5.2 14-FT BUBBLE CHAMBER RESEARCH AND DEVELOPMENT PROGRAM MECHANICAL DESIGN DETAILS OF MAGNET COIL*)

D.A. Kassner
Brookhaven National Laboratory.

Introduction

Early in the conceptual design phase of the proposed Brookhaven 14' bubble chamber, it was realized that additional research and development was required before the design of some components could be finalized. Rather than setting up a number of individual tests, it was decided to combine, where practical, all tests into one facility. In this manner, not only could the necessary research and development for each component be accomplished, but also the interaction of components could be determined. The scale of this test facility should be large enough so that the extrapolation of the results to the 14' bubble chamber will be reasonable. For these reasons, the design and fabrication of an essentially one-half scale model of the 14' bubble chamber, namely the 7' test facility, was undertaken at Brookhaven. One of the premises used in the design of the 7' test facility was that it should be built with a minimum cost consistent with providing the required information. Also, it was not conceived of as primarily a nuclear research tool, but rather as an engineering test facility - although the possibility does exist at some later date of converting the 7' test facility into an operating bubble chamber.

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*) Research performed at Brookhaven National Laboratory under the auspices of the U.S. Atomic Energy Commission.

One of the components requiring additional research and development is the superconducting coil. To date, only relatively small coils using the principle of superconductivity have been fabricated and tested. Also, these coils have been wound either using cable type construction, or strip conductors employing edge cooling only. Because of the irregular cross-sectional geometry of cables, they would be difficult, if not impossible, to support against the magnetic forces occurring in very large coils. For economic reasons it is desirable that the 14' coils not only be edge cooled, but also have a percentage of the conductor face area cooled, thereby substantially reducing the quantity of expensive material required -- namely by a factor of 5 or more.

Since none of the superconducting coils to date is of a size or design similar to that required by the 14' bubble chamber, there is a scarcity of needed design, fabrication and operating information. Therefore, in order to acquire the necessary knowledge, it was decided to incorporate into the 7' test facility a superconducting coil.

Except for field strength, every effort was made to use design concepts that could later be applied by scaling to the 14' magnet coil. Wherever calculations were required, they were done in parallel for both 7' and 14' coils. Decisions were based not necessarily on the optimum design for the 7' coil, but rather were based on techniques that eventually could be applied to the 14' coil. In regard to field strength, it was the opinion that the difference between the 20 KG of the 7' and the ultimate 30 KG of the 14' would not substantially alter the validity of the extrapolation. Certainly, a field as high as 20 KG would allow the verification of all calculations and design concepts but at the same time the lower field afforded considerable economics in construction.

Figure No. 1 is a listing of the basic design parameters used in the 7' test facility coil.

Figure No. 2 shows a vertical cross-section through the 7' test facility, detailing the coils and the coil dewar.

It will be noticed from the drawing that the coil dewar is not in an independent vacuum chamber, but rather is contained within the same vacuum chamber that surrounds the hydrogen chamber. Although this concept may represent some loss in flexibility in the utilization of the machine, as well as resulting in additional constraints during the initial construction and tests, the substantial cost reduction represented by a single vacuum chamber appeared to more than offset these disadvantages.

Also, it will be noted that the coils are contained within a single dewar rather than two separate dewars, one for the upper coil and one for the lower coil. The largest force that the coils must be supported against is the attractive force exerted between the coil halves. In the case of the 7' test facility, the total attractive force is 770 tons -- in the 14' bubble chamber the total attractive force is 9,300 tons. If the upper and lower coils are contained within separate dewars, these forces must be restrained by members that connect between the dewar at helium temperature and supports at ambient room temperature. Because of the magnitude of these forces, the cross-sectional area of these support members must of necessity be large, representing a considerable heat leak to the cold dewar. By using a single dewar these support members can be kept internal to the dewar. This means that the only expense in refrigeration resulting from these supports is during the initial cooldown.

The dewar with the coil inside is supported on three legs which in turn are supported by the three main legs of the test facility. These dewar legs are fixed at the bottom and pinned at the top, allowing them to deflect, compensating for the contraction of the dewar when it is cooled. These three legs represent a minimal heat leak since they must only support the weight of the dewar and coil.

The dewar consists of a 3/8" thick outer wall, a 5/8" thick inner wall, a 3/8" thick semi-circular top and a 1" thick bottom plate all fabricated from type 316 L stainless steel. The semi-circular dewar top is welded to the outer wall, and this assembled unit is then joined to the dewar inner wall and bottom plate by two sealed and bolted flanges. Consideration was given to the possibility of welding the dewar closed, but there is insufficient experience as to the reliability of this type of coil to chance semi-permanently sealing the dewar. Certainly a test facility should be designed so that components can be inspected and if necessary modified with minimum effort.

A complete coil assembly consists of 8 double pancakes below and 8 double pancakes above the beam centerline separated by a bridge structure. The lower coil unit rests on a one-inch thick stainless steel washer and is attached to the bridge by 1/2" diameter tie rods. In a similar fashion, the upper coil is also attached to the bridge. The bridge structure is designed so that it can be separated, allowing the upper and lower coil assemblies to be handled as units.

This modular construction allows the coils to be pre-assembled, including inter-pancake electrical connections, clamps, and etc. external to the dewar. By dividing the coils into two units, the weight of each unit is comparable to the weight of other major components, for example the vacuum chamber and the hydrogen chamber, resulting in optimum crane capacity.

Figure No. 3 shows the various components used in the coil winding itself. The stabilized superconductor strip consists of a number of parallel paths of Nb-Ti wires metallurgically bonded into O.F.H.C. copper. The strip measures 2 inches wide by .080 inches thick and has a current carrying capacity of about 4000 amperes under the conditions existing in this particular coil.

Turn to turn electrical insulation in the coil windings is provided by a .005 inch thick Mylar strip backed with adhesives which is wound in adjacent to the conductor strip.

To aid in supporting the stresses in the magnet windings, a reinforcing strip made of stainless steel .006 inch thick is wound in with the conductor. The stress in the copper could be limited by greatly increasing the amount of copper in the conductor beyond that required for stabilization. A less expensive technique is to use a separate support strip whose physical properties are superior to copper -- for example, stainless steel.

In a detailed analysis of the stresses produced in the conductor, consideration was given to (a) stresses produced by bending the conductor in the winding process, (b) the hoop stresses caused by the electromagnetic forces, (c) the local compression stresses produced by bearing of the spacer strip on the conductor, (d) the stresses produced by the conductor bending between points of contact on the spacer strip, (e) thermal stresses resulting from the use of stainless steel and copper.

Adjacent to the support strip is the spacer strip which provides cooling channels for the liquid helium refrigerant to make contact with one face of the conductor. One of the design problems that defied solution for a long time was this spacer strip. Contradictory requirements of maximum open area for helium flow, combined with the need for sufficient support of the conductors, complicated the solution.

Support requirements of the spacer strip result from a detailed analysis of the force transfer from one conductor to another. Figure No. 4 shows two typical adjacent conductors with the spacer strip between them, and also a force profile across the coil width. As a result of the magnetic field distribution, the innermost turn of the coil is subjected to a maximum force outward. This force reduces to zero near the outer turn and finally results in a small force inward on the outermost turns. Because of this force distribution, the spacer strip is required to transfer forces from one turn to the next so that the result will be an essentially uniform force across the width of the coil. It would be practically impossible to guarantee that the support areas of adjacent spacer strips would be located directly in line. Probably at some locations in the coil the support area of one spacer would be located between the support area of an adjacent spacer strip. Essentially this configuration results in the conductor acting as a continuous beam with a central load between supports. The maximum bending moment derived from this configuration is $M = \frac{f\ell}{8} (\ell - \frac{d}{2})$ where f is the unit load on a conductor, d is the circumferential width of support area, ℓ is the circumferential distance between centerlines of the support area.

If d is made equal to $\ell/2$, resulting in 50% support circumferentially, the maximum bending moment and thus the maximum bending stress varies as the square of the distance between centerlines of the support areas. For a value of $\ell = 1/4$ inch, this bending stress in the 7' coil conductor is about 1500 psi. To minimize the contribution to the total stress in the conductor from this consideration, it is imperative to limit the distance between support areas. Also, the support areas should be rigid in the radial direction since any deflections would result in non-uniform force distribution across the coil. The result of the support and cooling requirements is that the spacer strip should consist of small solid support areas located on a fine grid. Additionally, the strip should be: (1) inexpensive to fabricate, since 40,000 feet are required in the 7' coil and 120,000 feet for the 14' coil; (2) it should be produced using standard machines and techniques so that the expense and time involved in developing special machinery can be avoided; (3) it should have the same coefficient of thermal expansion as the conductor.

Figure No. 5 shows the details of a spacer strip that satisfies all the above-mentioned requirements. This strip is fabricated by a two step process using standard machine tools and techniques. In the first step, 8 equally spaced grooves .037 inch deep and 1/8 inch wide are either milled or rolled longitudinally in a .057 inch thick by 2 inches wide strip of copper. The cost of this process is about $.11 per foot. In the second step, sections of copper 1/8 inch wide and 1/4 inch apart are punched out of the strip transverse to the grooves at a cost of $.05 per foot. These two steps leave an array of rectangular "bumps" .057 inch high and 1/8 inch on a side whose centers are 1/4 inch apart. These bumps are carried by three continuous strips .020 inch thick by 1/8 inch wide, that remain after the punching process. The helium coolant may then flow through the longitudinal and transverse grooves between the bumps, resulting in about 75% of the conductor face area exposed to the helium. Including material and processing, the total cost of this spacer strip is about $.50 per foot.

The stabilized superconductor, spacer strip, insulation and stainless steel support strip are spirally wound to form double layered pancakes.

The layers of each pancake are supported and insulated from each other by 1/8 inch thick plastic cooling spacers which are slotted to provide for radial and axial flow of the liquid helium coolant. See Figure No. 6. In a similar fashion, neighboring pancakes are supported and insulated by spacers 5/8 inch thick. These spacers are fabricated from a fiberglass based phenolic that has the same coefficient of expansion as copper, and are located in position by slots that are guided on the tie rods connecting the coil face plates to the bridge structure.

Also shown on Figure No. 6 are the details of the radial clamps. The main function of these clamps is to secure the pancakes when they are removed from the winding fixture prior to installation in the coil units. Lifting of the pancakes will be accomplished by a fixture bolted to these clamps. These clamps are fabricated from phosphor bronze, having a top and bottom plate with slots for axial flow of helium, an inside plate contoured to match the inside coil radius and a front plate. The front plate contains four set screws that act against two pressure plates, providing a radial clamping force.

Figure No. 7 shows the details of an end clamp for constraining the conductor terminating ends of individual pancakes. The ends are essentially "hooked" around a phenolic clamping block and secured to it by a bolted pressure plate. This results in the ends acting against each other, "locking" up the forces within the pancake. Because the centerline of the end forces are displaced vertically, there results a torque on the clamping block. This torque is balanced by attaching the clamping block to two modified radial clamps that bear on the upper and lower horizontal edges of the coil.

Figure No. 8 shows the proposed configuration of an inter-pancake electrical connector. It consists of a phosphor bronze unit shaped on one side to match the outer coil radius, and on the other side it has an entrance ramp, a flat clamping area and an exit ramp. Ears containing tapped holes protrude top and bottom. Prior to completing the outermost turn, this unit is located in position. The outer turn is then displaced radially 3/4" from the adjacent turn by winding it around the outside face of the connector, allowing sufficient space above and below the conductor for bolts. To provide additional contact area, two parallel superconducting strips are clamped to the outer turn by a 3/4 inch thick pressure plate and six 1/2 inch diameter bolts.

Figure No. 9 shows the complete array of inter-pancake electrical connections. The pattern of electrical connections results in longer lengths of interconnecting strips, providing flexibility should there be any relative motion between pancakes during cooldown or operation. Current enters pancake No. 1 on the upper layer at point (A). It proceeds through the upper spiral, crosses to the lower layer at the interal cross-over, proceeds through the lower spiral, and exits at point (B) on the lower layer of pancake No. 1. The lower layer of pancake No. 1 is connected to the upper layer of pancake No. 2 at point (C) by the external connector. This stepping procedure is continued until the lower layer of pancake No. 8 is reached (point D). A jumper is provided around the bridge and connected to the upper layer of pancake No. 9 (point E). In a procedure similar to the lower coil half, the current is routed from pancake to pancake in the upper coil, ultimately exiting at the lower layer of the top pancake (point F). Current is returned from this point by a superconducting strip to the bottom of the coil where it exists through the dewar bottom plate completing the electrical circuit.

Figure No. 10 shows the details of the internal crossover. In order to transpose the conductor from the lower layer to the upper layer at the inside diameter of a pancake, it must be edge bent through a distance 2-1/8 inches. This is accomplished over a relatively long length, namely 90° of arc length, to minimize the stress in the conductor. A 1/2 inch thick "cross-over plate" milled on the coil side, providing clearance for the protruding cooling spacer fingers, is located against the inner coil radius. The conductor is guided to the inner face of this plate by an entrance ramp where it is edge bent, bringing it to the level of the upper layer, and then guided back to the inner coil radius by an exit ramp. The conductor is secured to this plate by bolted support clips. Three modified radial type clamps secure the cross-over plate in position against the inner coil radius. To avoid edge bending of the thin stainless steel support strip, it is terminated and joined by hard soldering at each end of the cross-over plate.

Due to manufacturing limitations, the longest length of superconducting strip obtainable is just sufficient to wind a single pancake layer, necessitating a splice joint on the inner radius. Since there is insufficient confidence in the capability of soft soldered joints to transfer the required force, and hard soldered joints degrade the current carrying capacity of the conductor, a combination of the two soldering techniques is used, eliminating the disadvantages of each method. The ends of the conductors are first hard soldered together. A superconducting strip is then soft soldered on both sides of the splice joint, bypassing the section degraded by the hard soldering. A radial clamp as previously described is located at each of the soft soldered joints, providing a mechanical clamping force on the joint.

A completed pancake is composed of the following components:

1) Coil winding components including superconductor, insulation, support strip and spacer strip.
2) Cooling spacers, 1/8" and 5/8" thick.
3) Radial clamps.
4) End clamp assembly.
5) Electrical connectors.
6) Internal cross-over assembly.
7) Internal splice joint.

Figure No. 11 shows a plane view of a completed pancake assembly, locating the above components.

Acknowledgements

The author wishes to acknowledge the very substantial contributions of the Bubble Chamber Magnet group, in particular G.T. Mulholland, A.G. Prodell and R.P. Shutt to the design of the magnet coils.

DAK:pm

FIGURE CAPTIONS

<u>FIGURE</u> 1 7' Test Facility Coil Parameters

2 7' Test Facility Vertical Cross Section

3 7' Test Facility Magnet Coil Components

4 7' Test Facility Force Distribution

5 7' Test Facility Spacer Strip

6 7' Test Facility Details of Cooling Spacers and Radial Clamp

7 7' Test Facility End Clamp Assembly

8 7' Test Facility Inter-Pancake Electrical Connector

9 7' Test Facility Inter-Pancake Electrical Ass'y

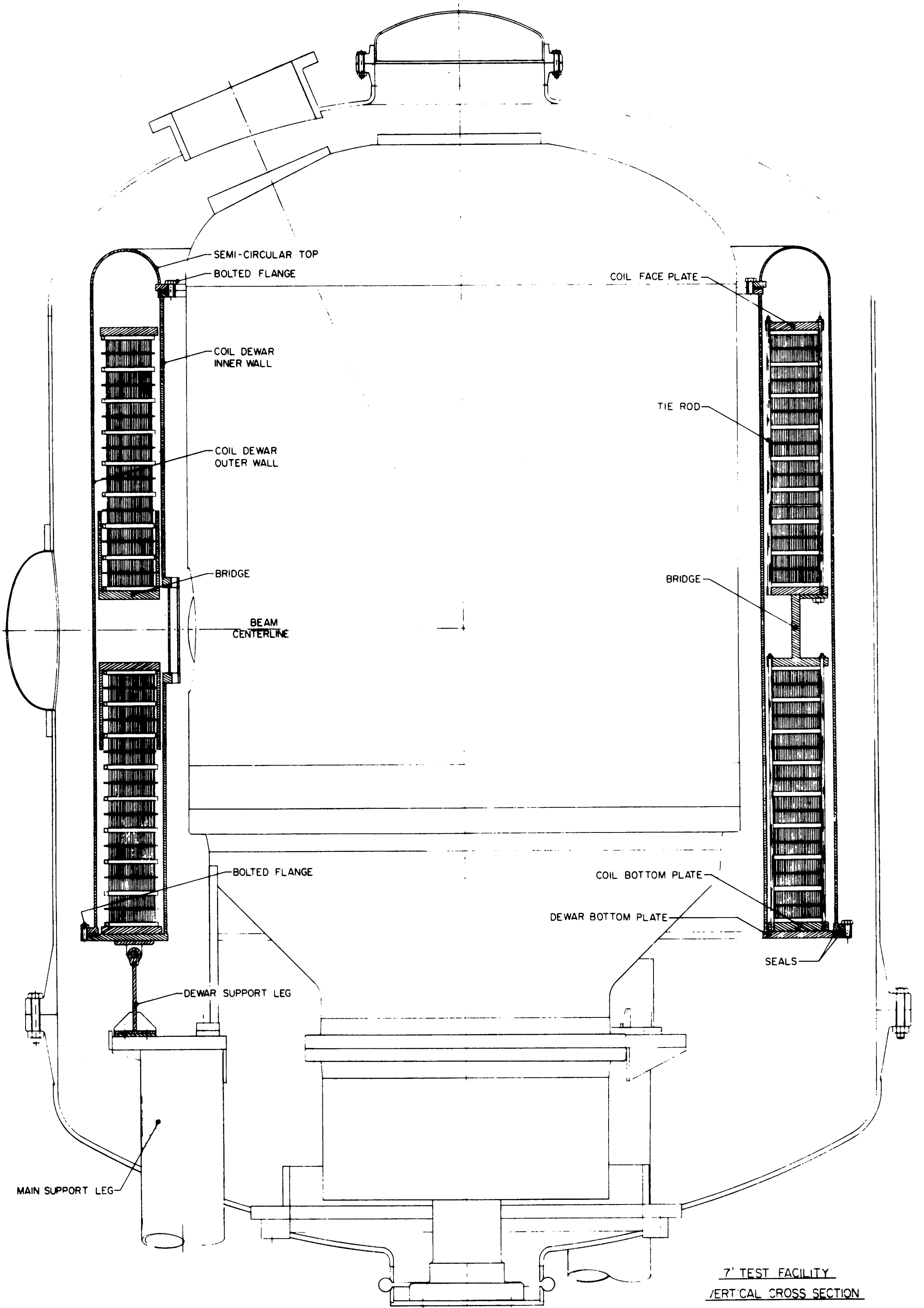
10 7' Test Facility Internal Cross-over

11 7' Test Facility Plan View Completed Pancake

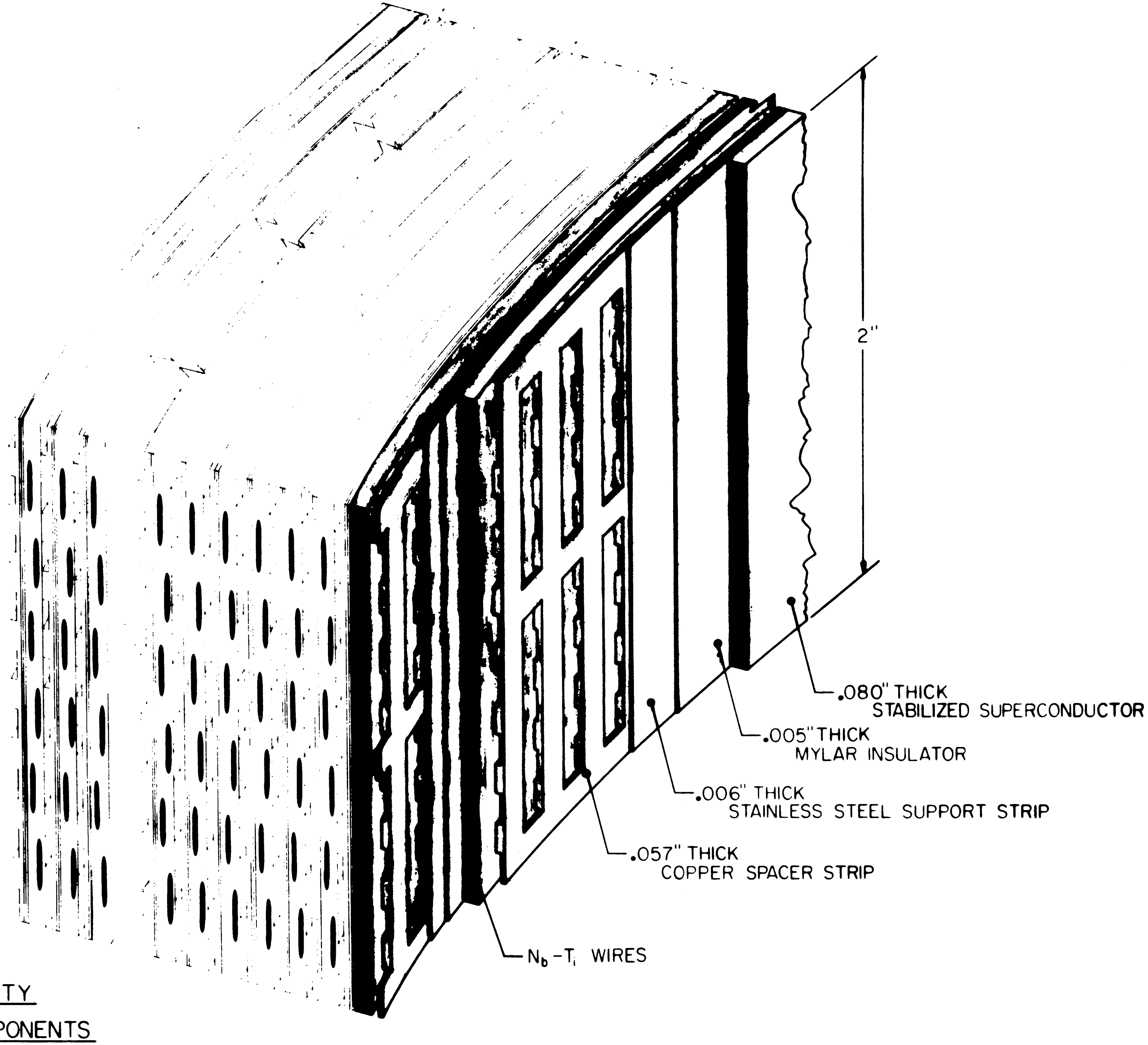
7' TEST FACILITY
COIL PARAMETERS

NUMBER OF DOUBLE PANCAKES	16
TOTAL NUMBER OF LAYERS	32
TURNS PER LAYER	45
TOTAL NUMBER OF TURNS	1440
COIL CURRENT (AMPERES)	4000
AMPERE TURNS	5.76×10^6
CENTRAL FIELD (KILOGAUSS)	20
MAXIMUM FIELD (KILOGAUSS)	27
DISTANCE BETWEEN SPLIT PAIRS (INCHES)	13.25
COIL INSIDE DIAMETER (INCHES)	94.75
COIL OUTSIDE DIAMETER (INCHES)	108.75
CONDUCTOR LENGTH PER LAYER (FEET)	1250
TOTAL CONDUCTOR LENGTH (FEET)	40,000
WEIGHT PER PANCAKE (POUNDS)	2,000
TOTAL COIL WEIGHT (POUNDS)	32,000

FIGURE I



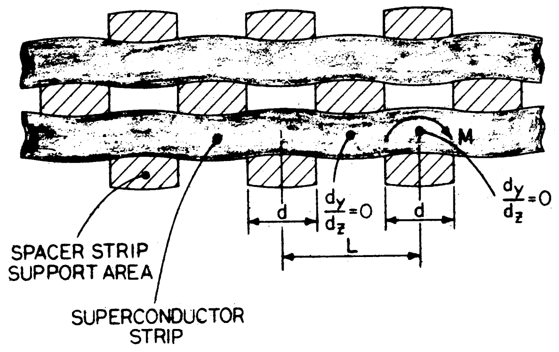
7' TEST FACILITY
VERTICAL CROSS SECTION
FIGURE No. 2



7' TEST FACILITY

MAGNET COIL COMPONENTS

FIGURE No. 3



$$M_{max}=\frac{fL}{8}(L-d)$$

Where

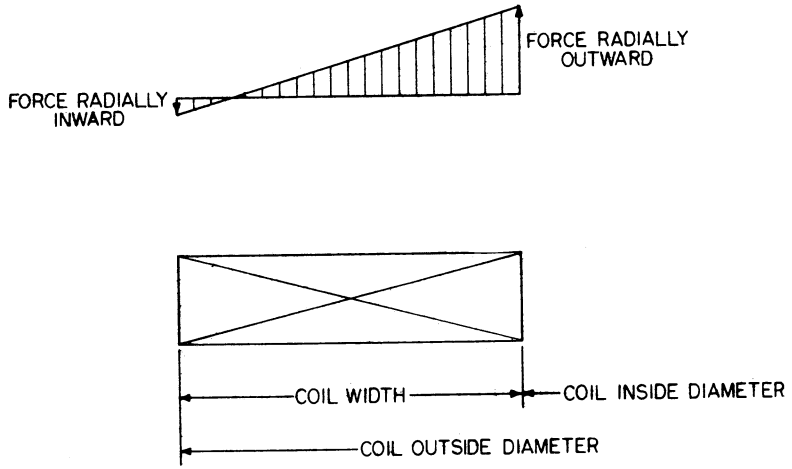
M_{max} = MAXIMUM BENDING MOMENT
f = UNIT LOAD ON CONDUCTOR
d = SPACER SUPPORT WIDTH
L = CENTERLINE DISTANCE BETWEEN SUPPORTS

If $d=\frac{L}{2}$

Then

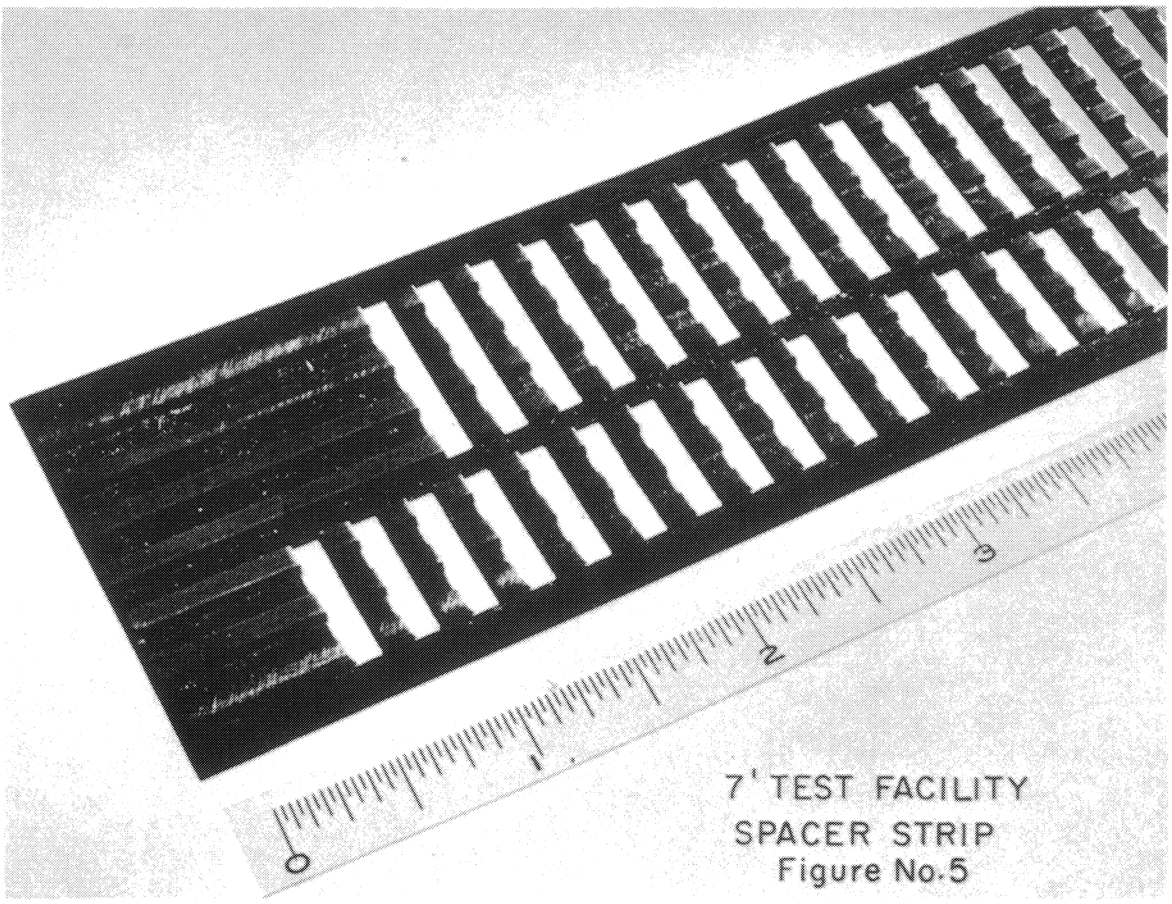
$$M_{max}=\frac{fL^2}{16}$$

FORCE TRANSFER THROUGH SPACER STRIP

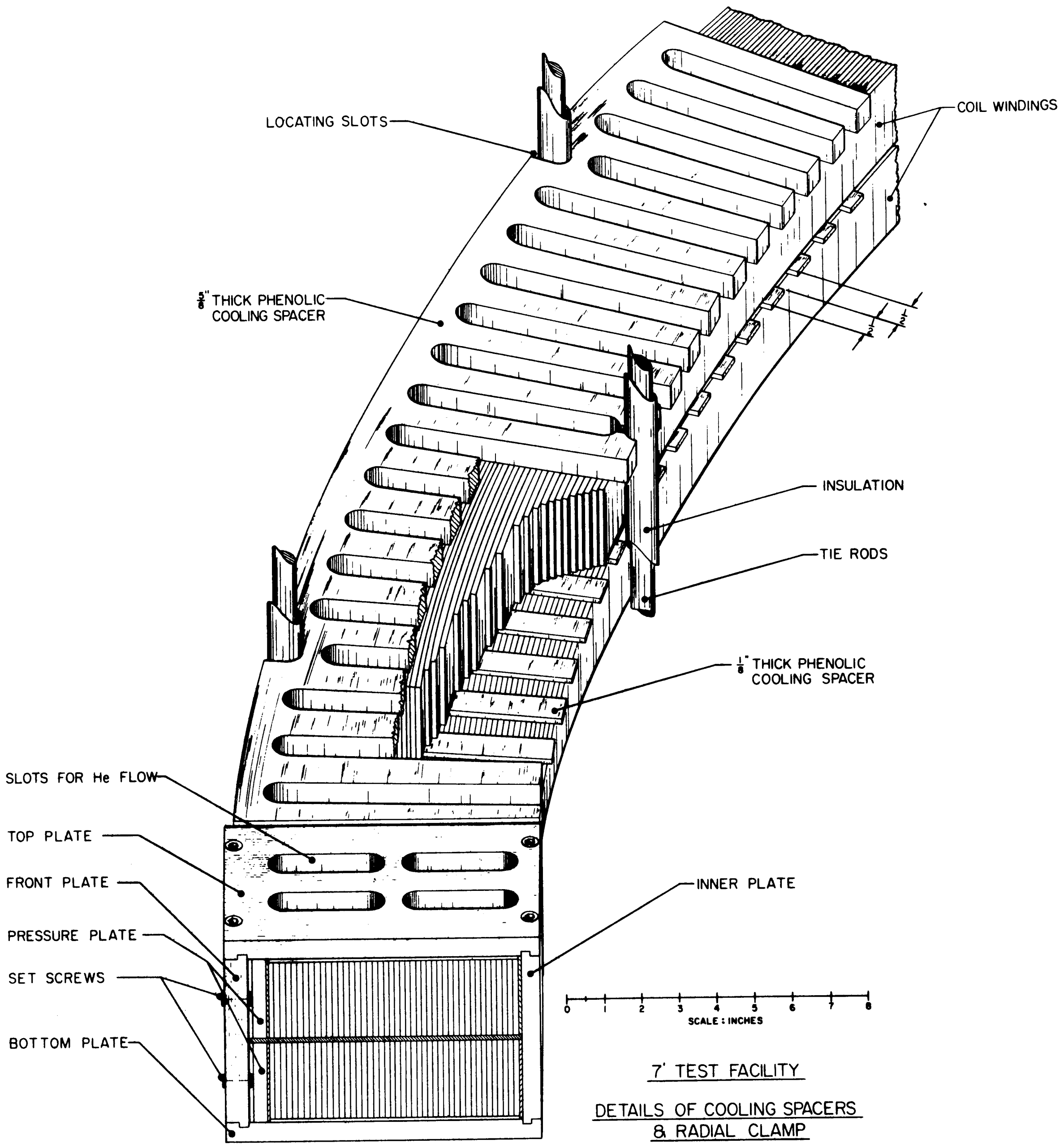


VARIATION OF RADIAL FORCE ACROSS COIL WIDTH

FIGURE 4
7′ TEST FACILITY
FORCE DISTRIBUTION



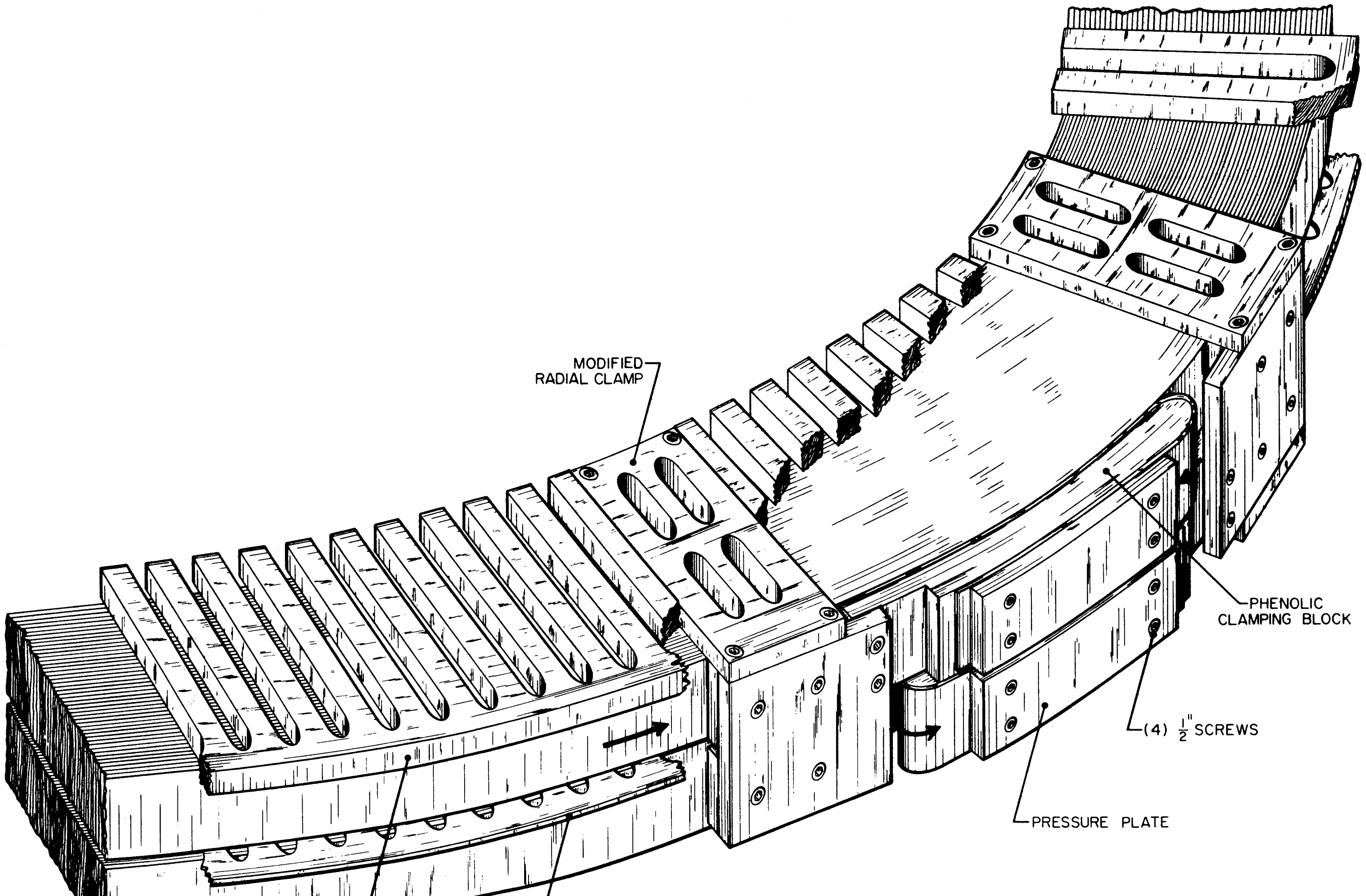
7' TEST FACILITY
SPACER STRIP
Figure No.5



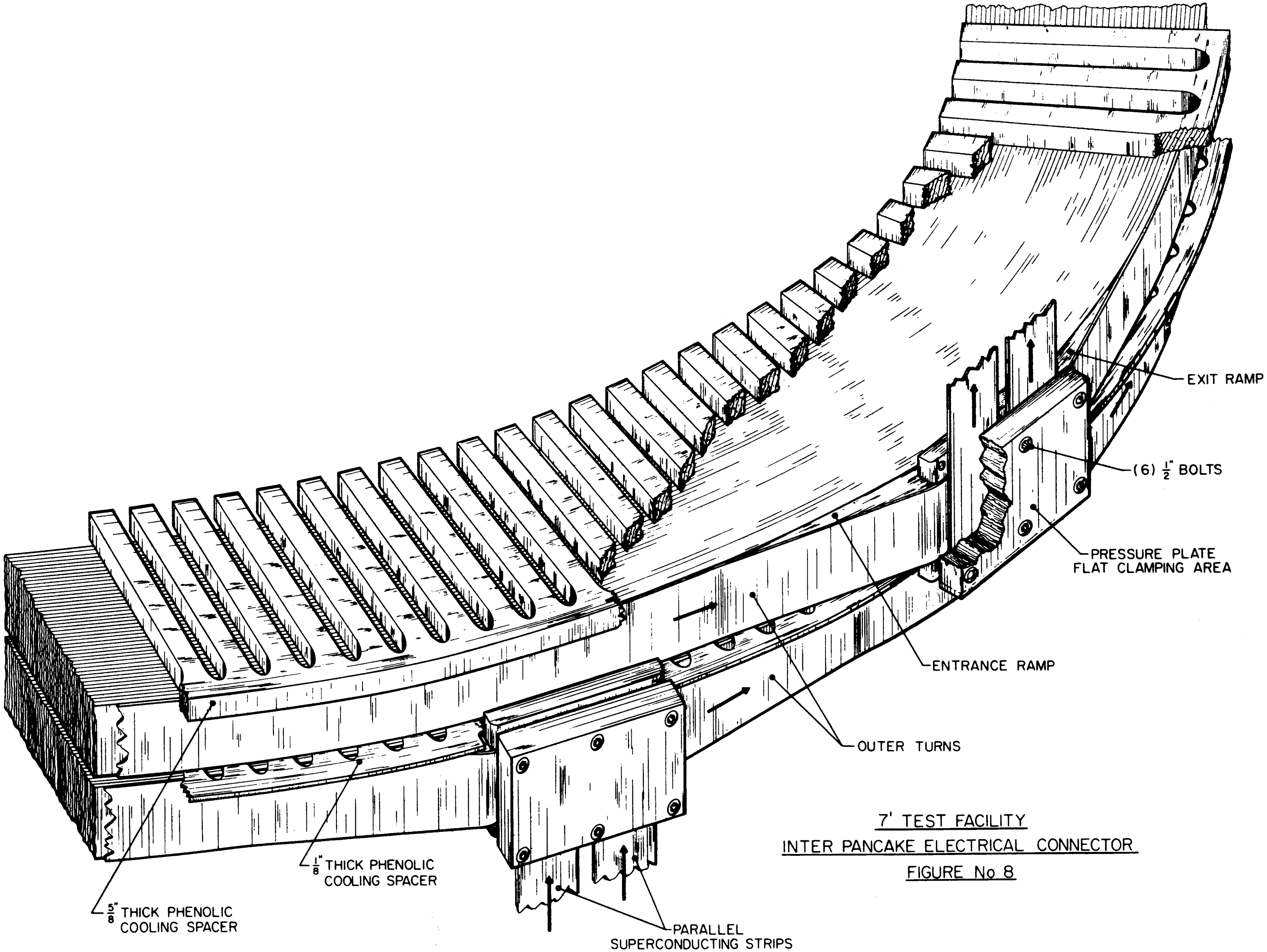
7' TEST FACILITY

DETAILS OF COOLING SPACERS
& RADIAL CLAMP

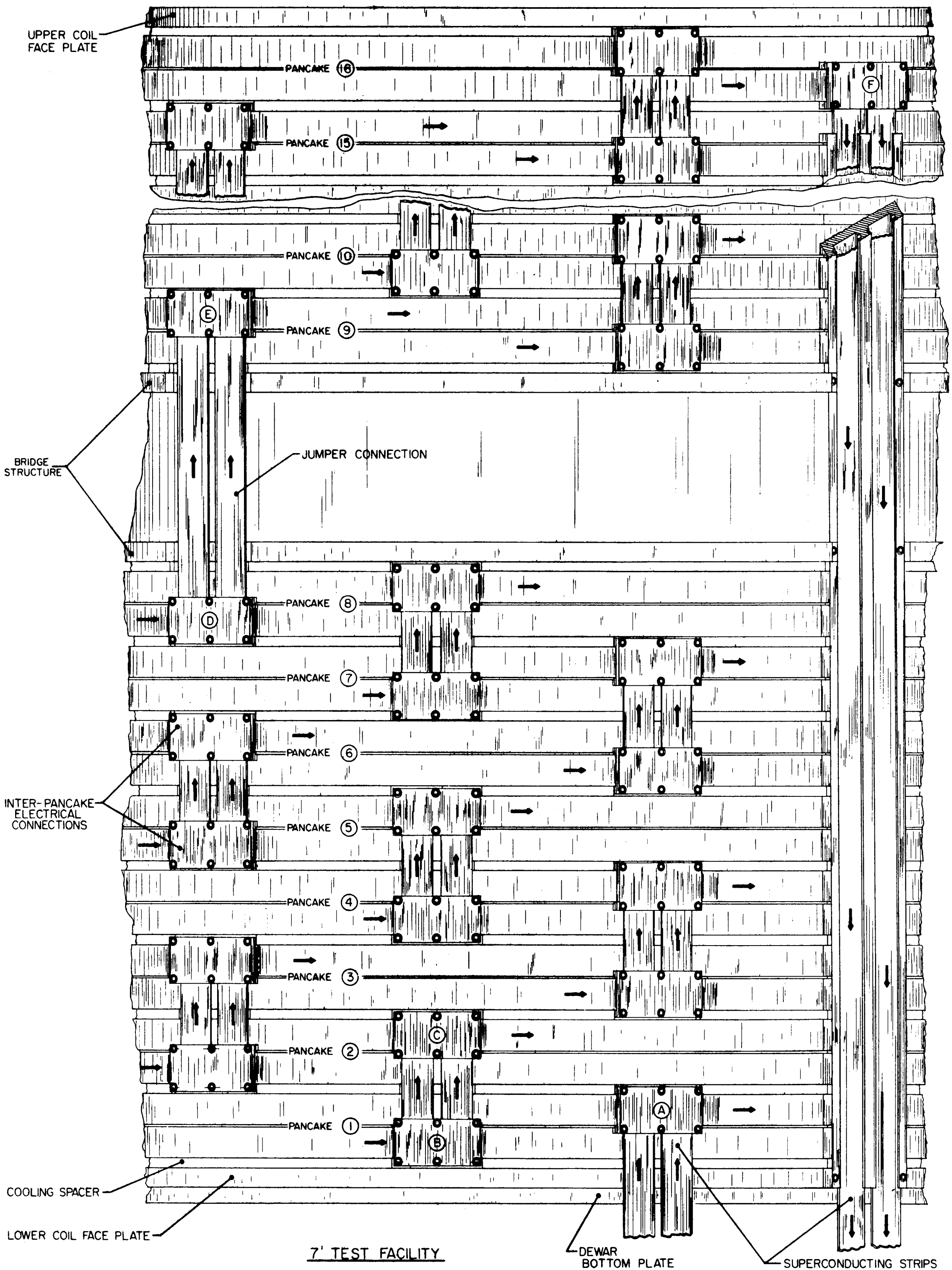
FIGURE No. 6



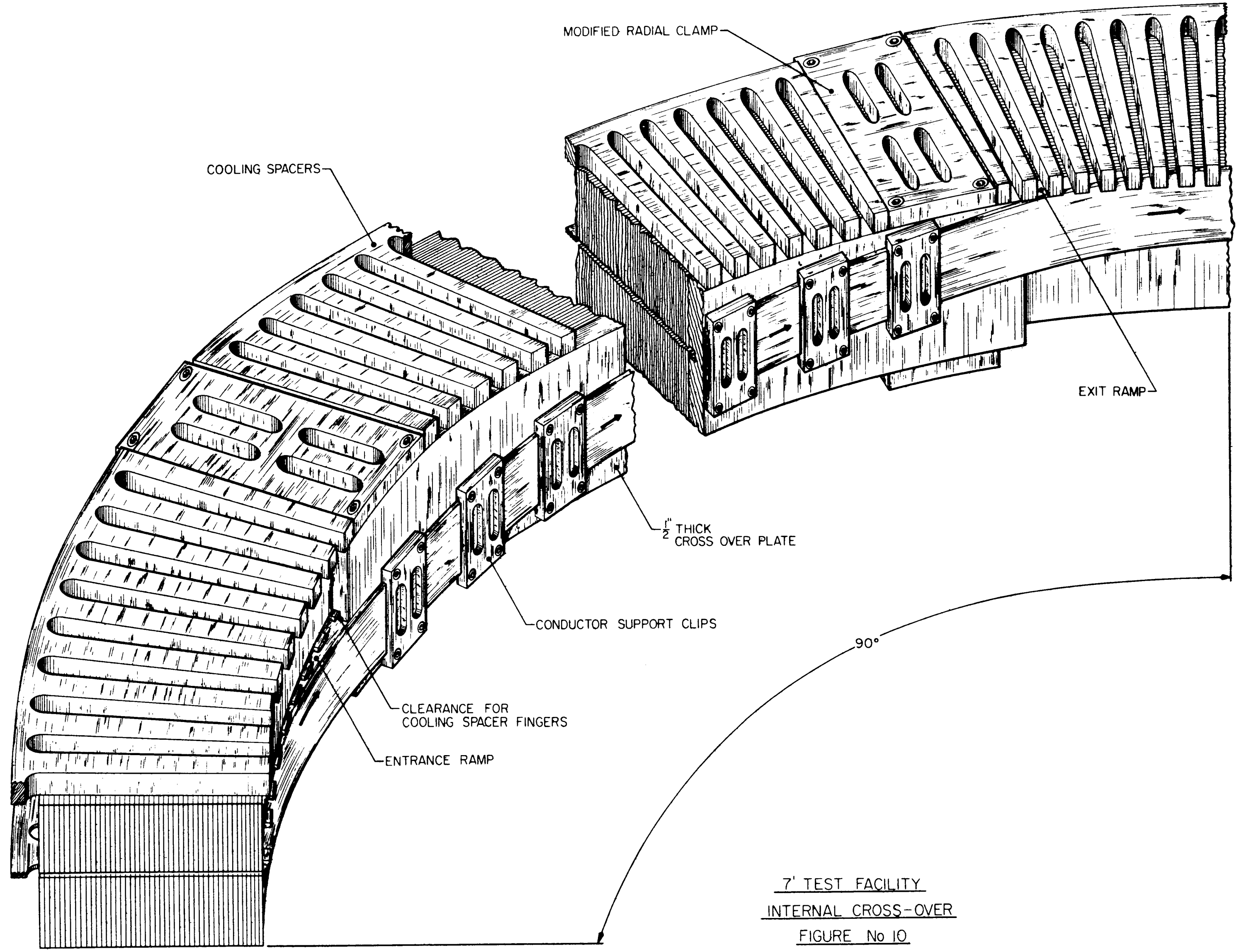
7' TEST FACILITY
END CLAMP ASSEMBLY
FIGURE No. 7



7' TEST FACILITY
INTER PANCAKE ELECTRICAL CONNECTOR
FIGURE No 8



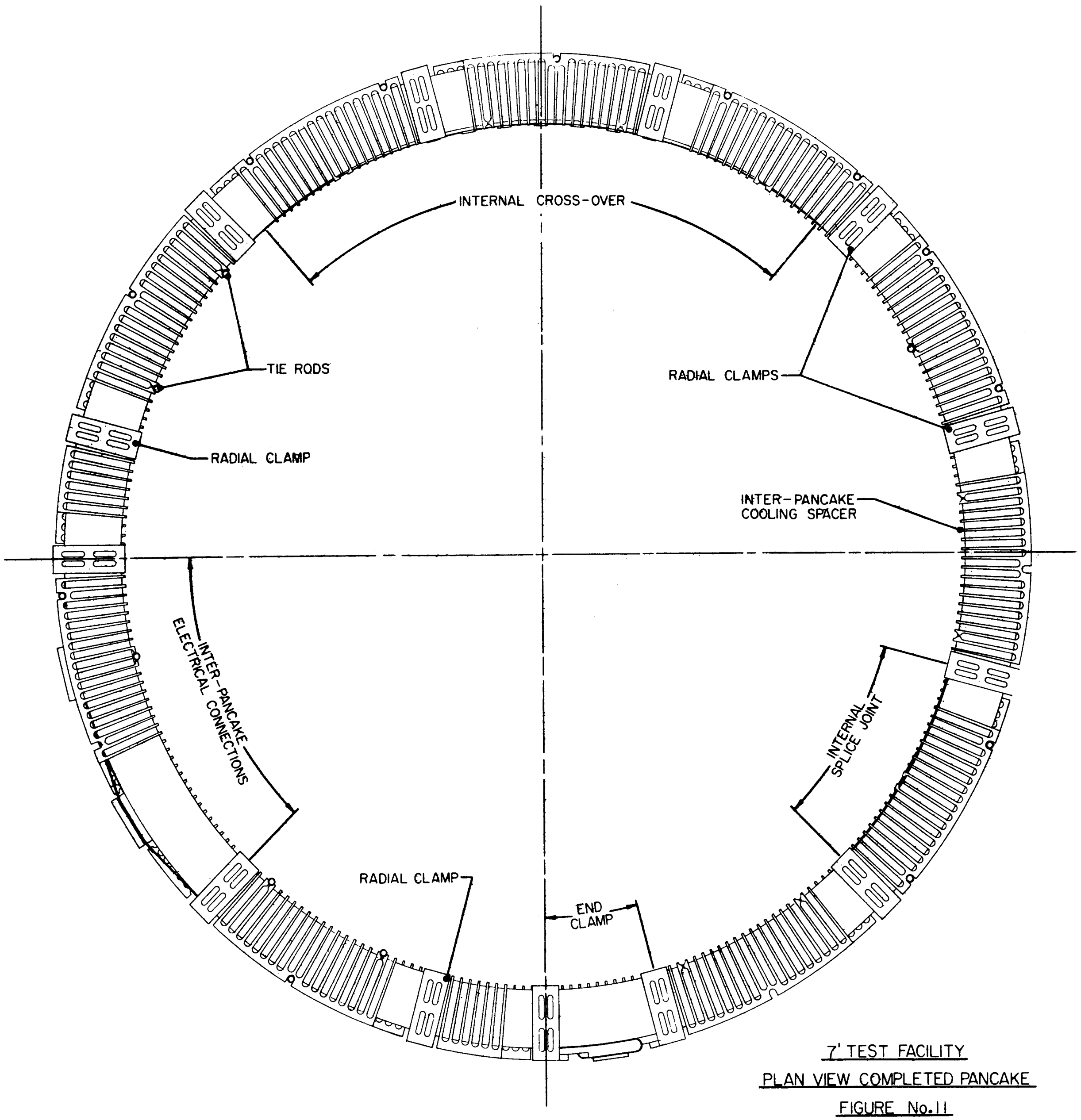
7' TEST FACILITY
INTER-PANCAKE ELECTICAL ASS'Y
FIGURE No. 9



7' TEST FACILITY

INTERNAL CROSS-OVER

FIGURE No 10



7' TEST FACILITY
PLAN VIEW COMPLETED PANCAKE
FIGURE No.11