NAL MAIN RING INTEGRALLY IMPREGNATED MAGNETS

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Abstract

The revised NAL Main Ring Magnet fabrication procedure consists of casting partially insulated coils, magnet cores, and vacuum tubes into an integral, void-free, monolithic structure. This design is regularly tested at 6000V after complete submergence in water for one week. Corona tests were also done on several magnets to insure that the insulation was sufficiently void-free to prevent the start of corona currents during operation.

Mica, fiberglass, and polyimide film are squeezed into the 0.047 in. thick available space from copper to iron and impregnated with a highly filled alumina, glass bead, radiation resistant epoxy system. Mica and glass insulation is also used between turns and layers. The insulation system readily withstands 3500V before impregnation and 6000V after impregnation. Other advantages of this method are:

1. No sanding or other detrimental processing of pre-impregnated coils is necessary to accommodate tight fits and essentially eliminates the possibilities for variations in the back-leg gap.

2. The sealing ability of the epoxy is uninterrupted from the copper well into the lamination spaces of the magnet.

3. Four impregnations are accomplished at once without discontinuity caused by the weakness of cohesively bonded joints from coils to core and from coils to other coils.

4. Pre-stressing of the copper is accomplished without introducing crack producing tensile stresses in the epoxy. The epoxy is actually in compression, thus offsetting the tendency for shrinkage cracks.

5. Considerable cost saving is achieved by eliminating the need for individual coil potting fixtures plus the cost of impregnation of individual coils, clean-up, sizing, inspection, etc.

One hundred and sixty Main Ring Magnets have now been made in this manner. Some quadrupole magnets have also been rebuilt using the same techniques of the one described here for the dipoles. Including the quadrupole magnets, over one hundred magnets of this type are in service in the main ring without a single failure occurring.

Introduction

The initial production of NAL Main Ring Magnets consisted of assembling pre-impregnated epoxy fiberglass coils into 20 ft long half magnet cores. The coil consisted of two "outer" coils and one "inner" coil placed on the magnet mid-plane just outside of the vacuum tube. See Figure 1. Due to the critical alignment and space requirements of the inner coil, a very minimum of clearance between the inner coil and the pole faces of the magnet could be tolerated.

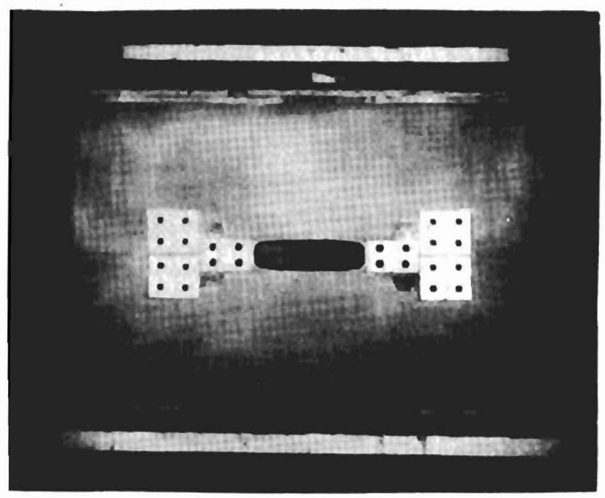

Fig. 1. Cross section of B-1 bending magnet

The coils were placed in the magnet in a "bed" of epoxy. The two half cores were clamped and welded to form a box structure. See Figure 2.

The magnets were heated by passing steam through the water passages. Additional filled epoxy was forced behind the coil cross-overs to pre-stress the copper.

This method of magnet assembly was simple and would have undoubtedly been successful in all cases if both of the following conditions had not existed:

a. The inner coil fit was so tight that

the inner coil would have had to be made more precisely.

b. The extreme moisture conditions during the first spring of Main Ring tunnel usage literally soaked the magnets with condensed water.

Fig. 2. Side view of B-1 Magnet

Even during production, however, a rejection rate of about 5% was experienced, which indicated that the magnets were not as high in quality as they should have been. This prompted an experimental program for the development of a means to refurbish these magnets as well as other methods of initial fabrication.

As the Main Accelerator was being brought up to power and the failure rate of the magnets was higher than expected, we were in a good position to rapidly mount a two prong program for rebuilding magnets; the first was a "fix" of low megger magnets which were removed from the Ring, baked out and vacuum impregnated to seal them from future moisture, and second, the production of rebuilt magnets with improved insulation in which the coils and cores were completely impregnated in one step. We call magnets built using this latter technique the integrally impregnated magnets.

General Description

The technique of integrally impregnating magnets consists of placing unimpregnated coils into magnet cores. The cores and coil ends are sealed off and the entire assembly impregnated in one operation. Included as part of this production technique was the replacement of some of the fiberglass insulation with mica to improve the ground wall insulation. To start off with, the individual conductors are wrapped, one serving half-lapped, with 7 mil B-stage tape integrated and cured immediately thereafter. This has several advantages:

1. It permits the critical inner coil to be precisely aligned in a curing fixture with only 14 mils of insulation between the conductors and the fixture.

2. It allows an opportunity for a reliable turn to turn short test.

3. It makes the coils rigid enough for subsequent handling without damage.

This pre-cure cycle is done in an oven at 160°C for two hours. After that, the first ground wrap, a 6 mil dry integrated mica tape -- again for improved breakdown resistance, is applied one serving of half-lapped 7 mil fiberglass tape for its better strength and finally, a butt lapped layer of 5 mil Kapton is added for abrasion resistance during assembly. It too provides added breakdown resistance.

The three individual coils and vacuum chamber are placed in the cores. The core itself is sealed to form the potting fixture for the entire length. The ends are covered with molds to cast the desired shape. Since the entire magnet assembly is placed in a vacuum tank for impregnation, the sealing need only prevent epoxy leakage and does not have to be a vacuum seal.

Another feature that is possible using this technique is that all of the coil end manifold brazing can be completed before impregnation. This eliminates the possibility of damage to the epoxy insulation from the high temperature experienced during brazing. Cleanup required following impregnation is minimal. Figure 3 shows a completed magnet using this technique.

Other advantages of this technique are:

1. No sanding or other detrimental processing of pre-impregnated coils is necessary to accommodate tight fits. In order to assemble a 20 ft long rigid coil into a 20 ft long magnet core with as little as 0.005 in. theoretical clearance, the components must be made to precise tolerances, which is extremely difficult to do with the copper conductor, particularly around joints and bends. If these variations are corrected after potting by sanding to size, two problems occur; the first is that the already small insulation

thickness using an all glass system is reduced; and second, severe sanding of the fiberglass opens up the pores of the fibers producing moisture paths and oftentimes creating blisters between the insulation and the conductor which absorb moisture. When integrally impregnating, the coils are assembled with dry tape; and if any variations in the copper exist, the insulation being compressible does not cause a fit problem, but the integrity of the insulation is maintained.

Proof that the inner coils with even more insulation (a nominal 0.047 in. instead of a nominal 0.042 in.) fit the space available is that the magnets consistently close down to zero back leg gap with much less clamping force than was used for pre-impregnated coils. The magnetic measurements also substantiate the fact that field is higher and more consistent than before.

2. The sealing ability of the epoxy is uninterrupted from the copper well into the lamination spaces of the magnet. There are no pockets adjacent to the coil which can hold moisture. The epoxy fills all the void areas around the coils and the gaps between laminations for at least several inches away from the coils.

3. Four impregnations are accomplished at once without discontinuity caused by weakness of cohesively bonded joints from coils to core and from coils to other coils. When epoxy cures, it leaves a glazed surface which even when sanded is weaker than continuous material with its long molecular chains binding it together.

4. Pre-stressing of the copper is accomplished without introducing crack producing tensile stresses in the epoxy. The epoxy is actually in compression, thus offsetting the tendency for shrinkage cracks. When pre-impregnated coils are prestressed, the epoxy on the coil is actually in tension. Since this radiation hard system is especially brittle, cracks could be caused by prestressing pre-cured coils. When the coils are integrally impregnated, the copper relative to the iron is in tension due to the differential thermal expansion rate of the two materials. As the epoxy cures, there is always a tendency for it to shrink; but in this case, the tendency is countered by the shortening of the magnet.

Insulation System

The insulation system consists of mica, fiberglass, and polyimide Kapton. The coil turns are insulated with one half-lapped layer of 7 mil B-staged mica tape, Macallen Number 27-5M-NP. In the case of the inner coils, precise alignment of the conductors is necessary; and therefore, they are precured in a fixture at this stage. The vertical layers of the coil are separated by 15 mil spacers in the less critical horizontal direction to assure good impregnation of the precured turns.

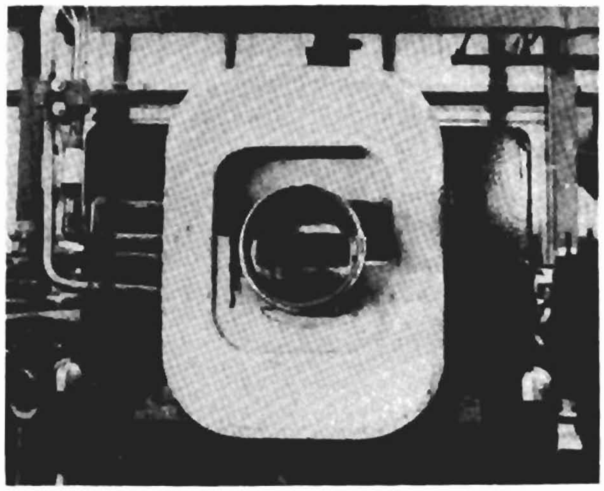

Fig. 3. Completed magnet using integrally impregnating method

The ground insulation consists of one layer of half-lapped 7 mil dry integrated mica tape, 3M Number X4724, followed by one half-lapped layer of 7 mil glass tape. Finally, a 5 mil butt-lapped layer of sandblasted polyimide Kapton is applied. The purpose of the Kapton is to prevent fraying of the fiberglass during assembly of the coils into the core as well as providing additional insulation. This total thickness of 0.047 in. is equal to the theoretical space available in the core. Assembly is readily accomplished, however, since the insulation at this stage is somewhat compressible.

The outer coils are insulated in the same manner except an extra layer of fiberglass ground wrap is added because the space is available, thus improving the margin of safety. These coils are also precured in the potting fixture, since the fixture was available and the coils are more rigid and therefore easier to handle. We have made others without precuring the B-staged mica tape, proving that it is not a necessary operation.

The vacuum tubes are insulated from the pole faces to prevent the eddy currents in the cores as well as to provide additional insulation for the inner coils. This insulation consists of a half-lapped layer of Kapton around the vacuum tube plus a single layer of pre-impregnated cured fiberglass tape 14 mils thick between the pole faces and the vacuum tube.

Assembly of Magnets

The lower half core is placed on an assembly table which supports it every two feet. See Figure 4. The support points arch the core upward 0.135 in. to offset the subsequent sag of the magnet when supported at the ends. The half core is very flexible and readily conforms to this shape. The coils and vacuum tube are placed on the half and the top half core lowered down over them.

Fig. 4. Assembly table with half cores, coils and vacuum tube

The magnets are assembled with less difficulty than was encountered with pre-impregnated coils. The addition of the mica and Kapton assures adequate voltage breakdown strength to withstand 3500V before impregnation.

Sealing

The magnet core is sealed by painting the exposed laminations on the sides and bottom with a filled room cure epoxy resin. The alignment and lifting holes are plugged with rubber stoppers and held by banding.

The magnet ends are sealed with gasketed aluminum covers which provide openings for the leads and the ends of the vacuum tube. See Figures 5 and 6. Note: Last magnet submerged in water. The vacuum tube is sealed on the outside with "O" rings leaving the inside of the tube exposed to the same condition as the outside of the magnet. Since the coils extend above and below the magnet, the magnet end faces are extended with teflon coated aluminum plates to provide sealing surfaces for the cover as can be seen in these Figures.

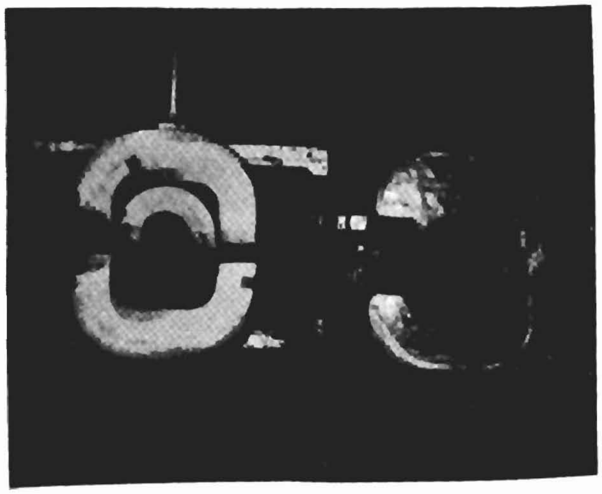

Fig. 5. Lead end potting fixture

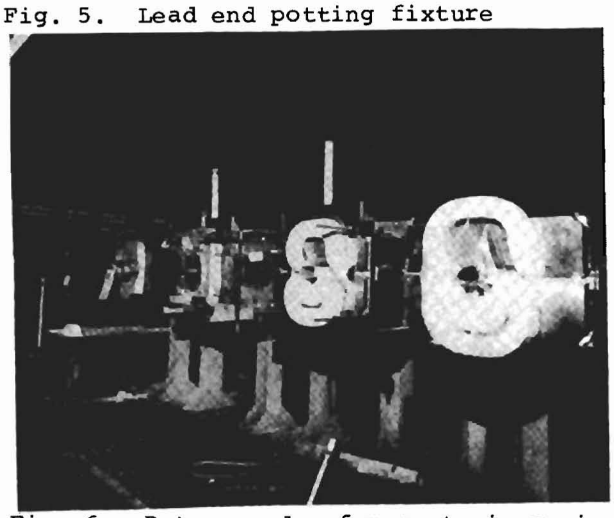

Fig. 6. Return ends of magnets in various stages of potting

The region of the leads is heavily clamped to overcome the tendency to push out the cover plate due to thermal expansion of the copper.

Impregnation

The impregnation takes place in large vacuum tanks. The filling is done at the bottom of the lead end with riser tubes coming through feed-throughs in the door of the vacuum tank. A fill line also goes to the bottom of the non-lead end for subsequent filling of the heavily filled resin. All four leads come out of the tank and then back in for vacuum pumping. See Figure 7. The rubber stoppers in the top alignment holes are removed before placing in the vacuum tank and the top of the laminations not sealed to improve evacuation of the magnet. The tank is heated so that the magnet reaches an impregnation temperature of about 50°C. The tank is pumped down to less than 100 microns (usually about 50). Pumping is continued for two hours.

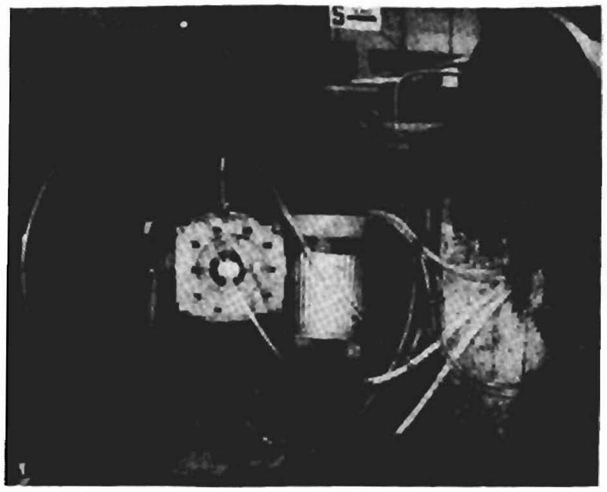

Fig. 7. Set-up in vacuum tank

The epoxy is mixed in three batches. One contains the resin and hardener only. The second batch contains 100 parts alumina (based on 100 parts of resin) plus 100 parts 120 mesh saline treated glass beads. The third batch contains 50 parts alumina and 250 parts glass beads. All batches are mixed under vacuum for two hours and another half hour after the addition of accelerator. After purging the lines of entrapped air, the unfilled resin is introduced at the bottom of the lead end. When the plastic tubing coming from the lead end riser becomes filled, it is pinched off on the outside of the tank. Fill continues until the riser tube from the non-lead end becomes filled, and this tube is also pinched off. The fill line is then switched to a pressure tank containing the second batch. The fill line is again purged to remove air pockets and filling continues with both return lines pinched off. Pressure is applied to the mixing tank up to 15 PSI producing a net difference in pressure between the inside of the magnet and the outside of 30 PSI. This condition is maintained until resin appears in the upper alignment holes through the laminations or for 20 minutes, whichever is sooner. Often, the epoxy does not appear at the outside of the laminations due to the tightness of stacking, especially in the region of the coils caused by crown of the laminations. In any case, however, going through this operation gives assurance that the epoxy penetrates well into the lamination spaces providing a good seal around the coil region.

The riser tubes are unclamped and pressure filling is continued. When the filled resin appears in the front riser and the color indicates that it is heavily filled, this tube is pinched off. Pressure filling continues until the heavy mix of resin appears in the rear riser tube return line. Alternate filling of one end and then the other is continued until all of the contents of a 25 gallon mixing tank are used up. This assures displacement of the thin unfilled resin from the larger cavities.

The vacuum tank is then let up to air and the magnet removed. The four connecting tubes are kept well above the magnet during moving. The magnet is placed on accurately aligned bases to assure straightness during cure. Fifteen PSI steam is connected to the coils to cure the magnet at 120°C for 12 hours. The magnet is completely blanketed with fiberglass insulation to assure uniform and complete cure.

Both the alumina and glass bead fillers gradually settle out. To offset this, the very heavily "loaded" third batch of resin is added during the early stages of heating. It is added to both the fill and riser tubes at both ends of the magnet. In the top riser tubes a smaller tube (1/2 in. thin walled pipe) is inserted inside of the 1-1/4 i.d. riser tubes down to within 1/2 in. from the top of the coil ends. The inner tube is filled with heavy resin and kept at 5 ft above the magnet. The outer tube has an overflow at 2 ft above the magnet. See Figure 8. This action displaces the thin resin at the top as the fillers settle to the bottom. Settling out is, of course, a slow process, so this is continued until it naturally stops due to thickening of the epoxy as a cure begins. This method completely eliminates cracks. It should be noted that no flexibilizers are used and that the inorganic fillers enhance the radiation resistance of the epoxy.

When cure is complete, the insulation and end covers are removed and the magnet allowed to cool on the alignment bases. Practically no clean-up of the ends is required.

Inspection and Testing

The individual coils are pressure tested with water at 2000 PSI as a check for leaks.

An induced voltage test is performed on each coil after the pre-cure is completed. With 32V at 60 Hz applied, the induced voltage must be greater than

30V per turn.

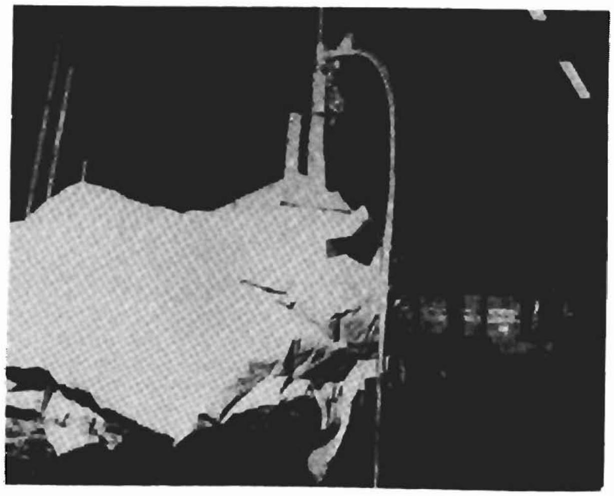

Fig. 8. Curing of magnet

A flow test of individual coils is also performed. The minimum flow must be 4 gpm for B-2 magnets and 6 gpm for B-1 magnets.

Half cores are inspected for proper dimensions and burrs which might cause shorts to the coils or vacuum tube.

As the magnets are assembled, a series of measurements are made:

1. $< 10\ \mu A$ at 3500V coils to ground and inner coil to vacuum tube.

2. Infinite resistance between vacuum tube and core using a Simpson meter.

3. Average back leg gap < 0.0005 in.

4. Vacuum tube aperture.

5. After manifolding $< 10\ \mu A$ at 3500V, coil to ground.

After sealing, the magnet is pressurized to 5 PSI dry nitrogen to determine leaks preparatory for impregnation.

After impregnation and cure, the electrical measurements are repeated with the requirement $< 3\ \mu A$ at 6000V. The vacuum tube to core measurement is repeated.

Each magnet is optically checked for alignment. The straightness in 20 ft must be within $\pm$ 0.010 in. The twist must not exceed 0.010 along the length with the ends in a zero twist condition relative to each other.

Every tenth magnet is completely submerged in water for one week. Upon completion, 6000V is applied to the coil. The leakage current is generally about 100 μA but this returns to its normal value after a few days.

Every magnet is magnetically measured. The magnetic measurements on the dipoles consist of a comparison of the quantity $\int B'dl$ at various positions in the horizontal plane against a reference. A 22 ft stretched wire probe consisting of two turns of 0.002 in. diameter tungsten wire is bucked against a signal coming from a reference magnet which is in series with the magnet under test. The comparison of the dc field is made at several fields from 9 kG to 22.5 kG. The data are recorded on line by a small computer. It has been noted that the field at a given current is a few hundreths of a percent higher for magnets which have been fully vacuum impregnated.

During the early production of magnets, corona tests were also done on several magnets to insure that the insulation was sufficiently void-free to prevent the start of corona currents during operation. The dielectric life of the magnets is influenced by the combination of ac and dc voltage stresses on the insulation.

In particular, partial discharges or corona may occur in undesired voids in the insulation, unduly shortening the service life. A non-destructive corona test using 60Hz ac was established in order to weed out incipient dielectric failures and check on the effect of production changes in the insulation system. The corona test detects voids or cavities in solid insulation by ionizing the gas in the cavity with an ac electric field. Only simple apparatus is required for the test.

A step-up tranformer, Variac controlled from the power line, provided a source of adjustable 60 Hz voltage. This source was connected between the coil under test and the laminations via a series resistor of impedance roughly equal to the capacitive reactance of the load. The resistor rating, 400 watts, was chosen to be safe on load short-circuit.

A high-pass LRC filter, transmitting 0.1 to 10 MHz, and sensitive oscilloscope was used to detect the small (millivolt or so) voltage spikes appearing superimposed on the 60 Hz waveform. The energy to be detected in a corona spike is of the order of 10^{-10} J; the spikes have a duration of a few nanoseconds, but were amplified and time stretched by a diode detector for ease of viewing.

The following technique was adopted. Starting from zero, the source voltage was increased until spikes signifying corona appeared. The measuring system without load had been previously tested to be corona-free, thus the corona level of the particular magnet insulation was established. The voltage was not raised above the level for onset of corona; instead, the voltage was lowered until the corona extinguished.

The significant result for each magnet tested is the corona extinction voltage. The typical values of corona extinction voltage for the mica-insulated, integrally impregnated magnets was 1100 V rms or higher, corresponding to a peak-to-peak voltage of 3,110 volts or more. Capacitance between coils and core ranged from 0.065 0.09 μF, measured at 60 Hz and 300V rms.

Quadrupoles

This paper has described the Main Ring bending magnets. The quadrupoles are processed in much the same manner. Figure 9 shows a finished quadrupole magnet. Testing is essentially the same except for magnetic measuring.

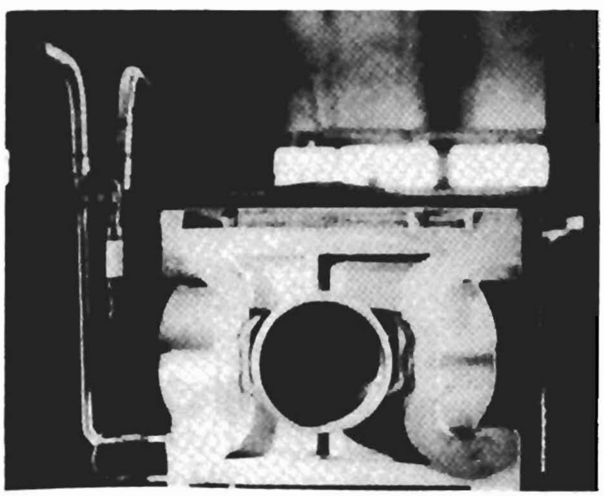

Fig. 9. Finished quadrupole magnet

A similar magnetic measurement is performed on the quadrupoles except that here the quantity $\int B'dl$ is compared against a reference, and the data are taken while the magnet is being pulsed so that the effect of eddy currents on the gradient is measured.

In addition to the magnetic measurements, the inductance is measured using a commercial impedance bridge. This measurement provides an additional check against possible turn to turn shorts within the magnet coil.

Cost Comparison

Considerable cost saving is achieved by eliminating the need for individual coil potting fixtures plus the cost of impregnation of individual coils, cleanup, sizing, inspection, handling, etc. The cost is increased by the use of mica, Kapton, and the labor of sealing the magnet Sealing and potting the magnet is now being done at a low production rate. If the tooling would be designed for high rate production, the cost per magnet would undoubtedly be less by the integral impregnation system than with the original pre-impregnated coil assembly technique. At the present low rate of production the cost differences are as follows, showing an increase of $239 or about 2% of the total cost per magnet.

Cost Change Per Magnet

Mica	+	$ 102.00
Kapton	+	33.00
Glass Tape	-	73.00
Epoxy	+	75.00
Sealing	+	30.00
Inner Coil Manufacturing	-	385.00
Outer Coil Manufacturing	-	813.00
Assembly and Potting	+	1,270.00
	Increase	$239.00

Summary

Over 400 magnets now in the Main Ring have been vacuum impregnated as refurbished magnets or as originally fabricated. Over 100 of these are integrally impregnated. They have proven to be vastly improved from all aspects:

1. Electrical break down under normal and severe moisture conditions.

2. Mechanical alignment and stability.

3. Magnetic field value and consistency.

4. Cost.

The technique lends itself to small production as well as large. Figure 10 shows one of two octupole magnets made in this manner.

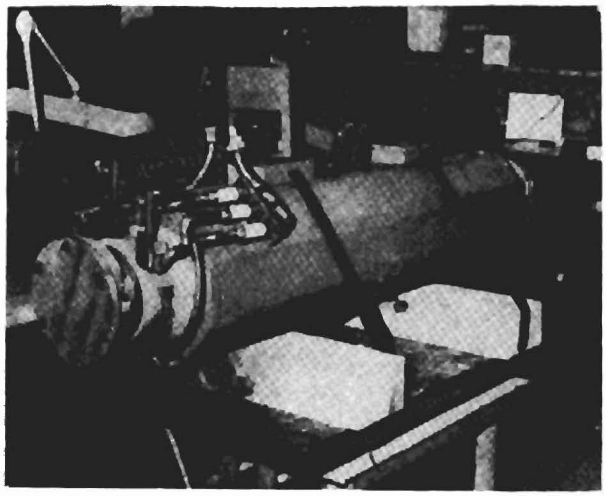

Fig. 10. Octupole magnet for slow extraction

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Technical Specification - Specification for B1 and B2 Outer Bending Magnet Coils Using Mica and Not Impregnated

The NAL Booster Magnets - R. Billinge, W. Hanson, P. Reardon, the 3rd International Conference on Magnet Technology, May 1970, p. 537

National Accelerator Laboratory Main Ring Magnets - H. Hinterberger, R. Sheldon, The 3rd International Conference on Magnet Technology, May 1970, p. 490

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Assembly Procedure and Check List

Preparation and Sealing Procedure and Check List

Impregnation Procedure and Check List

Quality Control and Testing Procedure and Check List

Acknowledgements

It should be pointed out that this work is an extension of the work done by the Main Ring Group in the earlier construction of Main Ring magnets and demonstrates that the insulation clearances and the mechanical tolerances on the magnet parts of the original magnet design are adequate. This design was developed by R. R. Wilson and his colleagues in the Main Ring, chief among which were R. Cassel, E. Malamud, H. Hinterberger, F. Shoemaker, R. Yamada, and R. Sheldon.

The authors are especially indebted to the people in the Main Ring Magnet Factory who accomplished both the development and production work, and to Q. Kerns who did the corona tests.