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ABSTRACT

A liquid-neon-cooled magnet has been designed to product 30 teslas in steady operation. Its feasibility was established by a previously reported parametric study. To ensure the correctness of the heat transfer relationships used, supercritical neon heat transfer tests were made. Other tests made before the final design included tests on the effect of the magnetic field on pump motors; tensile-shear tests on the cryogenic adhesives; and simulated flow studies for the coolant.

The magnet will be made of two pairs of coils, cooled by forced convection of supercritical neon. Heat from the supercritical neon will be rejected through heat exchangers which are made of roll-bonded copper panels and are submerged in a pool of saturated liquid neon.

A partial mock-up coil was wound to identify the tooling required to wind the magnet. This was followed by winding a prototype pair of coils. The prototype winding established procedures for fabricating the final magnet and revealed slight changes needed in the final design.

INTRODUCTION

As part of its research program on advanced propulsion and power concepts, Lewis Research Center has designed and constructed a number of high field magnets since 1960. These magnets have been made with water-cooled copper, liquid-neon-cooled aluminum and super-conductive

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windings. The maximum field of 20 tesla was obtained in an 11 cm bore magnet, cooled by free convection of liquid neon. A summary of much of this research and a projection of possible future work was presented in reference 1, which also discussed a concept for a steady-state 30-tesla magnet cooled by LNe. An analysis (ref. 2) showed that magnets with non-uniform structural support should be capable of fields in the 30 tesla range, and a design study of such a magnet was made (ref. 3). That study showed that substantial increases in current density beyond that in the existing cryomagnets would result if the amount of stress-bearing structure is varied according to local requirements in the coils and if forced convection cooling is used. These changes allow the average conductor packing fraction to be nearly doubled and the current density in the conductor to be more than doubled. The average current density can thus be increased by about a factor of four.

Some of the more important design values resulting from the parametric study (ref. 3) are shown in Table I. Although the magnet is designed for 32.7 teslas we do not intent to operate above 30 teslas. The parametric study identified some problem areas that required special tests before the final detailed design was made. This paper discusses some of these tests, details the resulting design, and describes the winding of a prototype pair of coils.

COOLING SYSTEM

The conceptual design of the magnet cooling system is shown in figure 1(a). The LNe is pumped around a closed loop at slightly above the critical pressure to prevent boiling in the magnet. There are two heat exchangers and the magnet is divided hydraulically into two halves. Heat absorbed from each half of the magnet is rejected in one of the heat exchangers to the boiling LNe bath before the coolant passes through the other magnet half. Intercooling gives a lower average magnet operating temperature than single-pass cooling. Thus the electrical resistance and power requirement of the magnet are reduced. Series rather than parallel flow was chosen in order to keep the pump and piping sizes reasonable.

Since forced convection heat transfer data were not previously available for LNe in the supercritical pressure range, tests were run to provide the required heat transfer relationship (ref. 4). It was found that the experimental data agreed with a Dittus-Boelter type correlation in the form of (Nusselt number)/(Prandtl number)$^{0.4}$ as a function of Reynolds number. Calculations based on the results of reference 4 show that two adjacent blocked channels would not cause burnout and that the imposed heat flux limit of 11 W/cm^2 in the parametric study is conservative.

The cutaway shown in figure 1(b) was made from design drawings. However, the pump will be placed downward into a suction pot under the crystat to improve inlet suction and to reduce the effect of the magnet's fringe field on the motor. Tests to determine the effect of pump motor orientation and location with respect to a magnet were made using a 7.0 tesla magnet. It was found that if the motor axis was parallel to the local field, the motor could operate without significant increase in operating current in fields of a few tenths of a tesla. For the magnet design discussed in this paper, the field calculation in reference 3 shows there is little effect of magnetic field on a pump motor if the pump is more than 1.2 meters from the centroid of the magnet. For the present design, a pressurizing pump and a circulating pump are needed. The circulating pump will be mounted vertically in its own cryo-vessel located near the magnet cryostat. It is important to locate the pumps close to the magnet to reduce pressure drop. Locating the pump motors in a cryo-vessel along with the pumps reduces the possibility of LNe loss.

The heat exchangers are made of roll-bonded copper panels having pressure-expanded tubulation. The panels will be arranged radially within the cryostat (fig. 1(b)), for other configurations strong induced forces due to eddy currents would result from a rapid change in the field of the magnet. A total of 174 panels of two different widths provide $6x10^5$ cm^2 of internal surface area at a total pressure drop of about 3 N/cm^2. The inlet and outlet headers are made of stainless steel. Copper tubing connects the headers to the panels. The headers will be welded to the pumps and magnet pressure vessel after installation.

MAGNET DESIGN

Figure 2 shows an expanded view of the magnet, its pressure vessel, and details of the hub region. Each turn in a coil includes insulation, stainless steel support structure, aluminum conductor, a slotted stainless steel ribbon that forms the cooling channels with edge rails attached and adhesive (fig. 2 inset). The insulation (0.015 cm thick) is bonded to one side of the stainless steel structure, and the aluminum conductor is bonded to the other side. The cooling channel ribbon is 70 percent open, and is bonded to the structure via the edge rails. Since the edge rails are the same thickness as the conductor, the lands of the cooling channel ribbon hold the conductor tightly in place after winding. This is important for the adhesive bond strength, since a cure time of 24 hours is required.

The alloy for the structure ribbon was changed from Inconel 718 (considered in the parametric study reported in ref. 3) to 310 stainless steel in the final design because of fabrication and cost advantages. Cold work of 40 percent to 75 percent is necessary to give the 310 stainless the required structural properties at liquid neon temperature.

An important aspect of the study reported in reference 3 and in fact the controlling factor in the magnet design is the variation in thickness of the structural member as a function of the local strength requirement. Figure 3 shows how the calculated thickness of the support structure varies to match local coil requirements. The first 36 turns are self-supporting. Then following a rapid but smooth reduction in thickness of the structural member, force is passed between turns. For simplicity all four coils are made to withstand the forces exerted on the inboard coils. The structural ribbon was cold rolled in a programmed fashion on a "precision" rolling mill to achieve the required variation in thickness. Thickness of the first turn is 0.7 mm, the last turn 0.12 mm and the thickness turn is number 28 at 1.26 mm. Excess thickness of any turn is less than about 0.003 cm. Ductility and tensile tests were made on samples of rolled material to verify attainment of the properties that are equal to or better than those of 718 Inconel. These tests were done at room temperature and liquid nitrogen temperature. The tensile stress where the steel is thickest and has the least cold work due to rolling, will be 725 MN/m^2, which is 60 percent of yield. In most of the other turns the steel will operate at about the same stress. But at 30 teslas central field it will be further from yield because the thinner steel has more cold work and because the edge rails and conductor carry a larger proportion of the load. At the hub, for example, the steel will operate at only 37 percent of yield. In the outer turns the stress is even lower.

The conductor is made of 99.999 percent pure aluminum. This conductor was made with some cold work to increase the tensile strength. The room temperature value was the minimum deemed necessary in the reference 3 study. The aluminum will operate at yield in most of the magnet.

The adhesive was selected from among several candidates which have good room temperature properties by testing the best six at cryogenic temperatures. The criterion for selection was lap shear tensile strength. The polyimide Pliobond 4001/4002 in the ratio of 25 parts 4001 to one part 4002 gave the best results and was selected for use. Its lap shear tensile strength was 39.9 MN/m^2 in liquid nitrogen and 39.6 MN/m^2 in liquid hydrogen and it has been used in other cryomagnets (ref. 1). It dries rapidly at room temperature and can be easily reactivated within 2 hours by heating to about 370 K. Both of these characteristics were advantageous in winding the coil.

Electrical insulation between magnet coils must be able to withstand the very high axial compressive loading and yet not significantly restrict coolant flow. These requirements are met with a system of radial insulating stringers. Because the surface of a coil is not smooth, and the materials in coil have various compressive properties, tests to determine the best stringer design were made on simulated coil surfaces at LN_2 temperature. The selected glass reinforced insulation is NEMA Grade G-10. The compressive test results and the expected axial compressive forces calculated from the radial magnetic field from reference 3 were used to determine, as a fraction of a turn, the required number of stringers, which is presented in figure 4. Greater strength at liquid neon temperature will provide an additional safety margin.

PRESSURE VESSEL

The magnet pressure vessel is designed to accommodate the 2.78 m^3/min neon flow rate at a pressure of 2.8 MN/m^2 (fig. 2). To assure uniform distribution of the neon flow through the magnet, flow tests using water in a half scale mock-up of the magnet and pressure vessel were made. These tests led to a design of a flow distribution chamber that would give uniform neon flow through the coils.

Each half of the pressure vessel has a metal plate at the centerplane to isolate the neon flow through each pair of coils. To insure electrical isolation of the coils from the vessel, each metal plate is insulated from its hub, and the hub is insulated from the pressure vessel at each end of the magnet (fig. 2). Flow around the magnet coils is prevented by a ring of insulating material and an O-ring between each coil and the pressure vessel.

FABRICATION METHODS

A partial mock-up of one coil was made in order to expose winding problems and to identify tooling requirements. Fabrication of a prototype pair of coils provided the rest of the information required to wind the final magnet coils.

The four coils in the magnet will be wound in pairs; coils in a pair will be wound on a common hub. The leads will be connected to the periphery of the coils, and to keep the current sense the same, one coil in each pair must be wound clockwise and the other counterclockwise. A high purity aluminum conductor strip connects the two coils at the hub (fig. 2 inset). The coils and the connecting strip will be insulated from the hub; consequently, to avoid damage to the insulation, the conductor for both coils must be welded to the connecting strip before winding begins. The conductor for the second coil must be carried on the winding turntable while the first coil is wound (fig. 5).

Figure 5 shows the various components being wound into the first coil of a pair. A brake on the stainless steel, as it is fed into a coil, provides the winding tension of about 580 newtons, less than 1 percent of the operating tension on the structure. This is unlike many magnets where the conductor serves as the structure and has a tensile strength much less than the structure in this magnet.

Because of the characteristics of the adhesive, the winding is done in a stepwise fashion on a turntable. A thin film of adhesive is applied to both sides of the stainless steel and one side of the conductor over a half-meter long section. The adhesive is reactivated after the section is in place on the coil by heating with hot air blowers until the outer surface of the stainless steel reaches 370 K. The last half turn is left unbonded until after the second coil is wound because the electrical lead, which must be welded to the end of the conductor, would interfere with winding the second coil.

After the first coil is wound, the radial insulating stringers are bonded to its top surface with the polyimide adhesive. The stringers are shown in place in figure 6, held by a split-ring jig.

Except for reversing the direction, the winding procedure for the second coil is the same as for the first. A partially wound second coil is shown in figure 7.

Electrical connections are welded to the conductor ends before bonding the last half turns. Then a band is placed around each coil to provide a small additional hoop force needed during operation.

SUMMARY

The objective of this program is to design and produce a 30 tesla, steady-state, liquid-neon-cooled magnet. Feasibility was first established by a parametric study. To ensure the correctness of the heat transfer relationships used, supercritical neon heat transfer tests were made. Other tests made before the final design included tests on the effect of the magnetic field on the pump motors, tensile-shear tests on cryogenic adhesives; and simulated flow studies for the coolant.

The magnet is made of two pairs of coils, cooled by forced convection of supercritical neon. Heat from the supercritical neon is rejected through heat exchangers which are made of roll-bonded copper panels and are submerged in a pool of saturated liquid neon.

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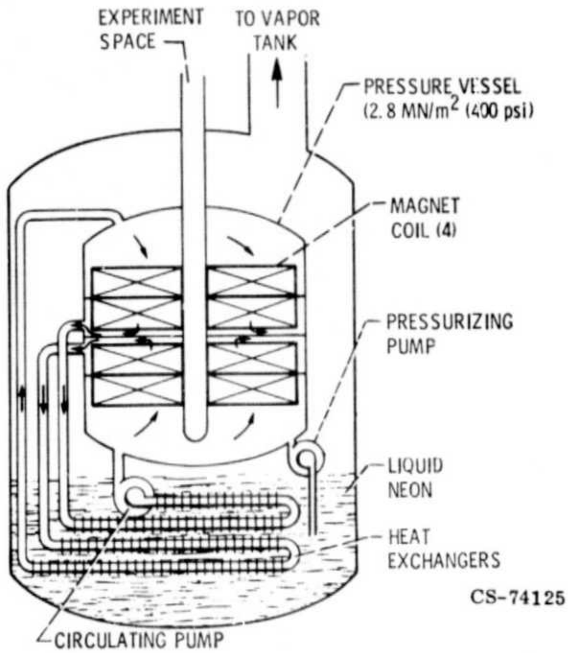
REFERENCES

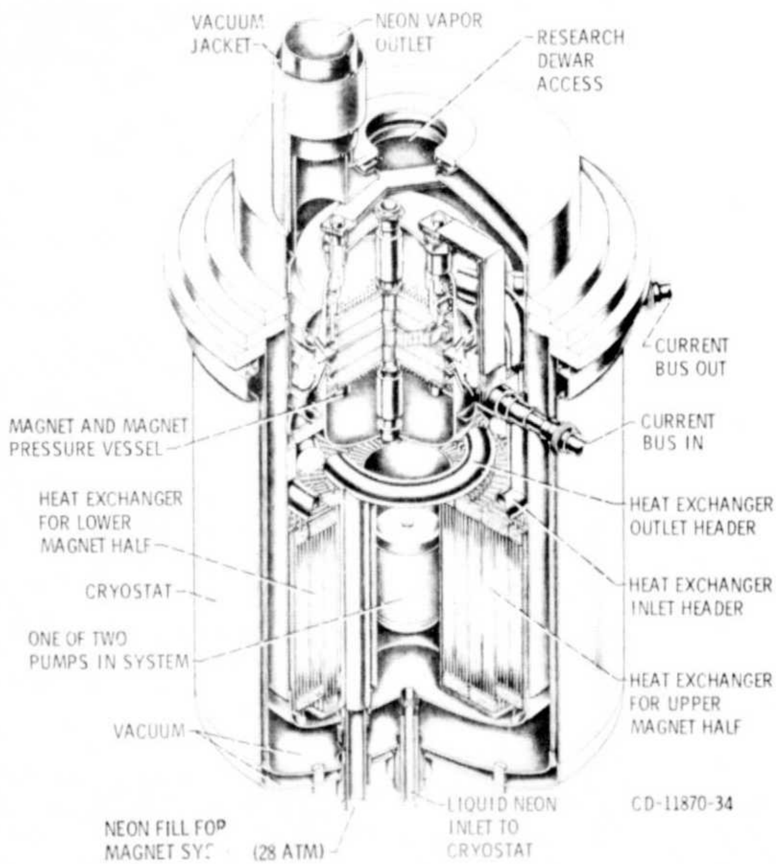
1. J. C. Laurence, et al., in NASA SP-226, p. 143 (1969).
2. G. V. Brown, in Proceedings of Symposium on Engineering Problems of Fusion Research, LA-4250, p. G7-1, Los Alamos Scientific Lab. (1969).
3. G. M. Prok, and G. V. Brown, NASA TN D-8337 (1976).
4. S. S. Papell, and R. C. Hendricks, in Advances in Cryogenic Engineering, Vol. 21, K. D. Timmerhaus and D. H. Weitzel, eds., p. 278, Plenum Press (1975).

Table I. 30 Tesla Magnet Design Parameters and Operating Conditions

Design parameters	
Magnet diameter, cm	54
Magnet clear bore, cm	6.4
Conductor width, cm	6.04
Conductor thickness, cm	0.180
Channel depth, cm	0.038
Channel width, cm	0.45
Channel spacing, cm	0.64
Distance between coils in a pair, cm	0.635
Coil separation at midplane, cm	3.05
Operating conditions for 32.7 teslas	
Conductor current, KA	40
Magnet power required, KW	855
Neon flow rate, m^3/min	2.78
Neon use rate, m^3/min	0.49
Neon operating pressure, MN/m^2	2.8
Neon inlet temperature, K	28
Neon temperature rise, K	5.0
Maximum conductor temperature, K	37



(a) Conceptual design.



(b) Cutaway.

Figure 1. - Thirty-tesla magnet system.

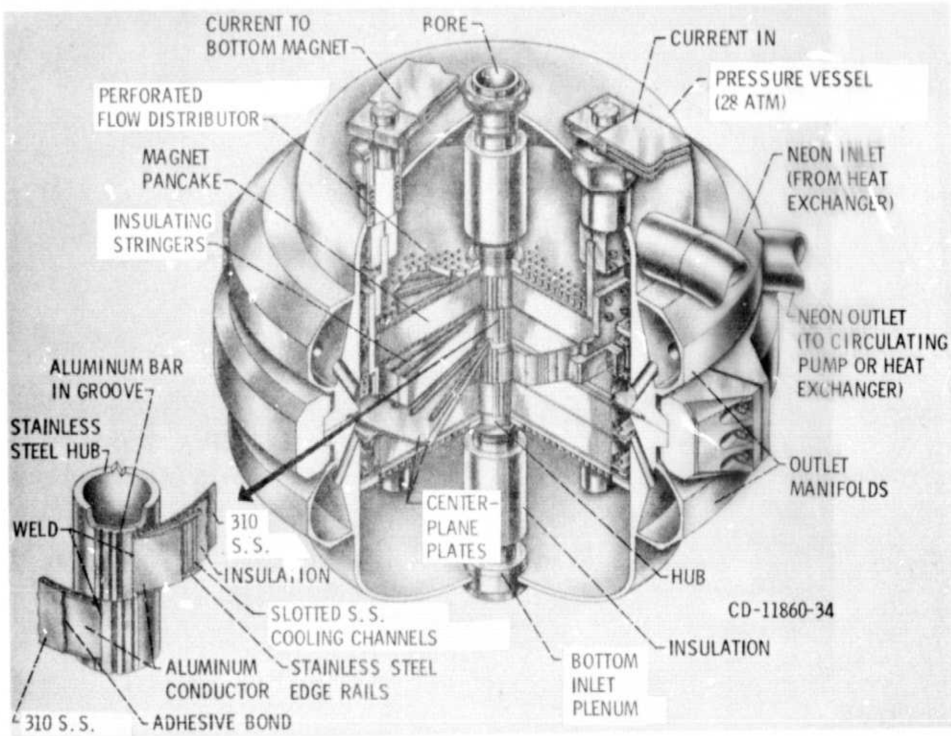


Figure 2. - Conceptual design of 30-tesla, liquid-neon-cooled magnet (entire system enclosed in cryostat).

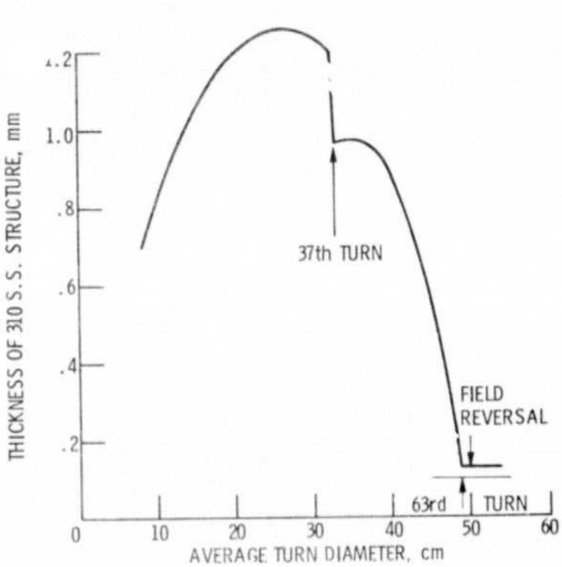


Figure 3. - Variation of structure thickness.

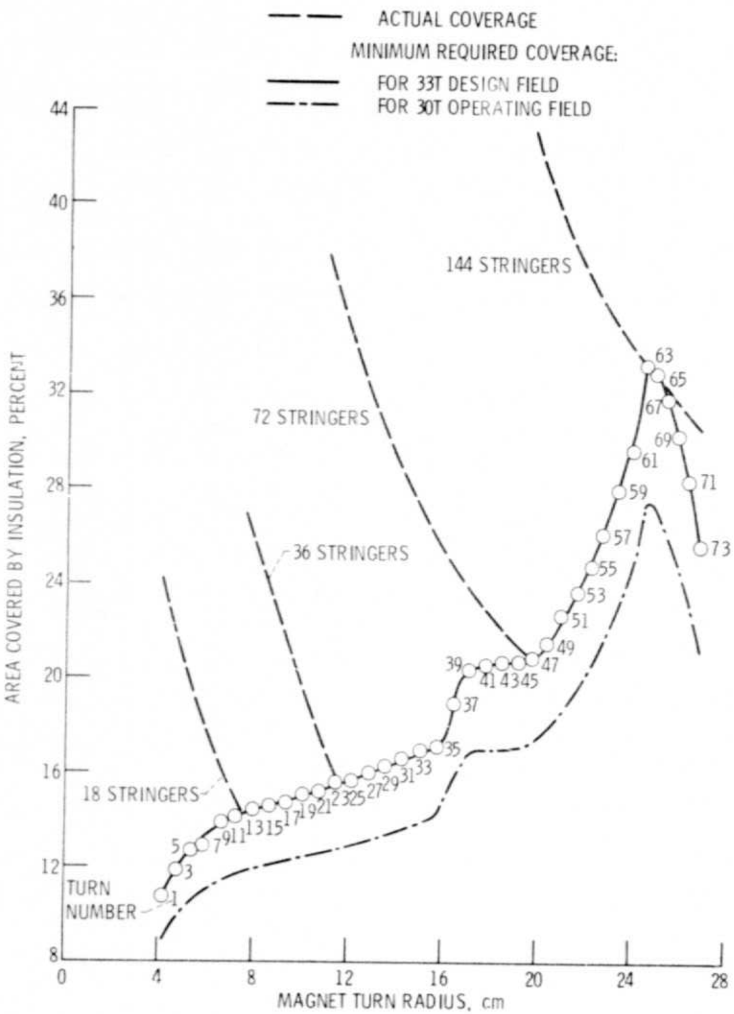


Figure 4. - Bearing area required for radial insulating stringers (0.36 cm wide) at 33 teslas and 30 teslas based on test results in LN_2 temperature.

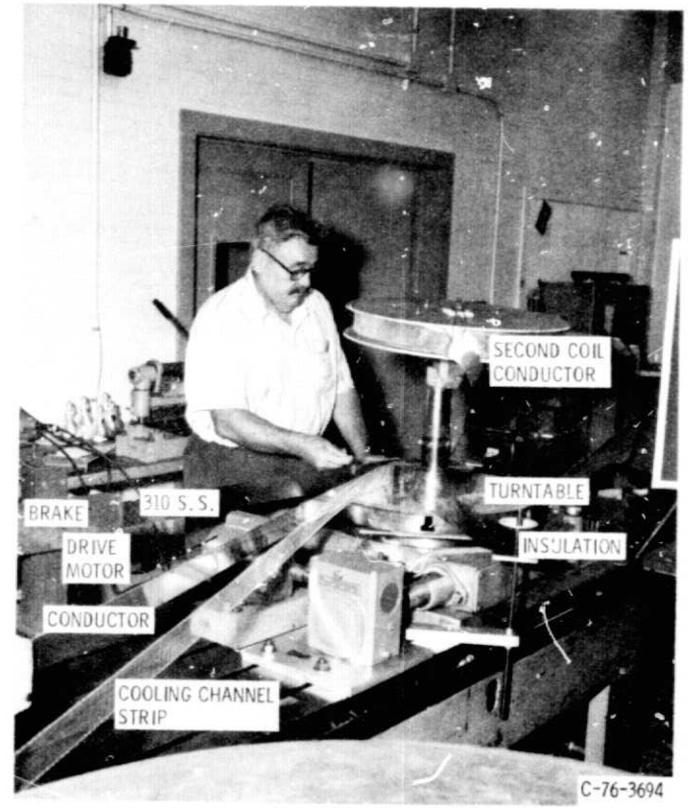


Figure 5. - Winding of first coil inboard coil).

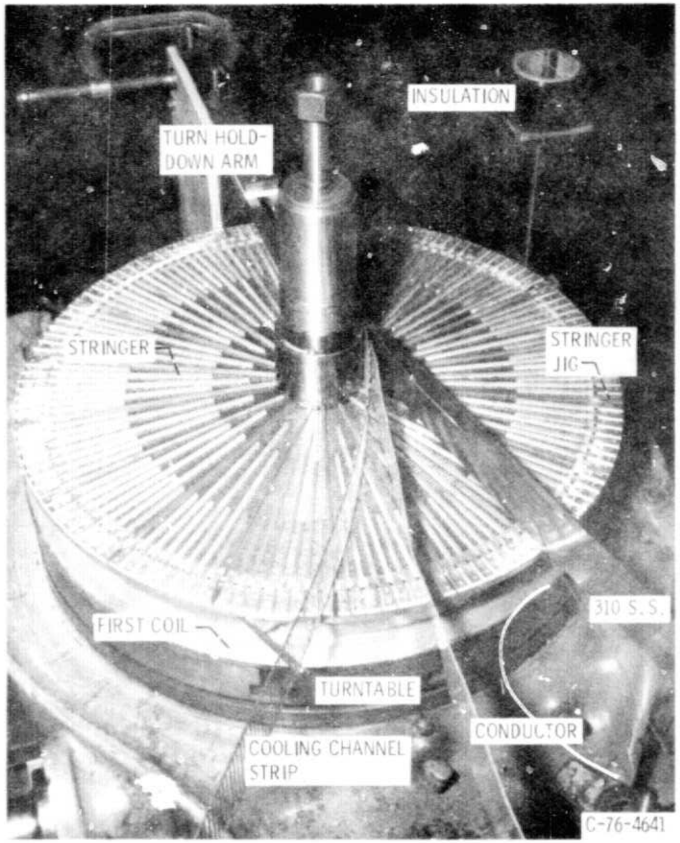


Figure 6. - Start of second coil (outboard coil) with stringers shown on first coil

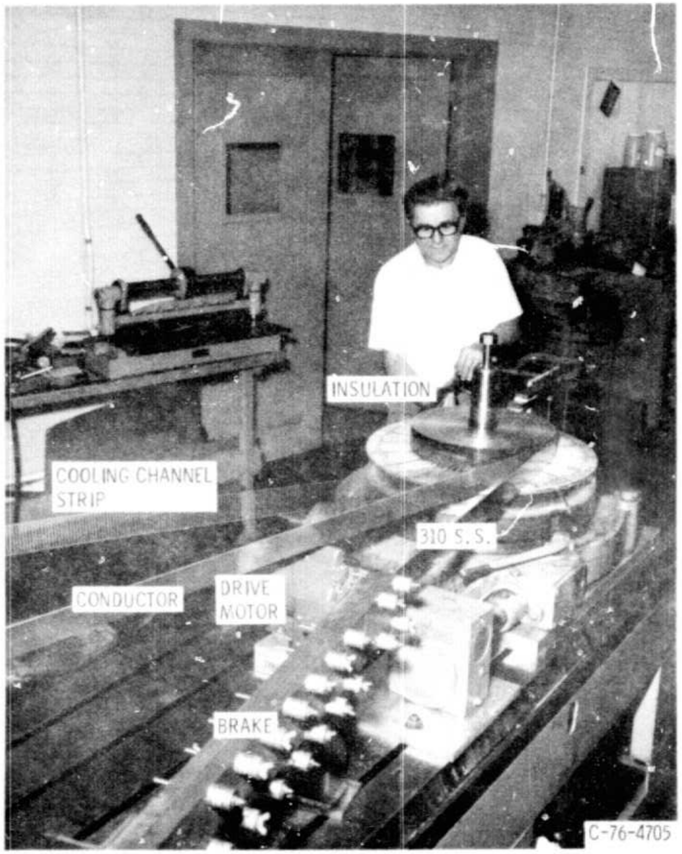


Figure 7. - Prototype coil winding with completed first coil and partially completed second coil.