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Manufacturing High Reliability Weapon Grade Transformers in Small Lots

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ABSTRACT

Sandia has used flyback transformers for many years, primarily to charge capacitors for capacitive discharge units. Important characteristics of the transformer design are to meet inductance, turns ratio, and high voltage breakdown requirements as well as not magnetically saturating during each energy transfer cycle. Sandia has taken over production responsibility for magnetic components from a previous GE/LM, General Electric/ Lockheed Martin, facility in Florida that produced ~ 50K units per year. Vanguard Electronics is working with Sandia to transfer many of these designs to Vanguard's small manufacturing facility in Gardena, CA. The challenge is to achieve the required high reliability and meet all the other electrical requirements with such small quantities of parts, ~ 100 per year. DOE requirements include high reliability ≤ 3 failures per 10000 components per 20 years while meeting numerous other environmental requirements. The basic design and prove-in required four lots of preproduction parts, extensive environmental testing, and numerous design changes.

The manufacturing problems that affected performance of the transformer will be presented. These include encapsulation voids and core alignment. Also, some extended life test data that predicts long term reliability of newly produced transformers versus older designs will be compared.

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Introduction

Martin Marietta Specialty Components (formally General Electric Neutron Devices-GEND) was the primary contractor for all magnetic components for the Department of Energy, DOE, Nuclear Weapons systems. At the peak of production, they produced approximately 50K components per year. As part of the DOE downsizing, DOE gave Sandia National Laboratories (SNL) production responsibility for magnetic component manufacturing. SNL's mission assignment is to produce about 250 components per year for weapons using two commercial suppliers as the manufacturers. The same reliability is required, less than 3 failures per 10^4 components over 20 years of field performance. This paper will cover the transfer of one design, a flyback supercharger transformer, and manufacture and shipment of 58 components. SNL is relying on the product realization process to guarantee the ultimate field reliability. The emphasis of the paper will be on covering all the project aspects that ensured the field reliability of the component.

Project Outline

SNL has transferred a flyback transformer design from GEND to an outside vendor, Vanguard Electronics. SNL set up a PRT, Product Realization Team, that included, design engineers, manufacturing engineers, quality engineers, and purchasing to carry out the project. The PRT worked with the supplier to improve the design, and to manufacture prototype, PPI (product prove in), TMS (tool made samples), and production parts. Vanguard and the PRT developed new improved manufacturing processes as the project progressed. These process improvements were initiated because at key milestones in the execution of the project, the PRT encountered significant problems. The yields, < 12%, from the first TMS lot were unacceptable since yield is a measure of quality. SNL and Vanguard initiated several quality initiatives that reduced subsequent defect rates. The first yields from the second TMS lot were much better. There were about 50% rejects for primarily cosmetic reasons, i.e., inconsistencies with the basic drawing that did not affect form, fit, or function. Vanguard has successfully shipped 58 WR parts to Allied Signal in Kansas City.

Specific Requirements

A basic set of customer requirements for this part did not exist. GEND manufactured the part to a set of drawings and a product specification, PS. The PS used by GEND did not include any environmental test requirements. The PRT, through a series of conversations and meetings, generated set of customer requirements including environmental test requirements. The PRT added additional guard bands to the PS to insure that the product would meet all next assembly requirements taking into account variations in vendor test system accuracy. A summary of the electrical requirements are found in the Table1 below:

Table 1 Electrical Requirements

Requirement	Reliability	Inductance	Voltage Ratio 1-2/6-7	Voltage Ratio 3-4/6-7	Resistances
Values	$\leq 3/10000$ parts /20yrs or less than 1.8 Fits*	145 to 165 uH	.455 to .475	.400 to .420	50m Ω max 440m Ω max 180m Ω max

One Fit is one part failure per 10^9 part * hours.
Shock requirements are per the following table:

Table 2. Shock Requirements

Direction	Level	Duration
+ x	1000g	8ms
- x	1400g	0.8ms
$\pm y, \pm z$	2700g	1ms

Component Design

The primary function of the transformer is to transfer energy, therefore the design is optimized to maximize the energy transfer per cycle. This requires a gapped core for the transformer to avoid magnetic saturation. The magnetic circuit has leakage flux that reduces the voltage coupling. The basic design of the component uses a gapped-ferrite-pot core, ferroxcube part number 1811P-A160-3B7 with a .013 inch gap. The primary (P) is 31 turns of 26 gauge wire, and there are 2 secondary windings, 13 turns of 34 gauge wire wound as secondary 1 (S1) and 15 turns of 34 gauge wire for secondary 2 (S2). The turns ratios for S1/P and S2/P are .42 and .48 respectively. However, the actual voltage ratio requirements are .41 $\pm$.01 and .465 $\pm$.01 respectively, reflecting the leakage in the magnetic circuit.

The design uses a Delrin bobbin, which fits inside the core to house the coil windings. After the bobbin is wound, the bobbin, core, and hardware assemblies are put together as Figure 1A. Figure 1B shows the completed part, and Figure 1C shows a section view of the part. The core halves are bonded together to assure minimum gap between the outside surfaces of the cores and no misalignment, i.e., the centerlines of the cores must align. The whole assembly is placed in an RTV mold and encapsulated under vacuum using EN7, polyurethane, as the encapsulating material. This material produces low stresses on the cores, is hermetic, and protects the assembly from the environment. The curing is done at ≥ 70 PSI which aids in eliminating internal voids. One post encapsulation machining operation is required to meet the component height requirements.

An isometric view of the transformer

Figure 1A

704102 Supercharger Transformer

Cross Section of Transformer

Project Execution

A project plan was used as guidance for the whole project. The PRT produced a project plan that meets all of the project needs as well as system requirements. The project has a three-phase development process that requires three groups of parts for evaluation. Prototypes are built to confirm the basic design, PPI parts

are built to evaluate projected yields, and the TMS parts are built to confirm manufacturing capability for WR products. The parts are 100% tested for all electrical requirements per the product specification. All electrical testing is done at the vendor's site with commercial equipment. The PRT required additional testing at SNL as a verification of the testing accuracy.

Manufacturing Problems

One aim of the project and the PRT process is to make the parts per the drawing set. In this regard, the manufactured parts showed improvements and setbacks as the project progresses. The manufacturing process was taking the normal mode of continuous improvement through PPI parts that had excellent quality. However, Vanguard had a change in some of their key personnel. This resulted in many new problems for the first lot of TMS parts. The first TMS Lot produced some WR, War Reserve, quality parts, but the yields were too low for the PRT to accept the product. The second TMS Lot did yield enough WR parts to meet committed schedules, but some problems persisted. SNL and ASFM&T introduced a root cause analysis process by training key Vanguard personnel and using the process to refine the corrective actions identified and implemented. The results were superb. Vanguard had a much improved yield (> 70%) on the first manufacturing lot which fulfilled the rest of the authorized quantities. The following Table 3 indicates the major problem areas at each stage of manufacture and the indicated corrective actions:

Table 3 Major Problem Areas

Manufacturing Lot	Problem Area	Corrective Action	Transformer Performance Consequences
Prototype Units	Low Inductance	New process established for locating and bonding core halves	Low inductance could affect charging circuit timing
	Encapsulation voids (see Figure 2)	Refine encapsulation process and cure under pressure	Lower voltage breakdown measured experimentally
PPI Units	No Significant Problems		
TMS Lot 1 Units	Routing of the wires per drawing	Vanguard engineers will retrain operator.	Possible shorting or voltage breakdown problems
	Scratches on wires	Add tape to cores and can as manufacturing aid for protection.	Possible shorting or voltage breakdown problems
	Solder splash on to magnet wire	Operator will take care to eliminate splash.	Possible shorting or voltage breakdown
	Encapsulation voids	Vanguard engineers will retrain operator.	Lower voltage breakdown measured experimentally
	Low inductance electrical failures	Vanguard will record inductance as in-process test.	Defective parts (fail PS requirements)
	Electrical polarity failures	Vanguard engineers will retrain operator.	Defective parts (fail PS requirements)
	Part height requirement out of specification	Vanguard will review process. Height requirement will be relaxed.	Defective parts per drawing requirement may affect next assembly
TMS Lot 2 Units	Electrical polarity failures	Wires will be labeled during processing.	Defective parts
	Marking not legible	SNL drawing 704102 changed location on unit of	Loss of ID by serial number but does not affect

		lot number and serial number marking.	performance
	Solder joints protruding outside the surface of encapsulant	Vanguard engineering added a note to their drawing to push down the wire connection flush to the header surface.	Performance not affected, could be a solder reflow problem at next assembly
	One unit was rejected for large void on the top (tear out) after rework to meet the height specification.	Engineering will write a procedure for trimming, cut down the component, also determine tools, speed and maintenance for the operation.	Performance not affected by surface voids. Internal voids in the region of the coils affect voltage breakdown.
	One unit misaligned within encapsulation	Operator has been instructed to follow exactly step 16(c) of Vanguard production drawing prior to encapsulation.	Performance not affected.
	Ten units were rejected for internal voids greater than 0.020 in. at final visual inspection	Vanguard engineers will retrain the operator.	Lower voltage breakdown
	Scratches on the wires were detected at in-process inspection.	Replace metal tweezers by ESD safe ones, made with softer material	Lower voltage breakdown
Manufacturing Lot 1	No significant problems		

Encapsulation Bubbles/Voids

Figure 2

Test Results

The testing performed on the part falls into two categories, one test to confirm that the part will meet the product specification requirements which are functional tests and D-Tests. The D-Test specification was added to meet new customer requirements. Part of the D-tests is to ensure that the part will function after being shipped and assembled. Part of our evaluation was to ensure that the transformers meet the 20-year life requirements. The basic approach was to measure the critical functional parameters before and after environmental stresses to assess long term reliability. The PS test requirements are set to meet all of the customer electrical test requirements, meet customer shock and vibration requirements, and meet hot and cold sample testing as proven with development parts. We have three sets of test data from prototype, PPI, and TMS parts. The prototype test data pointed to several problems with the manufacturing process. A serious electrical test problem was encountered with the inductance requirement. There was a dropout of 10% for low inductance, and the mean value was near the lower limit. A transformer with this core and with the 31-turn winding would have an inductance of $\sim 154 \mu\text{H}$ based on an inductance of 160mH for 1000 turns. The low inductance could be caused by several problems: stress on the cores, misalignment problems, cores cracking, bad core material, and inaccurate winding. Several parts were cross-sectioned (Figure 3) to determine if core problems were the root cause. The resulting analysis revealed a misalignment and gapping problem with the cores.

Misalignment of core halves

Prototype Test Data

The PRT designed an experiment to determine the effects of the encapsulation-curing environment. We also compared data collected at Vanguard versus data collected at SNL. The PRT compared prototype test data as follows in Table 4.

Table 4 Prototype Test Data

Prototype Test Data Comparing Encapsulation-Curing at Atmospheric and 80PSI			
Sample size=N=13, cured at atmospheric pressure			
Inductance, L, requirement is 145<L>155uH	<L>	Sigma	Cpk
Vanguard test data	150.5	2.87	0.64
SNL test data	149.7	1.98	0.79
SNL test data after 5 temp cycles	149.6	2.13	0.72
Sample Size N=14, cured at 80 PSI			
Inductance requirement is 145<L>155uH	<L>	Sigma	Cpk
Vanguard test data	144.8	3.21	-0.02

SNL test data	144.7	3.13	-0.03
SNL test data after 5 temp cycles	146.6	2.25	0.24
N=13 cured at atmospheric pressure			
Voltage ratio 1-2/6-7, V ratio requirement .455<V ratio<.475	<V ratio>	Sigma	Cpk
Vanguard test data	0.464	7.00E-04	5.24
SNL test data	0.467	7.00E-04	3.81
N=14 cured at 80 PSI			
Voltage Ratio 1-2/6-7, V ratio, Requirement .455<V_ratio<.475	<V ratio>	Sigma	Cpk
Vanguard test data	0.464	9.00E-04	4.07
SNL test data	0.467	6.20E-04	4.30
N=13 cured at atmospheric pressure			
Voltage ratio 3-4/6-7, V ratio requirement .400<V_ratio<.420	<V ratio>	Sigma	Cpk
Vanguard test data	0.409	7.00E-04	4.29
SNL test data	0.415	3.50E-03	0.48
N=14 cured at 80 PSI			
Voltage Ratio 3-4/6-7, V ratio, requirement .400<Vratio<.420	<V ratio>	Sigma	Cpk
Vanguard test data	0.409	9.60E-04	3.12
SNL test data	0.414	4.50E-03	0.44

The main benefit from pressure curing was the reduction of encapsulation voids. There did seem to be an effect on the inductance, i.e., parts cured at high pressure had lower inductance. This problem was solved via other process changes. Therefore, we retained the high-pressure cure. The data also shows a close correlation between Vanguard and SNL test systems.

PPI Test Data

The PPI test results were much better as shown in Table 5. This is for a sample of 34 PPI parts. This table shows a summary of electrical test results with the C_{PK} values:

Table 5 PPI Test Data

Parameter	Inductance	Turns Ratio 1-2/6-7	Turns Ratio 3-4/6-7
Requirement	145 to 165	.455 to .475	.400 to .420
Mean	151.9	.467	.410
Sigma	1.49	8.2e-4	7.7e-4
C_{PK}	1.54	3.08	1.54

These C_{PK} values indicated an excellent manufacturing process.

Shock and Vibration Results on PPI Units

After shock and vibration testing per the PS performed at National Technical Systems Test Report No. 673-1060-5, we obtained the following results in Table 6:

Table 6 Test Data after Shock and Vibration

Parameter	Inductance	Voltage Ratio 1-2/6-7	Voltage Ratio 3-4/6-7
Requirement	145 to 165	.455 to .475	.400 to .420
Mean	152	.469	.411
Sigma	1.5	5.67e-4	11e-4
Cpk	1.56	3.37	2.65

The following Figures 4-6 are the histograms for the 3 parameters, L, V ratio 1-2/6-7, and V ratio 3-4/6-7:

Figure 4

Figure 5

Figure 6

National Technical Systems could not perform the 1000G 8Ms-haversine-shock test in the +- X-axis. This customer requirement was not defined until the TMS review. Consequently, five parts from TMS #1 were

selected for this test. SNL Labs performed the tests. These five parts were also used for hot & cold. Both tests are for the customer requirements and are now specified in the PS. The results follow in Table 7:

Table 7 Test Data after Environmental Tests

Ratio	Part #	2	8	17	18	20	AVG	Req
1-2/6-7	pretest	0.46749	0.4683	0.469	0.4679	0.4666	0.468	.455/.475
3-4/6-7	pretest	0.41349	0.40991	0.41197	0.41162	0.41392	0.412	.400/.420
inductance	pretest	153.28	151.98	151.97	157.8	152.13	153.432	145/165
1-2/6-7	after shock	0.46748	0.46826	0.46854	0.4680	0.46659	0.468	.455/.475
3-4/6-7	after shock	0.4134	0.40984	0.41187	0.41163	0.41388	0.412	.400/.420
inductance	after shock	153.59	152.32	152.12	157.8	152.94	153.754	145/165

Hot and Cold Testing on TMS #1 Units

There are also a hot and cold tests required in the requirements drawing which is specified as deemed necessary in the PS. The hot and cold temperature tests are not D-Tests. The results are as follows in Table 8:

Table 8 Test Data after Hot and Cold Tests

Ratio	Part #	2	8	17	18	20	AVG	Req
1-2/6-7	-31C	0.4555	0.4565	0.4575	0.4570	0.455	0.456	.455/.475
3-4/6-7	-31C	0.4025	0.3995	0.402	0.4015	0.4035	0.402	.400/.420
1-2/6-7	25C	0.4555	0.457	0.457	0.4570	0.455	0.456	.455/.475
3-4/6-7	25C	0.403	0.4000	0.402	0.402	0.4035	0.402	.400/.420
1-2/6-7	82C	0.4555	0.4555	0.456	0.4560	0.454	0.455	.455/.475
3-4/6-7	82C	0.403	0.399	0.401	0.401	0.403	0.401	.400/.420

Quality Issues

Introduction

There were numerous problems in the manufacturing processes through tool made sample parts. Vanguard had such a low yield with the first set of TMS parts that a second TMS run was made. The second TMS units were better but still had enough problems that SNL instituted a corrective action program to improve the quality for the final production run. Vanguard shipped no low quality parts, but did have low yields < 30% which required extensive screening. Following is a series of significant quality issues, and their resolution.

Low Inductance

The electrical test results for the prototype parts indicated low inductance. Parts with good and bad inductance readings were selected for evaluation. The parts were cross sectioned and results for high and low inductance parts showed two factors that would affect the inductance; (1) the core halves were misaligned and (2) there were gaps between the core halves on the low inductance parts. The higher inductance parts showed good alignment and a gap about 1/5 of that of the lower inductance failures. The PRT team implemented new procedures for the PPI parts. The cores would be thoroughly cleaned, aligned, and adjusted for optimum inductance, clamped in position, and then bonded with a thin layer of epoxy around the outside edge of the cores. Vanguard added this process to the manufacturing process drawings. The PRT selected Hysol EA 934N as the bonding material, since SNL has used it on other product.

Encapsulation Voids

During manufacture of the pre-prototypes, voids in the encapsulation were a significant problem. SNL helped Vanguard with fine-tuning of the process. We also found out that MMSC was potting ≥ 70 -PSI pressure in order to eliminate voids. Therefore, the PRT decided to pot 1/2 of the prototypes at atmospheric pressure and 1/2 at 80 PSI. From the cross-sectioned part results and voltage test results (which showed a difference in voltage breakdown between the 2 groups), the PRT team concluded that encapsulation under pressure is required.

TMS Part Quality Problems

The PRT identified the following list of problems with the first TMS lot of parts. The first TMS lot had a yield of about 5 acceptable out of 40 parts. This was inadequate, so Vanguard made a second TMS group. The following are the identified problem areas and proposed Vanguard changes that the PRT identified from TMS # 1 (see Table 9).

Table 9 Production Problems and Solutions

Production Problem	Vanguard Improvement	Proposed Change
Routing of the wires per 704102	Inadequate training of personnel	Vanguard engineers will retrain operator.
Scratches on wires (see Figure 8)	No protection of wires from core and can	Add tape to cores and can for

		protection.
Solder splash onto magnet wire	Inadequate care in soldering operation	Operator will take care to eliminate splash.
Voids in encapsulation	Inadequate training of personnel	Vanguard engineers will retrain operator.
Low inductance electrical failures	No in process checking, inadequate check off procedure	Vanguard will require actual data to be collected for in process inductance measurement.
Electrical polarity failures	Inadequate training of personnel	Vanguard engineers will retrain operator.
Part height requirement out of specification	unknown	Vanguard will investigate. Height requirement will be relaxed.

Solder Protrusion through encapsulation

Scratched Magnet Wires

Summary

The second TMS lot was more successful. The yield was only 12/30 but the rejected parts were primarily rejected for reasons that would not affect reliability. The problem areas were: (1) Marking was not legible on some parts, (2) two parts had surface irregularities from the machining operations, and (3) on some parts the solder joints were not fully covered by the encapsulation (see Figure 7). The PRT approved all electrical and D-TEST data. SNL released the Quality Certification and the Department of Energy accepted 12 parts from the TMS lot.

Before the production run, Vanguard and SNL did a complete job of identifying problem areas. The PRT identified the root causes and set up a program to eliminate them. The final production run had a yield > 70%.