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PROCESSING EVALUATION
OF MAGNETIC PRODUCTS

PDO 6984353, Final Report

W. F. Moyle, Project Leader

Published September, 1972

Prepared for the
United States Atomic Energy Commission
Under Contract Number AT(29-1)-613 USAEC

**Kansas City
Division**

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Project Leader:
W. F. Moyle
Department 845

PDO 6984353
Final Report

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PROCESSING EVALUATION OF MAGNETIC PRODUCTS

BDX-613-518 (Rev.), UNCLASSIFIED, Published September, 1972

Prepared by W. F. Moyle, D/845, under PDO 6984353

Studies are reported on magnetic device core preparation, coil winding, electrical connection, assembly, and encapsulation of magnetic devices.

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THE BENDIX CORPORATION

KANSAS CITY DIVISION

KANSAS CITY, MISSOURI

A prime contractor for the
Atomic Energy Commission

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SUMMARY

As a result of work on PDO 6984353, processing problems were solved and new manufacturing capabilities developed for magnetic devices. The complete manufacturing process for encapsulated devices was studied. Of the 14 areas originally planned for coverage by this effort, 12 were evaluated and two were eliminated because of their relative importance, the lack of required equipment, funds, and time.

The work director, an in-process tester designed to compare a product with an acceptable standard unit, is ready for incorporation into the manufacturing process.

A system for preparing encapsulation material and pouring it directly into molds--without subjecting it to ambient pressure and temperature between the preparation and pouring operation--was developed.

Encapsulation of magnetic products by a transfer molding process was compared with the present method of encapsulation. Limitations and design requirements for the effective use of this process are defined.

A prototype of a "zero-ID" toroidal winder was designed, built, and partially developed.

Adhesive requirements were evaluated and a composite list of characteristics which fulfills existing manufacturing requirements was compiled. No single adhesive was found which would fulfill all requirements, but two materials were found which met all but one requirement.

An effort to reduce the size of toroidal coils which can be wound at the Bendix facility resulted in an investigation of the Boesch-Leesona Minitor Coil Winder, and a procedure was established for filling that machine's winding shuttle.

Free-standing coils were evaluated for winding time and cost savings.

An evaluation of conductors of various shapes and materials was made to determine what alterations would be necessary for use with existing coil-making equipment. The benefits and disadvantages of using different materials, shapes, and methods of electrical connection were evaluated. In the manufacture of PC boards with nickel conductors, a new method was developed by the Materials Engineering Department to reduce production cost and improve the quality of the resulting electrical connections.

Centrifugal casting for coil impregnation was developed as an alternate to vacuum encapsulation. This process improved coil impregnation and simplified the preparation and handling of encapsulation material.

The application of pressure casting to encapsulation was studied, but during the development of the vacuum impregnation process, present equipment could not be adapted to pressure casting; therefore, this part of the project was cancelled.

No action was started on the subject of insulation.

A redesign of the RTV mold used for magnetic devices eliminated the requirement for a connection-pin header. The pins were located in their proper position by a part of the mold which also served as an assembly fixture.

A mold-loading tool was designed for properly positioning small devices in a mold cavity without handling damage. A method of securing wound-tape cores by adhesive instead of steel banding and a seal was developed to save space by reducing the required size of the core opening in the wound coil.

Core processing was added to the project to develop an adequate method for sealing silicone-oil-filled cores. A plastic case was vacuum-formed around the core in two stages. This process removed the immediate need for the centrifugal casting process because it could be inserted into existing product processing with a minimum of alteration.

DISCUSSION

SCOPE AND PURPOSE

This final report presents the efforts and findings of PDO 6984353 under four headings: Work Director; Encapsulation (combining impregnation, transfer molding, and centrifugal casting); Coil Winding (combining toroid winding, shuttle filling, stick and coil form winding, and core processing); and Assembly (combining adhesives, other conductors, electrical connections, and assembly).

ACTIVITY

Work Director

In transformer assembly, it is difficult to ascertain that coil wires are attached to their proper pin connections. It was felt that the use of an in-process tester would give instant verification of voltage ratio and transformer-winding polarity and that connection errors could be discovered for correction during assembly. A work director was designed and built which compared a unit-under-test (UUT) to a standard reference unit (Figure 1). Designed specifically for the Y00000 and X00000, the basic work director design could be adapted for use with any transformer.

Figure 1. X00000 Tester Schematic

In the operation of the work director, a 1000-Hz voltage is simultaneously impressed across the primary winding of the unit under test (UUT) and the reference unit. Indicator V_1 is connected between like pins on the UUT and the reference unit. For acceptance, the voltage on either side of V_1 should be the same, and V_1 should remain at 0 volts. Small voltage differences are not considered cause for rejection; large differences indicate incorrect polarity, open windings, or open connections, and will cause a nearly full-scale meter deflection.

Information describing the original work director was given to the Test Equipment Design Department for review and a determination of the feasibility for expanding the work director's capabilities to test all transformers for acceptable turns ratio and coil polarity. The evaluation indicated that redesign would be so extensive that a new design was necessary. The principle of comparing the unit-under-test to a standard unit was retained.

The new work director gives a pass-fail indication which can be utilized by all magnetic-product production personnel. Equipment which gives a meter reading usually must be operated by a production test checker. This work director will have to be set up for a particular product by a test checker, but it can be operated by production personnel.

Variable parameters enable the work director to test any transformer in production at this time. "Open setup" test cables are used with clips, or adapters designed for a specific unit's pin configuration. The null detector is used as an indicator. The null condition indicates that the reference unit and the UUT are alike. Because various voltage ratios may be applied to the tester, a great variety of output voltages can be impressed across the null detector. Since the null aperture is a fixed percentage of the voltage across the null detector, the actual size of the null aperture can be influenced by the output voltage. To provide consistency in the output voltage, a precision automatic gain control (AGC) was placed in the circuit between the output of the transformer and the null detector.

The first amplifier ordered for the automatic gain control did not function as well as expected. This portion of the circuitry was redesigned for use with a Burr-Brown Model 4030/25 Divider. The new circuit was wired and tested and, after slight modification, it performed precisely as required. The remaining PC board assemblies for the AGC and the null detector were added. This work director is now complete and the Operating and Calibrating Procedure is included in this report as Appendix A. The tester has been checked using two Gertsch ratio transformers. Ratio check accuracy of 1 percent or better was obtained over most of the test range. Non-linearities at several points in the test range had decreased accuracies to between 2 and 3 percent. The non-linearities will be eliminated before the tester is released for use. The tester may be adjusted so that it will distinguish between two coils of different ratios. Coil polarity

is not a marginal parameter. Either it is correct or reversed. There are, however, other factors that influence the polarity check, such as an open or shorted coil. A provision has been designed into the tester to allow the operator to change the polarity of the test signal. This will effectively correct the polarity of the test signal and the tester will indicate forward polarity if wrong polarity is the only problem.

The tester is packaged in a bench cabinet which contains a sine wave oscillator, a power amplifier, and a control chassis. A connector on the control panel allows the use of either an open setup testing cable or an adapter for a specific transformer.

The following is a general discussion of circuit operation and the problems which may be encountered. The circuit block diagram given in Figure 2 may be used as a reference.

The ac power source, consisting of a sine wave oscillator and a power amplifier, is used to provide the required test signal to the reference and test transformers. The frequency and amplitude of this test signal is set by a digital readout, or it may be set when calibrated. The amplitude can be set for a specific transformer adapter so that when the operator uses that adapter, the test signal amplitude for that transformer is programmed. The test circuit has two channels: one for the reference signal and one for test signal. The first section of each channel is the range circuit. The purpose of this circuit is to amplify or attenuate the two signals so that the two output signals will always have a peak amplitude of between 1 and 10 volts for an input signal range of between 0.01 and 100 volts. This range should cover any coil ratio. The output signal must be between 1 and 10 volts in order for the next section of the circuit to operate within this linear range. Both range circuits are controlled by the reference signal so that any variation in ratio of the test transformer will have no effect on the range. It is important that the two range circuit channels be identical. Both must have the same gain and phase shift. Any signal distortion in one channel must be used for these range circuits since they offer the maximum uniformity of circuit layout. Precision components were also used where required.

This same problem also exists in the gain circuits. The gain circuits further condition the signals so that the gain output signals are always 1 volt in peak amplitude. Here again, both gain circuits are controlled by the reference signal so that the test transformer has no effect on the gain. The objective of the range and gain circuits together is that of a precision automatic gain control. This means that for any input test signal from the transformers within the range of 0.01 and 100 volts peak, the output of the range-gain circuit will always be a constant 1-volt peak. This allows uniformity in the comparison signals at the input of the ratio detector. For any ratio of the transformer, the ratio detector always compares the test

Figure 2. Block Diagram of Work Director Set-up

signal to a constant amplitude reference signal. This means that a constant aperture of plus and minus tolerances can be set in the ratio detector that will be valid for all transformer ratios. The ratio detector electronically subtracts the test signal from the reference signal and greatly amplifies the difference. It then converts the difference (a sine wave) to a dc level. This dc level is then compared to a set fail level and, if the dc level is greater than the fail level, the RATIO FAIL lamp lights. It should be noted that in this system the only way for a transformer to pass is for it to have the same turns ratio as the reference transformer. Either a wrong ratio, wrong polarity, or an open or shorted coil will cause a failure. In this way, the tester is safeguarded against passing a defective product.

The polarity detector converts the sine wave signals from the range-gain circuits to square pulses. It then tests for pulse coincidence. The pulses occur during the positive portions of the sine waves so that if the two pulses from the reference and test signals are coincident, the two signals are in phase or have the same polarity. The pulses are independent of the signal amplitudes so a wrong ratio will have no effect on the polarity indication. If a polarity failure is indicated, a ratio failure will also be indicated. The polarity reversal switch may be operated to change the polarity of the reference signal. This will cause a passing polarity indication and, if the ratio was correct, it will also indicate a passing ratio. If the ratio is incorrect, the ratio failure indication will remain.

All circuits use solid-state integrated-type circuits and precision low-drift components. This type of circuit design offers excellent stability with little maintenance.

Coil Winding

At present, all toroid coil winders require a shuttle to store the magnet wire which is wound onto the core. The inside diameter of a toroid coil can be no smaller than the size of the winding shuttle (Figure 3).

The manufacturers of toroid winding machines indicate a minimum coil inside diameter (ID) of 0.062 inch, using standard winding accessories; and 0.032 inch, using a special miniature winding head and a special shuttle. Both limits are too optimistic for actual production winding and minimum inside diameters of 0.090 and 0.045 inch, respectively, are more realistic figures.

Some coils require a finished inside diameter smaller than the cross section of the shuttle. When coils of this size are required, all or part of the coil must be wound by hand. At the present time in industry, coils for most shift-register type transformers are wound by hand. The basic solution to this limitation would be to develop a winder which did not require a shuttle. The only

Figure 3. Basic Toroid Coil Winding System

item which would pass through the center of the core would be the total length of magnet wire to be wound on the core in one operation. This wire would be in the form of large circumference loops of wire known as "storage loops" which would pass through the center of the core. As turns were added to the coil being wound, the supply of wire in the storage loops would be depleted. If everything came out even, it would be possible to convert the tail-end of the last storage loop into the last required turn of the transformer coil. The generic term for the type of equipment which performs this operation is the "zero-ID winder."

Different systems have been tried to achieve this capability, but at the time this project started, no one in the coil winding industry had developed a machine faster than hand winding. One early model used a needle made of a magnetic material. The needle was attached to the magnet-wire with adhesive and was moved with a magnet. The needle rested on top of a thin plastic plate and the magnet moved in a circle along the bottom surface of the plate. When the needle passed through the core, the magnet left the needle on the near side of the core and picked it up again on the far side. This design did not prove successful and the equipment is not offered for sale at this time.

Another design substituted a magnet-wire loop for the familiar shuttle. The wire to be wound on the core was cut with enough length to permit winding the coil and forming the wire loop. This loop was formed by attaching one end of the magnet-wire to itself after the loop was formed through the center of the core (Figure 4).

Figure 4. Zero-ID Winding System

The core was placed in a holding mechanism, and the wire loop was mounted on three pulleys (Figure 5).

Figure 5. Wire Storage and Core Support

The coil winding wire was stored in the form of multiple loops around the three pulleys with the drive loop. The free end of the coil winding wire was anchored to the core, and only the last length of wire was free of the pulleys to act as the winding loop. If more than one loop of wire were removed from the storage pulleys, the wire would not wind tight on the core. This also resulted in a tangle of wire which prevented further winding of the coil. After a rather lengthy period of development, this winder is still no faster than hand winding.

Some development work was done at Bendix to solve the winder problem. The first attempt was to hold the wire to the surface of a flexible belt by a flow of air through the belt. The wire was to be held against the inside surface of the belt so no obstructions would impede the winding of the wire onto the core. The initial phase of this development was to design a belt with a cross section which would control multiple loops of wire in a manner that would provide an orderly feed into the winding loop from the storage loops. A test fixture was built for this purpose (Figure 6). The body of the fixture was attached to a vacuum source and a length of belting was placed on its open side. The vacuum was applied creating a flow of air through the belt. Lengths of wire were laid on the surface of the belt to determine the force required to pull the wire along the belt's surface. However, the wire would not stay on the belt, and the test could not be made.

To further test this basic design, a cap was made which was similar to the body of the test fixture. The cap was attached to the body with the belt in between. The fixture cap was attached to the shop air manifold through a pressure control valve. The test was tried again, this time supplying air under positive pressure to try to hold the wire against the belt. This design was also unsuccessful.

A new design was conceived which did not involve air flow. In place of the belt, two O-rings were put side by side in a manner which allowed for a closely controlled gap between them. This gap was smaller than the magnet-wire to be wound so that the O-rings would grip the sides of the wire (Figure 7). To provide unimpeded space inside the winding loop, each O-ring moved on a separate set of rollers. The wire which formed the winding loop was pulled between the O-rings by tension on the winding-loop wire. To supply motion to the O-rings, a flat belt was laid along their outer periphery. This flat belt was moved by a drive pulley.

Figure 6. Belt Test Fixture

Figure 7. O-Ring Drive Cross Section

An open space was needed in the track of the O-rings to mount the core which was to be wound. The O-rings were routed away from the wire loops to idler pulleys and back. The flat, powered belt was doubled back on itself and was routed around the outside of the assembly (Figure 8). A model of this design was built and tested extensively. The O-rings were capable of gripping the magnet wire and moving it in the oblong race-track-shaped path. The rounded ends of this path imparted a curvature to the wire which remained and caused difficulty in directing it across the uncontrolled space left for mounting the core. The proper spacing between the O-rings to achieve a driving force for the wire, without impeding the ability to pull the wire between the O-rings, seemed to be very critical. It was necessary for the multiple loops of magnet-wire stored between the O-rings to remain in the sequence of their application. Any crossing of the wire of one loop over another tended to pull two loops of wire between the O-rings. This caused an excess of wire in the winding loop which would not allow a tight wind on the core and resulted in tangling and breakage.

Figure 8. Basic O-Ring Design

Two courses of action are possible to solve the problem of undesirable wire curvature where the path of the wire is straight. It is anticipated that a flat belt with a projection in the center would restrict the space between the O-rings and act to straighten the wire after it leaves the end pulley. This projection should also help to avoid the crossing over of wires within the storage loops. The second possibility would be to change the shape of the wire storage loops to circles. This would avoid the alternate bending and straightening of the magnet wire, which undoubtedly has a work-hardening effect, but it would complicate the design of the mechanism required to support and move the O-rings in this path.

For each pulley, the critical nature of the O-rings spacing adjustment is easily solved by use of a micrometer adjustment, instead of an individual screw adjustment, to locate the entire set of O-rings pulleys.

A number of design layouts have been made for mechanisms which hold a core in a precise location and rotate it at a variable rate. There are many confirmed methods of doing this; it is only necessary to determine which method can be most effectively miniaturized.

The problem of counting the number of turns of wire which are added to the coil has been approached from many different directions in our standard winding machines. All known methods are dependable to some degree, but all can be improved. This problem should be treated as a separate subject so that the solution can be applied to all winders. Recently, a machine using a new and rather complex method of handling the magnet wire during winding was exhibited at a show of production machines in Chicago. At that time, the machine was not in production and the exhibited unit was a prototype model. No further development is anticipated at Bendix until this new machine is commercially available and can be thoroughly evaluated.

Present equipment available at Bendix for winding subminiature transformer coils is the Boesch Leeson Minitor winding head, which is built to fit the standard TO-125 toroid coil winder. This miniature winding head uses a special shuttle with a different method of storing the wire to be used for winding. The magnet-wire is wound in the form of a spring and is pushed inside a toroidal shuttle by a special shuttle loader. Because it was necessary to wind transformer coils having smaller inside diameters, the equipment was evaluated and a setup procedure was established for the special shuttle loading equipment. The evaluation was started using the minimum wire size (42 gage) loaded onto the minimum size shuttle, 0.032-inch outside diameter. The specific problems with this shuttle loader were mandrel breakage and wire breakage (Figure 9).

Because the mandrel was extremely small--about 0.010 to 0.012 inch across the corners--the tension on the wire had to be closely controlled so that a coil could be wound small enough to fit in the shuttle. Too much tension on the wire would break the mandrel and too little tension would result in no winding, or would wind a coil too large to fit inside the shuttle. To provide the force necessary for the mandrel to wind the wire into a coil, the mandrel was hexagon-shaped in cross section. With wire tension set between 2 and 3 ounces, the shuttle filler operated consistently without mandrel breakage. A characteristic of this winding method is the helical build up of magnet-wire as it was wound on the coil. This helix is extremely shallow, but it still has a detrimental effect when it is necessary to pack many turns into a subminiature coil.

Figure 9. Minitor Shuttle Loading

Any space within the outside diameter of the helix which is not occupied by wire is lost to the coil. The helical pattern was integral to the basic method of loading the shuttle, and no way was envisioned to alleviate this condition. Before this shuttle loading and winding process could be used in production, the order for the units which generated its requirement was completed and the work was suspended.

One of the older processes used to make coils for magnetic devices is "stick" coil winding. In this process, multiple coils are wound simultaneously on a long paper-board tube or "stick" coil form. Although there is little reason to question the quality of the coils produced in this manner, the method is extremely time-consuming, especially in the operation required to anchor the end-turns of each winding layer.

The present method uses a strip of adhesive-backed Mylar tape to act as the anchor. Depending on the size and shape of the coil, from one to four pieces of tape are used on each winding layer. The length of the piece of tape is nearly three times the length of the coil. It is put in place and centered before the coil winding layer is started. Two turns of coil are applied and the excess tape on that end of the coil is folded over the turns and down against itself. The remaining turns of the layer are wound on top of the tape, locking it in place. When the coil layer is completed, the remaining free end of tape is folded up around the end coil and along the surface of the winding layer (Figure 10).

Figure 10. Present Stick Coil Cross Section

Some experimental coils were wound using a magnet-wire with a coating material over the regular insulation. This coating softens and adheres to itself upon the application of alcohol or heat. As the coating cools or the alcohol evaporates, the coating rehardens. Where the turns of wire are in contact, they become permanently joined. Coils made in this manner are self-supporting (Figure 11). Impregnation of these coils in subsequent potting operations is extremely limited. The electrical insulation of the magnet-wire must withstand any voltage potential between turns. It is possible to achieve some impregnation of the coil by inserting an impregnable material between winding layers (Figure 12).

Impregnation will occur in this area of separation, but will not occur between turns within the same layer. Adjacent turns within the layer will be bonded together and will cause the entire coil to be self-supporting. Generally, the voltage potential between adjacent turns in the same layer is so small that impregnation is unnecessary. Although all coils built for this evaluation were stick coils, the same procedure could be followed to eliminate the coil form used on many small pulse transformers. To hold the wire in place until bonding is complete, a tool would be required which could be disassembled for coil removal. Coil forms are expensive, occupying space equivalent to approximately two layers of coil winding. An additional two turns of wire could be added to each end of each winding layer in place of the flanges of the coil form. Coils could be wound on a Teflon mandrel with outside dimensions the same as the dimensions of the opening through the center of the coil form. The mandrel could be made in two or three parts so that it would collapse for easy removal from

Figure 11. Completely Bonded Cross Section

Figure 12. Layer-Bonded Cross Section

the coil. Mandrel-wound coils would be smaller in diameter by twice the thickness of the coil form tube wall. If this dimensional change were translated to the outside of the wound coil, the reduction in cross sectional area of the coil could be substantially greater than that of a coil wound on a forming tube.

Another method of winding self-supporting coils is to use a flat conductor instead of a round conductor. From the standpoint of lost space due to conductor insulation, flat conductors are less efficient than those of round cross section. A wire of 0.020 inch in diameter has a cross section area of 0.000314 square inch. If 0.004-inch insulation is added to that wire, the area becomes 0.000612 square inch. A flat conductor 0.005 by 0.063 inch would have the same cross sectional area, and if insulation of 0.004-inch thickness were added, the total area would become 0.013 by 0.071 inch or 0.000923 square inch, 50 percent more total area than an equivalent round cross section wire. The additional surface area may be desirable for heat dissipation, but that is a special condition which becomes a part of the overall design evaluation.

Because of the inefficient use of space, the process of coil winding using flat conductor material was not pursued further. If it became necessary to utilize flat conductor material, the transition to the present stick and coil form winding machines would present few problems.

Assembly

In the past, magnetic product assembly depended on adhesives. Adhesives used for this purpose had certain distinct characteristics which were adequate, but which could be improved to reduce assembly time or improve product quality. A survey was performed to define which characteristics were really desirable to determine if one adhesive possessed all of the required characteristics. The desired characteristics are as follows:

- No mixing required by production personnel. Although adhesive mixing is not a difficult or demanding job, it is time consuming. It also assumes that the condition of the component materials to be mixed will not vary from one batch to the next. This is not a realistic assumption. It would be better to obtain a material that is premixed by the manufacturer or that has only one part which requires no mixing or adjustment.
- High internal strength is necessary for any adhesive used to bond irregular or unmatched surfaces.
- High surface bond strength to epoxy, enamel (wire coating), paper, fiberglass, diallyl phthalate, or metal (tin-lead or copper) is necessary.

- Long work life is desirable to avoid waste of material which has become unusable because of elapsed time. This requirement takes on additional importance when the scheduled building of parts is intermittent and of short duration.
- Short cure time allows parts to be hand held until the adhesive is sufficiently cured to hold parts together during normal handling. This negates the requirement for using oven heat to initiate or affect the curing. No fixturing of any type is required to hold parts in their proper relationship during longer cure times or during oven curing.
- High-temperature stability after curing. The drying process which precedes encapsulation may subject the adhesive to temperatures up to 240°F. If parts are not supported in the proper position by the mold, the adhesive may be required to perform a supportive function at drying temperatures.

There are two basic types of adhesives in use at this time. One type of adhesive has no internal strength and must be applied as a thin film between well-matched surfaces. It is a fast-setting material, but in addition to its low internal film strength, it has low strength at temperatures of 160°F or higher. One material of this type is a solvent which will soften plastic mating surfaces and allow them to merge in a sort of welding action. This solvent produces a good bond, but it can only be used on certain materials. Another material of this type bonds to each of the mating surfaces; then, on contact bonds the two surfaces together.

The second basic type of adhesive has good internal strength after it is cured. This material is useful for bonding items which have irregular shapes or uneven, non-matching surfaces. Most of these adhesives are a mixture of some basic resin material and a curing agent which must be combined in a specific ratio measured by weight or volume. These two-part adhesives must be measured, mixed, and applied within a specific length of time. When that time has elapsed, the mixture must be discarded and replaced with a fresh mixture. Although this mixed adhesive will usually cure at room temperature, the time required for this is usually prohibitive. The curing reaction time is shortened by the application of heat.

One adhesive was found which embodied all desired characteristics except one: Elevated temperature was required to start the curing process. The adhesive, a premixed Class B adhesive, eliminates the time-consuming mixing process and the problems caused by the work life limit, since this material is stable at room temperature.

Major suppliers of adhesives were approached for information concerning just-developed products. One adhesive, Loctite 312 seemed to fulfill Bendix requirements. Loctite 312 is a two-part polyacrylate resin. If the base material is applied to one interface and the primer to the other interface, curing action

begins only when the two interfaces are brought into contact. After application, the life of the material is 30 minutes. Curing time is 10 seconds, and adhesive joint strength at room temperature averages 2800 ± 250 psi. Material strength holds to about 180°F , then falls to 10 percent of its room temperature strength at 250°F .

Loctite 312 was tested to determine compatibility with magnetic device materials. This testing established the design limitations of the adhesive. Compatibility and bond strength tests indicated a need for further study. The bond strength of Loctite 312 varied from 900 to 4630 psi on five samples. It appeared that a necessary technique of application was not covered by the directions received with the material. Materials which were compatibility tested were embedded in the adhesive in 1-ounce, uncovered containers. Each container was placed in a larger container which was sealed at ambient conditions (approximately 70°F and 30 percent relative humidity). The jar was placed in an oven and the temperature was raised to 160°F and held for 7 days. Since the container was sealed, no change in the weight of moisture could occur. The increased temperature caused a reduction in relative humidity of approximately 2 to 3 percent--low enough that any corrosion would have been caused by the adhesive. No corrosive effect was observed.

A second set of samples was prepared. A small amount of water was placed in the large container before it was sealed. These samples were also held at 160°F for 7 days. Relative humidity inside this container approached 100 percent. The adhesive turned dark, shriveled, and hardened. The sample of magnetic core tape turned rusty brown and the exposed copper surface turned dark. There was a strong acetic-acid smell.

A group of test samples was heated to 160°F in a circulating oven for 7 days. A variation of relative humidity had no effect on these samples and all traces of acetic acid were dispelled. It is suspected that 16 to 24 hours at this elevated temperature would be sufficient to dispell the acid. Most magnetic products are dried and preheated before they are encapsulated. This drying process would also accomplish the expulsion of any acetic acid which might be formed during curing of the adhesive.

A second series of tests determined an adequate surface preparation, adhesive application, and the correct bonding process to achieve consistent bond strength. The surfaces to be bonded were freed of any grease or oil prior to application of the primer or accelerator material. The surfaces were roughened and a 1-mil thickness of adhesive was applied.

Conductor shape and material may have a considerable effect in determining the method of making electrical connections in magnetic assemblies. Most magnetic products made at Bendix use an electrically insulated, round copper conductor. This effort studied conductors of different shapes and materials. Wire suitable for winding coils can be purchased in round, square or rectangular shapes. Of the three shapes, the round conductor has the greatest cross-sectional area for the least perimeter. Having the least perimeter ensures the least amount of electrical insulation per mil of thickness since a certain amount of space between round conductors is unused. Square conductors can be used with a space saving of 3.5 percent if the square conductor is always oriented with the same side toward the center of the coil and if adjacent turns have no space between them. The space factor would need to be extremely critical to warrant the effort required to achieve these two conditions.

It is possible to save weight by using an aluminum rather than copper conductor in a magnetic coil. Because of the difference in the conductivities of the two materials, 1.55 times more cross-sectional area is required to carry an equal amount of current through an aluminum conductor. The weight of the aluminum conductor would be 47 percent of the weight of an equivalent copper conductor. Coil size would be at least 1.5 times as great if aluminum were used instead of copper. It can be assumed that welded connections would be necessary if aluminum conductors were used. At the present time, welding is a more recently developed operation than soldering, and a large quantity of evaluation samples are required for weld joint acceptance.

Special circumstances may require the use of nickel alloy conductors. These conductors are usually joined by welding. To facilitate the use of nickel, a process was developed to produce a nickel-clad, nickel-plated PC board. Because the diffusion rate of nickel is much different from that of copper, it is not advisable to have both metals present in the same welded joint. Besides eliminating copper from the welded connection, the newly developed process reduced manufacturing operations by 43 percent and manufacturing flow time by over 50 percent. The cost of boards made in this manner is estimated to be 15 to 20 percent less than current boards. The work done by Materials Engineering on this problem is described in detail in a report on Weldable Printed Circuits (Appendix B).

Conductors other than copper and joining methods other than soldering have been investigated in more detail on other development projects. These capabilities will be available when required by future product design.

Redesign of the toroidal coil winding head was initiated to permit winding flat conductors or insulating tape with existing toroidal-coil production winders. (Existing winding heads were too large and two systems required a coil made of flat

insulated ribbon conductor). Although it was possible to convert present winding equipment to the application of flat conductors, precise location of conductor turns on the core made the use of any method other than hand winding impossible.

At present, insulation tape is wound on toroidal coils by hand. A consistent product is difficult to obtain. In an effort to replace hand winding, it was determined that a flat-bottomed, flanged shuttle could be used (Figure 13). The tape to be wound would be pulled from the shuttle through a slit in the bottom. The shuttle surface on which the tape was wound had to be as nearly friction-free as possible to allow the tape to slide in relation to the shuttle. A piece of masking tape was found to be the most effective method of anchoring the free end of the tape being wound because it did not create any clamping action of the tape on the shuttle. The process of loading the tape on the shuttle was very critical, and it appears that a more sophisticated shuttle design would be required to make this operation feasible for production use. This development may aid the capability to wind flat conductors on to toroidal cores.

Figure 13. Flat-Tape Winding

A limiting factor in the design of small, epoxy-encapsulated coils and transformers is the device which holds the connector pins in place prior to encapsulation. This design device, usually a printed circuit board or a molded plastic header, is size limiting, expensive, and generally serves no useful purpose after encapsulation is completed. The first idea presented to replace the pin holder proved to be the most expedient. This was in the form of an RTV mold. The bottom piece of an RTV mold cavity plug had a pattern of holes to hold the connecting pins in the proper location. This plug was used as an assembly fixture for soldering the coil leads to the connecting pins (Figure 14). The method was first incorporated on the Z00000 part. Later it was applied to three more transformers. Since at assembly the pins were already in place in the mold plug, it was determined that it would be better to make solder connections above the coil to avoid damaging the magnet-wire or coil insulation. To accomplish this, the pins had to go from the bottom of the coil past its outside diameter to the top of the coil. It was necessary to predict the outside diameter of the coil so that a minimum diameter pin circle could be determined which would contain the coil without requiring force to accomplish assembly. To accomplish this prediction an equation has been developed and is explained in detail in Appendix C. The application for force between coil and pins increases the risk of rupturing the coil wire insulation and bending the pins. Clearance between the inside of the circle of connection pins and the outside of the wound coil should be allowed. If space limitations prevent this, it may be possible to reshape the mold or to relocate the connecting pins through the center of the wound coil (Figure 15).

An attempt was made to hold a closer pin location tolerance by using an Adiprene L100 molded base plug. Different coefficients of thermal expansion for Adiprene, RTV, and the connecting pin metal caused distortion of the mold when it was heated prior to encapsulation. To counteract this condition, the entire mold was made of steel with a small insert of resilient material at each pin location. The maintenance cost of this steel mold was so high that it was less expensive to use a premolded header designed to hold the pins in position and hold the coil during assembly. The difference was caused by the required location tolerance of the connecting pins. If this diametral tolerance is less than 0.014 inch or ± 0.005 inch, the resilient mold is unsuitable and some other design should be used.

Small transformers are difficult to load into one-piece RTV molds since the mold cavity is sometimes smaller than the finger of the person performing the operation. To simplify this process, a loading tool was designed similar in operation to a hypodermic needle (Figure 16). The tool consists of a shell or tube large enough to contain the magnetic device and small enough to fit into the mold cavity. The plunger in this tool is shaped so that it applies pressure to the magnetic device only at points of sufficient

Figure 14. Combination Assembly
Fixture and Mold

Figure 15. Optional Pin Locations

Figure 16. Loading Tool Operation

strength. One loading tool is designed for each transformer. The device is loaded into the tube with the plunger retracted. The loaded tool is then placed into the mold cavity in position for mold loading. The plunger is depressed, forcing the device into the mold and, finally, the tube is withdrawn from the mold cavity. On completion of this operation the mold is correctly loaded and none of the fragile parts of the magnetic device have been subjected to any force. A series of tools of this type were designed to load several different transformers.

Steel banding material, used to hold wound tape transformer cores in place, is of no use as core material in the design of a magnetic device. Because the banding material is relatively thick compared to the core tape, a considerable amount of the core opening is used to provide space for the banding. Experiments were made using a transformer with a critical cross section of core to achieve core saturation in a given length of time. Instead of banding material, a spot of adhesive was applied to the underside of the last wrap of core tape. The tape was held in place by a special tool which applied tension to the tape as it applied pressure to the adhesive joint. This tool was left in place while the adhesive was cured (Figure 17). After curing, the tool was removed and the excess tape was cut off. Subsequent testing of these transformers did not show a reduction in quality when compared to production units with a core secured with steel banding. This procedure was established for several specific transformers. The process could be applied to any transformer with a core of tape wound in place after coil encapsulation. It could also be applied to the installation of externally installed, C, E, and I cores by applying the adhesive to the matching pole surfaces. Further testing to determine the effects of thermocycling and handling indicated no defects in the units resulting from either test. The tool designed to hold the tape in place during the adhesive curing is too cumbersome and difficult to set-up for production. If the adhesive-secured tape process is to be applied to any product, some other method of holding the tape during adhesives curing will have to be devised.

The use of oil-impregnated wound-tape cores caused new problems in the manufacturing process of toroid transformers. Cores received from the supplier consisted of a stainless steel case in which was wound a specified length of core tape. To protect the tape and hold it in place, a paperboard sleeve was added to the core assembly (Figure 18). This sleeve had four small holes to allow oil impregnation. Trouble was experienced in containing the silicone oil within the cavity of the core and in preventing the epoxy potting material used to encapsulate the wound coils from entering the tape cavity of two cores. Localized pressure or deformation of the core tape, such as could be caused by the encroachment of encapsulating material into the tape cavity of the core, has an adverse effect on the core saturation after the assembly has been mechanically shocked.

Figure 17. Wound-Tape Core Fixture

Figure 18. Oil-Impregnated Core

Both of the above cores were being hand painted with white hysol in the Bendix Painting Department to bond the cardboard sleeve to the interface of the stainless steel case. This required many hours of labor and from 4 to 6 weeks manufacturing lead time. Upon completion of this operation, the cores were oil impregnated by immersion in a container of oil. The container with the submerged cores was put into a vacuum chamber and subjected to a 3 mm Hg vacuum. The vacuum was broken and oil was forced into the core tape cavity. The impregnated cores were removed from the oil and the external surface wiped with paper tissues. The area around the fill holes was abraded and a small piece of pressure-sensitive lead tape was applied over the holes.

Hysol was then painted over and around the small piece of tape and cured. At this point the following new sealing methods were investigated. Cores that were known to leak were brush-coated with ER 2795 and 2793, then cured. Other cores were sprayed with five coats of Krylon and allowed to air dry or brush-coated with Eastman 910 over the entire surface. Using these methods, there was a 40 to 50 percent recovery of the cores known to leak; however, the yield was not adequate for further pursuit.

Vacuum-form sealing was suggested and an investigation was initiated to find a suitable process and material. A Plast-O-Craft vacuum-form machine was used for the development. Three types of thermoplastic materials were considered for the application: Lexan polycarbonate, cellulose acetate butyrate, and polyvinyl chloride. Approximately 200 samples were run with each material to determine which had the best forming characteristics, compatibility with epoxy cured with Shell "Z" Hardner, and the most consistent workability properties.

Previous experience with Lexan polycarbonate indicated that it was capable of withstanding the temperature which the assembly would experience during pre-encapsulation drying and material exotherm during the epoxy curing process. If, however, the material came in contact with oil, it crazed profusely and was unacceptable for this application. It was not known if silicone oil would have the same crazing effect, but extensive testing would be necessary for proof. Cellulose acetate butyrate softened at a lower temperature than the Lexan polycarbonate and flowed at 170°F, but since it was supported by a coil of magnet wire at the time the encapsulation material was applied, this characteristic was not considered detrimental. Polyvinyl chloride was too sensitive to elevated temperatures and to contact with trichloroethylene, a widely used cleaning agent. Cellulose acetate butyrate seemed the most likely to provide success.

A small vacuum-form board was made to cover 25 units at a time. Holes were drilled in the vacuum-form board slightly larger than the ID of the core to allow a complete draw through the core center. Figure 19 shows the sequence of operation.

Figure 19. Vacuum-Form Core Covering Process

After plastic forming, the bubble was trimmed off flush with the bottom of the core and each individual core was punched out of the sheet of plastic using a special tool. The excess material was then trimmed from the outside diameter of the core with another special tool. The trimmed core was placed on the vacuum form board with the unsealed side up and plastic was formed over the unsealed side to complete the seal. The trimming was repeated as before to produce a completely sealed core.

Various thicknesses of thermo-plastic film were tried: 0.001, 0.007, 0.010 and 0.015 inch. The 0.010-inch thickness was selected for maximum coverage within the dimensional limits of the completed coil. The vacuum formed cores were wound, assembled, and encapsulated as completed transformers. These units were tested in the same manner as previous production units and the level of acceptance improved decisively. No units were found to have leaked oil into the encapsulation material. Previously, units that leaked could be identified by a swirl of dark-colored material on the exposed surface of the encapsulation material.

Units in which encapsulation material had encroached into the core tape cavity were discovered by the characteristic of core saturation after the transformer had been subjected to shock loading in three mutually perpendicular axes. The acceptance level rose to just under 95 percent of the units tested for core saturation. Since factors besides core case leakage may affect the core saturation characteristic, units which failed this test were not considered to be leaking. This new design concept was incorporated into the product with the approval of the Design Agency. Because the cores were now effectively sealed against leaking, a lower pressure could be used during vacuum encapsulation. The previous minimum of 25 mm Hg was reduced to 0.5 mm Hg. This substantially improved impregnation which, in turn, contributed to the increased acceptance level of the units.

Encapsulation

Impregnation of magnetic coils, usually accomplished by vacuum encapsulation, has several characteristics which tend to improve the quality and reliability of magnetic devices:

- Shorting between coil turns is precluded;
- A specific value of interwinding capacitance can be provided; and
- Wires are locked in place so that they are not affected by high-level shock and vibration.

The process has been in use at Bendix for many years. First, the encapsulation material is heated in a standard oven. The material is then moved to an evacuation chamber which has a clear plastic cover to allow observation. The material is then transferred for

actual encapsulation to a special container which is affixed to the vacuum chamber (Figure 20). The process requires that the encapsulation material be subjected to ambient temperature and pressure between each of the three operations. The most obvious problem in this process--loss of heat from the encapsulation mixture--results in increased material viscosity. This increased viscosity reduces coil impregnation capability and defeats the basic purpose of the process.

A second problem results from the uncontrollable pressure differential between the encapsulation material in the reservoir and the mold cavity. The absolute pressure inside the vacuum chamber at the time the encapsulation material is poured into the molds is from 0.5 to 3.0 mm Hg. Since the surface of material in the reservoir is subject to ambient air pressure, the pressure differential is over 750 mm Hg. This causes the material to flow through the loading tube with considerable velocity, resulting in a great deal of splatter within the vacuum chamber. Part of this splatter is caused by impingement of encapsulation material against the mold and the unit being encapsulated; part is caused by the sudden expansion of gases still entrapped in the encapsulation material. It is possible that coil assemblies made with delicate wire can be damaged by the force of this impingement, although it has never been possible during past production to determine any one operation as responsible for wire breakage.

The Hull Model 5A-24 vacuum oven (BKC No. 33377) consists of two separate chambers which can be heated and evacuated separately. In addition, the large lower chamber can be pressurized to 100 psi. Conversion of this equipment was made so that encapsulation material could be mixed, heated, and evacuated in the top chamber, then dispensed directly into molds in the heated lower vacuum chamber (Figure 21).

The equipment in its original form had a large ball-type valve between the upper and lower chamber which allowed individual pressure control of the chambers. The opening through this valve was 1.00 inch in diameter, too large for the small molds used in magnetic coil encapsulation. The opening was also too far above the top of the molds. It was decided that the encapsulation material should be moved through a plastic tube which could be easily cleaned or which was inexpensive enough to throw away. The tube was attached to the bottom of a funnel built to fit in the top chamber. The conical shape allowed small batches of material to be mixed by the mixer element mounted through the top chamber cover (Figure 22). A pinch-off valve, operated by air or dry nitrogen under pressure, was designed and built to control the flow of encapsulation material. The valve, which was to control the flow of encapsulation material, was located at a level as close as possible to the top of the mold. The valve was controlled by a double acting piston which exhausted to the outside of the vacuum chamber to help preserve the low pressure. A three-position, hand-controlled valve was installed

Figure 20. Present Vacuum Encapsulation Process

Figure 21. Original Two Chamber Vacuum Oven

Figure 22. Adaptation Equipment for Vacuum Oven

between the air supply and the pinch-off valve to control the air flow applied to the double-acting piston. To place the control valve in a position convenient to the operator, an airtight fitting was designed for mounting on the door of the lower chamber. This mounting served also as a bulkhead feed-through for the pinch-off-valve air supply.

The funnel, plastic tube, pinch-off valve, and control valve were set up in the Materials Engineering test lab for an operational checkout prior to installation in the vacuum chamber. It was determined that a minimum of 25 psi air supply pressure on the pinch-off valve piston would shut off material flow having a 758 mm Hg pressure differential.

Use of the tube meant that some other method of sealing between the two chambers was necessary. To effect this seal, an RTV gasket was poured in place in the bottom of the upper chamber. The design of this gasket would not permit a lower pressure in the upper chamber than in the lower chamber. The design also does not provide for applying a positive pressure (higher than ambient) inside the top chamber, since the cover is held in place only by gravity or air pressure differential. This was not considered a problem for vacuum encapsulation, but it was considered detrimental to the process of pressure casting. The completed system was evaluated and the following conclusions were reached.

- The basic design of a system having two separate but interconnected chambers was sound and desirable.
- The two chambers should be separately heated and evacuated, but placed physically close together so material can be moved from one to the other through tubing and a flow control valve.
- For good visual accessibility, the top of each chamber should be no higher than a work bench surface and both chambers should have clear plastic covers.
- The Hull vacuum oven used to evaluate this concept was not suitable for conversion and no further work should be done on it for this purpose.
- The controls of the Hull vacuum oven lower chamber are sufficiently accurate to qualify for production work as a vacuum or pressurized oven within the operating limits specified by the manufacturer. The top chamber of this unit is of no real value.

Transfer molding of magnetic products has been evaluated to determine possible economic and quality advantages over encapsulation.

The economics of the process depends on the number of units to be built. The following costs are for magnetic products similar to those presently produced at this facility. (Since the cost of labor and material to encapsulate by transfer molding or poured encapsulation is approximately equal, these factors will not be discussed.) The tool costs for each method depend on the quantity of units to be built and are defined as follows.

Transfer Molding

A steel mold, hardened and polished, will cost \$1,500 and will last for at least 50,000 parts.

Poured Encapsulation

A mold master will cost \$750, and a sanding fixture, \$250, for a total of \$1,000. The sanding fixture will last for at least 50,000 parts. The RTV molds made by the mold master will each mold approximately five parts before they need to be replaced. For 50,000 parts 10,000 RTV molds will be required and these can all be made from one mold master. Each RTV mold will cost about \$15 for labor and material. Normal operation of either process will produce 25 parts in an 8-hour shift. Since poured encapsulation requires RTV molds at an average cost of \$3.00 per part, the breakover quantity for economical transfer molding is around 150 total parts for each set of tools.

Because other conditions must also be considered, the decision to transfer mold should be made before the part is designed. Successful transfer molding depends on an unimpeded flow of material throughout the mold. To prevent voids, sections of molding material should never be less than 0.015-inch thick.

If a thin section is adjacent to a large metal part in the assembly, it should be at least 0.030-inch thick. Molding material flow depends on temperature. Excessively low temperatures increase the viscosity and further restrict the flow rate. Metal absorbs large amounts of heat from the molding material and provides a reservoir of heat energy without an excessive reduction of material temperature. High temperatures accelerate curing of the material and also increase viscosity, causing the material to set up before the mold is completely filled.

Pockets may entrap air. All passages should be open on opposite ends, and if multiple passages exist, they should be parallel to improve molding material flow. If PC boards are used, they should be sufficiently clear of the mold cavity wall and provide as many clearance holes through the board as practicable.

In any sort of molding process, terminals are easier to keep clear of molding material and to position in the mold if they are larger than 0.030 inch in diameter.

If the molded part has a coil with more than one layer of magnet wire, the molding material will not penetrate beyond the outside layer. If the coil is open-wound, using 26 gage or larger wire, penetration will be deeper. Coil impregnation for winding insulation or control of interwinding capacitance is unwise when the transfer molding process is used.

Mold material flow is improved when a mold release material is added. This reduces the internal shear strength of the material during molding and facilitates removal of the part from the mold after curing. Another condition affecting the transfer molding process is that, with reduced adhesion between molding material and assembly parts, the mechanical shape alone locks parts firmly in the molded assembly. This is particularly critical where pins or wires protrude from the part.

One method of improving coil impregnation with encapsulation material is to subject the encapsulated unit to an atmospheric pressure of from 0.5 to 3.0 mmHg absolute while the encapsulation material is still fluid. Such exposure causes any gases trapped in the unit to expand and consequently to work their way to the surface. When the atmospheric pressure is restored, the encapsulation material is forced into the coil and a high degree of impregnation is achieved. When this process was applied to a silicone-oil-impregnated toroidal core, oil leaked from the core case. When the vacuum was broken, encapsulation material was forced into the core case. This deformed the core tape, causing local stresses which allowed magnetic saturation of the core to vary beyond acceptable tolerances. It was found that sealing methods and materials were not adequate and added considerable time to the production of the part. If the sealing process was combined with a reduced vacuum of 25 mmHg absolute, most of the cores stopped leaking, but impregnation became marginal.

The process of centrifugal casting was developed in response to the specific problem of marginal impregnation.

With the equipment available, it was predicted that a spin of 1200 rpm would be equivalent to pulling a vacuum of 1 mmHg in relation to coil impregnation by the vacuum encapsulation process. The centrifuge used for this development was a small unit which developed a force of about 6700 g's at approximately 2000 rpm. Since the unit did not have an automatic speed control, speed control was monitored with a tachometer, and a wire-wound rheostat was used to control power input to the motor. The wire-wound rheostat caused incremental change in speed, rather than a smooth continuous progression. Test speeds used were set as closely as

possible to 500, 1000, and 1500 rpm. The elapsed time during which the units were subjected to this force was arbitrarily set at 5 and 10 minutes. Experience with the encapsulation material in the vacuum impregnation process showed that the coil impregnation is greatly improved if the encapsulation material temperature is 160°F or higher. This temperature also accelerates the curing process but not to the detriment of impregnation. Since the extent to which centrifugal motion would affect the temperature of the unit was unknown, no provision was made to add heat to the centrifuge cavity. The formulation of the encapsulation material was as follows.

Epon 828	60.0 pbw
Mica Filler	40.0 pbw
Red color paste	3.6 pbw
Curing agent	12.0 pbw

Mixing and filling were as follows.

1. The epoxy resin (Epon 828), filler, and color paste were combined and mixed until the material appeared uniform.
2. The mixture was heated to $175 \pm 5^\circ\text{F}$ and the curing agent (at room temperature) was added.
3. Immediately after mixing, the material was placed in a chamber which was evacuated to a pressure of 0.5 to 3.0 mmHg absolute for a minimum of 5 minutes after the initial foam rise collapse.
4. Material temperature was $160 \pm 10^\circ\text{F}$ when the molds were filled.

The first group of units were poured into metal shields which became the outside surfaces of the completed transformers. Six filled shields were spun as a group, and there were seven groups. Two groups were spun at each speed, that is, 500, 1000, and 1500 rpm. One group from each speed range was spun for 5 minutes; the other for 10 minutes. The seventh group was poured, but was not spun in the centrifuge. The units were all cured in an oven for 2 hours at $175 \pm 5^\circ\text{F}$, followed by 6 hours at $250 \pm 10^\circ\text{F}$. The units were then sectioned and visually evaluated. All of the units, even the group which had not been spun, were free of voids in the encapsulation material. There was some indication of mica filler being forced to the bottom of the units in all groups which were spun. As expected, spin speed had more effect than the time of spin application. The loading on the units was estimated as follows.

RPM	G LOADING
500	419
1000	1675
1500	3771

An original assumption that the time variable would have a linear effect on the rate of settling proved incorrect. The rate of settling seemed to slow down as the length of spin time increased. Two conditions, one observed and the other surmised, could account for this fact. It was observed that the units lost heat very rapidly as they were being spun. This would tend to make the entire mixture more viscous, which would, in fact, slow the rate of filler settling. It is reasonable to assume that since the quantity of mixture is finite, the increase in ratio of filler to resin near the bottom of the unit would inhibit further intrusion of filler material.

To better observe the settling of the filler, encapsulation material was mixed without the red color paste. Without this color, the base resin material had a translucent amber appearance which was noticeably darkened by the presence of the mica filler material. The material was poured into shields which contained completed transformer coils. These units were spun at 500, 1000, and 1500 rpm for 5 minutes. The material temperature was approximately 160°F at the time of pouring. Settling was noticeable at all spinning speeds. Since coil impregnation was very good at all spinning speeds, it appeared feasible to lower the speed. No significant testing could be accomplished at speeds below 500 rpm using the available centrifuge. Below 500 rpm, the speed of the centrifuge could not be controlled within reasonable limits.

Because of the difficulty experienced in maintaining a temperature of $160 \pm 10^\circ\text{F}$ during the spin, encapsulation was attempted at room temperature. The first benefit noticed was an increase in the work life of the encapsulation material. No significant change in temperature was noted during the spin cycle. Units were spun at 1000 rpm for 5 minutes. After a complete cure, the transformers were sectioned and visually inspected (Figure 23). There was no indication of settling of the filler material in the mixture, and impregnation of the transformer coil was excellent. These sectioned units were compared with sectioned units prepared by the vacuum impregnation process (Figure 24). Other than a meniscus buildup of 0.030 inch or less above the surface of the encapsulation material, the surface of the pins were clean.

There are certain significant differences between the units which were sectioned and photographed. The units which were encapsulated by the vacuum process contained cores which were encased in a vacuum-formed plastic case. This process is described in the section on Coil Winding. These units were filled with encapsulation material at $160 \pm 10^\circ\text{F}$ and subjected to a vacuum of 0.5 to 3 mm Hg. Two of the four coils had voids between the turns of magnet wire. This indicated a lack of complete impregnation. There seemed to be a greater tendency for the encapsulation material to pull away from the surface of the shield. When the encapsulation material was poured into the unit in a heated condition,

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Figure 23. Transformers Potted by Centrifugal Casting

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Figure 24. Transformers Potted by Vacuum Encapsulation

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it gave off heat and, consequently, shrank in volume. Since the epoxy mixture shrank at a faster rate than the metal shield, the tendency was for them to separate. The epoxy also exhibited a tendency to pull away from the pins of the transformer, leaving a crater at the beginning of the interface. Although this condition is undesirable from an appearance standpoint, it probably does not affect part quality.

The cores used in the units which were centrifugally encapsulated were the Hysol-coated type. Although the cores showed leakage when subjected to vacuum, there was no indication that oil had leaked out of the core case or that encapsulation material had leaked into the core case. Centrifugal impregnation was superior to vacuum encapsulation. There was less tendency for separation of the epoxy resin from the shield and there was no separation from the pins. The pin surfaces were clean and the units from which the color paste was omitted showed no tendency toward settling of filler material. The darker color toward the bottom of the unit is caused by the shadow of the coil.

As a result of this work, the following procedure for the encapsulation of transformers by centrifugal acceleration was established.

1. Prepare the resin formulation as follows.

Epon 828	2140285	60 pbw
Mica filler	8511024	40 pbw
Red color paste	5060550	3.6 pbw
Curing agent	4704085	12 pbw

2. Mix the resin, filler, and red color paste until the mixture is uniform.
3. Add the curing agent to the mixture and thoroughly mix at room temperature until mixture is uniform.
4. Evacuate the mixture at 0.5 to 3 mm Hg for 5 minutes after the foam collapses.
5. Fill the units to be encapsulated to the level of the edge of the metal shield.
6. Place the filled units in the centrifuge and spin for 5 minutes ± 15 seconds at 1000 ± 100 rpm. If necessary, add encapsulation material until the level is at, or slightly below, the edge of the shield. No further spinning is required.
7. Place the units in an oven set at 175°F for 2 hours, minimum. Transfer the units to a 250°F oven and leave for 6 hours, minimum.

Appendix A

OPERATING AND CALIBRATING
PROCEDURE FOR GO/NO-GO
POLARITY AND RATIO TESTER

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Appendix A

OPERATING AND CALIBRATING PROCEDURE FOR GO/NO-GO POLARITY AND RATIO TESTER

GENERAL

The Polarity and Ratio tester was designed to be a go/no-go tester for indicating correct coil and coil polarity. It does this by comparing the output signal of the unknown transformer coil to that of a reference transformer coil with the same signal being fed into both transformers. If the two signals have the same phase and amplitude, within an adjustable percentage (about ± 3 percent as calibrated), the tester will indicate a GO condition for both correct coil and coil polarity. If the incorrect coil is connected to the tester, the two signals will have different amplitudes, and the tester will indicate a wrong ratio. If the coil polarity is reversed, the two signals will be out of phase and the tester will indicate incorrect polarity. The tester will also indicate incorrect ratio when a reversed polarity exists; however, when this happens, the test signal polarity can be reversed manually and, if the coil ratio is correct, the tester will indicate correct polarity and ratio.

Preliminary Setup

1. Verify that tester switch and control settings are as follows.

<u>Switch/Control</u>	<u>Setting</u>
Control Panel	
AC POWER	ON
SIG POWER	OFF
SIG POLARITY	FWD
WINDING	OFF
AC Power Amplifier	
POWER	ON
METERLINE	OUTPUT VOLTAGE
VERNIER GAIN	Fully clockwise
LOAD REGULATION	12 o'clock

Sine Wave Oscillator

POWER	ON
ATTENUATION	-0 db
VERNIER	Fully clockwise
Freq VERNIER	CALIB

2. Adjust oscillator FREQUENCY and DECADE controls for recommended transformer test frequency between 400 Hz and 20 kHz.
3. Adjust MANUAL SET control to recommended transformer test voltage. The dial indication is in rms volts. An indication of 25.0 gives a 25.0 volt rms test signal. The test signal voltage can be monitored on the power amplifier meter. Since the amplifier is set for an output impedance of 60 Ω , the meter voltage reading must be multiplied by 2 to obtain the correct reading.

Part Mating and Testing

1. To test a transformer of a certain type, a reference transformer of the same type, with known correct nominal ratio and polarity, must be available.

CAUTION: Autotransformers may not be tested. The signal input winding must be isolated from the winding under test. (See special test, paragraph 2.)
2. Connect the red (Hi) and black (Low) test clips of the REFERENCE cable to the Hi and Low test signal input pins (leads) of the reference transformer.
3. Connect the red and black test clips of the UNKNOWN cable to the same respective pins (leads) of the transformer under test.
4. Connect the green (Hi) and yellow (Low) test clips of the UNKNOWN cable to the two pins of the winding to be tested.
5. Connect the green and yellow test clips of the REFERENCE cable to the same respective pin of the reference transformer. To ensure correct polarity testing, the green clip of the REFERENCE cable must go to the same pin of the reference transformer as the green clip of the UNKNOWN cable goes on the test transformer. The same is true of the yellow clips.
6. For use of the open setup adapter cable, the WINDING switch must be moved to position 1.

7. To test the transformer winding connected to the green and yellow clips of the UNKNOWN cable, operate SIG POWER switch to ON position. If the winding of the test transformer is the same as the reference transformer, the POLARITY lamp will indicate FWD and the RATIO lamp will indicate PASS. If the RATIO lamp indicates FAIL and the POLARITY lamp indicates FWD, the ratio of the test winding is incorrect. If the RATIO lamp indicates FAIL and the POLARITY lamp indicates REV, both ratio and polarity may be incorrect. To check this, operate the SIG POLARITY switch to REV. If the RATIO lamp still indicates FAIL, both the ratio and polarity are incorrect. If the RATIO lamp indicates PASS, only the polarity is incorrect. Operate SIG POLARITY switch to FWD and SIG POWER switch to OFF.
8. If additional windings or transformers are to be tested, repeat paragraphs 2 through 8. If no more tests are to be run, operate WINDING switch to OFF position, and operate control panel AC POWER switch to OFF.

Special Tests

1. If precise test voltage and frequency are required, an external voltmeter and frequency counter may be used to monitor the test signal. The voltmeter must have a floating input and be connected to the power amplifier LO and HI terminals on the front panel. The counter may have a single-ended input with the high side connected to the red terminal of the oscillator front panel and ground side connected to the black terminal. Use MANUAL SET and FREQUENCY VERNIER controls to obtain correct voltage and frequency.
2. Autotransformers can be tested with the use of two 1:1 isolation transformers. The isolation transformers must be selected to operate at the test signal voltage and frequency without distortion. Connect isolation transformers as shown below, and perform part mating and testing paragraphs 6 through 8 to test.
3. For quantity testing of a transformer, a test fixture may be used to replace the open set-up cable. This would be an aluminum box about 4 inches square that would fasten to J1 on the control panel. The adapter would have a test socket on top to fit the test transformer. It would also contain the reference transformer and a programming resistance to program the test signal amplitude. The WINDING switch would be used to select the different test transformer coils to be tested.

Calibration Procedure

This tester should be calibrated on a 12-week basis, after tester maintenance of calibrated circuits, or whenever the tester indication appears to be faulty.

Equipment Required

Oscilloscope, Tektronix Model 531 with CA Preamplifier.
AC Voltmeter, ± 1 percent full scale, Hewlett-Packard Model 400F, or equivalent.
Frequency Counter, Beckman Model 7350A, or equivalent.

Calibration Setup

1. Verify that tester switch and control settings are as follows:

<u>Switch/Control</u>	<u>Setting</u>
Control Panel	
AC POWER	ON
SIG POWER	OFF
SIG POLARITY	FWD
WINDING	CAL 1
MANUAL SET	10.0
Ac Power Amplifier	
POWER	ON
METERING	OUTPUT VOLTAGE
VERNIER GAIN	Fully clockwise
LOAD REGULATION	12 o'clock
Sine Wave Oscillator	
POWER	ON
ATTENUATION	-0 db
VERNIER	Fully clockwise
FREQUENCY	2000.0
VERNIER	CALIB.

2. Connect standard counter to oscillator front panel output terminals. Adjust counter to read oscillator output frequency. Frequency shall be 2000 ± 20 Hz; if not, refer to the oscillator manual for adjustment procedure. Disconnect standard counter.

3. Connect standard ac voltmeter (floating input) low side to power amplifier LO terminal and voltmeter high side to amplifier HI terminal. Voltmeter shall indicate 10.0 ± 0.5 volts ac. If not, adjust R1 on rear control chassis for correct indication. Disconnect standard voltmeter.
4. Using two 4-foot BNC to BNC cables with banana plug adapters on one end each, connect standard oscilloscope CA plug-in A and B INPUT's to power amplifier with the A center conductor connected to LO terminal, the B center conductor connected to HI terminal, and both shields connected to CT terminal. Adjust oscilloscope as follows.

CA Plug-in

MODE	ADDED
AC/DC (both)	AC
VOLTS/CM (both)	0.2
VARIABLE (both)	CAL
POLARITY (both)	+
TIME BASE	
TRIGGERING MODE	AC
TRIGGER SLOPE	INT +
STABILITY	As Required
TRIGGERING LEVEL	As Required
TIME/CM	0.5 millisec

5. What is being displayed on the oscilloscope is the addition of two sine waves that are 180 degrees out of phase. If oscilloscope channels A and B were equally matched in amplitude and phase shift, there would be only a base line trace. This close match usually is not the case so the plug-in GAIN ADJ controls must be adjusted to obtain the smallest peak-to-peak waveform amplitude.
6. Disconnect oscilloscope from power amplifier and remove banana adapters from BNC cables. Connect BNC cables to CH1 and CH2 connectors on rear of control chassis. Adjust R37 on the A4 to obtain the smallest peak-to-peak waveform amplitudes on oscilloscope. Disconnect oscilloscope from tester.

7. Connect standard ac voltmeter bar to tester ground. Connect high to TP1 on the A5 card. Adjust R10 on the A5 card to obtain a minimum amplitude null on the voltmeter. Disconnect voltmeter from tester. This concludes the tester calibration.

Appendix B
WELDABLE PRINTED CIRCUITS

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Appendix B

WELDABLE PRINTED CIRCUITS

DISCUSSION

Scope and Purpose

When one new electronic assembly was designed, it required that certain electronic components be attached to a printed circuit board by soldering and that others be attached to the same board by welding. The board was designed to be tin-lead plated at the areas requiring soldering and to be gold plated at the areas requiring welding. The process used to make the board is long and involved. It requires 14 major operations, including two separate resist coat-expose-develop sequences (requiring two sets of art work), several plating and etching operations, and a fusing operation. The large number of processing operations multiply the chances for error, expose the board to a large number of chemicals and solvents, increase the handling required, and require five re-fixturings and eleven transfers between production departments. The purpose of the project described in this report was the development of a simpler and shorter process that would produce boards more rapidly and with less cost.

Prior Work

There was no previous work on this project.

Activity

Figure B-1 illustrates the present production process. Nickel-clad, epoxy-glass laminate is drilled (Figure B-1a), activated, and copper plated over all (Figure B-1b, Copper Plate No. 1). This is done to provide a surface that is easily cleaned and activated in subsequent plating steps. The laminate is then coated with photosensitive resist, exposed, developed, and etched to produce the desired circuit (Figure B-1c). The ferric chloride etchant dissolves both copper and nickel.

To make electrical contact to the various circuit paths and to produce a conductive coating in the holes, the whole board is next electroless copper plated and electrolytic copper plated (Figure B-1d, Copper Plate No. 2). Another photo-resist operation is performed to cover all but the parts of the circuit that require tin-lead plating. Then, another copper plating (Copper Plate No. 3) is done to produce the required through-hole conductivity, followed by tin-lead plating for solderability (Figure B-1e). The resist is removed and a chromic acid-sulfuric acid etch is performed that dissolves all of Copper Plates No. 2 and No. 3 that are not protected by tin-lead. This etch does not attack the nickel (Figure B-1f). At this point, an immersion

gold plating is done over the whole circuit (Figure B-1g) and, finally, the boards are fused in hot oil to melt the tin-lead and thus dissolve the gold in those areas (Figure B-1h).

The long and complicated nature of the process is dictated by the need for two different kinds of plating: tin-lead over copper and gold over nickel. In effect, two circuit boards are being produced on a single board. Significant simplification of the process required that a single plated finish be used that would be both solderable and weldable. Gold-plated nickel was selected. The nickel was essential for welding and the gold protected the nickel so that it also would be solderable and retain a constant welding characteristic. The use of nickel-clad stock presents a problem, however, since an active nickel surface must be retained during the several steps of electroless copper plating process necessary for the production of plated-through holes.

In the first experiments, it was decided to circumvent this problem by starting with copper-clad laminate and producing the required nickel by electroplating. Another early decision was to etch the circuit before gold plating. The latter approach was the one pursued since the galvanic reaction between the gold and nickel during etching would have produced severe undercut and a gold plate thick enough to be an etch resist would have been too thick for good solderability.

The following process was the first tried.

Process 1: Copper-clad board

1. Drill holes.
2. Electroless copper plate.
3. Electroplate nickel.
4. Photoresist
 - a. Coat.
 - b. Expose.
 - c. Develop.
5. Etch.
6. Gold plate.

Several printed circuit boards were made and tested for weldability. Visibly normal welds were formed, but the joint strength was very low. Metallography showed that the failure occurred between the copper and the nickel. It was hypothesized that the electroless copper did not form a good bond to the copper cladding. Some printed circuit processes used in industry call for sanding

before subsequent plating to remove the electroless copper from the copper cladding. Incorporation of sanding, however, added another step to the process, and the goal was reduction of steps.

Another group of printed circuit boards was made using the same process as before, except that electroless nickel was substituted for the electroless copper.

Process 2: Copper-clad board

1. Drill holes.
2. Electroless nickel plate.
3. Electroplate nickel
4. Photoresist.
 - a. Coat.
 - b. Expose.
 - c. Develop.
5. Etch.
6. Gold plate.

This process also yielded weak weld joints and, again, failure occurred between the nickel and the copper. It was also found that the adhesion of the electrolytic nickel to the electroless nickel was poor. A third run was made in which a Wood's nickel strike was incorporated between the electroless and electrolytic nickels.

Process 3: Copper-clad board

1. Drill holes.
2. Electroless nickel plate.
3. Wood's nickel strike.
4. Electroplate nickel.
5. Photoresist.
 - a. Coat.
 - b. Expose.
 - c. Develop.
6. Etch.
7. Gold plate.

The above process corrected the adhesion problem, but weak weld joints were still produced.

At this point, it was decided that the problem might be caused by the combination of copper and nickel. A change was therefore made to the nickel-clad laminate. Because electroless copper is used in the factory, first tests used this process to produce the conductive coating in the holes.

Process 4: Nickel-clad board

1. Drill holes.
2. Electroless copper plate.
3. Wood's nickel strike.
4. Electroplate nickel.
5. Photoresist.
 - a. Coat.
 - b. Expose.
 - c. Develop.
6. Etch.
7. Gold plate.

The problem at this point was entering the electroless copper bath with the nickel in an active state. It was found that if the nickel were activated prior to the catalyst dip, the nickel became passive and the electroless copper was not adherent. Therefore, the catalytic step was carried out before nickel activation. A Wood's nickel activation tended to remove the catalyst, resulting in spotty copper coverage in the holes. Cathodic activation in 10 percent sulfuric acid did not attack the catalyst and did not activate the nickel.

Boards were then made by the following process.

Process 5: Nickel-clad board

1. Drill holes.
2. Catalyze holes.
3. Sulfuric acid activate nickel.
4. Electroless copper plate.
5. Electroplate nickel.
6. Photoresist
 - a. Coat.
 - b. Expose.
 - c. Develop.

7. Etch.

8. Gold plate.

The plating had good adhesion, but once again, the weld joints were weak; the failure occurred in the electroless copper. Metallographic examination of the weld revealed voids at the electroless copper layer. These were possibly caused by the unequal diffusion rates of copper and nickel (Kirkendall effect).

It was decided to replace the electroless copper with electroless nickel, yielding an all-nickel circuit.

Process 6: Nickel-clad board

1. Drill holes.
2. Catalyze holes.
3. Activate nickel.
4. Electroless nickel plate.
5. Electroplate nickel.
6. Photoresist.
 - a. Coat.
 - b. Expose.
 - c. Develop.
7. Etch.
8. Gold plate.

Again, adhesion trouble was encountered between the nickel laminate and the electroless deposit. Several activation techniques (Wood's nickel, cathodic sulfuric acid, vapor blast, sanding, and striking in the electroless nickel) were tried without success. At this time a proprietary electroless nickel-plating process* (Shipley NL-61) was being used. It was known from other work that this process produced a nickel deposit with a relatively high phosphorus content (6 to 10 percent). Since the activation treatments that had been tried were effective with pure nickel, it was thought that the problem might be caused by the phosphorus. Accordingly, an electroless nickel process that yielded lower phosphorus contents was sought.

*Shipley Company, Newton, Mass.

Two proprietary** solutions that produced 4- to 7-percent phosphorus alloys were tried and, although adhesion still was inadequate, there appeared to be some improvement.

Published information was used as a guide, and a formulation was devised that would produce a low-phosphorus alloy. The bath (Table B-1) was prepared using basic chemicals and found to give 2- to 4-percent phosphorus alloys. With this solution, good adhesion was obtained. Printed circuit boards were made and found to weld satisfactorily. Several boards were then made and used to build actual circuits. Assembly was normal, except that a somewhat higher soldering temperature was required. The assembled boards were tested electrically and found to be satisfactory. Views of typical weld and solder joints are given in Figures B-2 and B-3. The several steps in the fabricating process are given in Figure B-4.

The process has two disadvantages: the electroless nickel solution has a short life, typically 8 hours; and as mentioned above, a higher soldering temperature is required in mounting components. It is believed that these can be eliminated by modification of the electroless nickel solution formula and by changing the immersion gold coating to a thicker electroless gold coating.

Accomplishments

A process was developed that required eight operations (43 percent fewer than now used), a single resist coat-expose-develop sequence, and a single etching operation. It is estimated that the flow time will be less than one-half that of the present process. The board is essentially a gold-plated nickel board that requires a simpler inspection procedure. The cost of a board made by the new process is estimated to be 15 to 20 percent less than the current boards.

Future Work

The electroless nickel plating solution formula will be revised to improve bath life. Proprietary borohydride electroless nickel processes will be evaluated because they reportedly deposit pure nickel. Electroless gold plating will be evaluated for its potential to improve solderability.

** MacDermid J-67, MacDermid Incorporated, Waterbury, Conn.
Enthone 415, Enthone Incorporated, West Haven, Conn.

Table B-1. Low Phosphorus Electroless Nickel

Solution	Concentration
$\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$	70 g/l
$\text{NaH}_2\text{PO}_2 \cdot \text{H}_2\text{O}$	10 g/l
$\text{NaC}_2\text{H}_3\text{O}_2$	41 g/l
NOTE: pH is 4.4 adjusted with acetic acid. Temperature is 90°C

Figure B-1. PCB Plating Sequence: Present Process

Figure B-2. Typical Solder Joints

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Figure B-3. Typical Weld Joints

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A. NICKEL LAMINATE

B. ELECTROLESS PLATED BOARD

C. ELECTRODEPOSITED NICKEL PLATED BOARD

D. ETCHED BOARD

E. IMMERSION GOLD PLATED BOARD

Figure B-4. PCB Plating Sequence: Proposed Process

Appendix C
TOROID COIL DIMENSION
COMPUTATION GUIDE

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Appendix C

TOROID COIL DIMENSION COMPUTATION GUIDE

To compute the finished dimensions of a wound toroid coil, certain factors inherent in the winding process must be considered. On cores having a rectangular cross section, the coil wire will touch the core only at the corners (Figure C-1). Between the points of contact, the wire will assume a path approximating a radius. The larger the ratio of the distance between contact points to the wire diameter, the larger the radius will be. A fair approximation for soft copper wire is a gap equal to one-half the wire diameter at the mid-point between the contact points. If the wire is wound in a perfectly smooth layup with no gaps or crossovers, the number of turns in the first layer inside the coil will be equal to

$$\pi \frac{D_I}{d} - 2$$

where, D_I = Inside Core Diameter

and d = Coil Wire Diameter (Including Insulation).

The factor of 2 in the equation takes into account the space between the core and the coil wire.

Again assuming a perfectly smooth lay-up, the second winding layer inside the coil will have exactly six less turns than the layer preceding it. To accomplish a winding of this sort, the rotation rate of the coil being wound would have to be adjusted after each winding layer is completed.

The following approximations will give adequate results in determining the size of the wound coil. The inside coil diameter (D_{CI}) can be found from the inside core diameter (D_I), the total number of turns of the coil (N) and the wire diameter (d).

$$D_{CI} = D_I - \frac{N (8d^2)}{10D_I} + d, \quad (1)$$

$$D_{CO} = D_O + \frac{N (8d^2)}{10D_O} + d. \quad (2)$$

Equation (2) will give the outside dimension of the coil from the total turns, wire diameter, and the outside core diameter. The maximum coil thickness will occur at a diameter approximately equal to the inside core diameter, plus two times the corner radius of the core cross section.

The thickness of the coil will equal

$$t_c = \frac{N (16d^2)}{10D_I} + t. \quad (3)$$

Each different wire size must be computed separately and, as each new computation made, the previously computed D_{CI} , D_{CO} , and t_c must be substituted for D_I , D_O , and t , respectively. For any computation after the first for each equation, the separate $+d$ factor should be dropped from equations (1) and (2).

Figure C-1. Toroid Coil Diagram