obtained from the physical characterization testing of the 828/Mica/Z and 456/Mica samples are summarized in Table 5. The materials were manufactured to the production process specifications used when processing the material for encapsulating the transformer. Physical testing, to measure the glass transition temperature (Tg), the coefficient of thermal expansion (CTE) and tensile modulus, was performed to compare data with previously run data.

Dynamic mechanical testing (DMA) was used to measure the Tg of the material. The CTE was measured over a temperature range of –50°C to 74°C with a Thermomechanical Analyzer (TMA). The tensile modulus was measured with an Instron load frame at a crosshead rate of 0.2 in/min using a rectangular shaped specimen.

GROUP#	SS	TC	F/C	F/O	TC	F/C	F/O	TC	F/C	F/O	T_F	FR
1	10	5	0	0	30	NT	2	105	0	2	4	40%
2	10	5	NT	0	30	NT	1	105	0	2	3	30%
3	10	5	0	0	30	NT	1	105	0	4	5	50%
4	10	5	NT	0	30	NT	1	105	0	3	4	40%
5	10	5	NT	0	30	NT	0	105	0	0	0	0%
6	10	5	0	0	30	NT	5	105	0	1	6	60%
7	10	5	NT	0	30	NT	1	105	0	2	3	30%
8	10	5	NT	0	30	NT	2	105	0	1	3	30%

Table 3.

Summary	SS	TC	F/C	F/O	T_F	TC	F/C	T_F/O	T_F	F/O_%	F/C_%
456_parts	197	30	2	2	4	>105	2	58	60	29%	2%
828_parts	48	30	0	0	0	>105	0	0	0	0%	0%

Table 4.

Property Measured	Value 456/Mica	Value 828/Mica/Z	Notes and Test Parameters
Glass Transition (Tg)	109°C	118°C	DMA test at 1Hz
CTE: -50°C to 22°C	53.5 ppm/°C	38.4 ppm/°C	TMA from -50°C to 74°C
22°C to 74°C	64.6 ppm/°C	43.0 ppm/°C	TMA from -50°C to 74°C
Tensile Modulus	694 ksi	898 ksi	Instron test at .2 in/min. Three samples each.

Table 5.

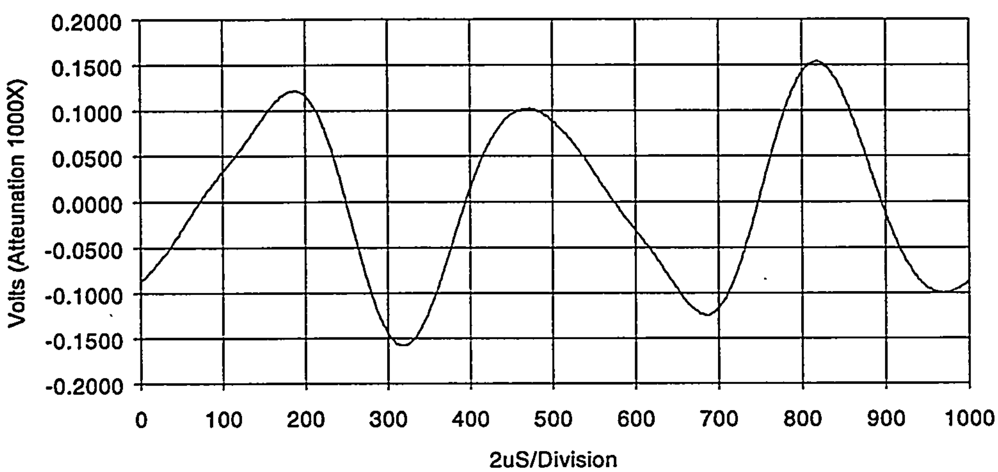


Figure 5. Good Transformer "No Corona"

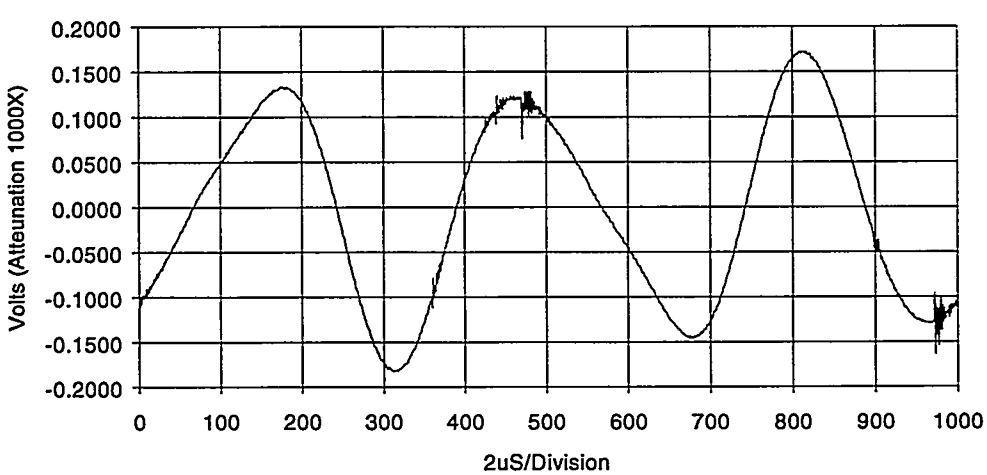


Figure 6. Defective Transformer "Corona Riding On Waveform"

Another summary that focuses on the different encapsulation material is shown in table 4.

An example of the results for a 6KV continuous sine into a coil is shown in figures 5 and 6. The two waveforms shown are typical for a good transformer and a defective transformer. The defective transformer demonstrates corona in the secondary winding.

New Improved Design

1. Bobbin -2616 size
2. Primary 20 turns of 30 AWG with center tap
3. Insulation over primary 3 layers of 2mil Kraft paper
4. Skein start & finish of secondary
5. Secondary 645 turns of 41 AWG, 43 turns/layer, 15 layers
6. Each layer of secondary separated by 2 layers of 2mil Kraft paper
7. Insulation over secondary 7 layers of 2mil Kraft paper, skeined high voltage output lead bedded in Kraft paper
8. Core -2616 size ferrite pot core
9. Surround Core/coil assembly with Glass micro-balloon filled Polysulfide boot
10. Solder start & finish primary & skeined start of secondary to appropriate pins on assembly fixture
11. Shrink red tubing over skeined secondary finish lead
12. Mold/impregnate/encapsulate with Epon 828/Mica/Z (Sandia formulation)

Kraft paper 0.370″ wide.

IV. Summary

The primary cause for the wire breakage was the difference in coefficient of thermal expansion (CTE) between the encapsulant Formula 456/Mica and the copper wire. As shown in table 5 the CTE for Formula 456/Mica is 53.5 ppm/°C, the CTE for copper is 17 ppm/°C. The difference is significant about 3 to 1. The CTE difference between the 828/Mica/Z and copper is about 2 to 1, which is still high but acceptable for this size package. Another fact considered is that we have approximately 25 years experience with 828/Mica/Z in this size package.

As stated in the abstract components designed for use in DOE systems must survive severe environmental testing. The original changes to the old design were considered significant, therefore the need to re-qualify the product. The fact that we had no failures out of the Prototype build or the PPI build has no real answer, other than to say the Formula 456/Mica used for those builds was not WR qualified material. WR qualified means the material was not purchased and tested to specific specifications (it was considered development material). The changes made prior to the qualification build were considered minor. These minor changes were implemented to try to eliminate voids in the winding. Narrower Kraft paper along with the higher vacuum accomplished this however narrower Kraft paper contributed to opens in the secondary. The reason the wider paper is better is that it fits snugly between the bobbin flanges, hence there is no slippage during winding. Besides reverting to 828/Mica/Z encapsulant, we also were able to incorporate the larger diameter secondary wire and were able to skein the start of the secondary. The results demonstrate a stronger/robust design.

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2. Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AI000.

References:

1. R. O. Sanchez, "A Method for Encapsulating High-Voltage Power Transformers", 11th Capacitor and Resistor Technology Symposium, March 1991, p. 42-47.