High Energy Facilities

Accelerator Development Branch

BROOKHAVEN NATIONAL LABORATORY

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Upton, New York 11973

SSC Technical Note No. 31
(SSC-N-25)

FABRICATION OF SUPERCONDUCTING COILS FOR SSC REFERENCE DESIGN D MODEL MAGNETS

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August 19, 1985

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Introduction

The superconductor coils for SSC Reference Design D model magnets have been fabricated using methods developed at BNL starting with coils for CBA prototype magnets. There are a few differences primarily in the end design. However, it seems appropriate to relate the techniques used for fabricating the coils and to include descriptions of the component parts. The coil molding techniques using a recure procedure are somewhat unique. The methods are described here with an evaluation of the sizes of the individual coils produced for a series of six SSC model magnets all constructed to demonstrate reproducible field quality.

DESIGN ORIGINS

Source Documents

The documents upon which the engineering design of the SSC Reference Design Dipole magnet coils is based are the SSC Technical Note No. 19, "Coil Design for the 40 mm Collared Coil Dipole (SSC-C5)" and SSC Technical Note No. 23, "The 1-in-1 SSC Dipole with C-5 Coils". These documents supplied the basic information which was used to develop engineering designs for the individual component parts of the dipole coils.

End Design

Although the cross section was fully detailed in the above mentioned documents, the end configuration was not specified and was left as an engineering function to be developed based upon various, and at the time, continuously changing magnet parameters. We will explain here the reasoning and basis for the development of the dog-bone or tapered end.

The design of the tapered end had its beginnings during the design of the 3.2 cm dipole coils. This magnet originally was designed to use Nb_3Sn and was a 2-in-1 design. Due to the brittleness of Nb_3Sn there is a minimum bend radius about which this cable may be bent. This minimum bend radius was used to determine the minimum end radius and therefore the minimum taper angle of the coil end. The chosen minimum cable bend radius was 1.4 inches based on electrical performance of Nb_3Sn cable samples subjected to various bend tests conducted by the Superconductor Materials R & D Section. The tests were only in one plane, in the bend direction to cause the most degradation. Since the actual end requires a compound bend of the cable we have chosen the compound radius to be a minimum of 1.4 inches. To determine the largest end radius allowable in the coil end one must look to the 2-in-1 aspect of the magnet design. Within a given yoke diameter there was a maximum distance by which each bore could be separated from the other and still maintain desirable magnetic characteristics within the magnet bore. This maximum separation distance determined the maximum bend radius of the magnet end to be 2.616". We therefore have a minimum and maximum radius specification within which to design the coil end. Of course one prefers, for Nb_3Sn, to design with the maximum bend radius allowed.

In addition to the bend radius criteria, there were other design requirements. It was determined earlier in the design process that it would be very desirable to have the midplane turn of the coils located at the geometric midplane of the coil for the entire length of the tapered region. There are two major reasons for this. First, the geometry of the tooling used to mold the coils can be greatly simplified resulting in reduced construction costs and there can be a reduction in the lead time required to produce the tooling. Secondly, the number of detail parts required to fabricate the ends can be reduced resulting in lower tooling costs and less time required to fabricate the ends of the coil during winding operation.

Design of the 4.0 cm SSC coils followed many of the criteria mentioned above since the original requirements of the 4.0 cm design included both the use of Nb_3Sn cable and the 2-in-1 (SSC Reference Design A) concept. Some design changes were incorporated in this effort as a result of experience gained in the 3.2 cm program and due to differences between the two magnet designs. However, there were two major changes incorporated in Design D. First, the tapered length was shortened since it was determined during the earlier program that a greater taper angle could probably be tolerated; this also allows an increase in the straight length of the magnet. In Design D it was decided to use a graded conductor as opposed to separate operating currents for inner and outer coils used in the 3.2 cm design. This change in design concept resulted in a simplified pole spacer. Since it was not required to bring out an additional pair of leads to power the coils separately it was necessary to provide, within the pole spacer extension, for an inner/outer coil splice.

Although Reference Design D incorporates tapered ends, there are ongoing studies aimed at simplification of the end configuration. This simplification is possible since there are no longer plans to use Nb_3Sn conductor for SSC. If this is done it would be possible to reduce significantly the amount of taper in the ends, or to eliminate it completely. The only consideration for minimum bend radius would be to maintain the mechanical integrity of the NbTi cable. In coil winding R & D done so far, one meter long inner and outer coils have been wound successfully and the techniques used there can easily be carried over to production. Figure 1 is a photograph of the end of the inner R & D coil with a straight end.

COIL COMPONENTS

Parts Catalog

A listing of parts used in the fabrication of a magnet coil is given at this time. Although the conductor cable is listed here, a detailed discussion of the cable and its fabrication is given in another Tech. Note.

Detail parts used in the R & D version of 4.0 cm SSC dipole magnet coils are as follows:

TABLE 1 - PARTS LIST

	Drawing No.	Part Description
1)	22-226.06-2	Wedge, Inner Lower
2)	22-226.07-2	Wedge, Inner Upper
3)	22-226.08-2	Wedge, Outer
4)	22-226.11-2	Outer Wedge Wrapping Sequence
5)	22-226.12-2	Inner Lower Wedge Wrapping Sequence
6)	22-226.13-2	Inner Upper Wedge Wrapping Sequence
7)	22-226.14-4	Inner Pole Spacer Extension Preform
8)	22-226.15-4	Outer Pole Spacer Extension Preformk
9)	22-226.16-5	Inner Pole Spacer Extension Return End
10)	22-226.17-5	Inner Pole Spacer Extension Lead End
11)	22-226.18-5	Outer Pole Spacer Extension Return End
12)	22-226.19-5	Outer Pole Spacer Extension Lead End
13)	22-226.27-3	Green Putty End Outer Coil Return End
14)	22-226.28-3	Green Putty End Outer Coil Lead End
15)	22-226.29-3	L.H. Feathering Wedge Outer Coil
16)	22-226.30-3	R.H. Feathering Wedge Outer Coil
17)	22-226.33-3	Green Putty End Inner Coil Return End
18)	22-226.34-3	Green Putty End Inner Coil Lead End
19)	22-226.35-3	L.H. Lower Feathering Wedge Inner Coil
20)	22-226.36-3	R.H. Lower Feathering Wedge Inner Coil
21)	22-226.37-3	L.H. Upper Feathering Wedge Inner Coil
22)	22-226.38-3	R.H. Upper Feathering Wedge Inner Coil
23)	20-000.49-4	Keystoned Cable and Insulation

Part Fabrication

In the following paragraphs fabrication of the individual detail parts which make up a dipole coil will be discussed.

a) Wedges

Items 1-6 in the table above are the set of drawings which make up the wedges used in the inner and outer coils of the magnet. In order to avoid repetition, the fabrication of a typical wedge will be discussed and this discussion shall apply to all three types of wedges used in the inner and outer coils as the fabrication of all three wedges is identical.

Wedges are extruded and rolled to the precise cross sectional geometry defined by the engineering drawing and rough cut to a length of 28" ± 1/8" by an outside vendor. The material used to fabricate these wedges is ASTM 102 OFHC copper (half-hard minimum). They are then cut at BNL to the precise length required, 26.417" ± .002". Wedges which have been cut to length are ready for insulation. After deburring and an alcohol wash, exposed ends of the wedge

are sprayed with three coats of GE-7031 Adhesive and Insulating Varnish. Two minutes drying time is allowed between coats. The wedges are then allowed to air dry for a period of 30 to 45 minutes. This air dry is required to prevent the formation of bubbles in the varnish during the bake cycle. After the air dry period the wedges are placed into an oven which has been pre-heated to a temperature of 155 ± 5 C for a period of 1 to 1-1/2 hours. Baking prevents flow of the varnish during subsequent coil curing at 135 C. The wedges are helically wrapped in a semi-automatic machine with .001" thick x 3/8" wide Kapton tape which is coated with polyester resin adhesive on one side. This tape (T-320) is manufactured by Scheldahl Inc. The Kapton is half-lapped, adhesive side out, to form a .002" thick layer of Kapton on the surface of the wedge. The ends of the Kapton are secured with .001 adhesive backed Kapton tape.

b. Pole Spacer Extensions

Items 7-12 in the parts list are those drawings used to define the various pole spacer extensions used in the construction of inner and outer coils. These parts define the end contour of the coils, both radially and azimuthally. Again, as for the wedges, the pole spacer extensions are treated as a group and we will describe the preparation of a typical part. Pole spacer extensions are machined using numerical control machinery to produce the outside contour of the part. This assures the accuracy of the contour which has been designed to keep the midplane turn of the coil at its proper location for the entire length of the taper. The pole spacer extensions are fabricated from ANSI 360 free cutting brass. To prepare the pole spacer for use in a magnet coil it must first have a layer of insulation applied to the surface which comes into contact with the first turn of the coil starting from the narrow end, extending along the taper and ending at the point where the large end radius is tangent to the taper. At this point Kapton is applied to the end region of the spacer in 1/2" wide strips extending from the inside to the outside surface of the pole spacer extension. This Kapton is .001" thick and is applied in three half-lapped layers forming a total thickness of .006". For extra protection at the point of connection between the tapered region and the rounded end, a piece of .001" thick x 3/4" wide Kapton is applied from inside to outside in the same manner as the Kapton on the ends. These insulation layers are applied so as to provide a creep path between the conductor and the pole spacer extension of 1/4" minimum. The pole spacer extensions are now ready for use in the coil. Fabrication of parts of this type in a production mode could be via injection molding using Rogers RX-630 glass filled phenolic. Producing these parts by injection molding would have the advantages of reduced fabrication costs and elimination of the insulation operation.

c) Green Putty End Spacers

Green putty end spacers which are used to square off the ends of the coils and serve as a bearing surface for the end restraints are described in items 13, 14, 17 and 18 of the Table. These parts are molded of Ciba-Geigy XD-580 Green Putty. At the present low rates of production these parts are molded in place on the coil mandrels during the winding operation. For slightly higher production rates these parts would be molded of green putty off line in a separate operation. In full scale production these parts also would be injection molded in Rogers RX-630.

d) Feathering Wedges

Feathering wedges are described by items 15, 16 and 19-22 in the Table. These small parts are used to smoothly taper the ends of the wedges and to create a smooth transition into the tapered end region. The feathering wedges are fabricated from G-10 fiberglass material which has been machined to the cross section of the wedge to which it mates. Although the present method of fabrication is to sand the contour of the feathering wedge by hand to match the drawing, production runs would be produced by injection molding of Rogers RX-630.

COIL FABRICATION

The fabrication method described here is based on the use of cable with an outer wrap of .004" B-Stage impregnated fiberglass tape. An experimental method of fabricating these coils without the glass tape is being investigated at Fermilab.

Fabrication of a magnet coil consists of two operations. First the coil is wound on a winding mandrel, then this mandrel is placed into a curing press and the coil is heated to form the individual turns into monolithic conductor blocks. The details of these operations will be discussed in this section.

This description of the winding operation will specifically discuss the winding of the outer coil. Winding of the inner coil is essentially identical to the outer coil except that there is a different number of turns in each conductor block and there is an extra set of wedges yielding three conductor blocks as opposed to two in the outer coil.

Winding

Prior to winding, the tooling and magnet parts are prepared. Winding tooling is cleaned of excess epoxy which may have accumulated during the previous cure operation and is inspected for any damage or other anomalies which may have occurred during the previous cure. Magnet parts are given a last visual check to insure that they are ready for the winding operation and that the proper quantities of each part are available. Figure 2 is a photograph of the coil winding fixture.

The following steps are required to wind an outer SSC dipole coil:

1) Bolt the pole spacer extensions to the winding mandrel.

2) Install tapered winding horseshoes onto the pole spacer extensions.

3) Apply Frekote 1711 mold release to the mandrel and pole spacer extensions.

4) Place one strip of Kapton 5/16" wide x .001" thick along each side of the centerpost covering the straight length of the coil. This Kapton strip serves as an additional mold release agent.

5) Spray Frekote mold release over the Kapton strips applied in Step 4) above using care not to apply mold release to the Kapton in the tapered region of the coil.

6) Apply Cycom 950 epoxy to the Kapton insulated region of the pole spacer extensions.

7) Initialize the coil winder. This action initializes the programmable controller and places the carriage of the coil winder in the proper position to allow off spooling of cable so that the cable can be anchored in the lead end pole spacer extension.

8) Place the cable into the lead slot in the pole spacer extension, lay cable into the circular cutout, and pass cable out of the slot adjacent to the center post. Secure the cable anchor in place on the mandrel. Activate the lump detector. This device sounds an alarm when it senses a lump on the cable of .015" or more suggestive of a cable misweave.

9) Mount winding horseshoes along the straight section of the mandrel. Clamp the first turn of conductor against the centerpost.

10) Wind thirteen turns of conductor onto the mandrel.

11) Insert wedges and wedge feathering tips between turns twelve and thirteen. Install one 3/8" wide x .005" thick x 1" long Kapton strip between turn twelve and the wedge and between turn thirteen and the wedge where the wedge and wedge feathering tip meet. Do this at both ends of the coil. This is to reduce the severity of transition from wedge to wedge tip.

12) Wind the remaining eight turns.

13) Verify the turn count and perform a visual coil inspection.

14) Clamp the conductor to the mandrel and cut the cable leaving 24" of extra cable.

15) Form green putty end spacers at the coil ends.

16) Mount and attach the pusher blade assembly to the mandrel. This assembly is used during curing to compress the coil azimuthally.

17) Apply Cycom 950 epoxy to the turns in the tapered coil ends. Place one strip of 3/8" wide x .005" thick x 1" long Kapton between the first turn and the center post at the point where the center post and pole spacer extension meet. Place this strip at four locations.

18) Tedlar wrap the coil using .001" thick half-lapped Tedlar. Use 2" wide material in the tapered region of the end and 6" width in the straight section. During application the Tedlar is tensioned at 20 pounds.

19) Remove completed wrap coil assembly from the winding fixture and transfer to the curing press.

Curing

The following procedure is used to cure an outer SSC dipole coil. This operation is described in graphical form in Figure 3. Figure 4 is a photograph of the cure fixture.

1) Clean and apply Frekote mold release to the cure fixture. Install hydraulic end pusher assemblies and tooling in the fixture.

2) Lower coil into the fixture and remove strongback from the mandrel assembly.

3) Seat coil in the fixture and install mandrel hold down bolts. Hook up thermocouple and strain gauge instrumentation.

4) Verify that the hydraulic pull rod clamps are in the retracted position. Then lower top hat into position, install stop shims and position pull rods for clamping. The stop shims will be described in more detail later. They provide an adjustable method of closing the molding fixture and thus assuring dimensional uniformity of the coil. They may be changed for different coils to allow for variations in cable thickness.

5) Apply 500 psi hydraulic pressure (4.2 ksi azimuthal stress) and heat the fixture through the top hat only to a temperature of 90 C. During this period of time relieve system hydraulic pressure at 10 minute intervals to allow the fixture to adjust for differential thermal expansion.

6) Reduce steam pressure and wait for 30 minutes at this temperature. After 30 minutes at 90 C again apply full steam pressure to the top hat and raise the fixture temperature to 125 C. Reduce steam pressure to 40 psi and allow the system to stabilize for 5 minutes.

7) Release hydraulic pressure and introduce steam to the form block.

8) Actuate the end pusher system and close the end pushers to stops by applying 1000 psi to system. Apply side pressure to close the fixture. Record the pressure required to close the fixture. Alghough it has been the practice in the past to apply side pressure first before applying end pressure, the procedure has been reversed for coils with tapered ends. During R & D with 3.2 cm coils it was found that due to the tapered end very high longitudinal forces were created that pushed the pole spacer extensions away from the straight section placing high stresses on the superconductor. By reversilng the order of applying pressure in the ends a lower net longitudinal force is seen by the pole spacer extensions and no longitudinal motion of the pole spacer extensions is observed.

9) When the fixture reaches 130 C begin the cure cycle timing. Cure the coil at 135 ± 5 C for a period of 90-105 minutes. During the cure period cycle the fixture pressure every 1/2 hour to allow for differences in thermal expansion.

10) After 1-1/2 hour turn off steam supply and allow the fixture to cool by natural convection for a period of 1/2 hour. After 1/2 hour open the cold water supply 1/4 turn and allow to cool further for 1/2 hour. After trickle cooling for 1/2 hour apply full cold water flow and cool the fixture to 30 C maximum. During the entire cooling process cycle the system hydraulic pressure at 10 minute intervals.

11) Reduce side pressure then end pressure to zero psi. Remove stop shims.

Apply 9000 ksi azimutal stress to the coil and measure the fixture gap.

12) With the fixture gap at an acceptable size the coil is removed from the fixture and transported to the coil assembly area for further assembly.

COIL SIZES

Discussion of Cure Methods

Early in the development of this type of coil using Rutherford type cable (i.e., for CBA coils) it was believed that two competing and conflicting requirements had to be fulfilled in order to produce a coil with the desired characteristics of consistent size and uniform elastic modulus. Intuitively one can say that size uniformity is important from the standpoint of uniform conductor location and for uniform pre-stress after assembly of coils in collars or yokes. It is also important for pre-stress that coil modulus be uniform from coil to coil. Ideally one should be able to produce a design which yields both the proper coil size and modulus. It seems, however, that uniform size and uniform modulus would be conflicting requirements. This is because of the dimensional variations, such as bare cable mid-thickness, one must live with when dealing with detailed parts made in the real world. One might assume that if coils were molded using a constant size stop shim then the goal of uniform size would be met. However, coils of varying modulus might result due to variation in the cable mid-thickness dimension. Alternately if one varied the stop shim so that a uniform modulus resulted, coil size might vary unacceptably.

With these ideas in mind, development of real coils was initiated. It was found that variation of conductor mid-thickness had a slightly different effect than anticipated -- a phenomonon known as overshoot was observed. Simply put, it was observed that if coils were produced using a constant size stop shim the coil modulus remained fairly constant. However, the size of the coils varied. Coils generally wound up measuring smaller than the size that would have been anticipated based upon the stop shim used. This dimensional difference was dubbed "overshoot". It is also possible for the coil to have zero overshoot, in which case recure is not required, or negative overshoot. Using this result a method of curing coils was developed which allowed the coils to be cured to a desired size with constant modulus of elasticity. This is accomplished as follows:

1) Cure the coil initially with a stop shim approximately .010" larger than the expected final shim size. A shim is used during coil molding so that the curing fixture can be closed, thus insuring a uniformity of dimensions. Measure the as cured coil size while still in the fixture (this measurement procedure will be described later).

2) Compare the measured coil size to the ideal coil size calculated from the shim size used. Calculate the overshoot obtained.

3) From an emperically determined plot of first cure overshoot vs. recure overshoot determine the amount of overshoot which can be anticipated after a recure of the coil.

4) Select a stop shim for the recure which will yield the proper coil size based on the expected overshoot. Recure the coil.

5) Measure the recured coil and remove from fixture if properly sized, otherwise perform a second recure. In most cases only a single recure will be required.

Initially, because of schedule requirements, SSC coils were not cured using the more precise cure/recure process. They were cured using only a single cure using a shim corresponding to the final coil size. Based on analysis of CBA coil data, this results in coils with an rms error band approximately twice as wide as recured coils.

b) In-fixture Coil Measurements

Since it would be very difficult to place a cured coil back into the cure fixture to do additional cures it was necessary to design the fixture in such a way that the coil size could be measured in the fixture. Referring to Figure 5, with a coil in place and sized to be precisely at the midplane and the stop shims removed one can see that a gap exists between the top hat and the form block. This gap is by design 1/16" nominal; the as built gap of each form block is carefully determined and recorded for use in coil size calculations. At the end of a cure stop shims are removed and the system hydraulics are activated so as to apply an azimuthal stress of 9000 psi to the coil. The gap size is measured and compared to the as-built gap. We can now calculate the size of the coil relative to the midplane without removing the coil from the fixture. This is also the effective size of the assembled coil since it is measured at the nominal assembly pre-stress.

The validity of these gap measurements has been verified by measurements of coil size outside the fixture using a coil compression gauge. With the coil compression gauge taken as the standard of measurement, comparison of gap measurements are repeatable and the correlation between the two measurements is constant.

c) Coil Size Data

Table II summarizes the size data for SSC coils which have been manufactured to date. The cure fixture sizes are measurements of the fixture gap referred to in Figure 5 and are used by coil factory personnel in the calculation of shim sizes to be used in recures and to determine if additional recures are necessary. The significance of these measurements should only be considered relative to the coil sizes produced as measured by the coil compression fixture. Compression gauge measurements are believed to be more accurate and are used to define coil sizes. Sizes stated in Table II for compression gauge measurements are relative to the theoretical midplane of the coil. Zero indicates the coil is exactly at the midplane, positive indicates the coil is oversize or above the midplane, negative and the coil is undersize or below the midplane. The L (Left) and R (Right) size measurements in the cure fixture and compression gauge are actually the overages of five measurements on each size of a coil equally spaced along the length.

Looking at the inner and outer coils as two groups we calculate using the results in Table II an overall average gauge measurement size for inner coils of 3.3 mils with an rms variation of 1.3 mils. Overall average for outer coils is 10.9 ± 1.4 mils. Absolute sizes required for coils are determined through an iterative process. Coils are assembled in a yoke and are squeezed to the midplane

size. Coil prestress is measured and a determination is made as to the correct coil size. This information is fed back to the coil manufacturing operation and an adjustment is made in the as built coil size if required. Small variations in coil size for field quality magnets are accommodated in the yoke assembly by small variations in the magnet prestress.

CONCLUSIONS

The procedures used to construct this set of coils for SSC Design D model magnets have proven to be very satisfactory. The coil winding and molding operations have become completely routine procedures which could easily be used in industrial production. The coil sizes resulting from these procedures appear to make it possible to demonstrate field quality performance for even this short production sequence of six model magnets. However, testing and magnetic field measurements can only show if these requirements are met.

ACKNOWLEDGEMENTS

Most of the tooling used for winding and curing the coils described here was designed by Y. Elisman and W. Stokes. The extremely competent technician staff in Building 924 is responsible for the high quality of the coils produced. The individuals with this responsibility are: J. Benante, C. Biggs, D. Ince, G. Jochen. R. McCluskey, R. Otten, W. Sandhoff, D. Schiappia, M. Stone, H. Strelecki, B. Vogt, M. Williams. Appreciation is extended to all of these individuals who have made possible the success of the coil construction.

TABLE II

COIL CURE DATA

COIL	SHIM SIZE	MEASURED SIZE CURE FIXTURE			MEASURED SIZE COMPRESSION GAUGE		
		L	R	AVG	L	R	AVG
I-1	58.0	54.3	55.8	55.1	1.6	1.5	1.55
I-2	70.0	60.2	65.2	62.7	5.0	4.7	4.85
I-3	70.0	59.6	65.0	62.3	2.6	2.1	2.35
I-4	70.0	60.0	66.0	63.0	5.1	4.8	4.95
I-5	70.0	59.6	63.3	61.4	1.9	1.3	1.60
I-6	70.0	67.3	73.6	70.5	-	-	-
	63.0	59.8	66.5	63.1	4.8	4.2	4.50
I-7	63.0	51.0	70.5	60.8	-	-	-
	64.0	57.6	65.5	61.5	4.1	3.5	3.80
I-8	63.0	57.3	64.6	61.0	1.7	1.6	1.65
I-9	64.0	60.5	65.8	63.2	3.3	2.9	3.10
I-10	75.0	63.7	69.7	66.7	-	-	-
	70.0	61.0	67.0	64.0	4.4	4.3	4.35
I-11	75.0	67.3	76.0	71.7	-	-	-
	64.0	61.5	67.8	64.6	-	-	-
	62.0	61.2	67.0	64.1	4.4	4.8	4.60
I-12	75.0	69.0	73.6	71.3	-	-	-
	62.0	59.3	63.5	61.4	1.5	2.3	1.90
I-13	75.0	68.6	73.6	71.1	-	-	-
	63.0	58.8	65.0	61.9	3.2	3.0	3.10
O-1	70.0	68.3	75.2	71.8	9.3	10.1	9.70
O-2	65.0	63.0	64.5	63.7	-	-	-
	70.0	63.0	73.0	68.0	8.8	8.5	8.65
O-3	68.0	67.0	73.0	70.0	12.3	9.8	11.00
O-4	67.0	66.5	68.5	67.5	-	-	-
	68.0	68.7	70.5	69.6	9.2	9.6	9.40
O-5	68.0	68.0	70.0	69.0	10.6	10.2	10.40
O-6	68.0	66.5	69.5	68.0	9.9	7.8	8.85
O-7	68.0	66.5	74.5	70.5	11.8	12.0	11.90
O-8	80.0	73.5	78.5	75.8	-	-	-
O-9	80.0	77.1	81.1	79.1	-	-	-
	68.0	72.7	77.8	75.3	-	-	-
	66.0	67.1	71.0	69.1	12.6	12.4	12.50
O-10	80.0	75.7	79.7	77.7	-	-	-
	66.0	67.1	71.5	69.2	13.8	11.9	12.85
O-11	80.0	75.1	80.5	77.8	-	-	-
	65.0	66.1	69.1	67.6	11.5	10.0	10.75
O-12	80.0	76.1	80.5	78.3	-	-	-
	66.0	65.5	70.0	67.7	11.0	13.0	12.00
O-13	80.0	76.5	79.2	77.8	-	-	-
	66.0	67.1	68.3	67.7	13.0	11.5	12.30
O-14	80.0	78.2	76.8	77.5	-	-	-
	65.0	68.1	68.0	68.0	11.1	10.3	10.70

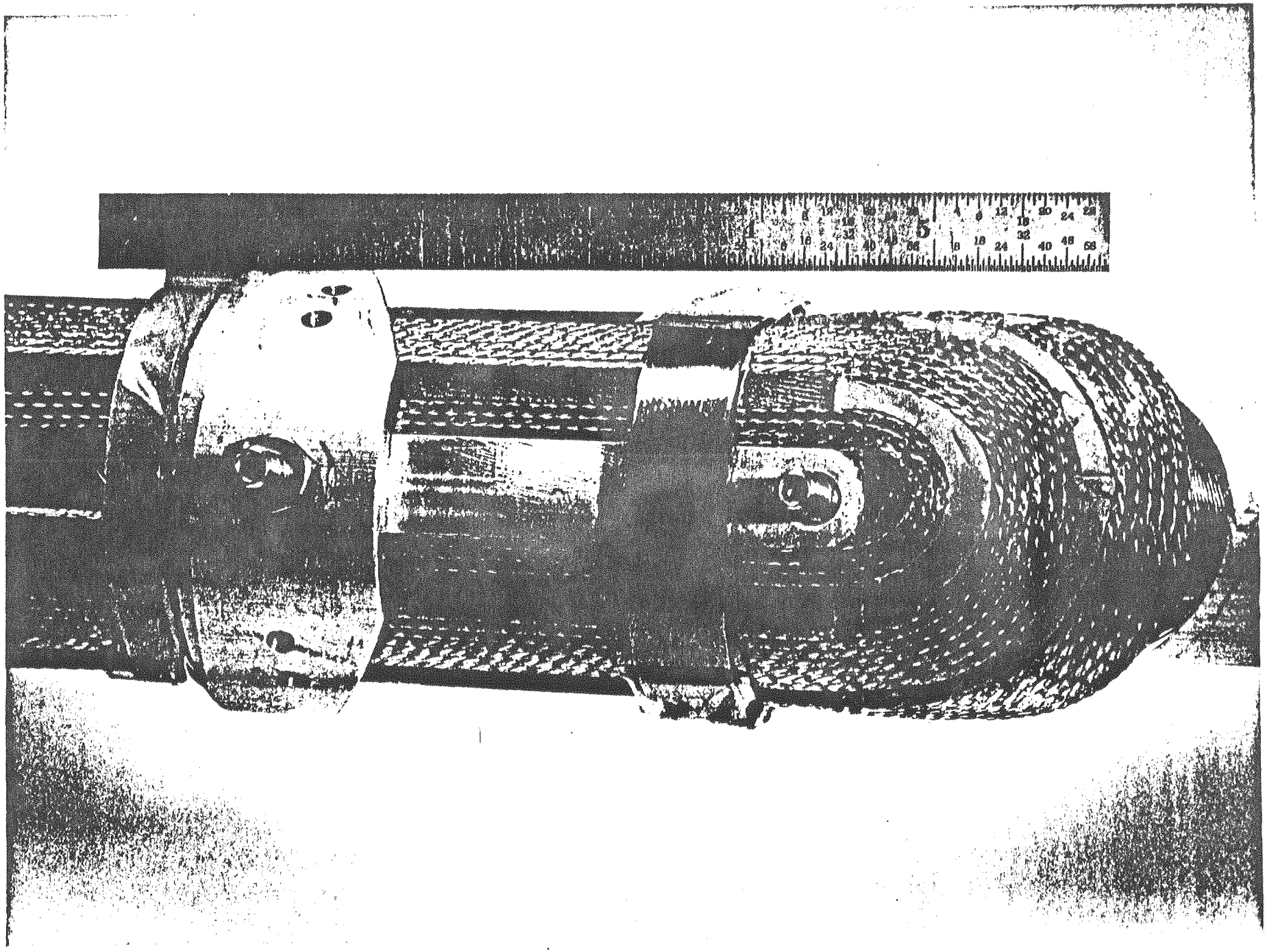


Fig. 1. Prototype Inner SSC Coil with Straight End

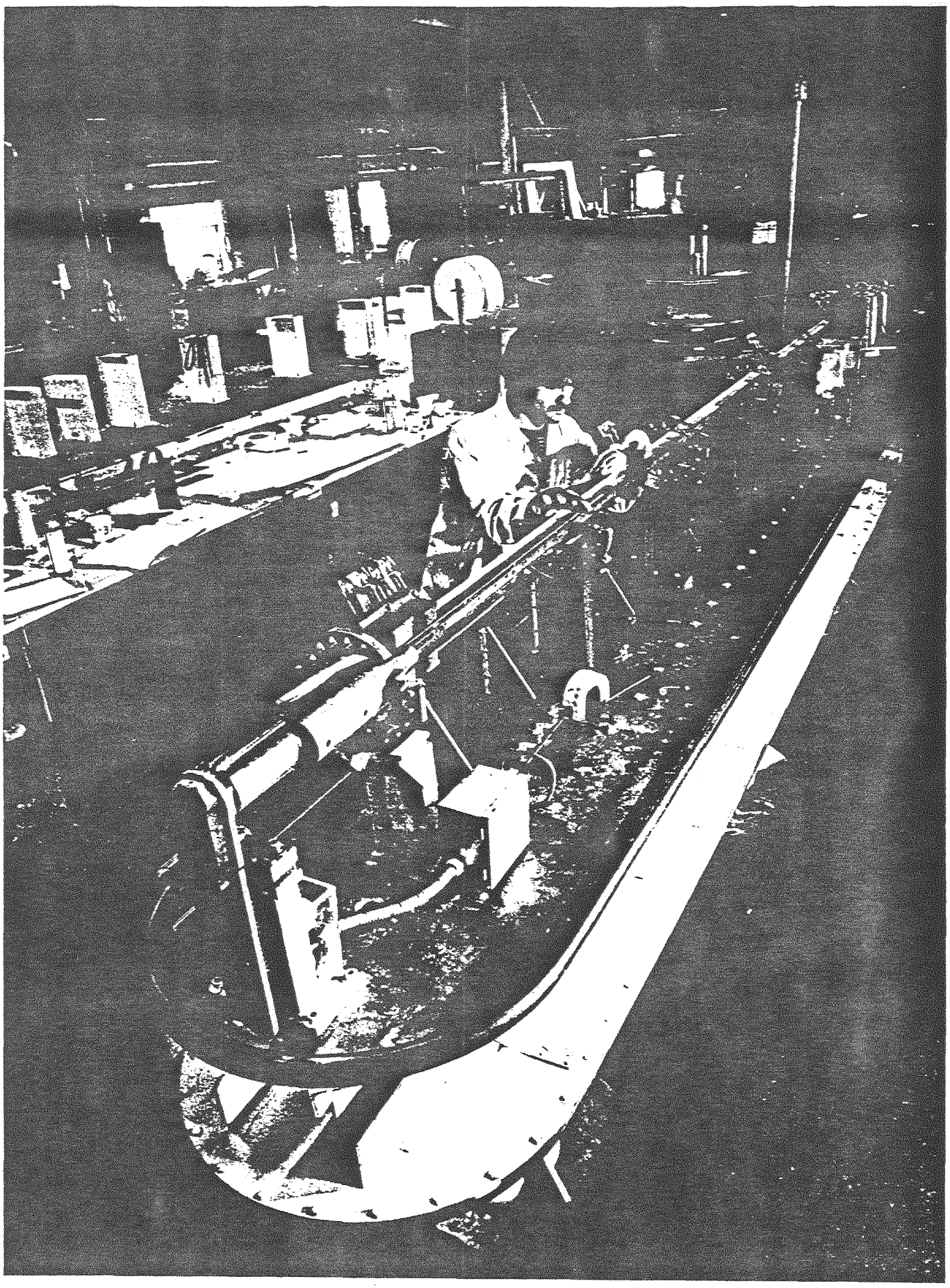
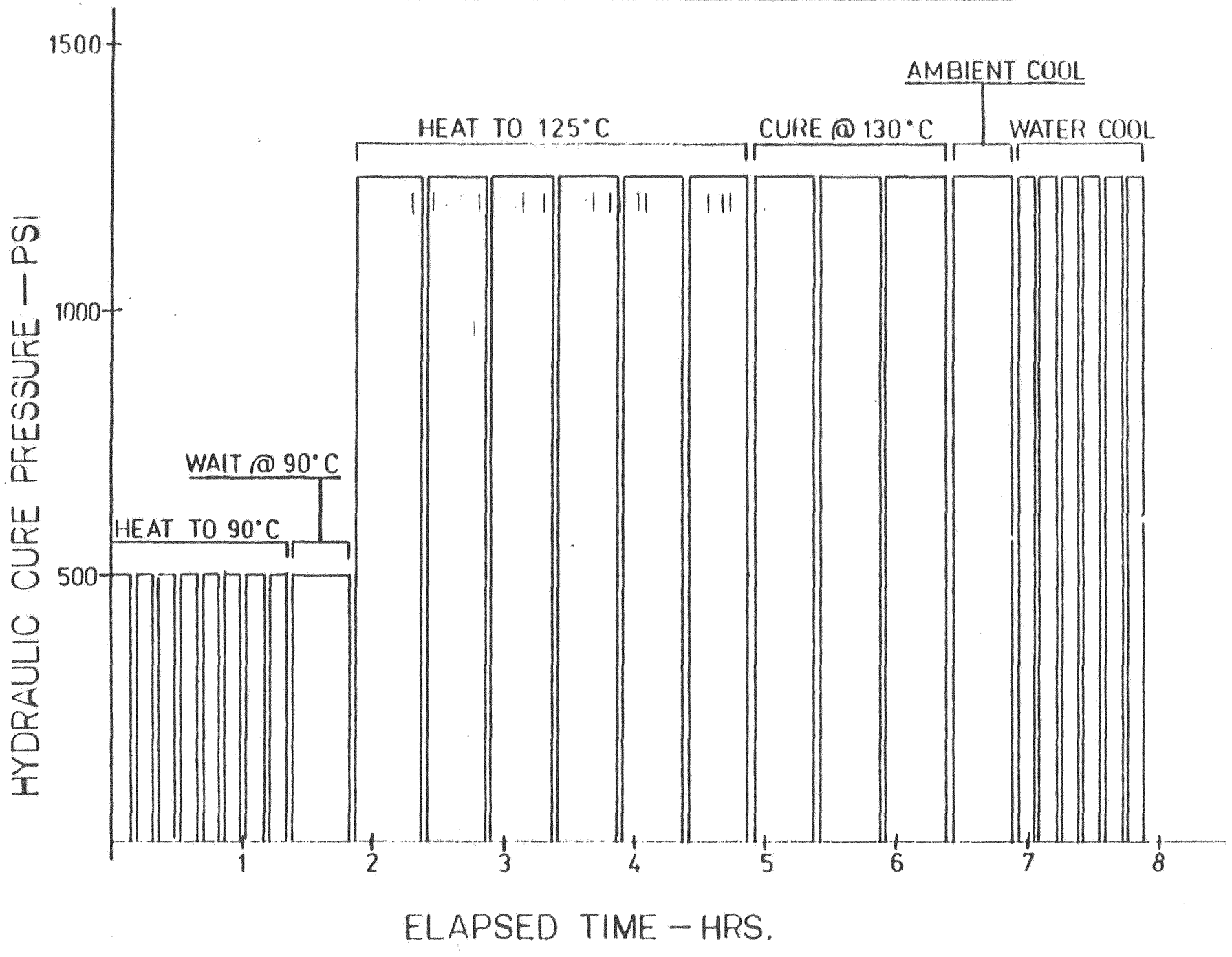


Fig. 2. Dipole Coil Winding Fixture

FIGURE 3 - CURE CYCLE SCHEMATIC



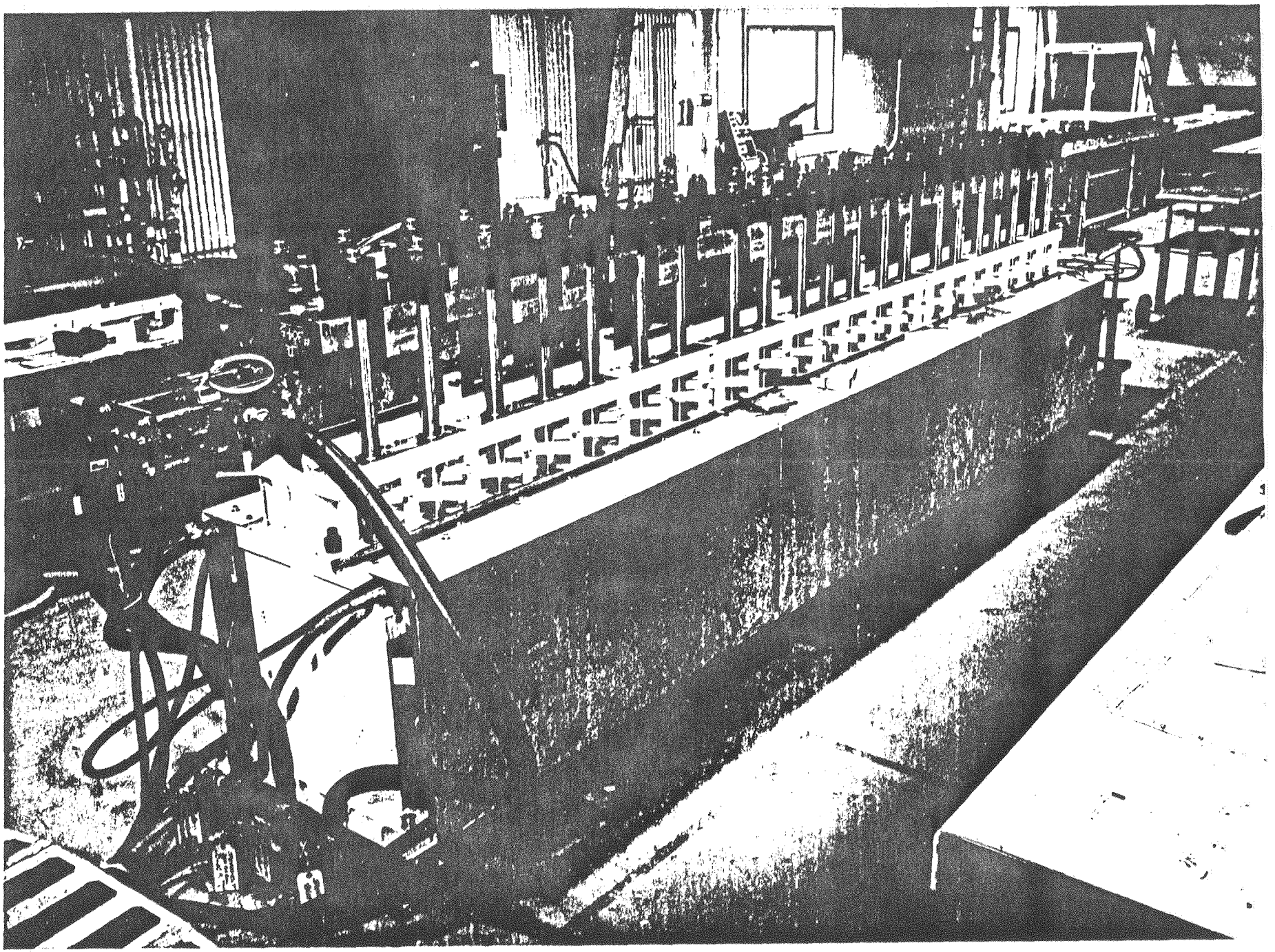
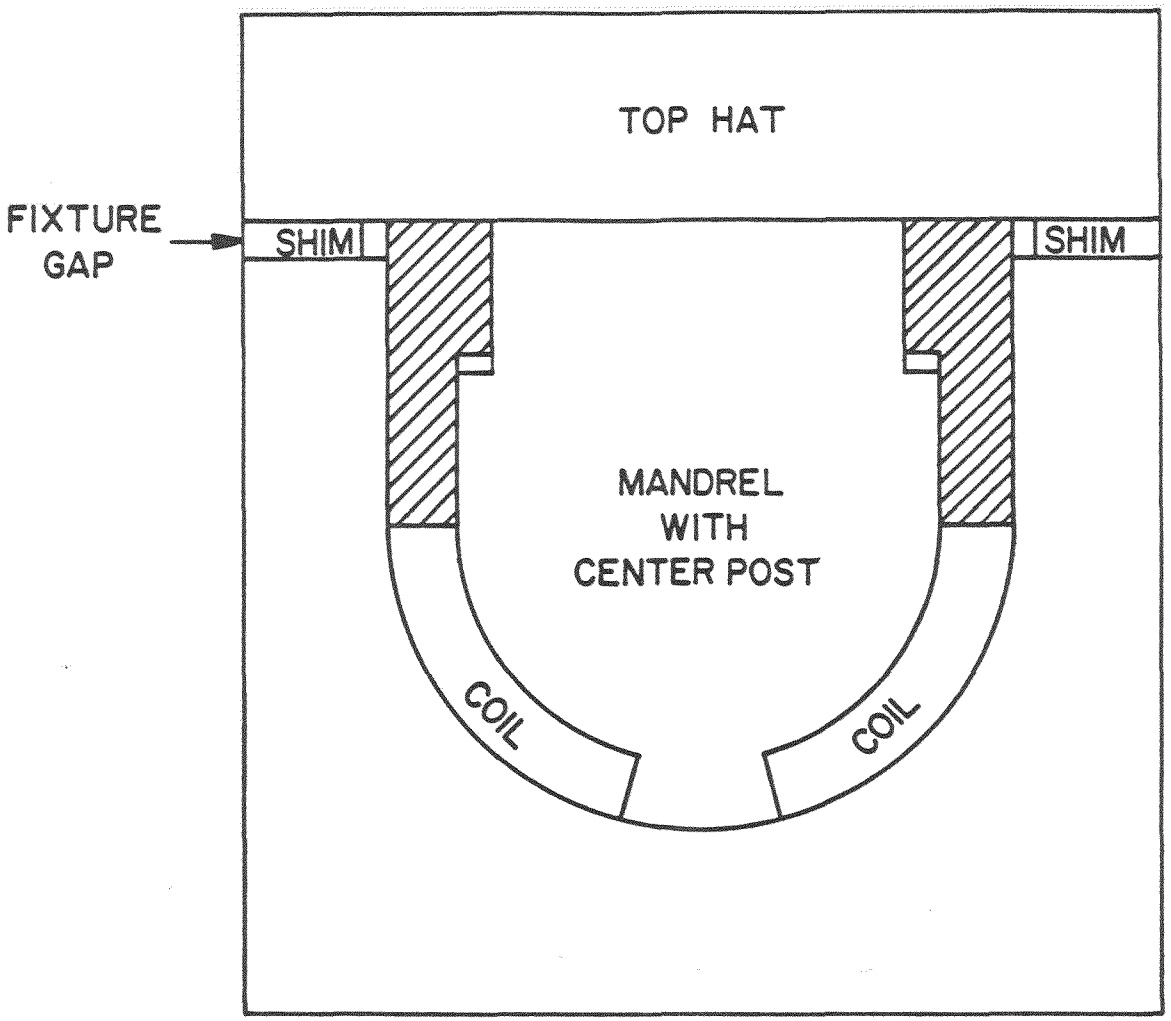


Fig. 4. Dipole Coil Cure Fixture



CURE FIXTURE	NOMINAL GAP (MILS)	AS-BUILT GAP (MILS)
INNER	62	60
OUTER	62	66

FIGURE 5-CURE FIXTURE SCHEMATIC X-SECTION

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