

CONF-830971--4

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Manufacturing Development Of The Westinghouse
Nb₃Sn Coil For The Large Coil Test Program

DE84 000717

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ABSTRACT - The Westinghouse Nb₃Sn Magnet for the Oak Ridge National Laboratory Large Coil Program (LCP) is currently well into the manufacturing phase. This paper identifies the manufacturing processes and development tasks for this unique, advanced coil. (1)

COIL DESIGN

The goal of the Westinghouse Large Coil is to demonstrate the potential of Nb₃Sn for large scale applications to either high field or high current density magnets. The unique modular, distributed structure concept incorporated in this coil provides many manufacturing and design advantages. The distributed structure prevents the accumulation of forces which would lead to high conductor strain and insulation stresses. It also provides better distribution of structure and conductor over the cross-section of the coil and delivers a higher effective field on plasma when applied to a Tokamak Toroidal configuration. The modular construction permits parallel winding operations and eliminates the need for heavy structural welds.

The coil utilizes a cabled Nb₃Sn conductor which has been encased in a stainless steel jacket. The conductor is insulated with Kapton tape and then formed and inserted into spiral slots machined into the 24 aluminum plates. The 48 conductor lengths are formed, four at a time, with each set of four sufficiently long to wind 2 plates (see figure 1). The coil is wound in 2 halves which will be assembled together with close fitting stainless steel studs to form a consolidated structure. The conductor is cooled by flowing liquid helium into the cable through headers which have been formed around the conductor joints between the wound plate pairs. After the coil halves have been assembled, the headers are connected to the inlet and outlet manifolds. During the conceptual and final design of the coil, engineers experienced in manufacturing and manufacturing planning were an integral part of the design team. Manufacturing processes which were extrapolatable from normal large electrical equipment manufacture were incorporated into the design. For all key process steps, plans were established and implemented to build prototypes, conduct qualification trials and to train and qualify personnel.

Table 1 lists some of the more important prototypical tasks. In every case, the completion of these tasks resulted in ~ modifying the process we were

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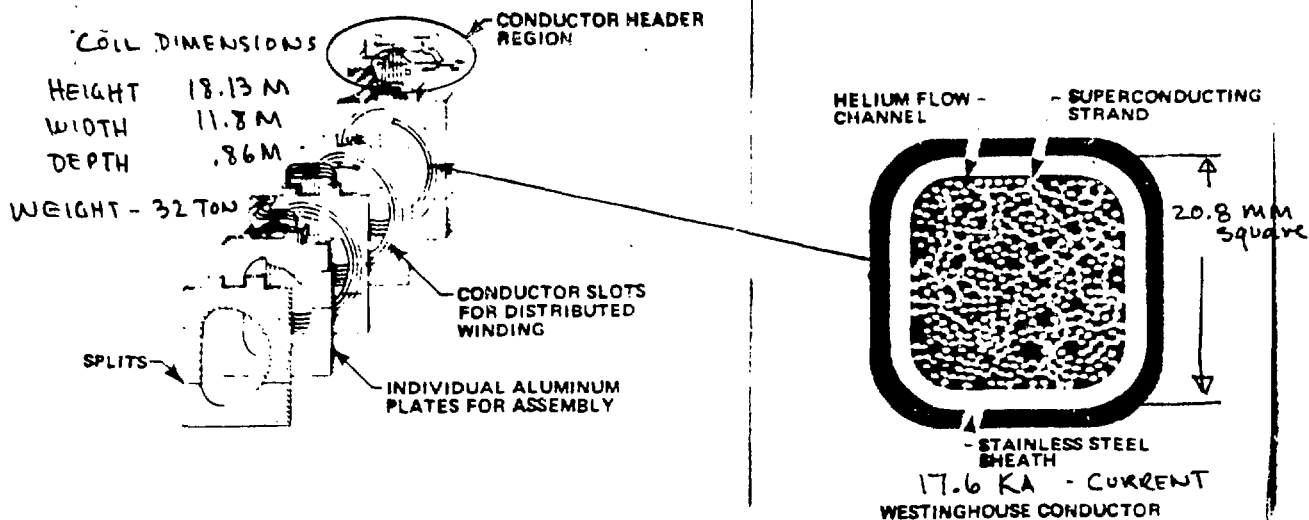


FIGURE 1. WESTINGHOUSE COIL CONSTRUCTION

simulating prior to actual commitment to manufacture. Adoption of this philosophy was an invaluable aid to assuring the quality of the coil.

TABLE 1 MANUFACTURING DEVELOPMENT TASKS

● HEADER AND MANIFOLD WELDING	● WINDING PROCESS TRIALS
● WELDER QUALIFICATION	● INSULATION WINDING TRIALS
● CONDUCTOR BUTT WELDING	● COATED INSULATION CRYOGENIC TRIALS
● CONDUCTOR BRAZING	● CROSSOVER BENDING TRIALS
● CONDUCTOR JOINT PULL TESTS	● STRUCTURAL PLATE MACHINING
● X-RAY SENSITIVITY ON BUTT WELDS	● CONDUCTOR STRAIGHTENING
● BUTT WELDER CONSISTANCY	● CONDUCTOR LEAK TESTING
● WINDING TOOL TRIALS (SPRINGBACK)	

MANUFACTURING SEQUENCE

The layout of the manufacturing aisle is shown in figure 2. The conductor is received from Oxford-Airco reeled on 2.5M O.D. flat spiraled reels. The first step is to straighten the 110M lengths of conductor in a conventional 8 roll straightener (see figure 3). The conductor is then cleaned and any sharp features which could damage the insulation are removed. Although the conductor is leak tested by the supplier at liquid Nitrogen temperature in its reeled condition, it is rechecked after straightening to determine if any leaks have developed during heat treating or straightening. This is accomplished by enclosing a 6M length of conductor in a moveable vacuum chamber at room temperature while helium gas is introduced at 30 atmospheres (see figure 4). This system detects leak rates as low as 5×10^{-8} SCC/sec. To date the reliability of the welds has been 100%, and no leaks have developed subsequent to manufacture. After the leak check the conductors are taped with 7 half lapped layers of Kapton to provide the turn to turn and ground wall insulation (see figure 5).

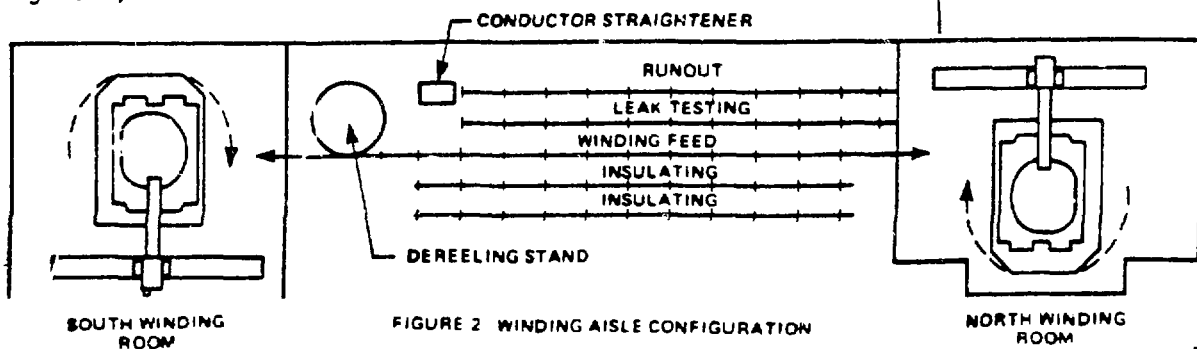


FIGURE 2 WINDING AISLE CONFIGURATION

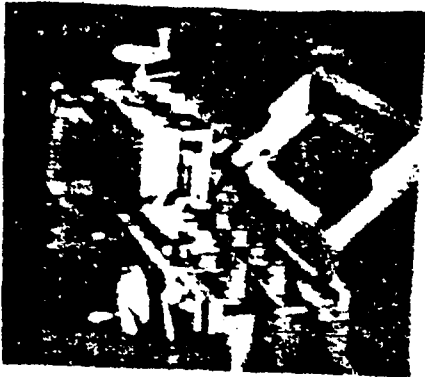


FIG. 3 CONDUCTOR STRAIGHTENING



FIG. 4 LEAK TEST



FIG. 5 TAPING

The winding of the conductor is accomplished by forming the conductors to the exact contour of the grooves which have been milled into the aluminum plates (see figure 6). Pre-manufacturing trials were held to establish the tolerances and finishes attainable. These trials also proved that warpage due to material removal would not be a problem and plate thickness could be held very accurately. The aluminum plates are then fastened to a rotating table. The center of the table has provisions for the mounting of the forming tools. The conductor is then formed by clamping the insulated conductor to the former and rotating the table while applying a force to the free, extended end of the conductor through a hydraulically activated roller (see figures 7 and 8).

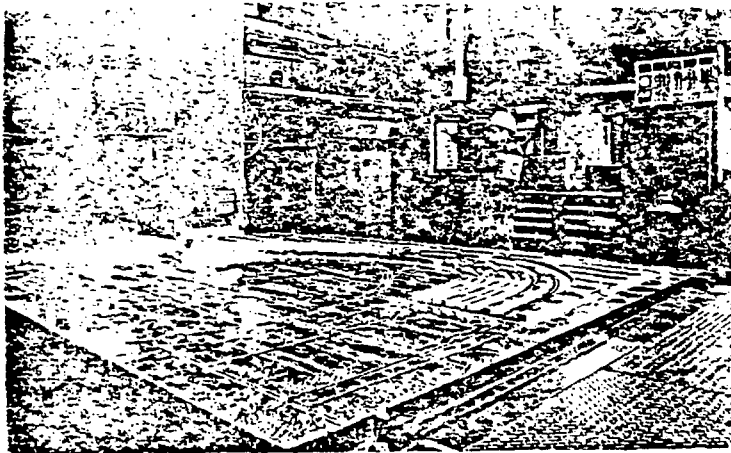


FIGURE 6 PLATE MACHINING

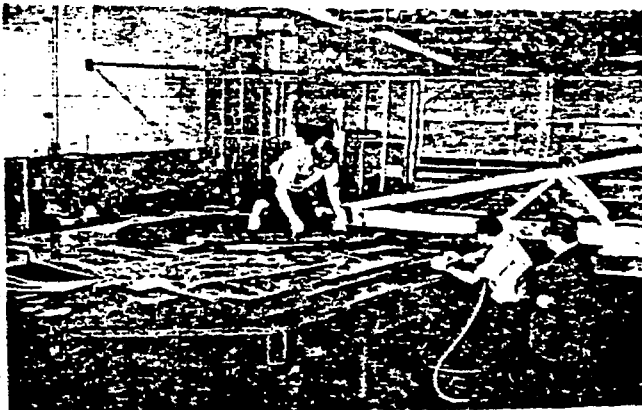


FIGURE 7 WINDING TABLE

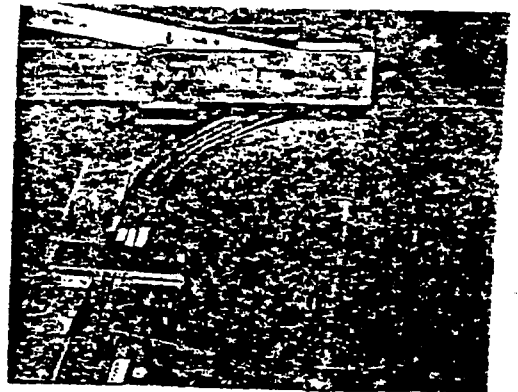


FIGURE 8 CONDUCTOR FORMING

The winding trails, using dummy conductors proved extremely worthwhile. We established the need for a mylar tape slip layer between turns, and decided to adopt more turns of thicker Kapton tape than originally planned, for additional protection against winding damage. Valuable experience was also gained regarding the effect of conductor springback on conductor forming. Empirical data was generated to establish the tooling shapes which would provide congruity of the conductor and the structural slot configuration. In addition the proper location of tool placement was established to assure the proper start and finish of each radius.

After winding each pair of plates, the four conductors are joined to the conductors for the next pair of plates. Terminals have been formed on each end during conductor manufacture by swaging copper tubes over the cable. These terminals are joined by an electrical resistance butt weld. After X-ray examination of the butt weld a splice collar is brazed over the joint for added strength (see figure 9). After these joints have been made, they are enclosed in a stainless steel header box which will be connected to the helium manifold. An extensive program of welding technique development, joint testing and welder qualification has given us great confidence in the quality of all these joints.

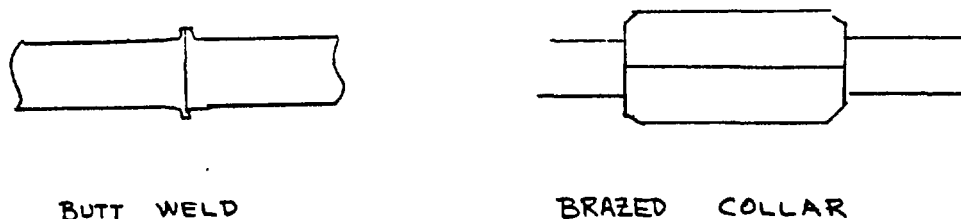


FIGURE 9 CONDUCTOR JOINT

After all of the plates of both coil halves have been wound, they will be assembled together, the stud holes will be line reamed and the studs will be assembled and torqued. At this point the manifold system will be assembled, welded and leak checked by pressurizing with helium while the coil is situated in a vacuum box.

CONCLUSION

During the development and implementation of this manufacturing process much was learned about the manufacturing techniques required to build a large advanced Nb_3Sn forced flow cooled magnet. To date, we have encountered no problems which would prevent scaling this concept to the larger sizes presently being conceptualized for Tokamak reactors. We have every reason to believe we will be able to capitalize on the advantages of this concept to provide compact, high current density coils.

References

- (1) C. Heyne, D. Hackworth, S. Singh, J. Young, Proc. of the 8th Symp. on Eng. Probl. of Fusion Eng., San Francisco, Calif. Nov. 1979 p.1148-53.

This work was sponsored by Department of Energy and Oak Ridge National Laboratory under Union Carbide Corporation No. 22X31747C.

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