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AN OVERVIEW OF HIGH RELIABILITY TRANSFORMER ENCAPSULATION MATERIALS

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Abstract: Sandia National Laboratories (SNL) has been encapsulating electronic components for over 40 years. Several formulations have been in use and tested for 30 years. A prime objective in using formulations that have not changed lies in gaining a better understanding of the encapsulants long term aging and compatability characteristics. We have developed several formulations that are tailored to withstand a variety of environments. In some instances commercially available formulations have been used. Depending on the formulation and the component requirements, the encapsulants are used to attenuate or mitigate shock, provide improved mechanical properties, or improve electrical properties. Formulations that we have developed include epoxies, urethanes, and silicones. Filler materials such as Mica, Glass Micro Balloons (GMB), and Al_2O_3 may also be incorporated into these formulations.

The intent of this paper is to present an overview of encapsulation formulations that have been utilized for magnetic and transformer component applications.

I. INTRODUCTION

Sandia National Laboratories has been developing technologies for encapsulating electronic components for over 40 years. Over this period of time, our laboratory has developed numerous encapsulants that are designed to withstand a variety of environments. As an example, a component ambient temperature could range from –55°C to 80°C. A system could see humidity, shock, vibration, acceleration, or exposure to radiation during years of storage and transportation, and the hardware must still be functional, and ready for use. Therefore, depending on the environment the component is expected to see, it may be encapsulated in a variety of polymeric materials that are tailored to specific requirements.

Fillers are often used in encapsulation formulations to: (1) change the material density; (2) increase resistance to thermal or mechanical shock; (3) reduce exotherms; (4) lower the coefficient of thermal expansion (CTE), and; (5) reduce cure shrinkage. Our job as materials engineers is to combine the component requirements, materials and processes into a formulation that provides a high reliability product.

In some instances we employ commercially available formulations or our formulations are similar to comercially available ones. One reason for developing our own formulations is to meet the demanding reliability requirements asssociated with weapon design. SNL has determined that it is necesasary to minimize the variabilities that may be encountered in similar materials obtained from outside sources. For example we know that vendors may change a constituent without our knowledge that may ultimately affect outgassing, aging and/or material properties. To ensure that we understand the formulation, SNL conducts thorough characterization studies. This has resulted in a unique set of materials and processing specifications that are not necessarily consistent with MIL Specifications. Our formulations typically are highly loaded with fillers and our process specifications leave little room for deviation. The strict adherence to formulations and processes has resulted in our ability to provide highly reliable encapsulated components. Almost all problems with our formulated materials can be traced to unintentional deviations in materials or processing parameters.

The intent of this paper is not to review all of our formulations, but rather to provide an overview of several encapsulation formulations that have been utilized on Magnetic and Transformer components.

II TYPES OF MAGNETIC AND TRANSFORMER COMPONENTS

Sandia has more than 100 designs of weapons components that have been fielded in weapons subassemblies. As part of our requirement to provide high reliability components, SNL has been studying the long term effect of aging on various component designs. Encapsulation materials for several types of components will be discussed.

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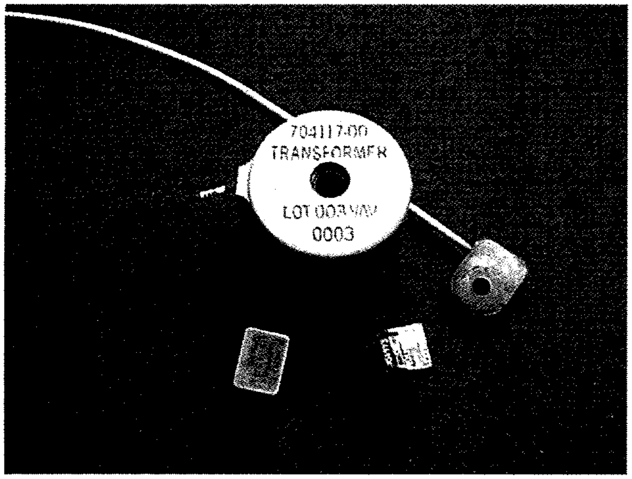


Encapsulated components

Power Transformer
A typical power transformer consists of a primary winding of 24 turns of 28 gage copper magnet wire, and a secondary winding with 765 turns of 38 gage magnet wire. The primary is a single layer separated from the secondary by Kraft paper. The secondary contains 18 layers. The coil is assembled into a ferrite pot core. These units may have surge voltages of 8 kV between windings. This type of component is usually encapsulated with an epoxy. Problems associated with this type of component encapsulation are typically component cracking and wire breakage.

Pulse Transformer
A typical pulse transformer contains a toroidal core that is encapsulated in a epoxy formulation. Problems associated with this type of component encapsulation are typically primary inductance change and leakage inductance change.

Current Viewing Transformer (CVT)
The typical SNL CVT design uses a toroidal core with a primary winding that has a resistor in parallel with the primary and is usually encapsulated in epoxy.

Other types of components such as inductors and flyback transformers are also encapsulated usually using urethane formulations.

III. Filled Encapsulants

Although unfilled resin formulations may be easier to process due to typically lower viscosities, they normally cannot be used where large volumes of encapsulant are required due to exotherms or cure shrinkage or where the component design produces internal stress concentrations that result in encapsulant or component cracking due to thermal cycling. It is therefore necessary to fill these formulations which can reduce internal stresses by (1)reducing cure shrinkage, (2) lowering the CTE, or (3)reducing exotherms. Fillers may also benefit by improving (1) strength, (2) impact resistance, and (3) thermal and electrical properties.

One of the first fillers that was used at SNL over 30 years ago was Mica. A specific powdered mineral filler, 4X Mineralite, obtained from Mineralite Sales Corporation was the only processable Mica filler found. This 4X Mica comes from only one mine located in South Carolina, and at the loading levels we employ was the only Mica filler we were able to process. The Mica imparts significant reductions in CTE, cure shrinkage, exotherms and improved electrical propeties.

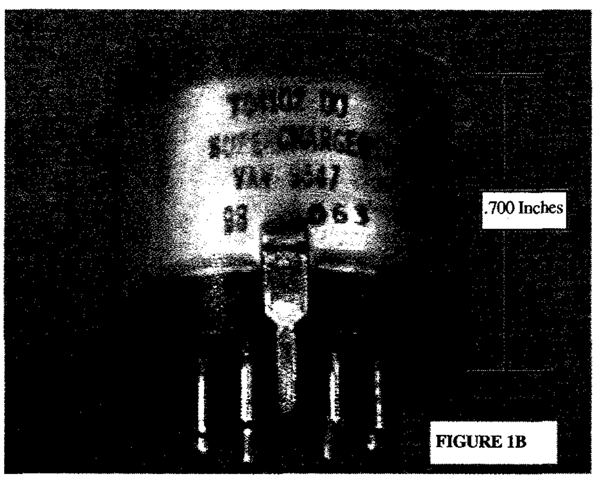
Epoxy resins became commercially available in the 1950's. One of the most commonly used epoxy resins is the reaction product of bis-phenol A and epichlorohydrin, these are typically referred to as Bis A epoxies. Two of the most common epoxies used at SNL are, Shell 828 and Shell 826, with the 826 having a lower molecular weight and viscosity. It should be noted that similar resins are available from other companies as well.

SNL utilizes several curing agents for our epoxy formulations. In selecting a curative we look at the temperatures a component can survive along with the temperature at which the component will be operated. One design criteria requires the encapsulant to exhibit a T_g (glass transition), after cure, that is above the use temperature of the component. This avoids degradation of the encapsulants physical properties above the encapsulant's cured T_g. Our formulations are also processed at elevated temperatures which reduces viscosity, permitting better impregnation of transformer windings, but increasing exothermic reactions with elevated temperature processing and cure temperatures. As materials engineers we must take into account all of these process variables to achieve the most robust encpsulant for the component and it's operating environment.

One of the first curatives to be incorporated into our formulations was Diethanolamine (DEA). DEA is a liquid curative that, when processed and cured at 71°C, gives us an encapsulant with a T_g of approximately 80°C and with a low exotherm. Some physical properties of the 828/Mica/DEA formulation along with the base formulation in parts by weight (PBW) are listed in Table I.

As our component requirements evolved and a higher use temperature material was required, we began utilizing aromatic amines as curatives. Specifically Shell "Z", which has now changed to Ancamine "Z" , has been used. Shell "Z" is a eutectic mixture of methylene dianiline (MDA), and metaphenylene diamine (MPDA). The "Z" cured formulation, when processed at 71°C and cured at 93°C, gives us an encapsulant with increased temperature capability, improved toughness, electrical properties, and solvent resistance. The 828/Mica/Z cured formulation is our most commonly used encapsulant for transformer applications. The use of this formulation requires that the components can withstand the higher cure and exotherm temperatures. Physical properties along with the base formulation in parts by weight (PBW) are listed in Table 1.

In the early 1990's OSHA reagulated the use of MDA because it is a suspect carcinogen. Since Ancamine "Z" contains MDA, efforts have been undertaken to develop alternatives to our "Z" cured formulations. Two formulations have been developed at Sandia[1]. These are aliphatic amine cured epoxy systems. Formula 456 consists of Shell 826 epoxy, a Dow phase- separated acrylic rubber modifier, and is cured with a blend of Jeffamine D-230 (a flexible polyether diamine) and Ancamine 2049 (a cycloaliphatic diamine). Formula 459 does not contain the acrylic rubber modifier. These systems have been filled with Mica and have been used on some transformer applications. The 456 and 459 formulations have been discussed in a previous EMCW conference presentation and physical property data is listed in the proceeding of the 1995 EEIC/EMCW conference proceedings publication.

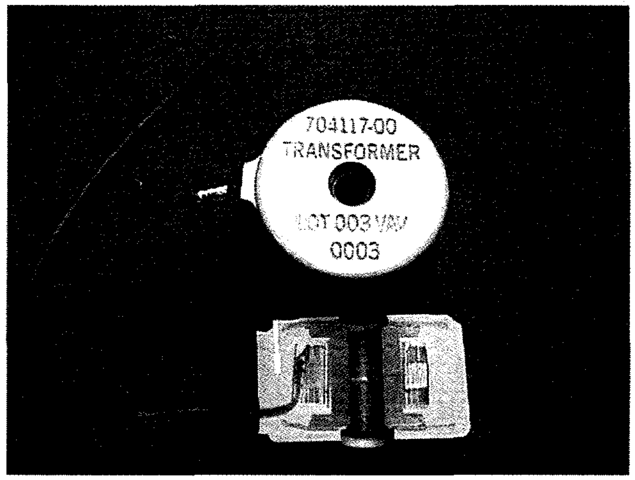


Conap EN-7 encapsulated Transfomer

IV. UNFILLED FORMULATIONS

All of the epoxy formulations that have been discussed can be used without the Mica filler for specific applications. Physical property data for two unfilled epoxy systems are listed in Table I.

Our most widely used unfilled encapsulant though is a commercially available urethane, specifically Conap EN-7. The EN-7 system, like our formulated epoxies, has been in use for many years; in fact SNL has been using this system for encapsulation for over 20 years. The formulation is a low outgassing, temperature cured encapsulant that exhibits outstanding electrical properties. Transformers such as the one pictured above have traditionally been encapsulated with this formulation.



Cross section of encapsulated/Impregnated Transformer

V. ENCAPSULATION PROCESSES

Although it is not the intent of this paper to present an overview of the encapsulation/impregnation processes, it would be prudent to discuss some of the aspects of the encapsulation processes that are critical to the success of using our formulations for transformer applications.

Coil Drying

Coils are dried prior to encapsulation to remove moisture. Typically coil drying is done at 110°C for a minimum of 4 hours, and at a vacuum of 1-3 Torr. The vacuum is then broken to atmosphere using dry nitrogen. The units are then stabilized at the required pre-heat temperature for the encapsulation process.

Filler Drying

The Mica filler is dried at 107°C for 4 hours minimum. The filler is placed into drying pans, not over 2 inches in depth. If required, the filler can then be stabilized at the required encapsulation process temperatures.

Vacuum Encapsulation

Vacuum encapsulation is critical to achieving impregnation and void free encapsulation. A typical encapsulation process would include a vacuum degas of the encapsulant and introduction of the encapsulant into the mold at a vacuum level of 1-3 Torr. Once the mold is filled it is evcauated for 2-5 minutes at 1-3 Torr, and then the vacuum is broken to atmosphere slowly. To minimze void size in the finished product the molds are sometimes cured under a pressure of 80 psi.

TABLE I
Epoxy Formulations Physical Properties

	EPON 828- 100 pbw DEA- 12 pbw	EPON 828- 60 pbw MICA- 40 pbw DEA- 7.2 pbw	EPON 828-100 pbw Ancamine Z-20 pbw	EPOPN 828- 100 pbw Mica- 100 pbw Ancamine Z- 20 pbw
Tensile, ASTM D638				
Stress, psi	11.600	8,350	13,000	7,430
Strain, %	No yield	No yield	No yield	No Yield
Modulus, psi x 10^6	0.41	0.88	0.44	---
Compressive, ASTM D695				
Stress, psi	25,300	23,000	61,800	19,120
Strain, %	4.4	3.3	8.7	4.6
Modulus, psi x 10^6	0.56	1.03	0.50	0.84
Flexural, ASTM D790				
Stress at rupture, psi	15,200	12,000	19,100	11,920
Modulus, psi x 10^6	0.47	0.83	0.46	0.91
Dielectric Constant, ASTM D150				
10^3	3.85	4.71	4.18	4.45
10^4	3.84	4.61	4.09	4.14
10^6	3.69	4.36	3.77	3.71
Dissipation Factor, ASTM D150				
10^3	0.003	0.022	0.008	0.054
10^4	0.003	0.023	0.018	0.041
10^6	0.018	0.025	0.030	0.031'
Volume Resistivity, ASTM D257				
Room Temp., ohm-cm	6.7×10^{10}	1.3×10^{15}	7.6×10^{15}	7.0×10^{15}
200°F 500V	1.5×10^{10}	1.2×10^{10}	9.7×10^{14}	2.0×10^{14}
Dielectric Strength, ASTM D149				
V/Mil	445	420	480	420
Coefficient of Thermal Expansion, D696				
-55 to RT in/in/°C	53×10^{-6}	44×10^{-6}	49×10^{-6}	33×10^{-6}
RT to 74°C	82 x 10'6	52×10^{-6}	59×10^{-6}	40×10^{-6}
Glass Transition, °C	70	71	117	121
Density, g/cc	1.2	1.52	1.2	1.6
Peak Exotherm	88°C	83°C	155°C	98°C

VI. CONCLUSIONS

Sandia National Laboratories has developed formulations for the encapsulation/impregnation of transformer and magnetic devices that are required to support various Department of Energy weapons programs. To provide high reliability components that will survive a variety of environments, SNL has developed epoxy and urethane encapsulation formulations. Utilizing these formulations and specific processing parameters, SNL has been able to provide high reliability components for over 30 years. These formulations have been extensively tested and are well characterized.

VII. REFERENCES

1) R. O. Sanchez, Linda Domeier, Shelton Gunewardena, "Impregnating Magnetic Components With MDA Free Epoxy", EMCW '95 Proceedings, 1995, pp141-146.

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Key Words:

Encapsulation, Impregnation, Epoxy, Urethane, Transformer