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FERRITE-CORE TRANSFORMER
BONDING AND POTTING

PDO 6984742, Final Report

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Internal Distribution January 1974

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**Kansas City
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BDX-613-992, UNCLASSIFIED Final Report, Internal Distribution
January 1974

Prepared by W. J. Kirk, D/845, under PDO 6984742

This work was conducted to develop methods of maintaining thermal stability in inductors enclosed in ferrite pot cores and encapsulated into assemblies. Satisfactory bonds between the core halves were obtained with EA934 adhesive at processing temperatures to 80°C. However, the force applied to the core interfaces during bonding is critical. Ferrite toroid and pot-core test coils encapsulated in rigid epoxy exhibited large inductance losses after potting despite the application of a thin layer of silicone rubber over the core surfaces. These losses were significantly reduced by adding 68 parts by volume (pbv) of Beta Eucryptite to the epoxy, thereby approximately matching the thermal coefficient of the encapsulant to that of the ferrite, approximately $10 \mu\text{m}/\text{m}/^\circ\text{C}$. Satisfactory impregnation of small pot-core coil windings was obtained with filler concentrations to 46 pbv; however, additional work will be necessary to obtain adequate impregnation with higher filler concentrations.

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SUMMARY

New pot-core bonding processes were developed because of reliability requirements on assemblies containing coils enclosed in ferrite pot cores. These processes are expected to provide adequate control of inductance in ferrite-core coils potted at temperatures to 80°C; however, further work will be required to obtain sufficient control at higher potting temperatures.

Previous work had resulted in stress-free potting of molybdenum permalloy toroids, but the scope of that work did not reflect significantly on the present application.

The investigation of bonding two-piece ferrite cores together after assembly included evaluation of three adhesives systems and development of techniques to minimize the air gap between the core halves. Hysol EA934 adhesive yielded acceptable bond strength and workability for transformers potted at temperatures below 80°C. Control of the magnetic gap between the core pieces was obtained by applying an optimum force when bonding the core sections together. The optimum assembly force was determined for a variety of core materials and sizes. An effort to bridge the magnetic gap with ferrite-filled adhesive produced only a slight increase in coil inductance and did not contribute to closer control of the air gap.

Two filled-epoxy systems that approximated the thermal expansion coefficient (CTE) of the core material (approximately $10 \mu\text{m}/\text{m}/^\circ\text{C}$) were developed. These systems were obtained by combining 68 percent by volume (pbv) of either Foote Mineral Company Beta-Eucryptite or Glasrock Products fused silica (SiO_2) Glasgrain GP31 with Shell Epon 828 and Miller-Stephenson Diaminodiphenyl Sulfone (DDS) hardener.

Although the CTE of the epoxy and ferrite cores were nearly balanced, the required additional stress relief was obtained by coating the ferrite core with a thin layer of silicone rubber. The layer thickness was calculated as a function of the dimensions of the core and the CTE of the core material. The amount of filler was altered for various test specimens to obtain the effect of the filler on the inductance of a ferrite toroid. All filler ratios used had a similar catastrophic effect on inductance when a silicone rubber coating was not used. A gradual increase of inductance with increased filler content was noted on toroids that were coated with silicone rubber. Although the inductance of the best test samples was not quite as high as unpotted specimens, enough data was compiled to indicate that a slightly thicker coating will be sufficient to eliminate the potting stress. Since the EA934 adhesive ferrite bond failed at 140°C, the potting stress effect on ferrite pot core inductance was inconclusive.

An ideal potting process for a ferrite core would provide a CTE equal to that of the ferrite, and at the same time, would easily impregnate the coil winding. These two design criteria are diametrically opposed; therefore, some compromise must be obtained. A low CTE requires a high degree of filling, whereas complete impregnation requires a low degree of filling. To obtain the knowledge necessary to improve the impregnation of highly-filled epoxy, various potting methods and materials were evaluated. Epoxy filled with Beta-Eucryptite provided significantly better impregnation than epoxy filled with fused silica. The impregnation of heavily-filled mixes (above 46 pbv) was poor when using DDS hardener. Further work must be done to obtain a filled epoxy system with better impregnation properties. Until then, use of epoxies with more than 46 pbv filler must be restricted to small coils with large wire, or the coil will have to be preimpregnated. Careful attention to epoxy flow paths and filler filtering in the coil design will increase impregnation depth in marginal coil designs. Until all of the identified methods of improving impregnation are combined and evaluated, good impregnation with highly-filled epoxies should not be expected.

A slight improvement in dimensional control of silicone rubber molds was obtained by adding 30 parts by weight (pbw) of GP7I silica in General Electric RTV 630. The improvement in dimensional stability was so slight that addition of filler to the RTV 630 should be reserved for products where improved dimensional stability is more important than additional cost.

Additional work should be done to obtain a better adhesive system for use with the 140°C potting processes. A better 140°C epoxy hardener and filler material combination is needed to improve the impregnation of pot core coils while maintaining the CTE required to yield stress-free potted cores.

DISCUSSION

SCOPE AND PURPOSE

Bonding two-piece ferrite pot cores to control coil inductance was evaluated to establish a satisfactory process for holding the cores together after assembly. The technology and experience gained from the evaluation will be applied to the manufacture of transformers currently in development. Information obtained from this work is expected to be useful also in solving problems encountered in a general class of core configurations where two or more ferrite pieces must be bonded together to complete a magnetic path.

The activities associated with ferrite-core bonding are divided into three major areas: selecting and evaluating adhesives, determining the optimum process that will produce a minimum air gap at the core interface, and evaluating techniques to reduce the effective air gap by introducing a magnetic path which shunts the physical air gap at the core interface.

Ferrite cores are used commercially without applying any type of potting around the core; thus the ferrite is free of stress. The severe environments encountered with AEC systems require that transformers be potted to maintain a high level of reliability. The ferrite material must be free of potting stress for a ferrite transformer or inductor to perform satisfactorily over a temperature range of -55 to +100°C. Two approaches have been suggested. One is the use of a flexible potting material that will not transmit stresses to the core material. The other is the use of a potting material with the same CTE as the ferrite core material. Both approaches have been evaluated. Polyurethane (Adiprene) with a polyol additive provided a stress-free unit, but it was very flexible. Because of the severe environmental requirements, an alternate approach was developed: a rigid filled epoxy with an appropriate CTE. Previous experience in potting a powdered-molybdenum permalloy core indicated the filled epoxy approach should be satisfactory if a thin cushion of some very resilient material such as silicone rubber were used to provide a slight amount of additional stress relief. The processes required to apply a thin coat of silicone rubber to the core and to obtain an epoxy with a low CTE were developed.

The coil winding must be completely impregnated so the magnet wires will not move in severe environments such as acceleration, and so high-voltage transformers will receive adequate voltage protection. One solution to this problem is to coat the core with silicone rubber, impregnate the winding with

a very thin unfilled epoxy, and encapsulate the assembly with a filled epoxy. Unfortunately, this method involves considerable processing expense. A system which allows the impregnation and potting to be performed with one material and one processing operation saves considerable time. The same materials evaluated for stress relief were evaluated for impregnation. The epoxy impregnation included comparison of various process temperatures, evacuation techniques, and filler materials.

Transformers used in miniature electronic circuits require closer dimensional control than transformers used in larger assemblies. One approach to dimensional control improvement is to increase the dimensional stability of the molds. Another approach is to reduce the CTE of the potting material so more consistent results can be obtained. Silicone-rubber mold materials were filled with additional inert fillers in an effort to obtain a more stable mold at the processing temperatures and yet retain adequate pourability and mold-release properties.

PRIOR WORK

A lithium/aluminum/silicate-filled epoxy that yielded a CTE of approximately $15 \mu\text{m}/\text{m}/^\circ\text{C}$ was developed in 1965. In 1967, Curlee¹ reported similar results with fused silica filler. The current project is basically a refinement of these processes for application to ferrite pot cores with the greater problems of lower thermal expansion coefficient ($9.1 \mu\text{m}/\text{m}/^\circ\text{C}$ from 25°C to -50°C ; $11.4 \mu\text{m}/\text{m}/^\circ\text{C}$ from 25°C to 100°C) and presence of an air gap which must be carefully controlled.

ACTIVITY

Bonding

Magnetic Principles

A minimum air gap between the interfaces of core sections is necessary to obtain the maximum inductance in a given coil/core combination. Control of that gap is necessary for repeatability in manufacturing processes. While a minimum air gap is desirable for maximum coil inductance, reducing the gap makes it more difficult to control for best coil-to-coil repeatability. Since the permeability of air is much less than that of the ferrite coil materials (unity, as compared to permeabilities of about 25 to 6000 or more, depending on the core material) the smallest attainable air gap still results in a significant reluctance between the core sections,

thereby reducing the inductance of the coil enclosed in the core.

Therefore, variations in the length of the air gap make it more difficult to maintain inductance tolerances and adversely affect the Q of the coil in applications where circuit impedance and selectivity are critical.

In gaps between the interfaces of core sections it is more difficult to control a small dimension to a given percent tolerance than to control a larger dimension to the same tolerance. Therefore cores that are intentionally gapped are easier to control than nongapped cores that are bonded in close contact. However, where maximum inductance is desired for a given core configuration, nongapped cores must be used.

Adhesive Evaluation

Three adhesive systems were evaluated: Eastman 910 MHT, EA 934, and ferrite-filled EA 956. The desired properties of the adhesive are bond strength, reasonable ease of application, and adaptability to production processing. The bond strength is required to prevent changing of the air gap during core encapsulation or as a result of forces caused by temperature exposures. Increasing the air gap will decrease the inductance of the enclosed coil.

Eastman 910 MHT, a pressure-sensitive adhesive that cures rapidly at room temperature, was chosen for investigation principally because of possible processing advantages. The nearly instantaneous setting of the adhesive with pressure was expected to reduce assembly time and simplify process tooling.

EA 934 is a filled epoxy system that requires an ambient or an elevated-temperature cure cycle. This adhesive was included in the investigation because of previous successful use in bonding ferrite materials, thus providing a useful reference point for the evaluation of the other adhesive systems.

Ferrite-filled EA 956 was included in the investigation to determine the advantages of using an adhesive with higher permeability than that of air or of the nonferrous adhesives.

Eastman 910 MHT exhibited a relatively short work life, approximately 30 seconds, which seemed to be influenced by moisture content in the working environment. Low bond strength was another disadvantage of this adhesive.

An excessively-thick film, about 25 μm , resulted when this adhesive was applied to the mating surfaces, thereby increasing the air gap between the core interfaces.

EA 934 proved the most acceptable of the systems evaluated. The working life is over 30 minutes, and the viscosity is such that the adhesive can be applied with a small syringe. Bond strength was comparable to the filled EA 956 and was superior to that of Eastman 910 MHT.

The ferrite-filled EA 956 was difficult to work with at the high filler loadings, with a material texture similar to that of moist clay. Bond strength was determined at several filler-loading ratios to evaluate the effects of filler content. Bond strength was comparable to that of EA 934 and considerably better than that of Eastman 910 MHT.

The bond strengths of the three systems were compared by preparing five core samples of each adhesive and stressing the bonds until failure occurred. A Ferroxcube 2616P-LOO-3E7 26mm-diameter core was used. Figure 1 is a diagram of a typical core assembly.

The bonding procedure with the Eastman 910 MHT adhesive system was as follows.

- The cores were cleaned with trichloroethylene at 60°C in an ultrasonic cleaner for 4 minutes and exposed to 10-percent relative humidity for 24 hours.
- Individual sets of cores were assembled in an arbor press on a 5.41 mm diameter pin by using a die spring to control the 60-pound force (267 N) applied to the cores.
- Eastman 910 MHT was applied with a metal spatula to the outside surface at the parting line.
- Clamping pressure was released, then reapplied after 5 seconds.
- The cores were held under stress for 5 minutes.

EA 934 and Ferrite-filled EA 956 were bonded by this procedure.

- The cores were cleaned by the ultrasonic method as for Eastman 910 MHT.
- Five sets of cores were assembled on a 5.41-mm diameter rod by using a die spring to exert 60-pounds of force (267 N) at the core interfaces.
- An adhesive reservoir was fashioned from 25 mm diameter polyvinyl chloride tubing with openings over the bonding area.

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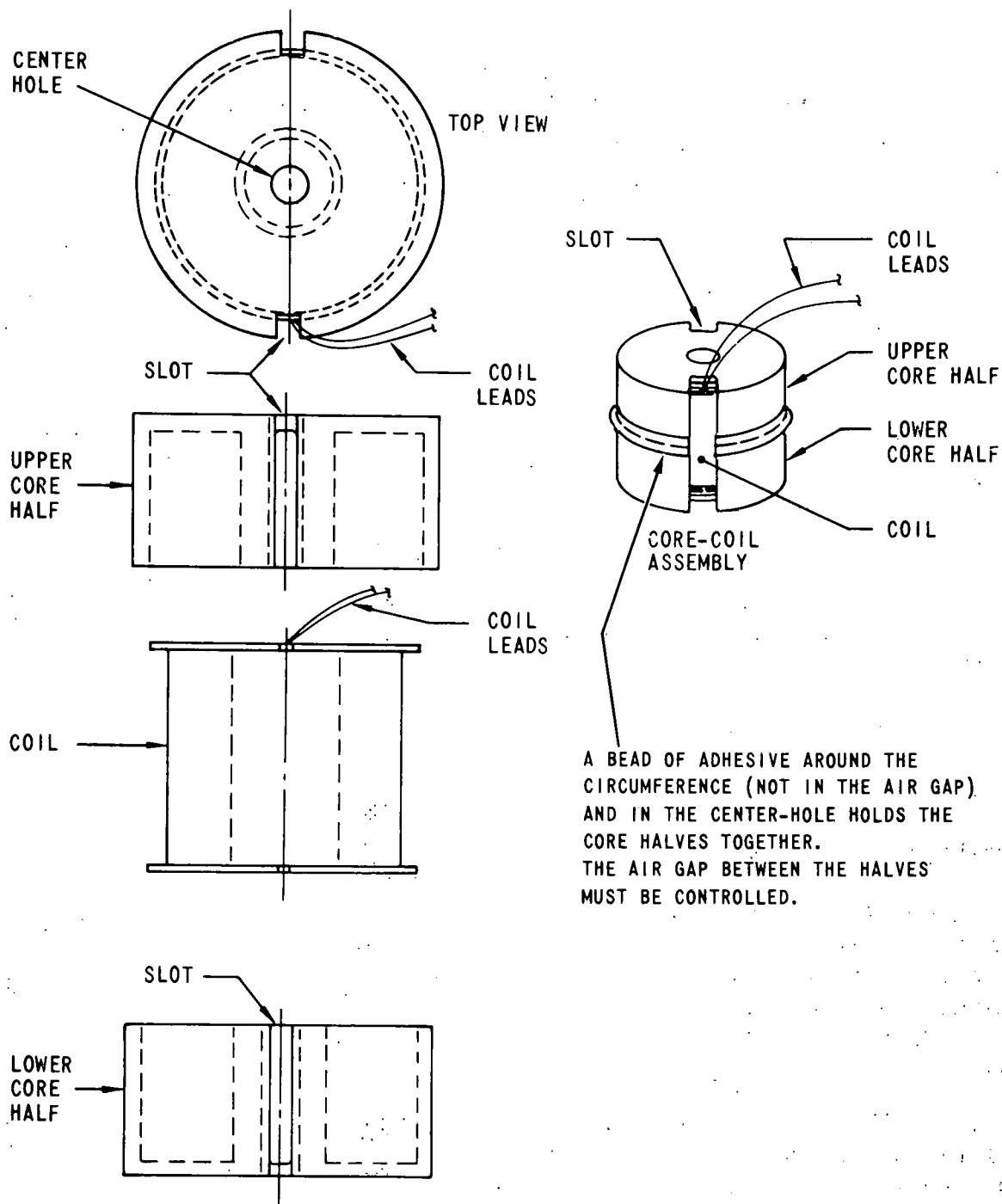


Figure 1. Pot-Core Coil Configuration

- The adhesive was worked into the reservoirs over the outside diameter of the cores with a metal spatula (EA 934 without filler and EA 956 filled with 85-pbw Magnetics, Incorporated, J-Perm ferrite powder).
- Rubber bands over Teflon film were used to hold the adhesive against the outside diameter of the core during cure.
- The cores were cured 1 hour at 80°C after a 2-hour minimum gellation period at room temperature.

Five samples from each of the three sets were prepared for pull testing.

- Threaded aluminum end plugs (test adapters) were bonded to each of the core samples.
- A 5.41 mm diameter pin was used to maintain the center line of the test specimen.
- An epoxy adhesive one-to-one ratio of Versamid 125 and ERL 0510 was used to bond the test sample to the aluminum end plugs.
- The specimens were cured 24 hours at room temperature.

The tensile strength results are listed in Table 1.

Processing Considerations

Experiments to obtain the minimum effective core gap were conducted to determine the amount of force required during bonding to produce the maximum inductance in a standard test coil enclosed in the core. Various core sizes and several types of Magnetics, Inc. core materials were included to provide a general Rule-of-Optimum-Force which could be applied to nongapped two-piece ferrite cores.

Force was applied only to the outside edges of the cores to prevent cracking in the center-post region. This axial force was increased in small increments through a value where maximum inductance was obtained. Increases in force beyond that point usually caused lower coil inductance, indicating that the core was overstressed. These data were normalized to the peak inductance measurements and were plotted against clamping force. Typical graphs are shown in Figures 2 through 6.

Text continues on page 25.

Table 1. Bonded Core Tensile Strength

Sample	Pull Strength* (lb) (N)	Location of Failure
Eastman 910 MHT		
1-1	8 (36)	Core Interface
1-2	203 (903)	Core Interface
1-3	82 (365)	Core Interface
1-4	75 (334)	Core Interface
1-5	78 (347)	Core Interface
EA 934		
2-1	178 (792)	Adapter
2-2	210 (934)	Adapter
2-3	93 (414)	Core Interface
2-4	110 (489)	Core Interface
2-5**		
85 Percent J-Perm Ferrite in EA 956		
3-1	77 (343)	Adapter
3-2	141 (627)	Adapter
3-3	192 (854)	Adapter
3-4	105 (467)	Core Interface
3-5	158 (703)	Adapter
<p>*Pull force was applied at a rate of 1.27 mm per minute.</p> <p>**Failed during bonding.</p>		

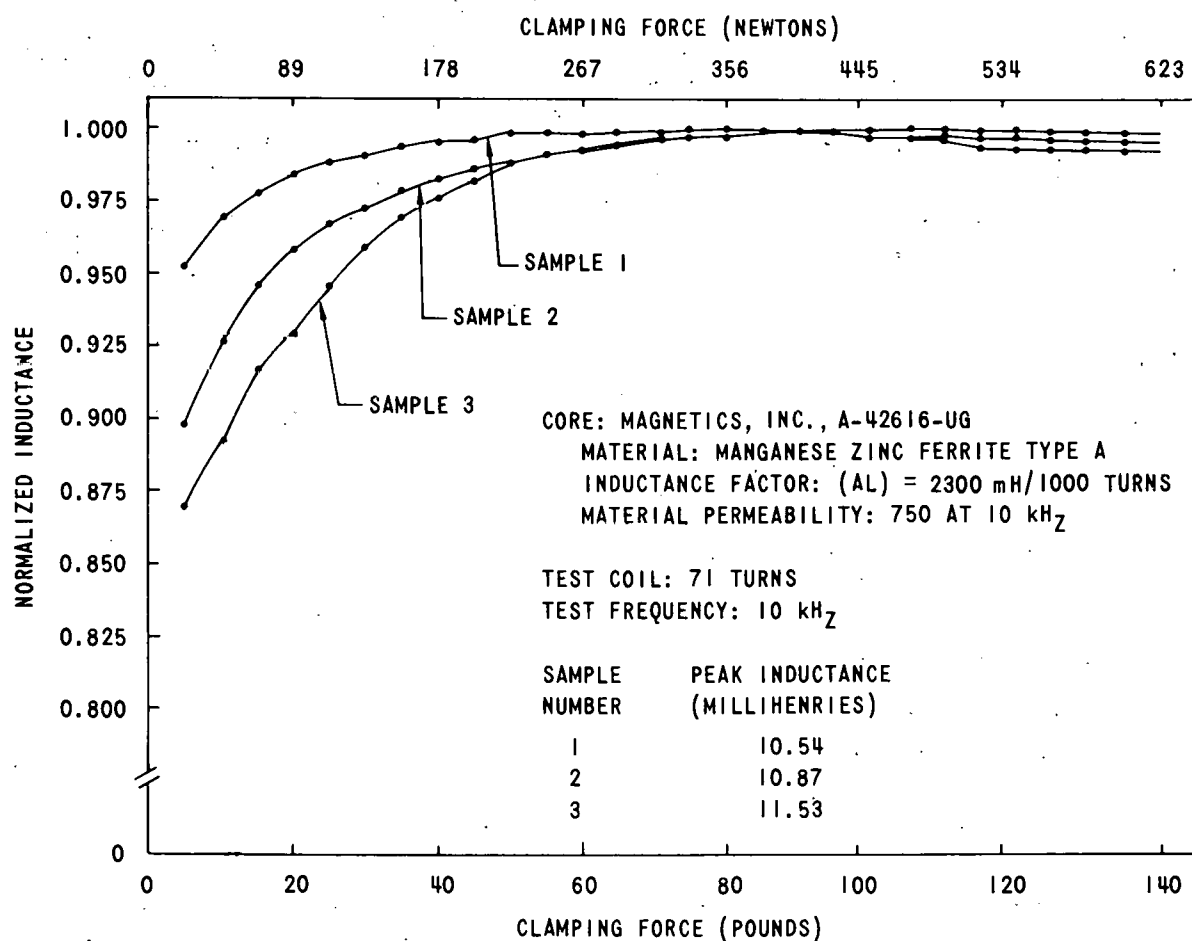


Figure 2. Inductance Versus Clamping Force, A-42216-UG Core

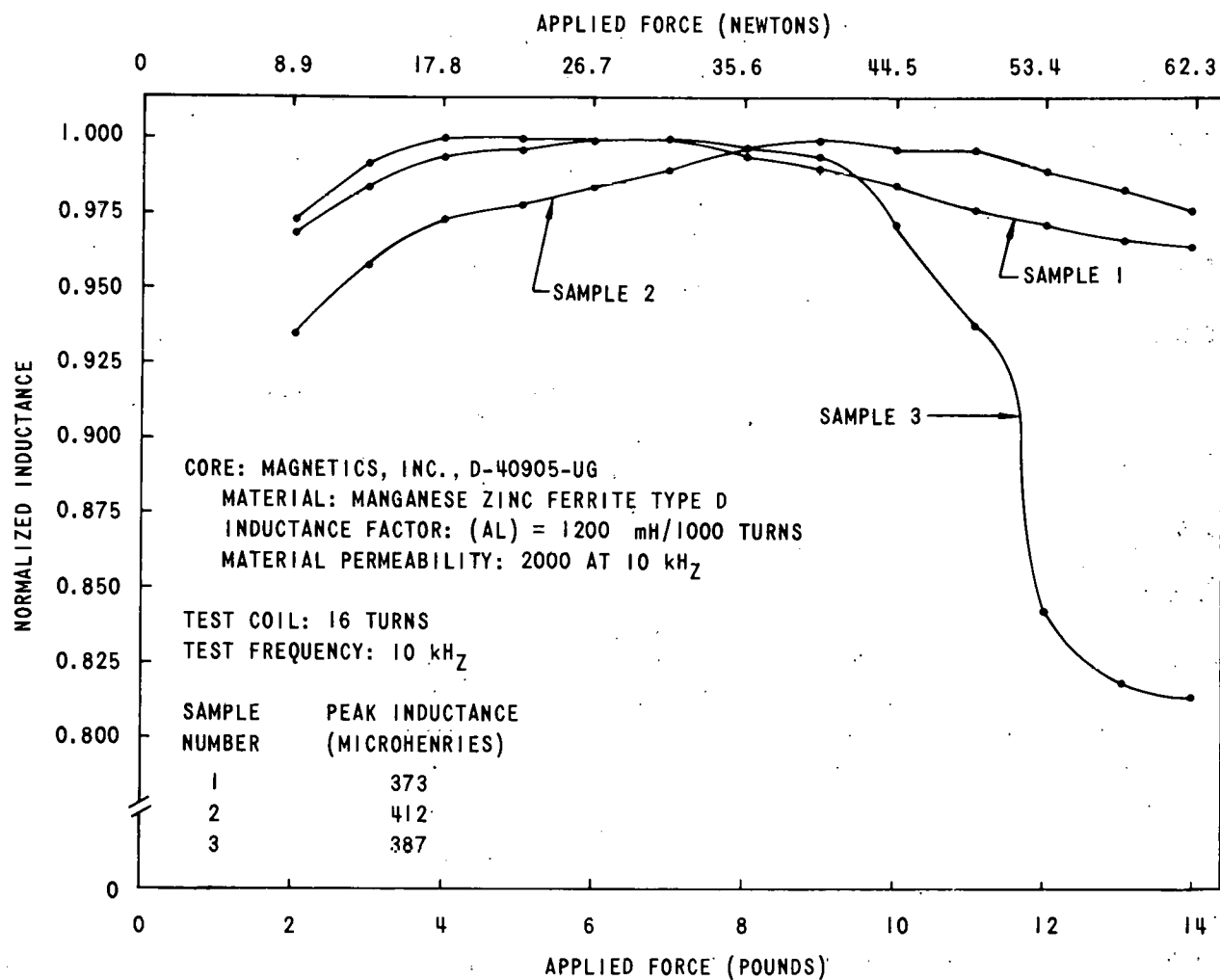


Figure 3. Inductance Versus Clamping Force, D-40905-UG Core

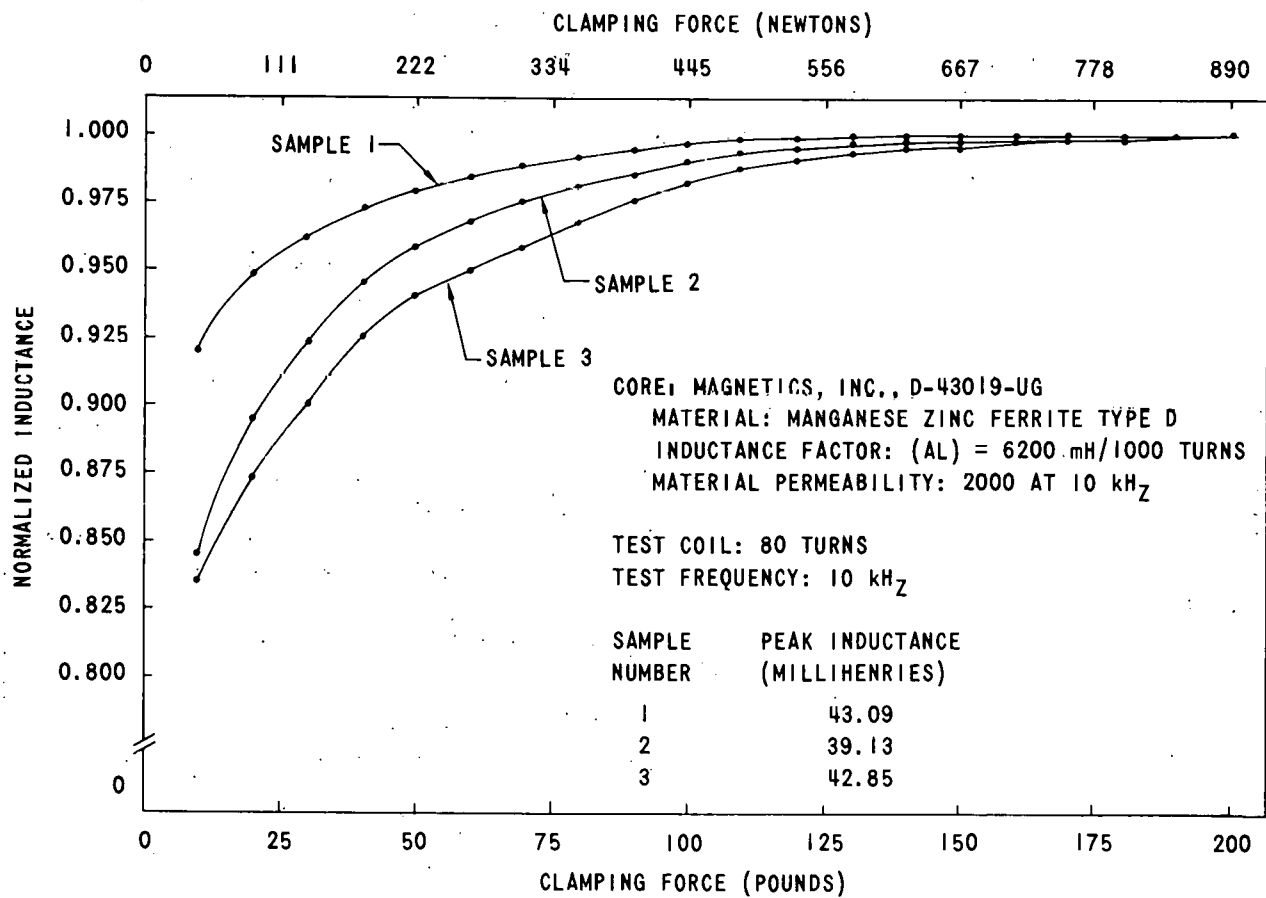


Figure 4. Inductance Versus Clamping Force, D-43019-UG Core

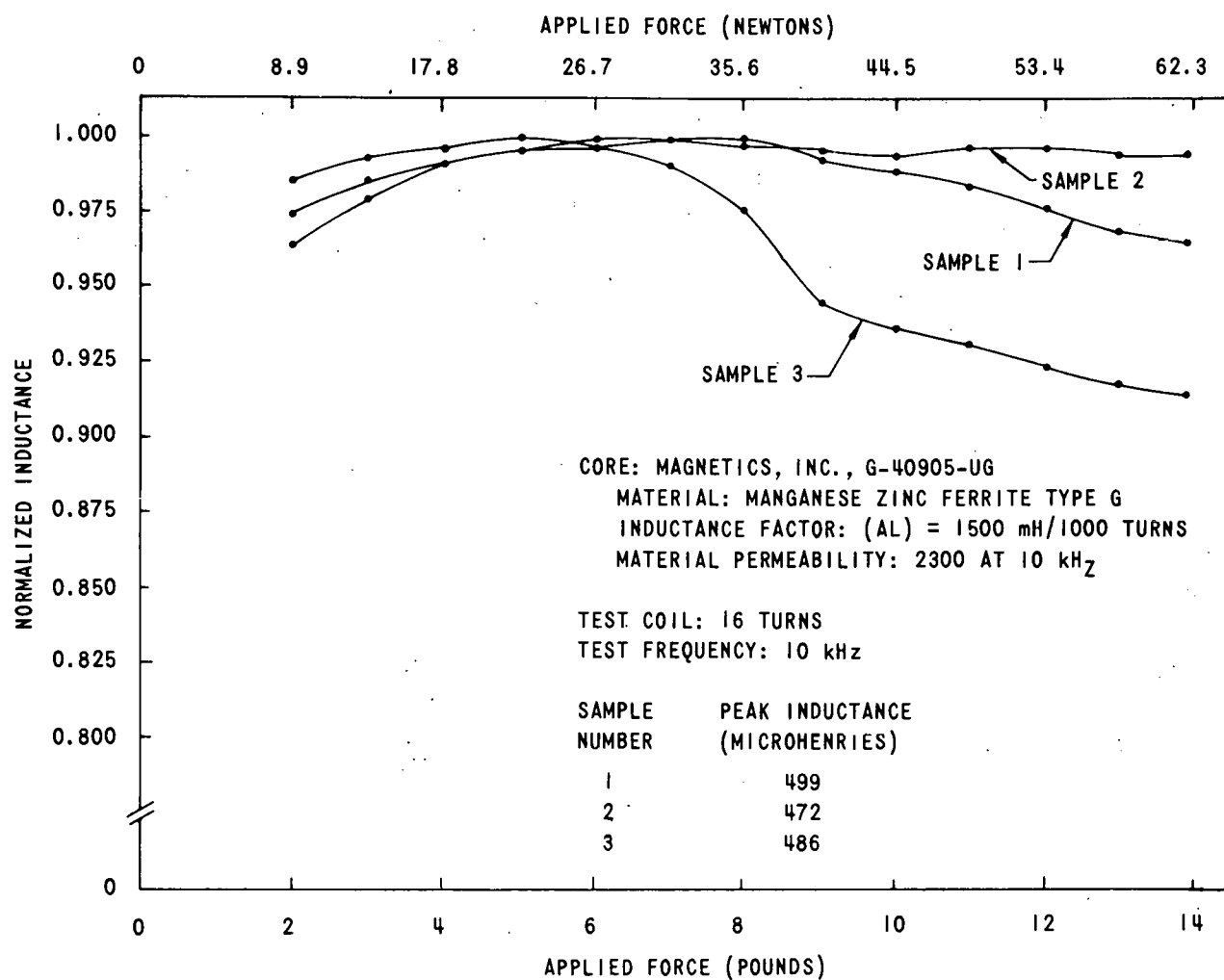


Figure 5. Inductance Versus Clamping Force, G-40905-UG Core

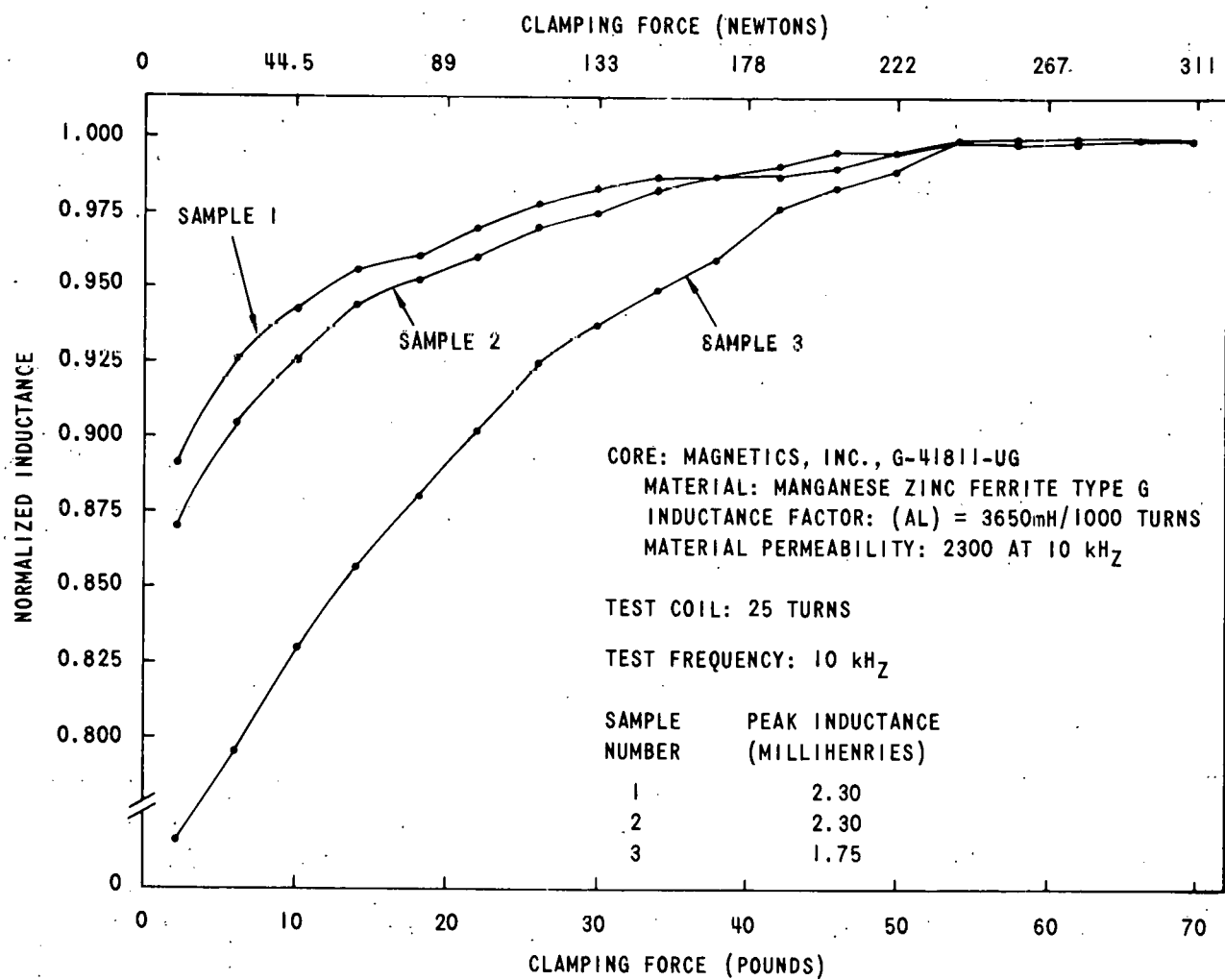


Figure 6. Inductance Versus Clamping Force, G-41811-UG Core

Forces required to obtain 98 percent of the maximum coil inductance with each of four pot-core diameters and three types of core materials are shown in Figure 7. An attempt was made to correlate these data to two published relationships:² applied force = 1 pound (4.4 N) per millimeter of core diameter, and stress constant at 27 pounds per square inch (186 kPa). However, the Bendix data did not correlate with either of the published conditions shown in Figure 7.

Reduction of Effective Air Gap

A third area in the evaluation was an attempt to reduce the effective air gap by providing an alternate magnetic path bridging the gap. As a preliminary step, the characteristics of an adhesive system filled with a high permeability ferrite powder were explored. Table 2 summarizes the properties of the three ferrite powders used. EA 956 was selected as the epoxy resin to be filled with the ferrite powders. Filler loading concentrations, magnetic characteristics, and bond strength were the properties evaluated.

Table 2. Properties of Ferrite Powders, Manufacturer's Specified Characteristics

Type	Supplier	Initial Permeability	Maximum Permeability	Particle Size
0-5	Indiana General	3000	4800	60 Mesh
A-Perm	Magnetics Inc.	650	----	100 Mesh
J-Perm	Magnetics Inc.	6000	----	100 Mesh

All three ferrite powders were loaded at 50, 60, 70, 80, and 85 pbw of filler into EA 956. The mixing was accomplished by adding the proper weight ratio of dry ferrite powder to the B-component of EA 956 with both preheated to 85°C. The mixture was allowed to cool to room temperature and the A-component was added in the proportion of 100:58 parts A:B.

The high loading ratios were quite thick, but there was no detectable difference in working characteristics between the 60-mesh and 100-mesh particle sizes. Because of the high volume ratio of filler to adhesive, loading above 85 pbw was not attempted.

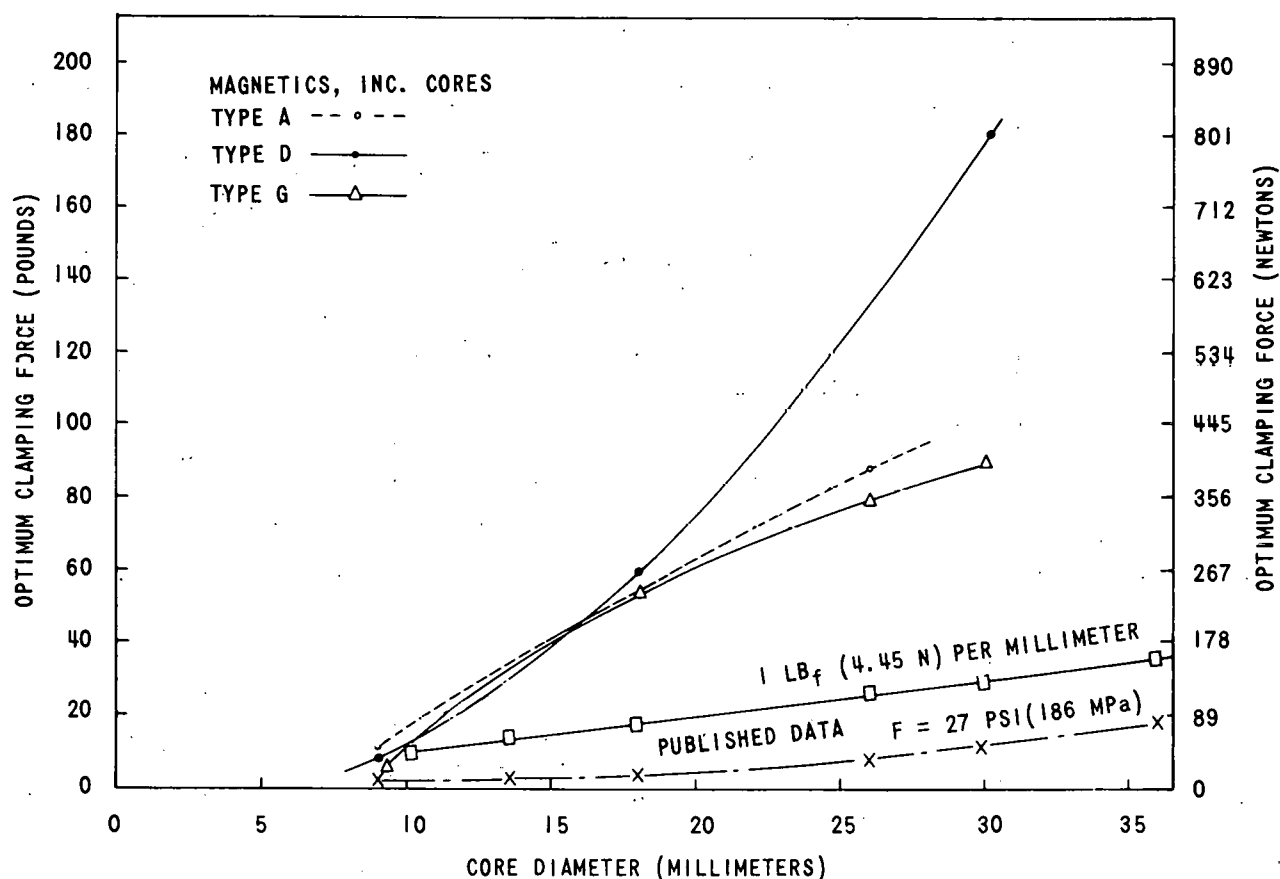


Figure 7. Optimum Clamping Force Versus Pot Core Diameter

The magnetic properties of the filled adhesive were determined by calculating the relative permeability of samples cast into the shape of toroids. The nominal dimensions of the toroids were 12.7 mm OD, 7.92 mm ID, and 6.35 mm height.

Five samples were prepared for each filler ratio and for each of the three ferrite powders. A 61-turn test winding was placed on each sample and the inductance of the coil was measured. The relative permeability of a sample was calculated by dividing its inductance reading by an average inductance reading of three unfilled toroidal samples of the same shape and size. The test results are presented in Table 3.

Table 3. Inductance of 61-Turn Test Coil on Toroids Molded of EA956 With and Without Ferrite Loading

Filler Ratio (pbw)	Measured Inductance (Microhenries)						Average Permeability
	1	2	3	4	5	Avg.	
Group 1: 0-5 Ferrite Powder at 100 kHz							
50	6.1	5.9	6.0	6.1	6.0	6.0	2.0
60	6.5	6.6	6.6	6.6	6.7	6.6	2.2
70	10.9	10.6	10.4	10.5	11.0	10.7	3.5
80	16.7	15.4	15.5	15.9	15.5	15.6	5.2
85	26.3	26.6	26.3	27.0	26.7	26.6	8.8
Group 2: A-Perm Ferrite Powder at 100 kHz							
50	6.2	6.5	6.5	6.6	6.0	6.3	2.1
60	7.9	7.9	8.0	7.6	7.8	7.8	2.6
70	10.2	10.8	10.5	10.6	10.2	10.5	3.5
80	15.8	16.3	16.2	16.3	16.3	16.2	5.4
85	23.4	24.6	24.5	24.7	24.3	24.4	8.1
Group 3: J-Perm Ferrite Powder at 100 kHz							
50	6.2	6.3	6.3	6.2	6.3	6.3	2.1
60	7.9	7.9	8.0	7.6	7.8	7.8	2.6
70	11.3	11.0	11.4	11.0	10.8	11.1	3.7
80	15.2	14.6	15.0	14.8	15.0	14.9	4.9
85	23.4	23.9	23.6	23.7	23.2	23.6	7.8
Group 4: Adhesive Only, No Ferrite at 100 kHz							
0	3.1	3.0	3.0	—	—	3.0	1.0

Figure 8 shows a plot of the average permeability versus filler ratio for each of the three ferrite materials. The permeabilities of the filled adhesives were quite low compared to that of the ferrite material when the filled adhesive was cured without pressure; however, a relative permeability of about 8 was obtained at 85 pbw filler. A denser particle packing obtained by curing the filled adhesive toroids under pressure produced a relative permeability of about 10 for J-Perm powder at 85 pbw filler.

The bond strength of the filled adhesive was measured at the higher filler ratios and compared to that of the unfilled EA 956. Test samples consisting of 25 mm aluminum adherents with a 0.08 to 0.13 mm bond line were prepared

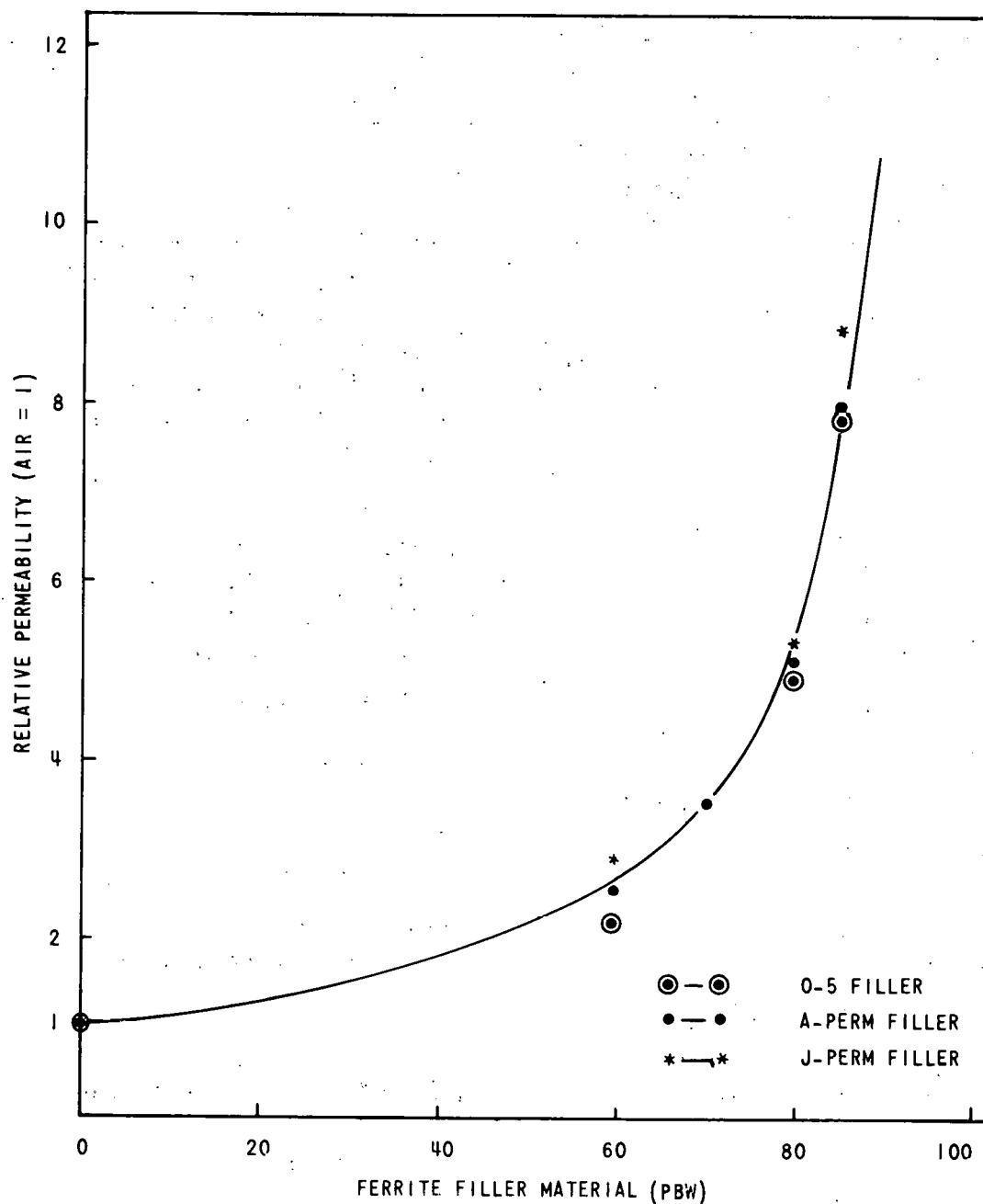


Figure 8. Relative Permeability of Ferrite-Filled EA956

for 0- , 70- , 80- , and 85-pbw loadings of both J-Perm and 0-5 powders. The tensile strengths of the samples are shown in Table 4. Even at the highest filler ratio (85 pbw), the reduction in bond strength was less than 15-percent.

Table 4. Bond Strengths of 25 mm Square Test Samples

Sample	Bond Pull Strength* (psi) (MPa)			
	Unfilled	70 pbw	80 pbw	85 pbw
1-1	3830 (26.4)	5220 (36.0)	3380 (23.3)	3610 (24.9)
1-2	3630 (25.0)	5220 (36.0)	4160 (28.7)	3000 (20.7)
1-3	3180 (21.9)	5220 (36.0)	4200 (29.0)	2380 (16.4)
1-4	4200 (29.0)	4780 (33.0)	3900 (26.9)	3520 (24.3)
1-5	4020 (27.7)	5150 (35.5)	3860 (26.6)	3800 (26.2)
Average	3772 (26.0)	5118 (35.3)	4000 (26.9)	3262 (22.5)
2-1		5200 (35.9)	4810 (33.2)	3820 (26.3)
2-2		5000 (34.5)	4600 (31.7)	4000 (27.6)
2-3		4190 (28.9)	4490 (31.0)	2550 (17.6)
2-4		4470 (30.8)	4680 (32.3)	4290 (29.6)
2-5		4380 (30.2)	4710 (32.5)	2510 (17.3)
Average		4740 (32.1)	4638 (32.1)	3434 (23.7)
*Pull force was applied at a rate of 1.27 mm per minute.				

The following procedure was used to assemble and test pot-core samples.

- The cores were cleaned with trichloroethylene.
- Five cores with 70-turn coils were assembled on the clamping fixtures.
- Inductance was measured and recorded at room temperature.
- Ferrite filled adhesive with 85 pbw J-Perm powder was applied around the circumference of the core bridging the interface at the core halves and cured at 80°C for 1 hour after a 2-hour gellation period at room temperature.
- Inductance readings were taken at room temperature.
- The center hole of the assembly was filled with ferrite-filled adhesive to bridge the interface of the center post, adhesive was then cured as above, and inductance was measured at room temperature.

The above steps were repeated with EA 934 instead of the ferrite-filled EA 956. The results in Table 5 show an improvement of less than 2 percent in the measured inductance on cores assembled with the ferrite-filled adhesive.

Table 5. Inductance of Test Coil Enclosed in Ferroxcube 2616P-L00-3B7 Pot Core at 10 kHz

Sample Description	Measured Inductance (Millihenries)			
	Before Bonding	After Outer Surface Bonding	After Filling Center Hole	Change From Initial Value
Group 1: Bonded With 85 pbw J-Perm in EA 956				
1	29.450	27.625	26.878	-2.572
2	27.674	27.060	24.555	-3.119
3	27.587	26.420	23.038	-4.549
4	21.092	20.120	18.455	-2.637
5	28.358	26.832	25.742	-2.616
Average				-3.098
Group 2: Bonded With EA 934				
1	29.060	26.816	26.000	-3.060
2	28.810	27.398	24.736	-4.074
3	30.066	29.180	27.698	-2.370
4	31.562	29.851	27.948	-3.614
5	29.884	26.940	25.850	-4.034
Average				-3.430

Adhesive Bond Failures

The 80°C cure used for EA 934 was adequate for the adhesive evaluation and for coils potted in epoxy at 80°C. However, numerous bond failures occurred during the 140°C potting evaluation discussed later. Several possible failure modes were identified.

- The adhered surfaces of the core may not have been clean.

- Moisture on the adhered surface has been reported to cause core bond failure,² but it was not identified in this study.
- The adhesive expanded, causing the air gap to open.
- When cooled to room temperature after the adhesive cure, the ferrite failed. When the adhesive expanded during the 140°C potting preheat, the air gap increased.

The ferrite failed on the sample shown in Figure 9, indicating that one of the latter two failure modes may have occurred. Increasing the cleanliness of the adhered surfaces and increasing the adhesive cure to 145°C produced some bond improvement, but numerous failures still occurred.

Stress-Free Potting

Silicone Rubber Protective Coating

During previous work to match the CTE of an epoxy to that of a core, minor differences from batch to batch of epoxy and cores affected the resultant stress from epoxy to core. A thin coat of silicone rubber applied to the core absorbed minor variations in expansion and prevented stress from reaching the core. This prior investigation was done on a toroid on which all surfaces could be coated with silicone rubber.

The air gap between the halves of a pot core must be controlled. All surfaces of the core must be coated with silicone rubber except the mating surfaces of the air gap and the surfaces required to bond the core together.

Required Thickness. The thickness of silicone rubber on a ferrite toroid had a significant effect on the inductance value. Figure 10 shows that even semi-flexible epoxy stressed the ferrite material significantly; therefore, rigid epoxy was expected to have an even greater effect.

The thickness of silicone rubber required to absorb stresses created by a difference in CTE of the epoxy and core was calculated. The required thickness of silicone rubber depends on the size of a part, temperature range required, and the CTE of the core, potting material, and silicone rubber.

The following assumptions were made in determining the equations.

- The CTE of the potting material is greater than the core.
- The CTE of both the core and the potting material are constant with temperature. (The highest value within the temperature range is used.)

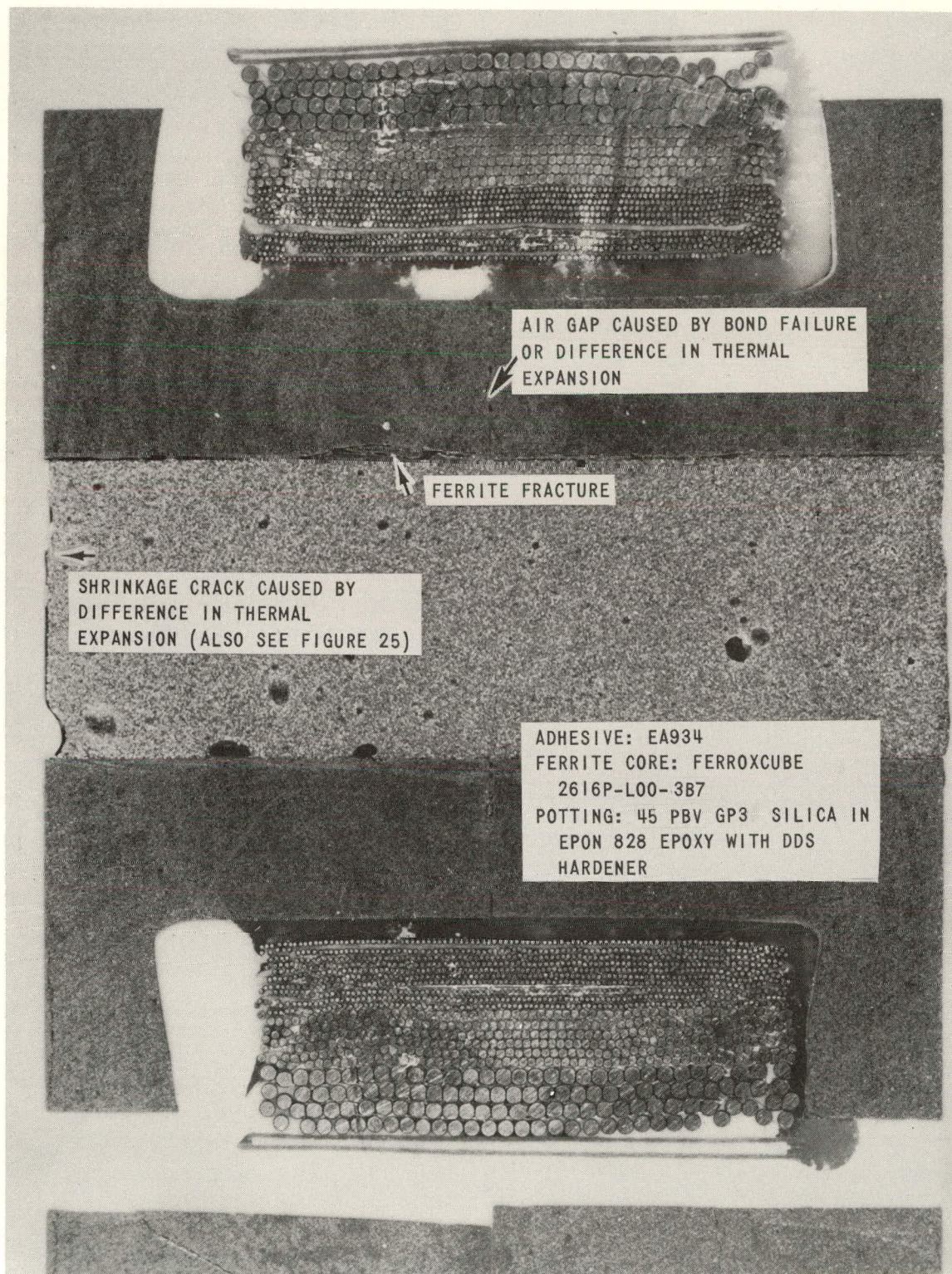


Figure 9. Bond Failure in Ferrite Material

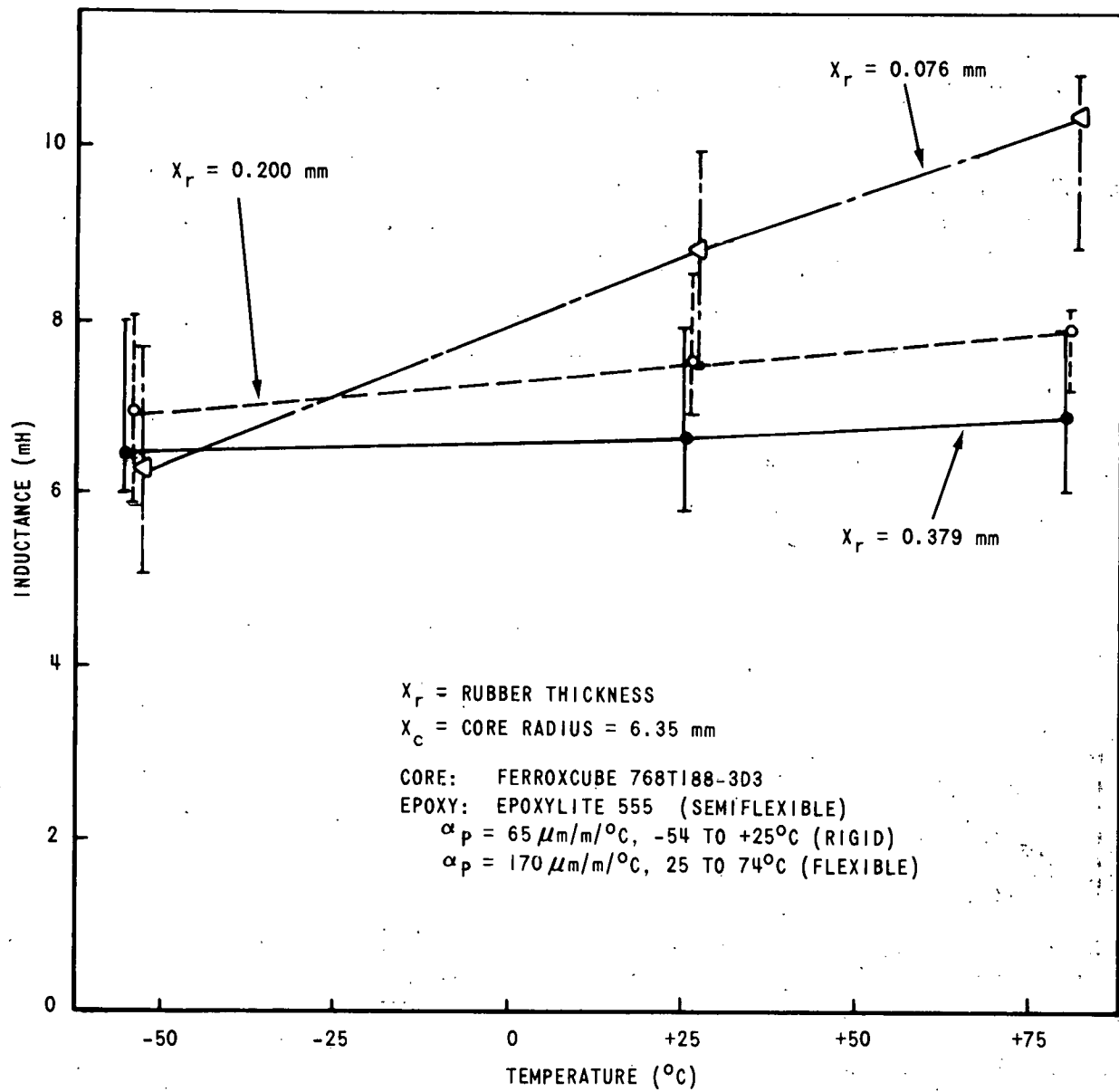


Figure 10. Ferrite-Core Inductance/Temperature Characteristic Versus Silicone-Rubber Thickness

- The calculated rubber thickness will be adequate to exactly fill the void between the potting and the core on the exterior surfaces of the core over the required temperature range.
- The cure temperature of the potting material will exceed the highest-use temperature of the unit so silicone rubber coatings thicker than the required minimum will not expand and create a stress.
- Potting material inside the core will shrink away from the core below the cure temperature; therefore, mold release properties of the silicone rubber coating will be adequate to eliminate tensile stress.
- Cure shrinkage is negligible with high filler ratios.

These assumptions are described in Figures 11 and 12.

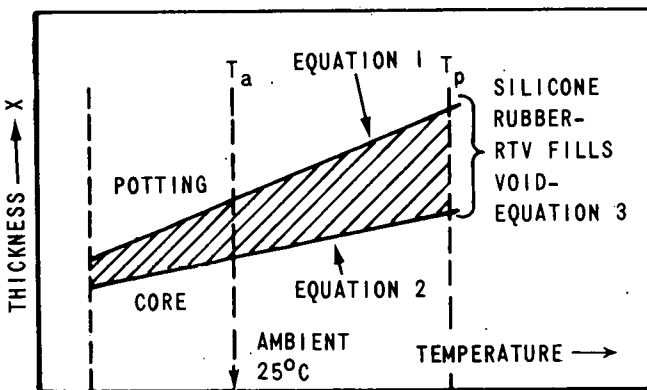


Figure 11. Thermal Interface Profile, Potting Outside of Core

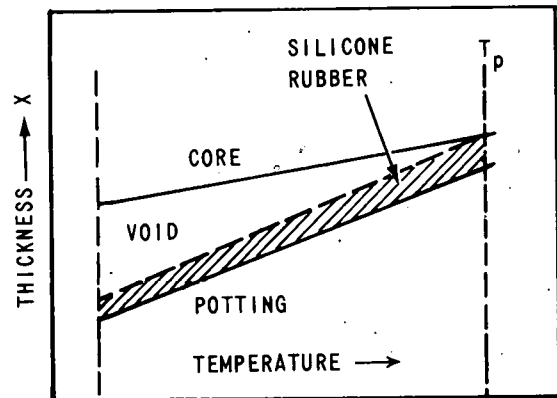


Figure 12. Thermal Interface Profile, Core Outside of Potting

Using the relationships in Figure 11, the following equations are obtained.

$$X_p = X_{p_a} [1 + \alpha_p (T - T_a)], \quad (1)$$

$$X_c = X_{c_a} [1 + \alpha_c (T - T_a)], \quad (2)$$

$$X_r = X_{ra} [1 + \alpha_r (T - T_a)], \text{ and} \quad (3)$$

$$X_p = X_c + X_r \quad (4)$$

where

α = CTE,

T = temperature,

X = thickness,

Subscripts:

p = potting,

c = core,

r = rubber, and

a = ambient temperature (25°C).

Solving for X_{ra} ,

$$X_{ra} = \frac{\alpha_p - \alpha_c}{\alpha_r - \alpha_p} \cdot X_{ca}, \quad (5)$$

which is the minimum required rubber thickness at ambient temperature (25°C).

Figure 13 expresses Equation 5 for a typical core.

Example:

If $X_{ca} = 10\text{-mm radius}$

and $\alpha_p = 15 \mu\text{m/m/}^\circ\text{C}$,

then $X_{ra} = 0.094 \text{ mm}$ (from Figure 13).

The semiflexible epoxy (from Figure 10) required less silicone rubber than calculated from Equation 5.

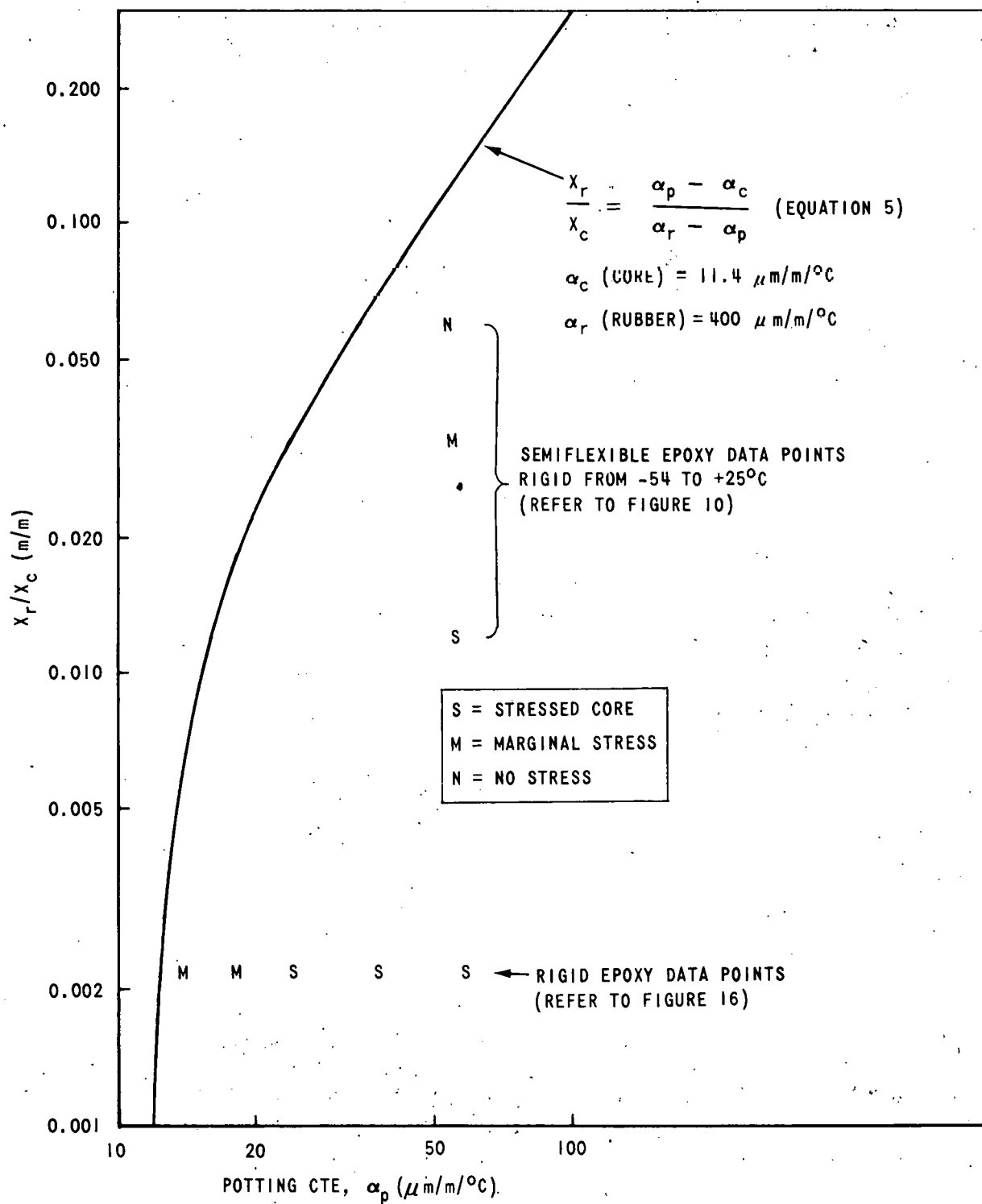


Figure 13. Silicone-Rubber Thickness Required to Protect a Ferrite Core From Potting Stress

Application Process. The process to coat pot cores with silicone rubber is detailed below. Except for the use of Vydax on the pole face of the core and plugging the hole of the core, this process is adaptable to toroids or other shapes of ferrite cores. The general process used is detailed in Figure 14 and expanded below.

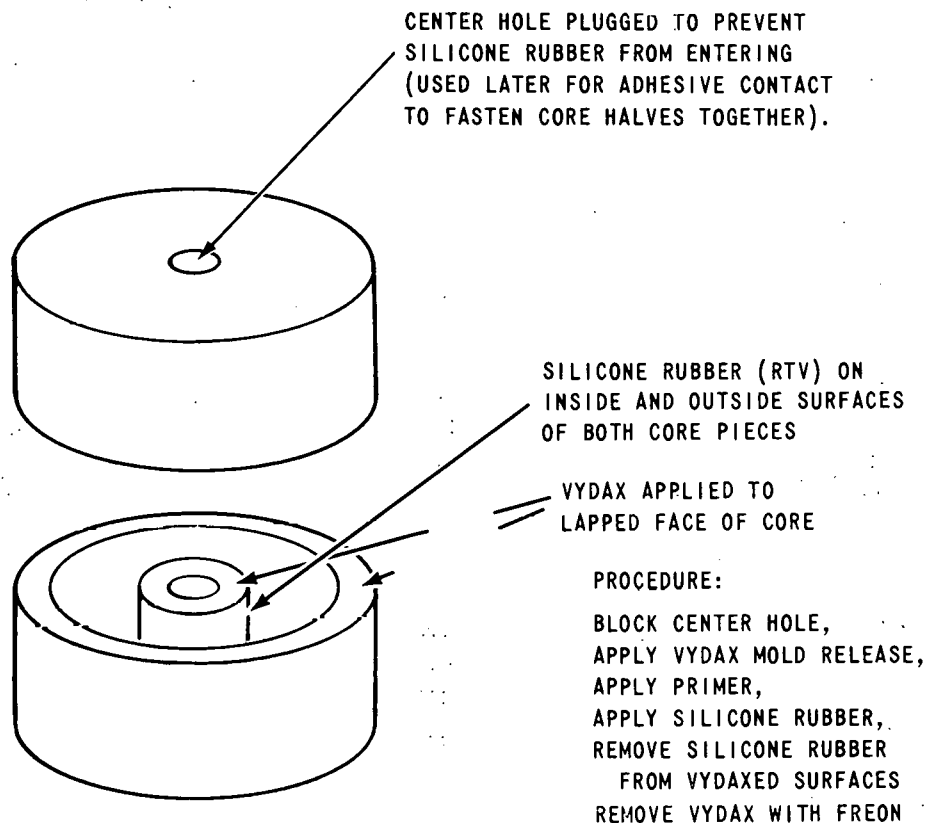


Figure 14. Ferrite Pot-Core Silicone-Rubber Coating Process

Preparation of Core. Toothpicks or similar objects, preferably wood, were placed in the center holes of the core halves and cut flush with the center boss on the cavity side of the core with a razor blade. These toothpicks were used as handles to hold the cores throughout the spray coating process. The cores were then spray cleaned with trichloroethylene.

Mold Release. Vydax mold release was diluted with 10 pbv of Freon. A stamp pad was saturated with this thin mold release and kept moist during the mold release application. The ferrite cores were placed cavity down on the stamp pad to moisten the mating surfaces of the core with the Vydax. The Vydax was allowed to dry approximately 10 minutes.

Primer. All surfaces of the core were sprayed with a silicone primer until the primer turned a pink color, indicating adequate coverage. The primer then was allowed to dry for at least one hour.

Silicone Rubber Spray. The silicone rubber elastomer was thinned with acetone before spraying to a mix ratio of 63.90-pbw RTV 511, 35.78-pbw acetone, and 0.32-pbw catalyst. A thin film of the silicone resin mixture was sprayed on all surfaces of each core for approximately 30 seconds and allowed to cure at room temperature for 24 hours. The acetone content may be reduced or spraying time may be extended if a thicker coating is required for a specific application.

Cleanup. The silicone rubber and primer were removed from the flat mating surfaces of the core with a razor blade. The toothpick or plug used for handling was then removed and the cores were sprayed with Freon to remove any trace of the Vydax mold release.

Epoxy Process

The most significant effort of the entire project was devoted to obtaining an epoxy with a CTE to match the CTE of ferrite cores. A major portion of this work was reported by McIlroy.³ Significant portions of McIlroy's report are repeated here, together with critical process details required to obtain high filler ratios. Of the several materials reported by McIlroy, GP3I fused silica filler provided the best pour viscosity with a high filler ratio. Beta-Eucryptite filler was almost equivalent to fused silica, but cost more. Therefore, the primary work was done with fused silica. Both fused silica and Beta-Eucryptite have very low CTEs. Fused silica CTE is $0.45 \mu\text{m}/\text{m}/^\circ\text{C}$.¹ Beta-Eucryptite CTE is -5 to $-7 \mu\text{m}/\text{m}/^\circ\text{C}$.⁴

Mixing Process. GP3I silica, a very finely ground powder, produced a lumpy mix with normal mixing methods. A shear mill was necessary to break up the lumps.⁵ GP3I fused silica produced a thinner mix than either the Beta-Eucryptite or coarser grades of fused silica when the agglomerate lumps were broken apart.

Of the following processes, only the two-roll rubber mill properly mixed 68 pbv of fused silica in Epon 828.

Hobart Mixer. The 68 pbv filled epoxy could not be mixed with a Hobart Model N-50 power mixer normally used for production mixing. GP7I silica could not be properly wetted, even at 175°C . The mix had the consistency of moist clay and was unsatisfactory for any potting process.

Colloidal Mill. A Morehouse Industries Model 225 colloidal mill provided the necessary shear action to break up the lumps of GP3I silica. By heating the colloidal mill to 120°C a relatively thin mix was obtained with 65 pbv filler in Epon 828 epoxy. However, the grinding wheel on the mill rotated so fast it would not adhere to the thicker 68 pbv mix and force the mix through the mill.

Three-Roll Paint Mill. A heated three-roll paint mill (J. H. Day Company, Model 5 x 12) was used to mix a 65 pbv epoxy mixture; however, it would not blend the desired 68 pbv mix. The three-roll mill depends on differential roll speed and roll gap for mixing. The material made only one pass through the rolls. It was necessary to make several passes through the mill to obtain proper material mixing. The mixture of the filler and epoxy was poured onto the slowest roll. The differential roll speed then caused the material to transfer to the middle roll, then to the end roll. A blade was used to remove the mixed material from the last roll. Because several passes were required and the mill leaked oil, efforts on the three-roll mill were stopped and a better way of mixing was pursued.

Two-Roll Rubber Mill. A Thropp Model 6 x 12 heated two-roll rubber mill successfully provided the high shear required to obtain a 68 pbv mix of GP3I silica in Epon 828. The mixing was accomplished by a high shear action due to the differential roll speed and a narrow gap between the rolls. Partly mixed material was banded on the faster roll to provide a continuous mix. The roll temperature and roll speed were frequently adjusted to keep the material banded on the rolls, depending on the batch size, type of filler, volume of filler, and viscosity of the mixture. No attempt was made to standardize the process. To achieve the 68 pbv loading, part of the resin filler was preheated, hand blended with epoxy, and heated to 140°C. Additional filler was slowly added to make a lumpy slurry. The roll temperature was adjusted to about 65°C and the slurry was slowly added to the rolls. The roll speeds were adjusted from a starting point of 6 meters per minute back roll and 9 meters per minute front roll to keep the material banded. The remaining filler was slowly sprinkled on the banded material and mixed. The temperature was slowly increased to a maximum of 160°C to reduce the viscosity enough to accept the required amount of filler. Sixty-eight pbv Beta-Eucryptite in Epon 828 also was mixed with the two-roll mill.

On several occasions during the evaluation period the filled epoxy was stored overnight in an oven heated to approximately 175°C. At least twice, the epoxy cured without the addition of a catalyst, indicating a possibility of catalytic action in the fillers being used (silica and Beta-Eucryptite). Mixed compounds of Epon 828 and fused silica (or Beta-Eucryptite) should not be exposed to temperatures above approximately 160°C.

Potting Process. In addition to the mixing process on the two-roll rubber mill, the process of potting an actual unit such as a transformer is also rather critical. One of the most critical points of potting with a highly filled material is control of the temperature during processing and pouring the epoxy mix. The mixing process was designed for a pourable 68 pbv mix; however, the mix was so thick it would not pour through a 9.5 mm ID tube used for vacuum impregnation. Some voids were obtained when a normal pour in the atmosphere was followed by vacuum. The following process was satisfactory when the 68 pbv mix previously described was thinned with epoxy to obtain a 63 pbv mix.

- Place the epoxy, the epoxy-filled premix, and a power mixer beater into a mixer bowl. Place the mix into a preheated oven set at 145 to 160°C until the temperature of the mix is 130 to 145°C. Place the preweighed DDS hardener into the same oven to preheat. Do not preheat longer than necessary because the epoxy may cure without hardener at the elevated temperature.
- Remove the filler-resin mixture from the oven and mix until the mixture is uniform in color (approximately 10 minutes).
- Return the mix to the preheated oven set at 145 to 160°C until the temperature of the mix is 145 ±5°C.
- Remove the heated mix from the oven and add the DDS hardener. Power mix the material for 3 ±0.25 minutes. (The pot life of the mix is 45 minutes maximum after addition of the hardener.)
- Immediately after mixing, place the mix into a heated vacuum chamber and evacuate the chamber to an absolute pressure of 0.5 to 3 torr (67 to 400 Pa) for 5 ±0.25 minutes.
- Without breaking the vacuum, introduce the mixture into each mold. During the filling operation the absolute pressure should not exceed 5 torr (667 Pa). After the molds have been filled, return the chamber to atmospheric pressure (101.3 kPa). Re-evacuate the chamber to 0.5 to 3 torr absolute for 5 ±0.25 minutes. Return the chamber to atmospheric pressure. Apply a positive pressure of approximately 40 psig (377 kPa absolute) to the chamber for 15 to 17 minutes. Return the chamber to atmospheric pressure.
- Cure the units 16 hours minimum in a preheated oven set at 140°C.

Electrical Results of Potted Ferrite Cores. To separate the variables of pot-core air gap control and potting stress, ferrite toroids were used to evaluate potting stress. Epoxy mixes with filler contents of 0 to 63 pbv caused the catastrophic loss of inductance shown in Figure 15 for toroids potted without a protective coating of silicone rubber. Addition of a very thin coat of silicone rubber ($X_r/X_c = 0.002-0.007$ m/m) provided coils with the greatly increased inductance values shown in Figure 16. Direct correlation of 25°C inductance with filler content was obtained. Selection of thicker silicone rubber as indicated in Figure 13 would have provided more complete stress relief. The X_r/X_c value was measured on the corner of the cross section at the outer circumference of the toroids. This appeared to be the most critical point for stress-relief control.

Several problems were encountered in obtaining meaningful information on the effect of potting stress on pot cores. The first problem was a mechanical interference between the expanding silicone rubber and the Delrin coil form used to hold the wire. The expansion of both these materials at the 140°C potting temperature was sufficient to crack the ferrite material and the adhesive bond which held the core halves together. A second attempt with a non-interfering coil form also failed because the adhesive used to hold the ferrite pieces together lost its bond during the potting process. Therefore, the air gap was not controlled during potting and correlation was impossible. During these first two attempts the adhesive was cured at 80°C for 2 hours. Because the potting temperature of the heavily filled epoxy was 140°C, the adhesive cure temperature was increased to 145°C for 1 hour. The 145°C cure and a more-thorough cleaning process produced some inductors with good air gaps, although the majority of the test units had air gaps (as large as 0.05 mm). The inductance data shown in Figures 17 and 18 represent a mixture of air gap and potting stress effects which are not separable. Data indicated by dashed lines represent cores in which potting in the air gap was detected by postmortem analysis. The significance of the air gap control problem is clearly evident in these figures.

Text continues on page 47.

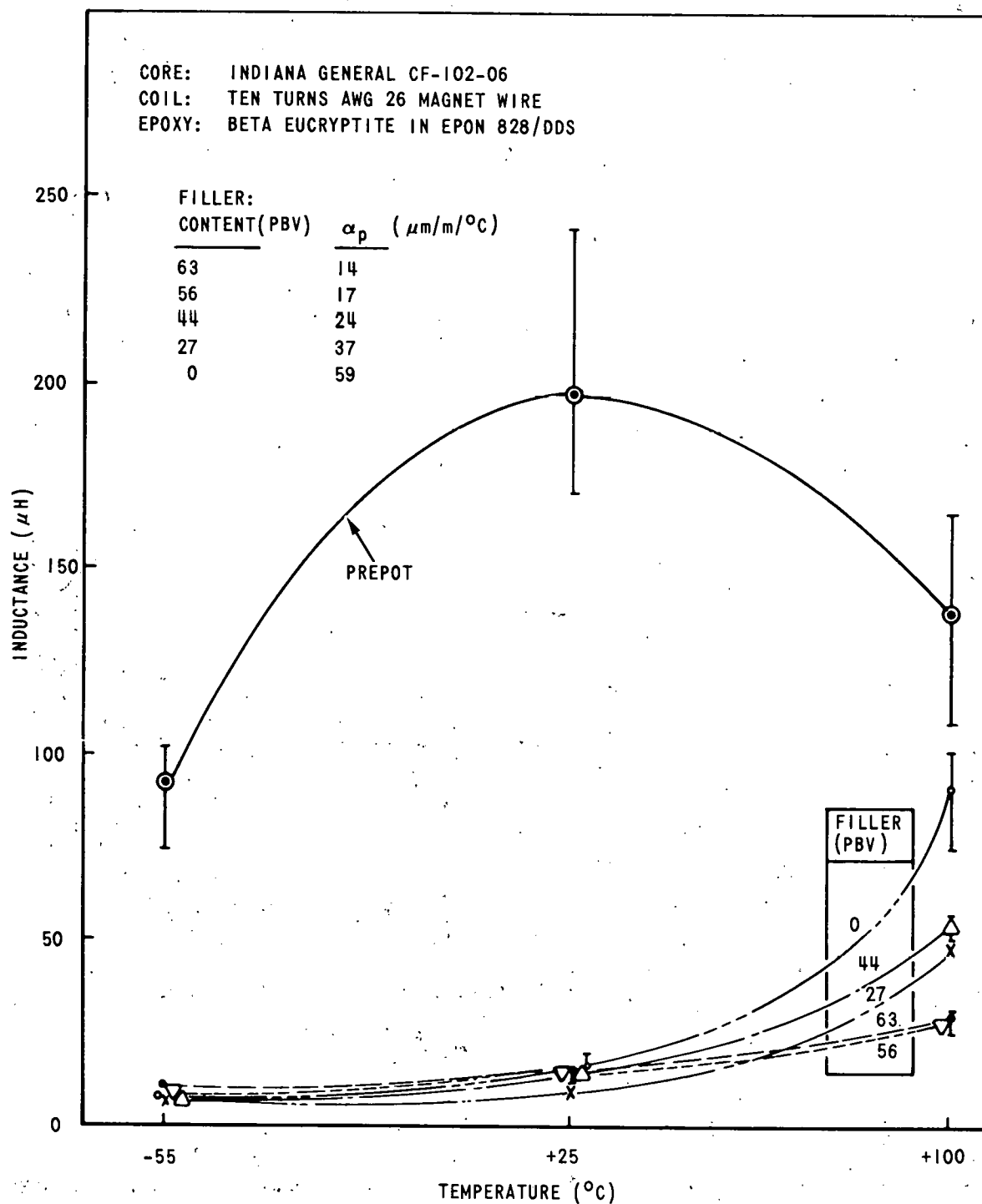


Figure 15. Inductance Versus Temperature, Uncoated Ferrite Toroids Potted in Filled Epoxy

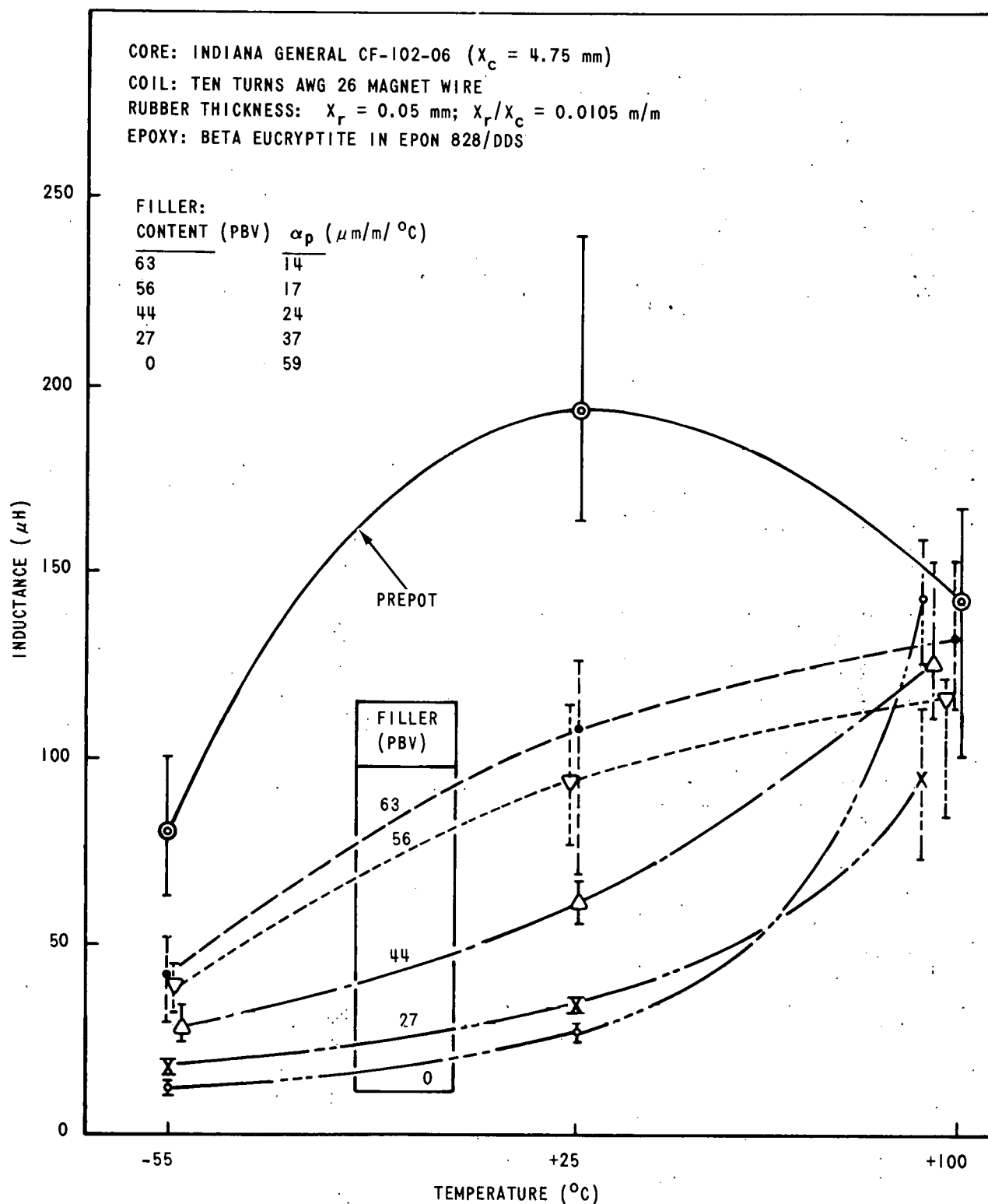


Figure 16. Inductance Versus Temperature, Rubber-Coated Ferrite Toroids Potted in Filled Epoxy

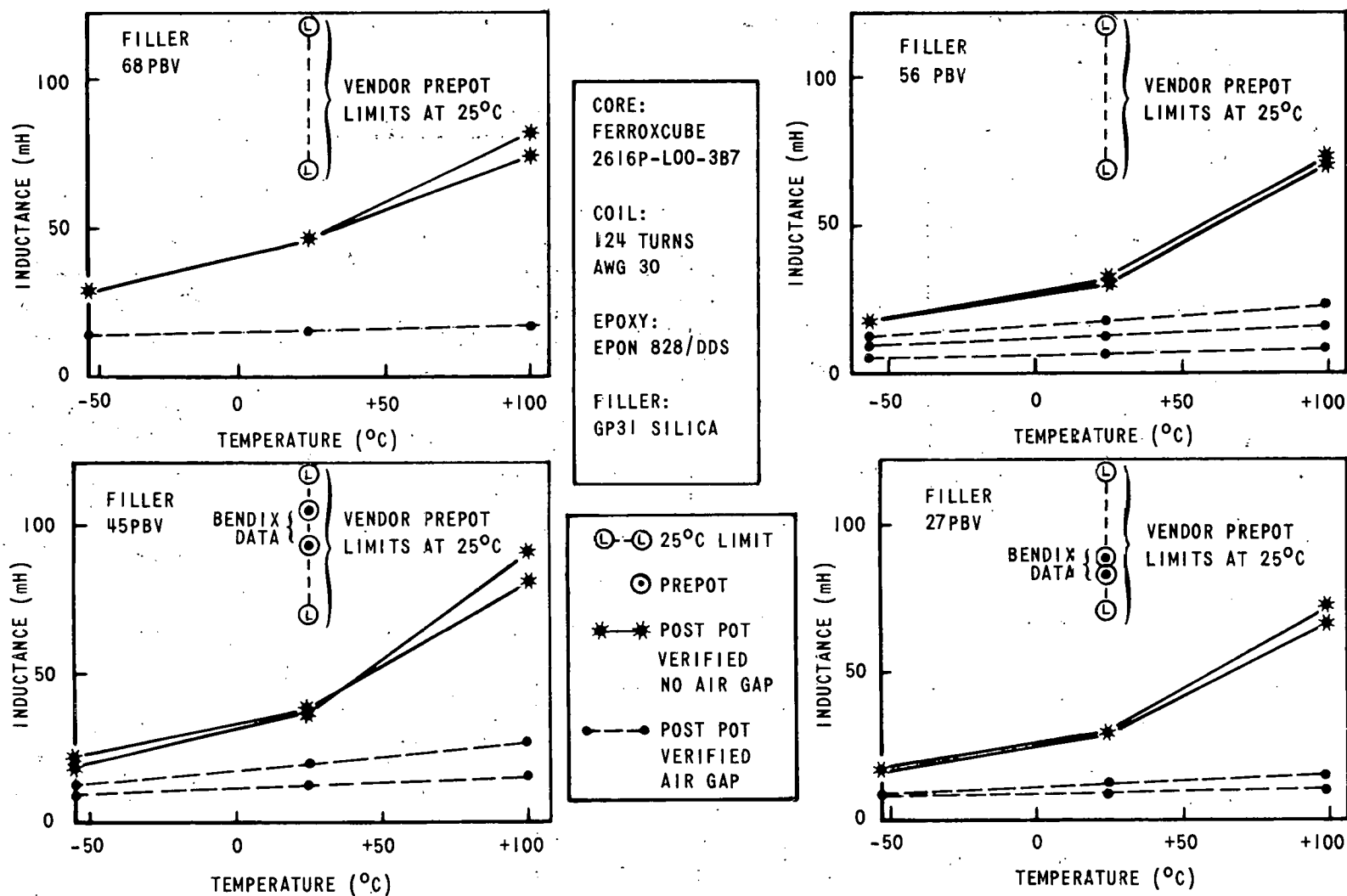


Figure 17. Inductance Versus Temperature, Uncoated Ferrite Pot Cores Potted in Filled Epoxy

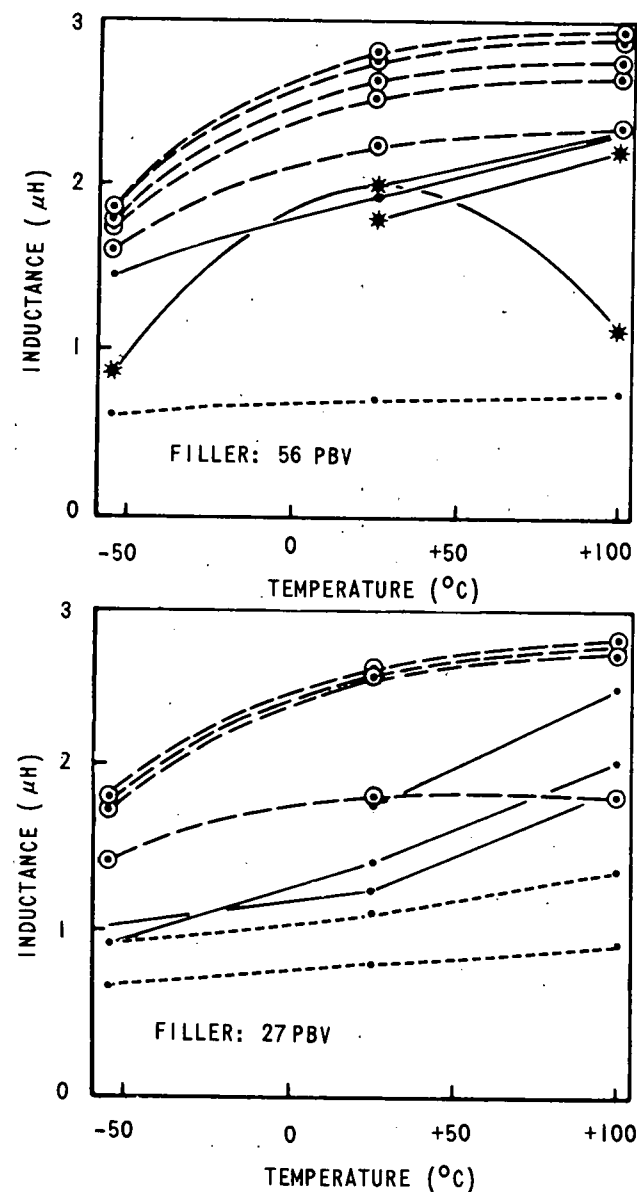
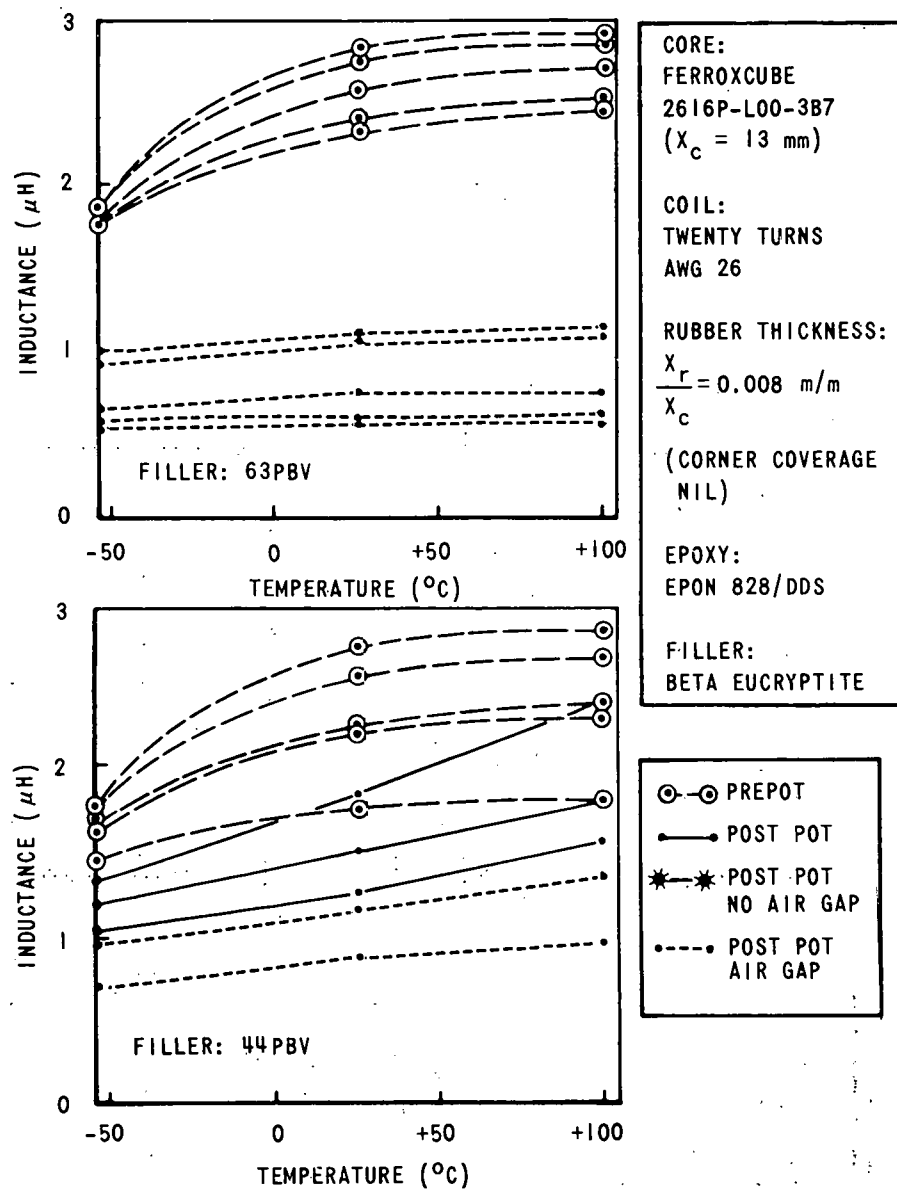
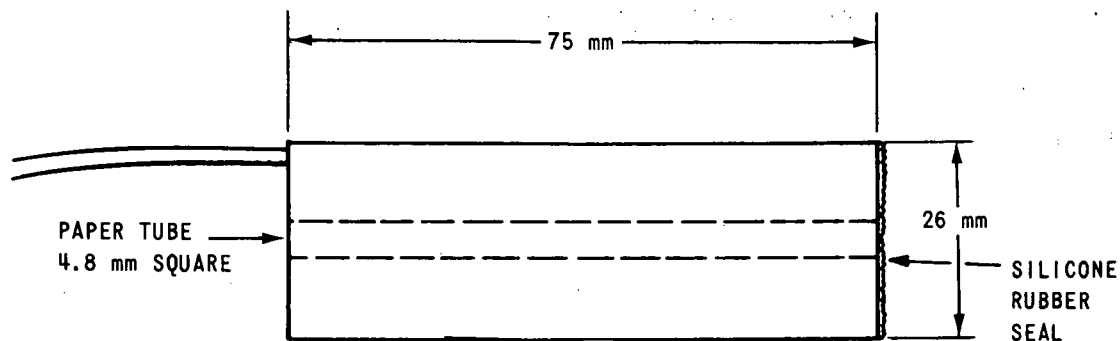


Figure 18. Inductance Versus Temperature, Rubber-Coated Ferrite Pot Cores Potted in Filled Epoxy

Coil Impregnation

A criterion essential to determine the degree of impregnation is the design of a test coil where all processes will not completely impregnate the winding. Such a coil (Figure 19) provided this requirement. This coil made of several layers of kraft paper and magnet wire represents a typical type of coil construction. This coil was open-ended so maximum penetration of the epoxy would occur without the normal problems associated with individual coil design. The 75-mm-long test coil was sealed on one end with silicone rubber so the impregnation could occur only from the other end. The coil then approximated one 150-mm-long winding. Three sizes of magnet wire (AWG 30, 36, and 42) were used to represent the normal range used in electronic transformers at Bendix. Figure 20 shows a pot-core test coil. The coil selected was made large compared to most pot cores to provide maximum information on impregnation.



COIL 1: 30 LAYERS AWG 42 DOUBLE-INSULATED MAGNET WIRE, MIL-W-583, TYPE T2
INTERLAYER INSULATION-- 1 LAYER 0.001 INCH KRAFT PAPER, ASTM D1305, TYPE I
INSULATION OVER COIL -- 1 LAYER 0.001 INCH KRAFT PAPER

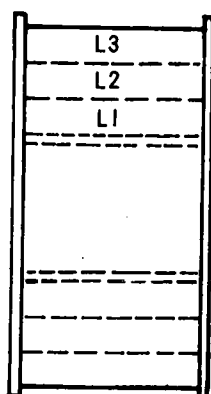
COIL 2: 17 LAYERS AWG 36 DOUBLE-INSULATED MAGNET WIRE
INTERLAYER INSULATION--1 LAYER 0.001 INCH KRAFT PAPER
INSULATION OVER COIL --1 LAYER 0.001 INCH KRAFT PAPER

COIL 3: 10 LAYERS AWG 30 DOUBLE-INSULATED MAGNET WIRE
INTERLAYER INSULATION--2 LAYERS 0.001 INCH KRAFT PAPER
INSULATION OVER COIL --2 LAYERS 0.005 INCH KRAFT PAPER

MARGINS: APPROXIMATELY 3 mm

HOLD-DOWN TAPE: SMALL PIECES OF ADHESIVE TAPE, MIL-I-15126, TYPE MFT 2.5

Figure 19. Stick-Wound Impregnation Test Coil



DELFIN BOBBIN

COIL 1: 10 LAYERS AWG 42 DOUBLE-INSULATED MAGNET WIRE

COIL 2: 6 LAYERS AWG 36 DOUBLE-INSULATED MAGNET WIRE

COIL 3: 4 LAYERS AWG 30 DOUBLE-INSULATED MAGNET WIRE

INTERLAYER INSULATION: 1 LAYER 0.001 INCH KRAFT PAPER

INSULATION OVER COIL: 2 LAYERS 0.005 INCH KRAFT PAPER

Figure 20. Pot-Core Bobbin Impregnation Test Coil

Inspection Technique

Numerous methods of determining the depth of impregnation were attempted by using microscopic inspection of polished cross-sections:

- Movement of wires with a small tool;
- A Scanning Electron Microscope;
- Dark-field polarized light;
- Use of a dye-penetrant;
- Use of an ultraviolet penetrant and ultraviolet light; and
- Use of 365-nm ultraviolet light to make the epoxy and the filler fluoresce weakly.

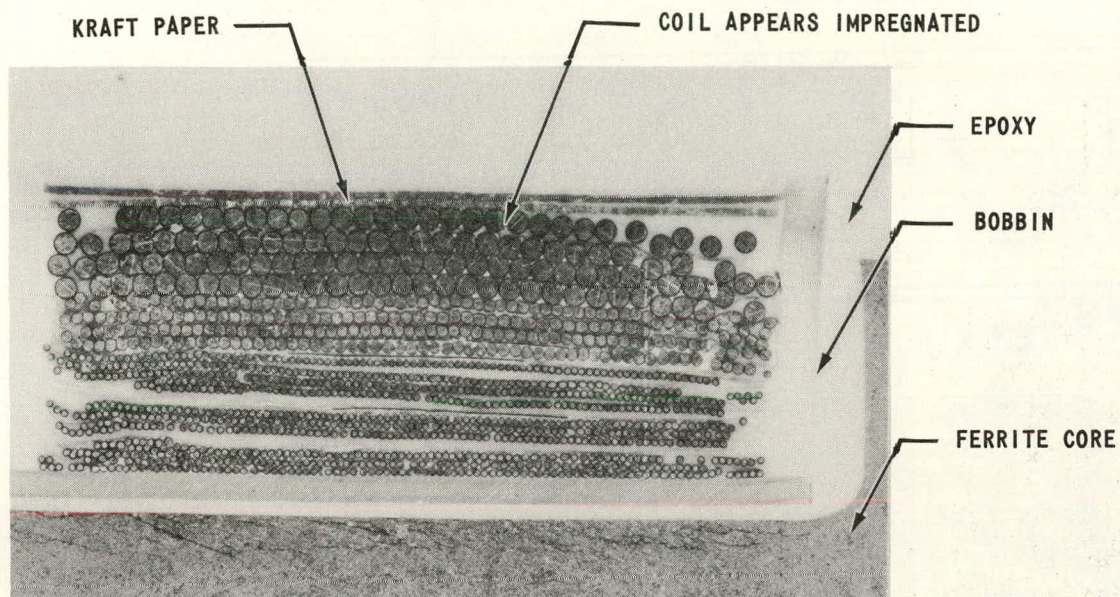
The only successful technique combined epoxy fluorescence under ultraviolet light and wire movement under incandescent light. Figure 21 compares the appearance of a partly impregnated winding under incandescent and ultraviolet light. The ultraviolet light was positioned at an angle which prevented reflections from the polished copper wire and made the copper appear black. The slight fluorescence of the epoxy was carefully studied in a dark room. Large areas of unimpregnated and impregnated windings were determined, as shown in Figure 22. Careful examination under 40 to 60X magnification was required to determine the precise point at which impregnation stopped. There were small regions of unimpregnated winding in many coils that were indicative of anomalies such as layers of kraft paper being inadvertently stuck together with adhesive tape. Therefore, the most correlatable impregnation depth ignored these anomalies and considered an "environmental" impregnation depth (assuming the magnet wires were protected from vibration damage). This depth may not give thorough protection against electrical corona.

Filler Filtering

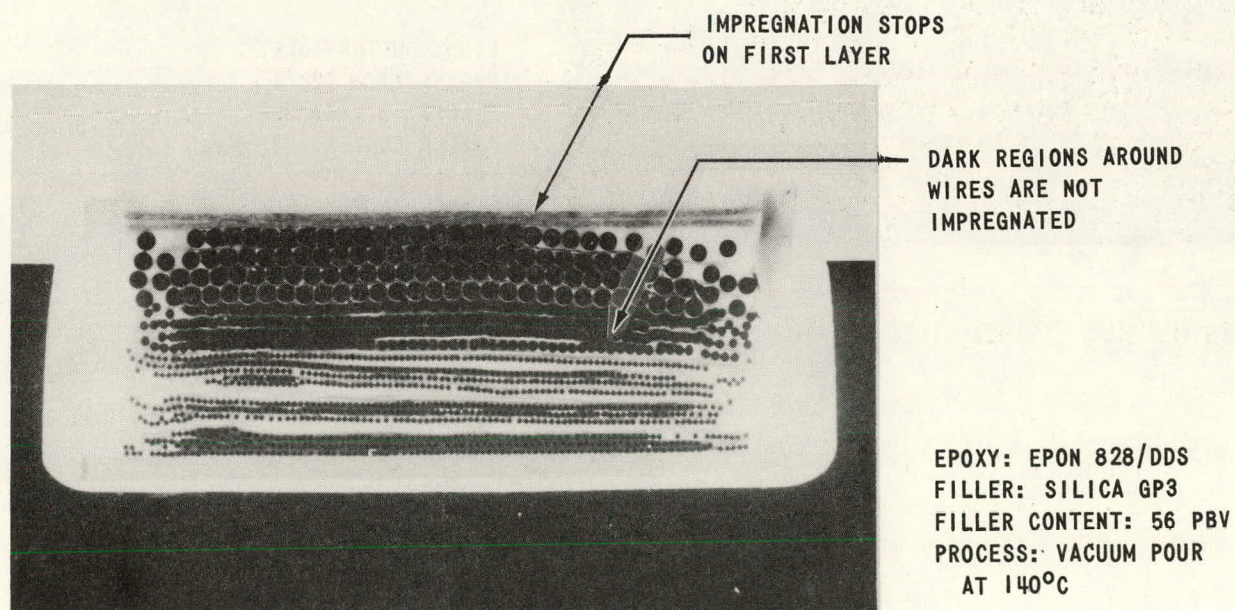
Careful attention to individual coil design will be required to achieve the desired penetration of filled epoxy. The filler materials did not generally penetrate into the coil winding. Figure 23 shows a typical test coil where filler filtering is obvious. The kraft paper and closely-spaced magnet wire blocked the filler, allowing only the epoxy to penetrate and impregnate the winding. The filler-rich region also acted as a filter by retarding the flow of epoxy through the filler. Several steps can be taken to minimize this progressive filtering action by moving the filtration point as near the magnet wire as possible:

- Reduce the margin between the wire winding and the end of the paper,
- Use a stiffer (thicker or denser) interlayer insulation to reduce wire fall-over and reduce the tendency of adjacent insulation layers to bunch together; and
- Eliminate adhesive tape from the epoxy flow-paths.

Text continues on page 52.



A. BOBBIN COIL ILLUMINATED WITH INCANDESCENT LIGHT



B. BOBBIN COIL ILLUMINATED WITH 365-nm ULTRAVIOLET LIGHT

Figure 21. Inspection Method to Determine Epoxy Impregnation Depth

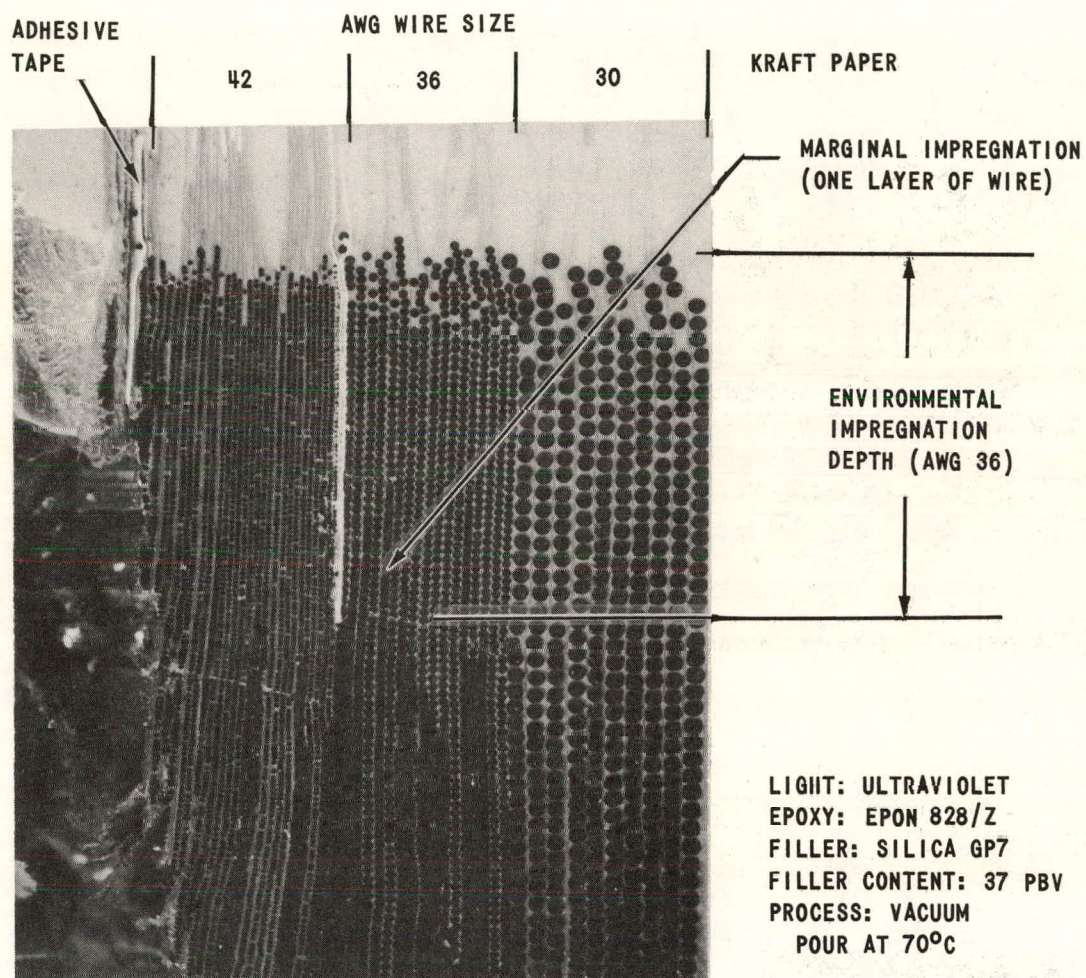


Figure 22. Partly Impregnated Test Coil

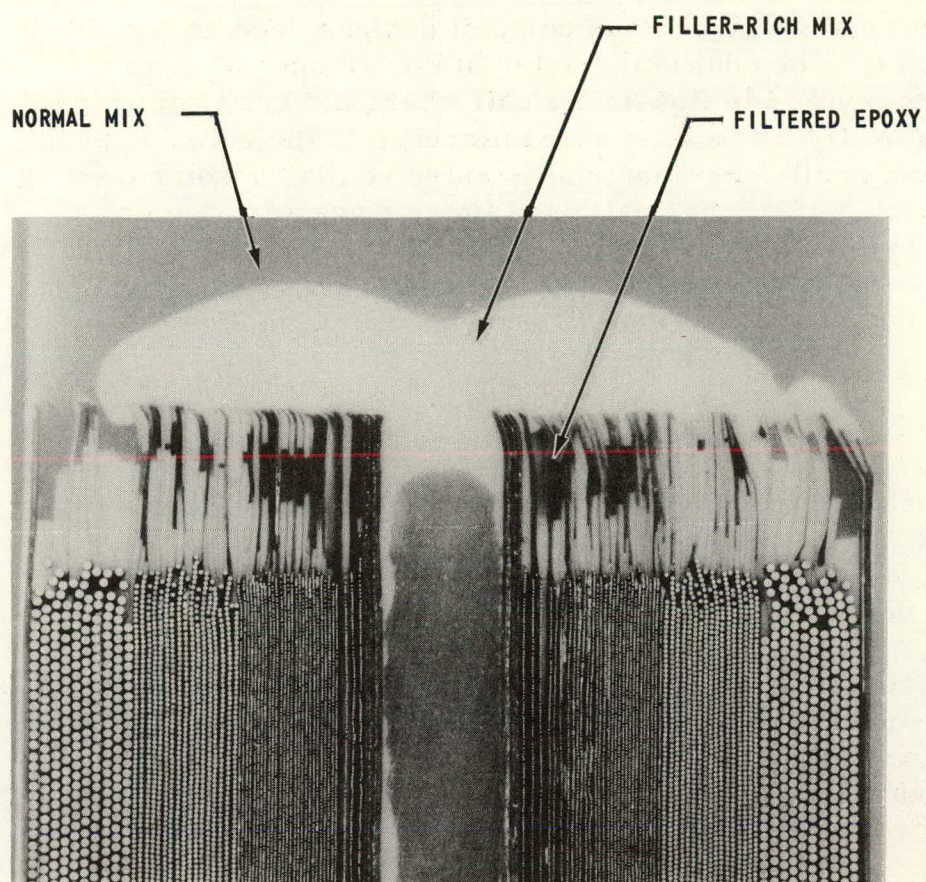


Figure 23. Filler Filtering

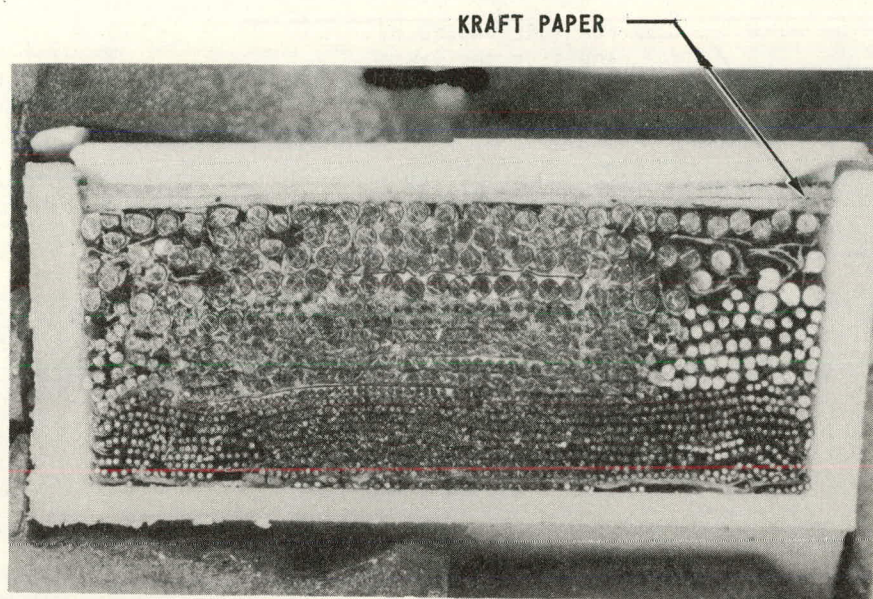
Special consideration must be given to unique coil designs such as the bobbin coil shown in Figure 24. The addition of holes in the bobbin coil flange allowed the viscous epoxy mix to flow into a coil where the kraft paper outer wrap blocked epoxy flow from the outer circumference of the coil. Even though the Delrin bobbin coil-form material is rated at 130°C, some melting occurred. A combination of mechanical force (interference from thermal expansion), 140°C processing temperature, and chemical reaction with adjacent materials may have caused the effects shown in Figure 25. The melted bobbin conformed to the ends of the coil on several test units, preventing any epoxy penetration.

Impregnation Depth

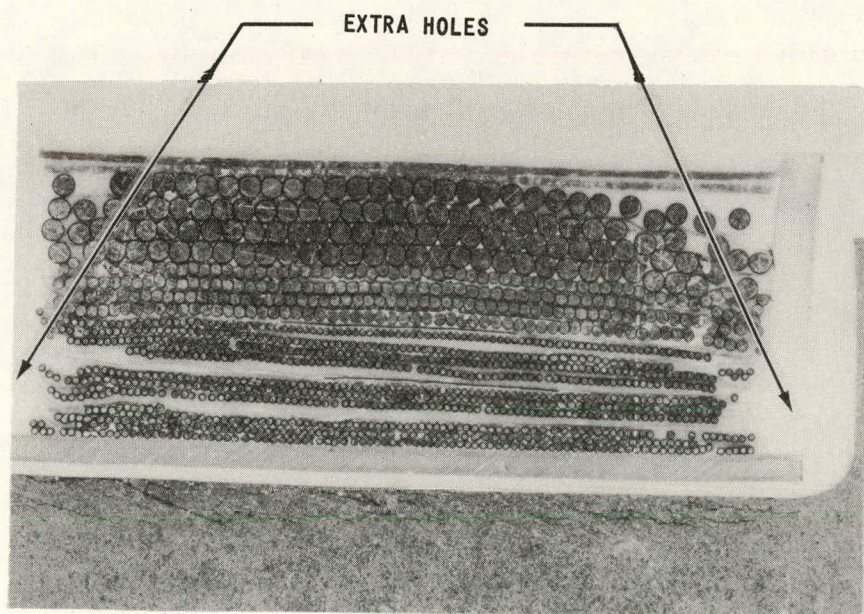
The test coil described in Figure 19 was impregnated with a variety of potting materials and processes. These variations are shown in Figures 26, 27, and 28. Several interesting and unexpected observations were made from the data shown in these figures.

- Impregnation was significantly improved by having both the impregnating material and the coil in a vacuum at the time the material was poured into the coil. Pouring the epoxy into the coil under atmospheric pressure followed by a vacuum yielded more erratic results and less impregnation depth.
- Magnet wire size affected the depth of impregnation. The impregnation of coils wound with AWG 42 magnet wire was significantly deeper than coils wound with AWG 36 or 30. This difference was true for filler ratios up to approximately 20 pbv. At approximately 25 pbv and above, the AWG 42 magnet wire did not exhibit as good an impregnation as larger magnet wires. This effect is most obvious in Figure 28A. This implies that coils which require high filler ratios should have as large a wire size as possible.
- Epoxy filled with Beta-Eucryptite provided better impregnation than epoxy filled with fused silica, but not as good as epoxy filled with 4X Mineralite Mica. The plate-like particles of mica allowed more epoxy to filter through the filler than the irregular, somewhat spherical particles of Beta-Eucryptite and silica.³ Mica appears to be the preferred filler for impregnation. However, the plate-like shape of the mica particles prevented heavy epoxy loading. Pouring viscosity became excessively high at filler ratios of approximately 40 pbv and above. The surface area of the Beta-Eucryptite filler was much smaller than that of GP3I silica, and may have had a significant effect on the impregnation depth.³

Text continues on page 58.



A. FLOW PATH BLOCKED BY WIDE KRAFT PAPER OUTER WRAP



EPOXY: EPON 828/DDS
 FILLER: FUSED SILICA GP3
 FILLER CONTENT: 56 PBV
 PROCESS: VACUUM POUR
 AT 140°C

B. FLOW PATH OPENED BY EXTRA HOLES IN BOBBIN

Figure 24. Epoxy Flow Path in Bobbin Coil

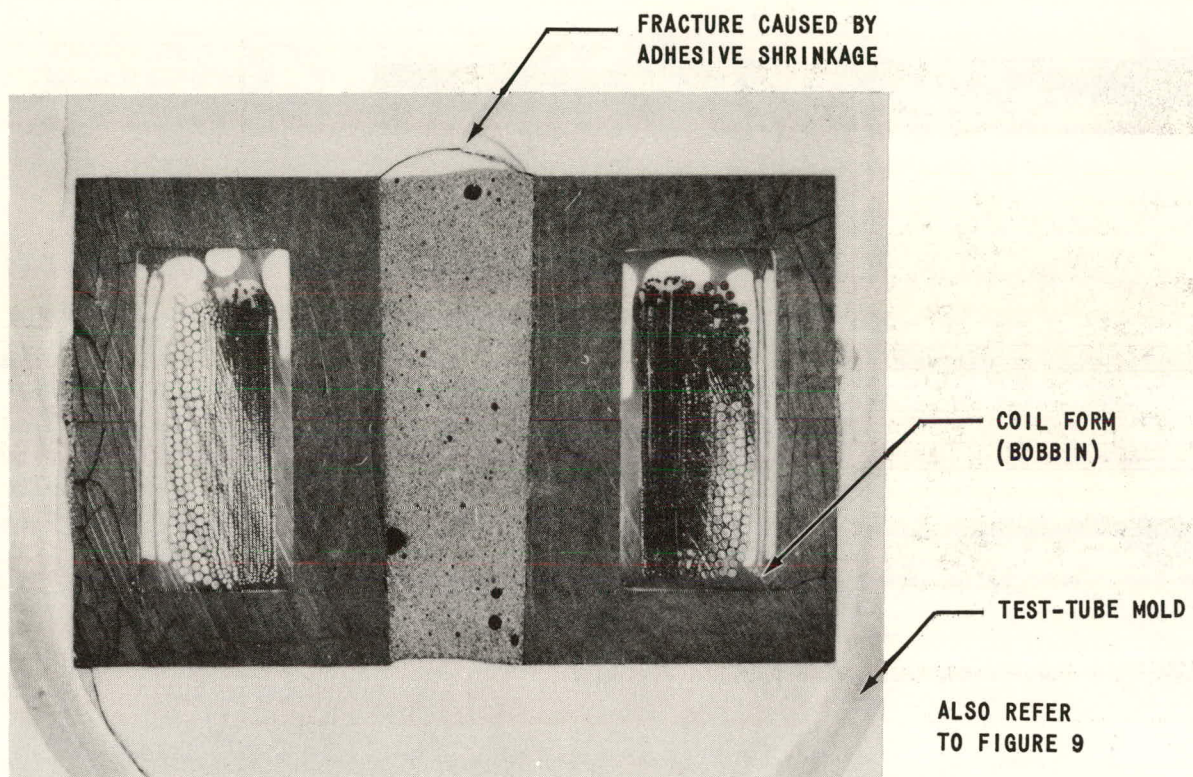


Figure 25. Bobbin Melted by Excessive Processing Temperature

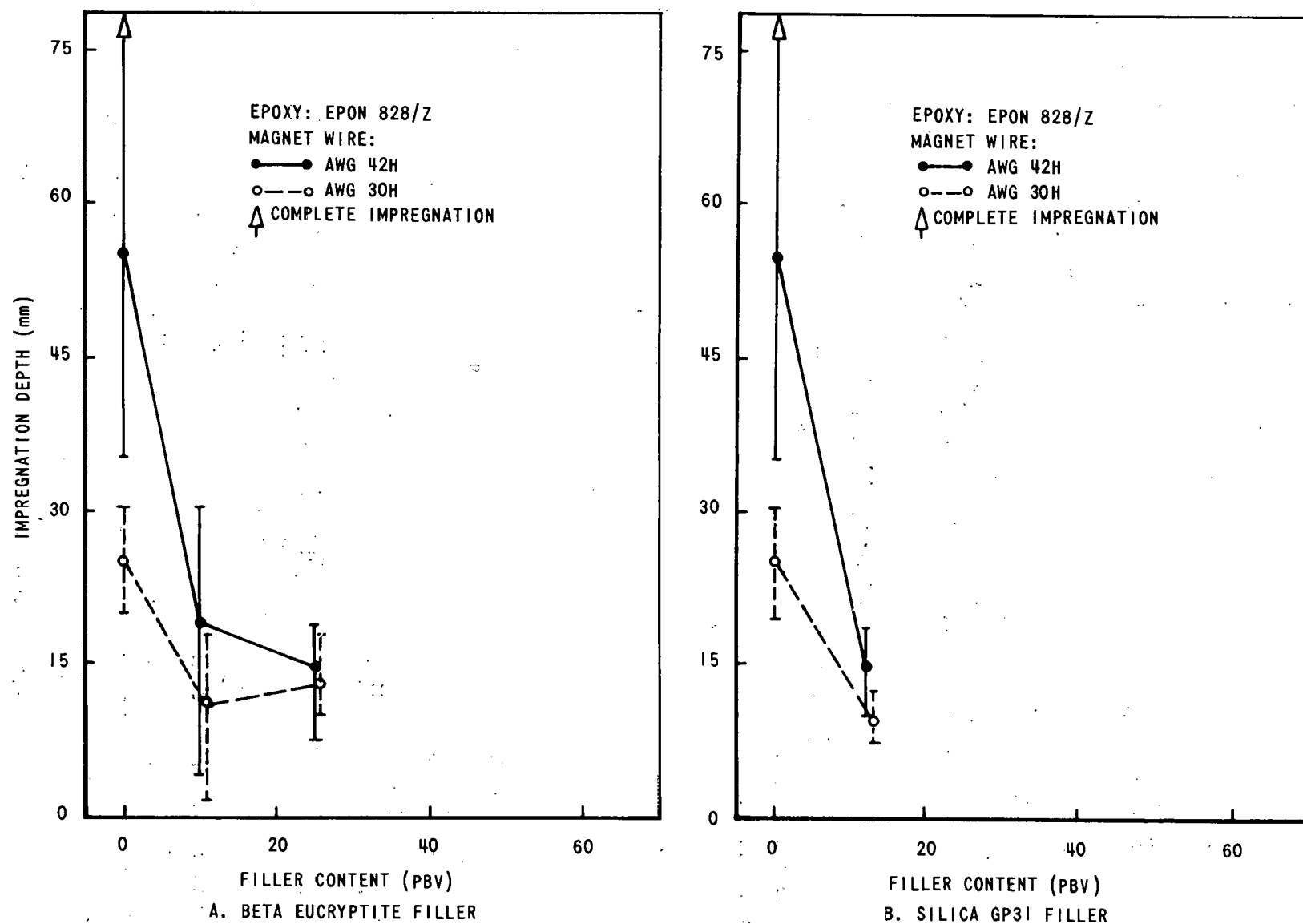


Figure 26. Environmental Impregnation Depth for Filled Epoxy Poured at 70°C and Atmospheric Pressure, Followed by Vacuum

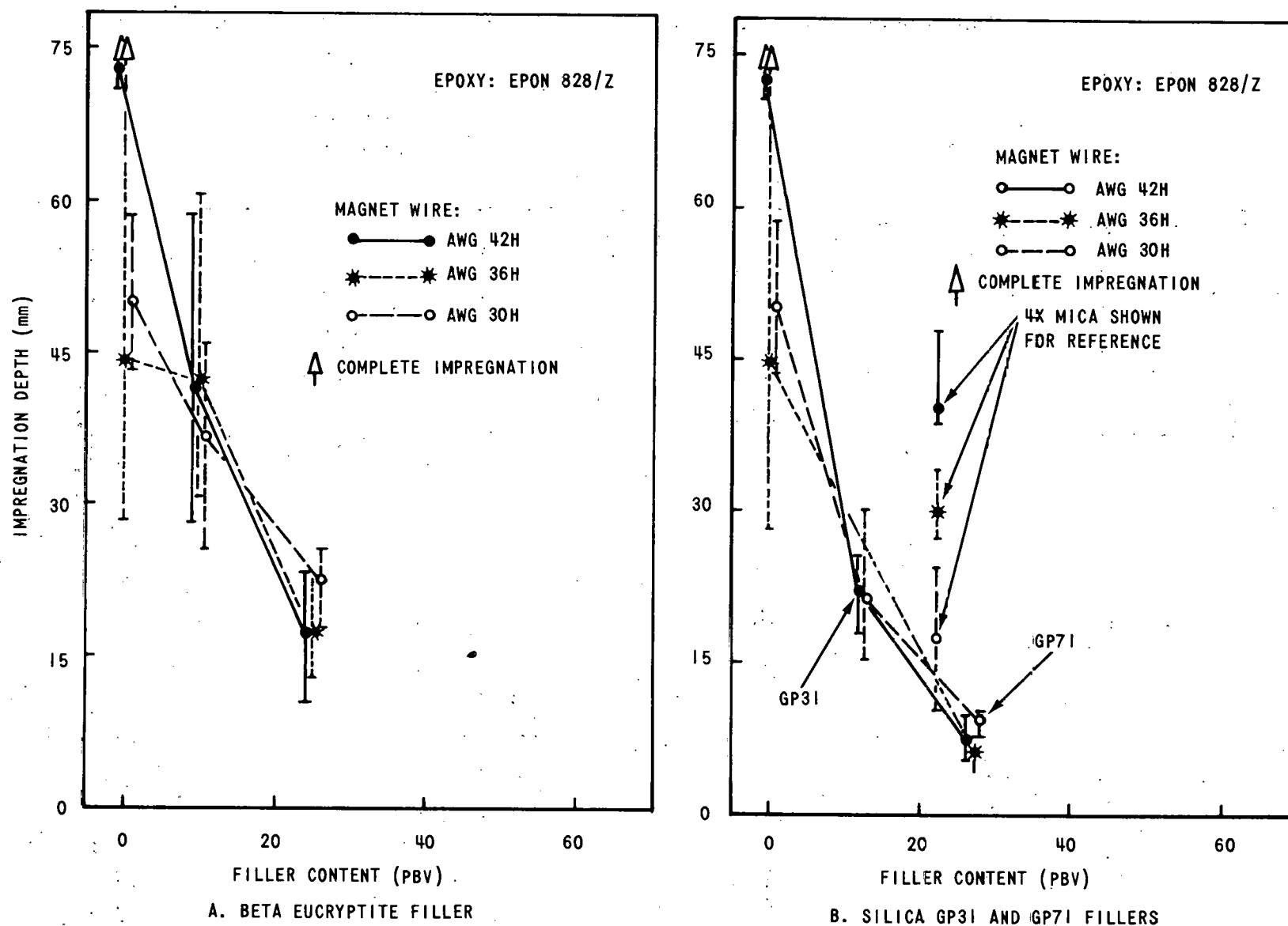


Figure 27. Environmental Impregnation Depth for Filled Epoxy Vacuum Poured at 70°C

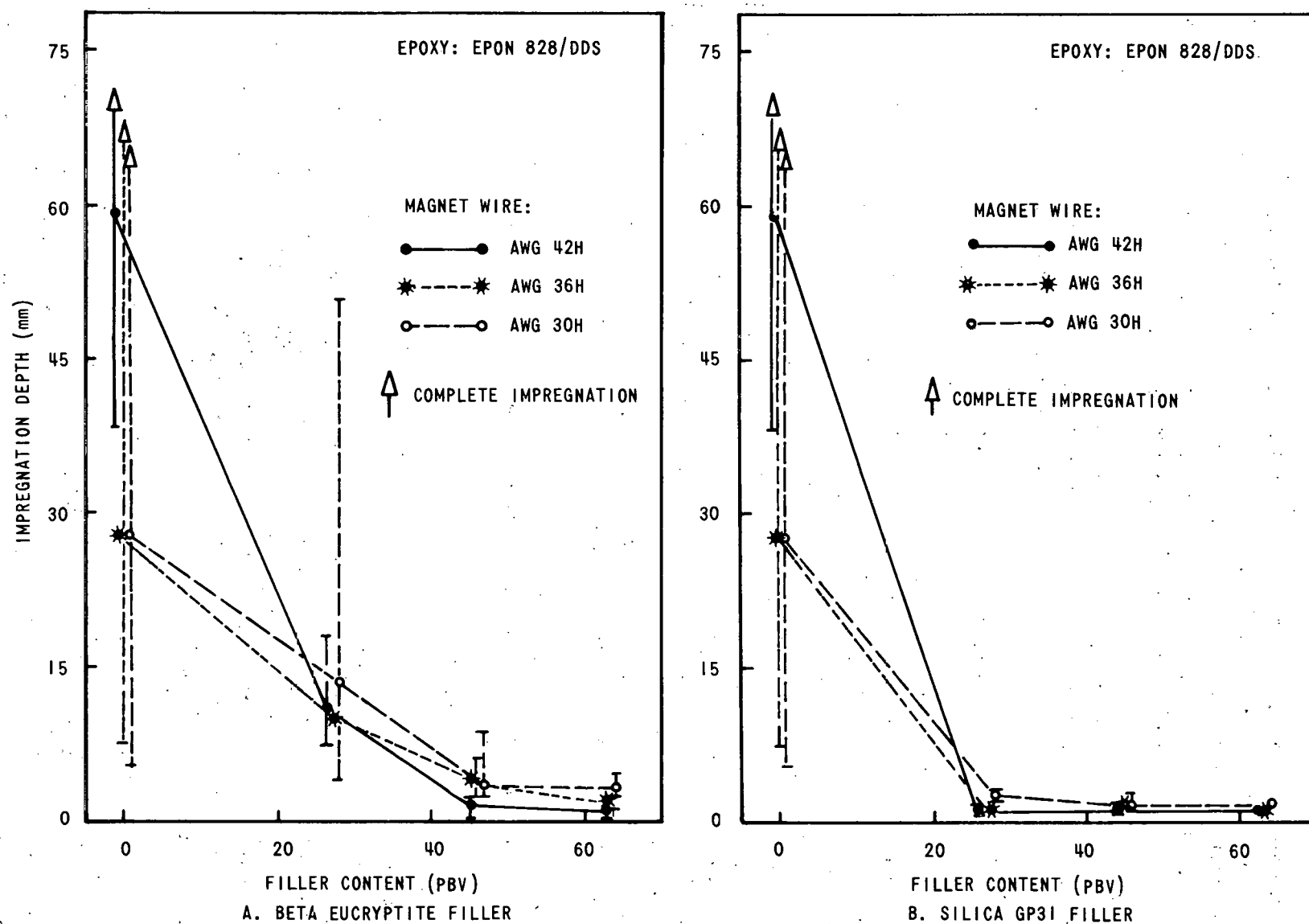


Figure 28. Environmental Impregnation Depth for Filled Epoxy Vacuum Poured at 140 °C

- Epoxy with Z hardener provided significantly better impregnation at 70°C than epoxy with DDS hardener at 140°C. This difference probably resulted from a difference in viscosity, but may have been caused by wetting properties of the hardener. Further work should be done to select a 140°C hardener that has better impregnating properties than DDS.

The pot core test coil described in Figure 20 was impregnated with Beta-Eucryptite filled epoxy with a 140°C vacuum-fill process. Adequate impregnation for small pot cores (up to Size 1811) was obtained with filler ratios as high as 46 pbv. Epoxy filtered out of the filler quite nicely and impregnation was better than expected. A rapid falloff of impregnation depth occurred at 56 pbv filler content. The data shown in Figure 29 (for 46 pbv and lower) represents small unimpregnated portions of single layers of the coil. The addition of holes in the bobbin flanges and selection of a better epoxy hardener should be enough help to give total impregnation of the Size 2616 bobbin. Epoxies with more than 46 pbv filler will not provide a reliable impregnation with the materials and processes evaluated. There are two alternatives for ferrite pot core coils that require both impregnation and stress relief:

- Preimpregnate the winding with a suitable epoxy, followed by potting with a heavily filled material to provide suitable stress relief for the core, and
- Find a more suitable high-temperature epoxy hardener and filler-particle shape-and-size distribution to provide better one-step impregnation.

Small coils can be impregnated with heavily filled epoxy if suitable processing controls are established to provide adequate epoxy flow paths.

Dimensional Control of Molds

Two silicone rubber mold materials were evaluated to determine whether additional filler⁶ would improve dimensional stability of molded products. Both RTV 630 and Dow Corning Silastic G were filled with up to 50 pbw of fused silica and Beta-Eucryptite fillers. Material properties of the cured mixes are shown in Table 6. The GP7I silica produced the highest strength. The GP3I silica filler had such a small particle size that it clumped badly and was difficult to mix properly. The two roll rubber mill was not used; the materials were hand mixed and evacuated before use.

Transformer molds were made from a 30-pbw mix of GP7I silica in RTV 630. Molding properties were satisfactory; however, the molds broke apart when they were removed from the dummy molded transformer. The mold was a one piece cavity in which considerable flexibility was required for removal without mold damage. A two-piece mold design such as shown in Figure 30 was required when more than one use of the mold was obtained.

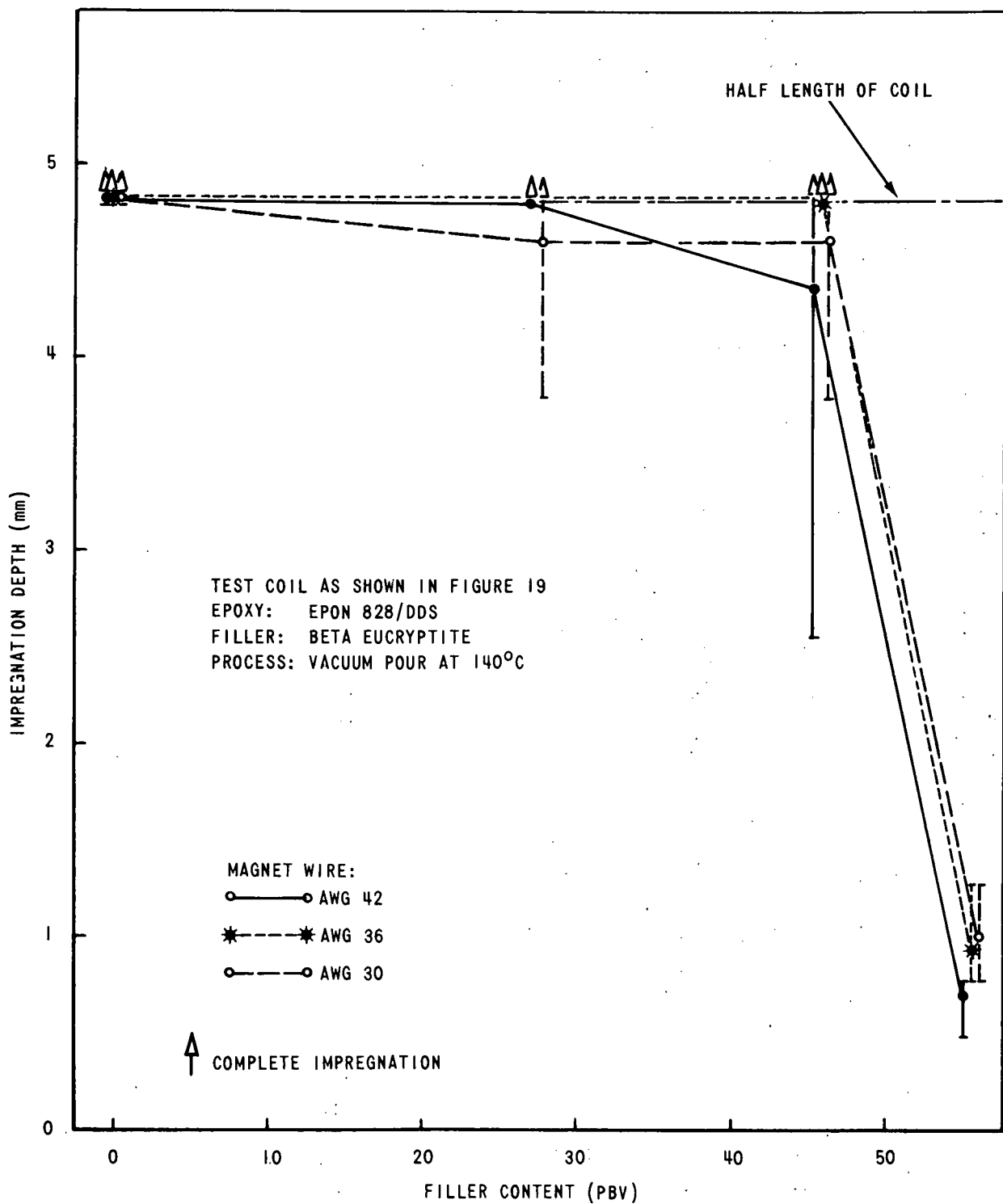
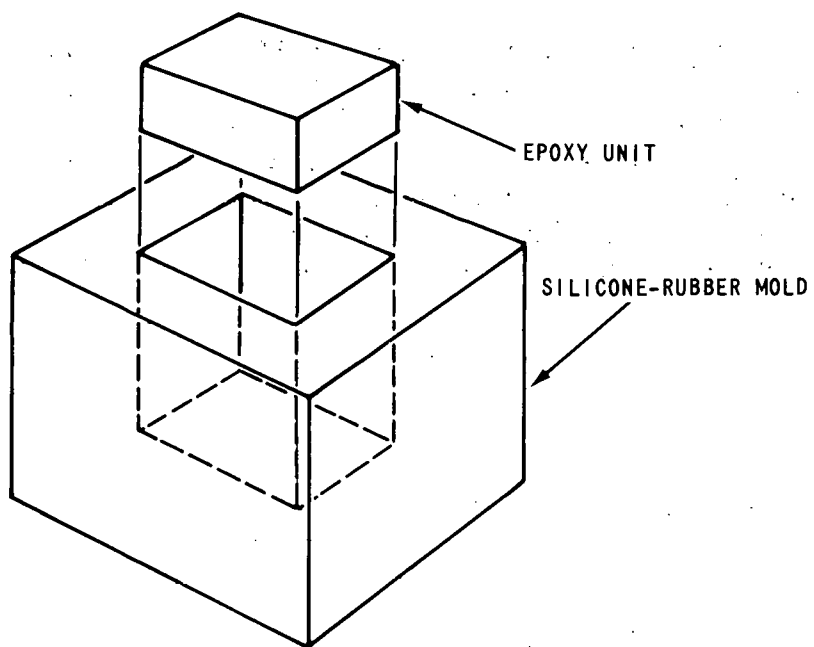


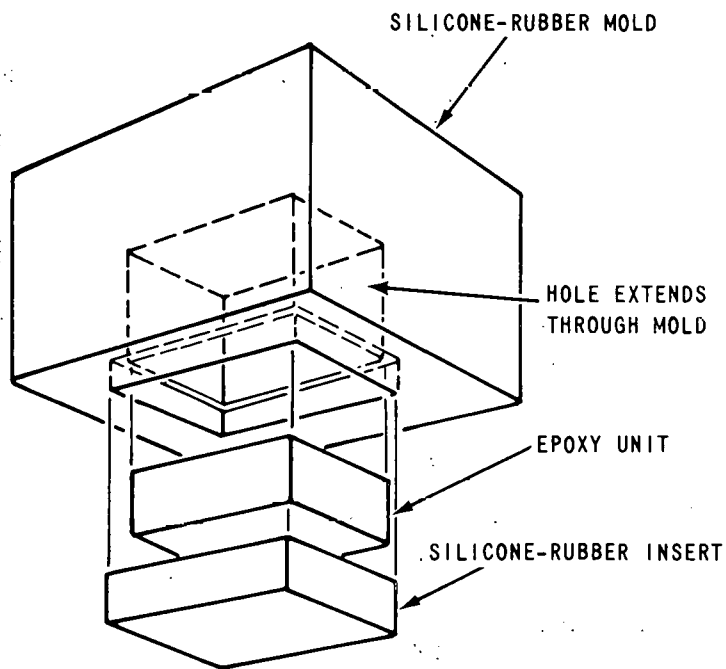
Figure 29. Environmental Impregnation Depth of Bobbin Coil in Ferrite Pot Core

Table 6. Mechanical Effects of Adding Filler to Silicone Rubber

Silicone Rubber	Amount of Filler (pbw)	Filler	Tear Strength (lb/in) (kN/m)	Tensile Strength (psi) (MPa)	Percent Elongation	Shore A Hardness
RTV 630	30	GP7I Silica	100.48 (17.60)	749.6 (5.168)	72	74.2
	30	GP3I Silica	89.92 (15.75)	693.0 (4.778)	70	63.2
	30	Beta-Eucryptite	92.54 (16.21)	663.5 (4.575)	78	65.0
	50	Beta-Eucryptite	89.22 (15.62)	724.6 (4.996)	68	80.2
Silastic G RTV	30	GP7I Silica	73.62 (12.89)	547.8 (3.777)	124	43.2
	30	Beta-Eucryptite	75.50 (13.22)	427.8 (2.950)	122	41.8
	50	GP7I Silica	61.76 (10.82)	613.8 (4.232)	72	52.0
	50	Beta-Eucryptite	58.36 (10.22)	387.8 (2.674)	71	55.6



A. ONE-PIECE DESIGN



B. TWO-PIECE DESIGN

Figure 30. Silicone-Rubber Molds

Test samples of two epoxies were made in both the unfilled RTV 630 molds and in molds which were filled with 30 pbv GP7I silica. One epoxy was unfilled Epon 828/Z. The other was filled with 51 pbv GP7I silica in Epon 828/Z. Repeatability of dimensions for both of the processes was evaluated and compared in Figure 31 to the original mold master dimensions. These data indicate that dimensional stability can be slightly improved by use of filled silicone rubber; however, its use should be reserved for products which require increased dimensional stability.

Materials and Sources

Vydax (mold release--a fluorocarbon telomer in a fluorocarbon solvent):
E. I. Du Pont de Nemours and Company, Incorporated, Wilmington,
Delaware

Freon PCA (trichlorotrifluoroethane): E. I. du Pont de Nemours and
Company, Incorporated, East Chicago, Illinois

Silicone Primer SS-4004: General Electric Company, Waterford,
New York

RTV511, RTV630 (silicone elastomer): General Electric Company,
Waterford, New York

Thermolite (dibutyltin dilaurate catalyst for RTV 511): Nettle and Thermit,
Rahway, New Jersey

EA934, EA956: Dexter Corporation, Hysol Division, Olean, New York

Beta Eucryptite: Foote Mineral Company, Exton, Pennsylvania

GP3I, GP7I (Glasgrain): Glasrock Products, Incorporated, Atlanta, Georgia

Epon 828 (epichlorohydrin bisphenol-A): Shell Chemical Corporation,
Oak Brook, Illinois

Z Hardener (aromatic amine): Shell Chemical Corporation, Oak Brook,
Illinois

DDS (diaminodiphenyl sulfone): Miller-Stephenson Company, Incorporated,
Los Angeles, California

Eastman 910 MHT (cyanoacrylate): Eastman Chemical Products, Incorporated,
Kings Port, Tennessee




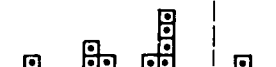
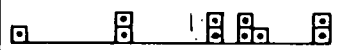



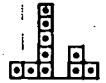

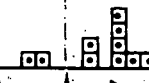
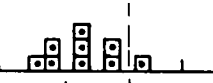
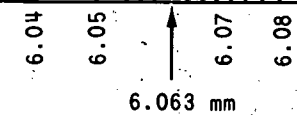
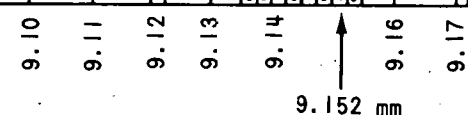
FILLER	WIDTH (mm)			LENGTH (mm)		
	DISTRIBUTION	MEAN	STD DEV	DISTRIBUTION	MEAN	STD DEV
NO MOLD FILLER						
NO EPOXY FILLER		6.0576	0.00859		9.1478	0.00742
GP71 51PBV EPOXY FILLER 1st RUN		6.0604	0.00645		9.1394	0.00942
2nd RUN		6.0645	0.01593		9.1468	0.02380
SILICONE-RUBBER MOLD FILLED WITH 30PBV GP71 SILICA NO EPOXY FILLER		6.0663	0.00587		9.1481	0.00625
GP71 51PBV EPOXY FILLER 1st RUN		6.0665	0.00384		9.1488	0.00422
2nd RUN		6.0676	0.00653		9.1420	0.00909
MOLD MASTER	 6.063 mm			 9.152 mm		

Figure 31. Effects of Silicone-Rubber-Filler Materials on Mold Dimensional Control

J-Perm, A-Perm (ferrite powder): Magnetics, Incorporated, Butler, Pennsylvania

O-5 (ferrite powder): Indiana General Electronic Products, Keasbey, New Jersey

ERL 0510: Union Carbide Corporation, New York, New York

Tygon (polyvinylchloride tubing) Fisher Scientific Company, Pittsburgh, Pennsylvania

Teflon: E. I. du Pont de Nemours and Company, Incorporated, Wilmington, Delaware

Versamid 125: General Mills Chemical Division, Kankakee, Illinois

Delrin: E. I. du Pont de Nemours and Company, Incorporated, Wilmington, Delaware

Silastic-G: Dow Corning Corporation, Midland, Michigan

Mineralite 4X Mica: Mineralite Sales Corporation, Mineola, New York

ACCOMPLISHMENTS

Significant gains toward the major objective of building a pot-core transformer in which the air gap is completely controlled, the coil winding is fully impregnated, and the core is potted in a stress-free medium are as follows.

- The length of the air gap at the interface surfaces of the ferrite pot core sections was minimized by establishing workable assembly and bonding processes.
- Acceptable bond strength was achieved by using EA934.
- Inductance was controlled within reasonable limits by determining the clamping force required to produce maximum inductance on specific core/coil combinations. The EA934 was applied while the core pieces were held together under optimum pressure and the adhesive was cured at 80°C before the pressure was removed. Curing the EA934 at 145°C improved the bond integrity for 140°C cure potting systems, but did not provide a

consistent bond. EA934 was satisfactory when using 80°C cure potting systems. EA934 was the most suitable of the adhesives evaluated for applications similar to those investigated.

- Ferrite-filled EA956 was applied at the sides of the air gap in an effort to reduce the effective air gap with a high permeability material. Ferrite filling did not appreciably increase the inductance of coils enclosed in the high permeability pot cores used in this investigation.
- Two epoxy systems which had a thermal expansion coefficient (CTE) approximately equal to that of the ferrite core material were developed. The epoxy mix of 68 pbv of Beta-Eucryptite in Epon 828 with DDS catalyst gave the lowest thermal expansion coefficient of any epoxy known to exist, $8.9 \mu\text{m/m}/^\circ\text{C}$ at -50 to 25°C and $11.9 \mu\text{m/m}/^\circ\text{C}$ at 25 to 80°C . This balance of CTEs potentially offers low-stress potting around the ferrite core. However, extra stress relief in the form of a thin silicone rubber coating on the core was required to keep the inductance of the ferrite core reasonably high.
- Filler concentrations in the two epoxy mixes were varied to investigate the effect of different CTE's on the inductance properties of ferrite cores. The silicone rubber coating material on the core of the test samples evaluated was too thin to completely eliminate potting stress. However, a significant improvement was obtained with the use of silicone rubber and a thermally balanced epoxy. Careful control of the silicone rubber thickness will be required to obtain good stress control.
- A suitable inspection technique to determine impregnation depth used a sharp probe to move the wires while alternately viewing the cross-sectioned coils under both ultraviolet and incandescent light. A high degree of confidence in the results was obtained. The relationship between impregnation depth along the coil length and epoxy filler content was observed on both stick-wound and bobbin coils.
- As expected, the vacuum filling process provided much better impregnation than a process of filling the coil under atmospheric pressure followed by a vacuum. This supported previous findings of uncontrolled studies. Epoxy containing Beta-Eucryptite filler impregnated coil windings significantly better than epoxy filled with fused silica. Even so, the impregnation obtained with Beta-Eucryptite filler was not good in filler ratios above 46 pbv. The DDS hardener used with the 140°C filled epoxies did not impregnate as well as Epon 828/Z hardener processed at 80°C .

A number of special problems which should lead to better impregnation of individual test coils with filled epoxy were identified, and the following procedures are suggested.

- Use a stiff interlayer insulation to reduce falloff of the wire at the coil end.
- Eliminate adhesive tape from the coil winding if possible.
- Provide a better epoxy flow-path in bobbin coils by adding holes in the flanges at the ends of the coil.
- Provide a coil design in which filler filtering can occur as close to the magnet wire as possible.
- Reduce winding margins at the ends of the coil.
- Use a bobbin material which will not melt at the potting process temperature.
- Use as large a magnet wire as possible.

The dimensional stability of silicone rubber molds made of RTV 630 was improved by adding 30 parts by weight of GP71 fused silica. The slight improvement obtained by filling the silicone rubber would not normally justify the extra expense required to fill the mold material.

FUTURE WORK

A better adhesive for use in the 140°C potting process is required. EA 934 is too strong for the ferrite material. A lower-modulus adhesive with good bond strength should be developed for a 145°C cure. The same filled epoxy used to pot the core should be evaluated as an adhesive, since low thermal stresses should exist.

Toroids identical to those used in this investigation should be coated with a thicker silicone rubber coating and repotted in the 63 pbv mix of Beta-Eucryptite and Epon 828/DDS. This experiment would prove the validity of the investigation conducted. An improvement in corner coverage of silicone rubber on the pot cores is needed to obtain a more uniform production process. It is possible that molding the silicone rubber will be required to obtain this coverage. A new Thiokol foam material which was not available at the time of the investigation is now available. This new foam should be evaluated to determine whether it is more suitable than silicone rubber for the stress relief required on ferrite cores.

A pot core coil form which has CTE as close as possible to $10 \mu\text{m}/\text{m}/^\circ\text{C}$ should be made to provide thermal compatibility with the other materials being used.

Impregnation with filled epoxies must be improved. The first step should be to find another 140 to 160°C epoxy hardener that will give better impregnation. Particular properties of fillers (such as surface area, particle shape, and particle size distribution) should be varied to find the properties that affect impregnation.

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- ⁵W. H. Hoback, "Pigment Dispersion--Theory and Practice, " American Paint Journal, September 13, 1954, pp 68-94.
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Appendix

RELATIONSHIP BETWEEN PERCENT BY
VOLUME AND PERCENT BY WEIGHT
FOR SILICA AND BETA EUCRYPTITE

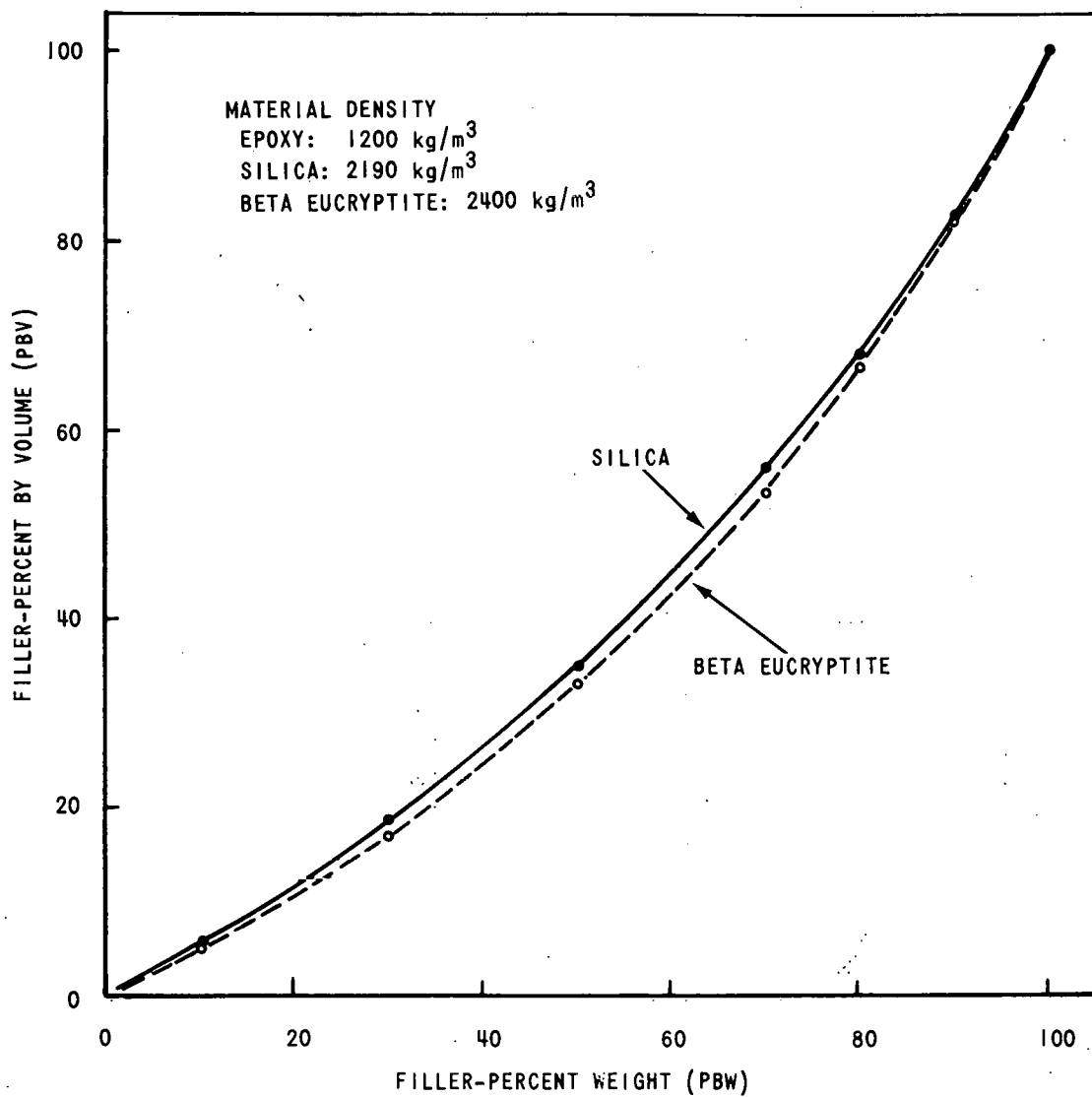


Figure A-1. Percent by Volume (pbv) Versus Percent by Weight (pbw) of Epoxy Fillers