N 2.2/5

STRUCTURAL DESIGN OF DEALS MAGNET

P. BEZLER, S. Y. HSIEH

Brookhaven National Laboratory, Structural Analysis Group,
Department of Nuclear Energy, Bldg. 129, Upton, L.I., New York 11973, U.S.A.

T. BALDERES, T. BROWN, J. BUNDY

Grumman Aerospace Corporation,
Bethpage, New York 11714, U.S.A.

Abstract

The DEALS magnet is a new type of superconducting magnet for large fusion reactors. Instead of winding large planar or multi-axis coils, the superconducting coils are made from several prefabricated straight conductor sections. These straight sections are easily transported to the facility site where they are interconnected via soldered joints to form a continuous coil. Subsequent removal of a defective coil is readily achieved by joint separation and straight section removal, operations which can be made without disturbing the blanket structure. Since the joints are allowed to slip, the magnet loadings, both in-plane and out-of-plane, must be supported by an extraneous support structure.

An extraneous magnet structure designed to support all the magnet loads was developed. The structure consists of two demountable structural systems designed to support the in-plane and out-of-plane loads, respectively. The in-plane loads are resisted by a cold central bucking cylinder and pin connected, plate-beam structural members following the outer periphery of each coil. The out-of-plane, torsional loads are resisted by the concerted action of the central bucking column and a continuous plate structure interconnecting all the coils. The adequacy of the structures were assessed by application of finite element analysis methods.

The design study proved the feasibility of resisting the magnetic loadings with a demountable support structure which is extraneous to the superconducting coil. The resulting magnet system, although estimated to be higher in cost than a continuous coil, incorporates a means for complete coil replacement in a time scale commensurate with conventional nuclear power plant repairs and without the dismantling of the toroidal blanket and plasma shell systems.

Work performed under the auspices of the Department of Energy"

Introduction

The toroidal field magnets in conceptual Tokamak fusion reactors are typically large planar, continuous, superconducting coils. Although these configurations are well suited to their role as current carriers and readily support toroidal field magnetic loads, they pose major fabrication and maintenance problems associated with their continuous nature. Obviously the fabrication and transportation of a relatively thin continuous coil of 10m bore poses special problems. Alternately, the removal and replacement of such a coil requires the dismantling of the potentially contaminated toroidal blanket and plasma shell systems. For these reasons a concept for a toroidal field magnet designed to circumvent these problems was developed.

The DEALS magnet [1,2,3] is a new type of superconducting magnet for large fusion reactors. Instead of winding large planar or multi-axis coils, the superconducting coils are made from several prefabricated straight conductor sections. These straight sections are easily transported to the facility site where they are interconnected via soldered joints to form a continuous coil. Subsequent removal of a defective coil is readily achieved by joint separation and straight section removal, operations which can be made without disturbing the blanket structure. Since the joints are allowed to slip, the magnet loadings, both in-plane and out-of-plane, must be supported by an extraneous support structure.

A magnet design for a TF coil with a 5m x 8m bore and a maximum field of 12T, based on the DEALS concept, was developed. Some pertinent parameters for the magnet were: coil cross section, 0.567m; Nb_3Sn superconductor cross section, 1.5 cm^2; operating current, 2×10^5 amps; peak field at conductor, 12T; and field at plasma center, 6.8T. The magnet consists of six, joined, straight conductor sections forming a hexagonal-shaped coil. Each conductor section consists of an alternate layered arrangement of Nb_3Sn braided wire--coper plate conductors and ceramic plate insulators enclosed in a stainless steel case, Figure 1. The cryostable conductors are pool boiled helium cooled at 4.2°K, the coolant passages being machined channels in the copper plates. At the joints corresponding copper plate elements are interleaved and soldered to form the continuous coil. Since the joints are allowed to slip during magnet cooldown and load application, mechanical means are employed to maintain joint contact pressure at a suitable level.

At the outset of this design investigation two questions were of paramount concern regarding the feasibility of the concept. First, was it possible to design a support structure which was both strong enough to resist the magnet loads and yet easily removed to permit magnet demounting; and second, could the joints absorb the relative motions associated with cool down contractions and still exhibit the low electrical resistance required in a superconducting coil. This paper summarizes the results of a design study undertaken to resolve the first question.

Support Structure Design

It was decided at an early phase that it would be impractical to develop a support structure containing active elements that could absorb or conform to the contractions associated with magnet cool down. Therefore, as a basis for this study, it was assumed that cool down contractions are absorbed by slippage at the conductor joints with each straight conductor leg contracting axially to its center span point which is fixed to the support structure. This assumption then limited the design task to the selection and arrangement of passive support elements in such a way as to adequately resist all the magnet loads and yet be demountable. Other design features of the structure were: major support elements to be maintained at room temperature, the in-plane load support structure to be independent of the out-of-plane load support structure, the cold coil case to serve as a load transfer beam but to support none of the hoop loading and glass/epoxy pads to serve as load transfer members between the cold case and the warm structure. Lastly, to minimize the system weight, materials with high yield strength, HP-94-20 alloy steel for the room temperature structure, 304L SS for the cold coil case,and Nitronic 40 for the cold structure were used.

The first task in defining candidate structural arrangements that could meet the envelope requirements and provide the support of the TF coils was to consider the in-plane loads acting on the TF coils, independently of the out-of-plane loads. Preliminary load calculations were made based on the expected current density of the TF coils and the dimensional parameters established for the machine. Four candidate configurations were considered and are shown in Figure 2. Also shown in this figure are the loads resisted by each member of each configuration. In each the inward radial load is supported by a central bucking cylinder while the remaining loads are supported by the concerted action of a central column and pin connected beam elements. From a consideration of load distribution and beam member size, configuration two was selected for further investigation.

Figure 3 shows the resulting in-plane and out-of-plane loading for this coil arrangement. The in-plane load increases from 130,000 lbs/in. along the outer vertical magnet leg to 360,000 lbs/in. acting on the inboard vertical leg. Out-of-plane loading resulting from the poloidal fields is significantly lower than the in-plane forces. The out-of-plane load is shown to peak midway between the first and second joint; it remains somewhat uniform through the third joint and decreases thereafter.

Using these loads, two and three dimensional finite element modeling techniques were used to assess and optimize the support design. Figure 4 shows the complete machine configuration. The in-plane loads are reacted by the composite action of warm, pin connected, thick plate, beam members, the warm central tension column and the cold, central bucking cylinder. The out-of-plane torque loads are reacted by the cold central bucking cylinder, cold, upper and lower torque plates and a warm outer torque cylinder made up of shear webs and truss elements located between the outer vertical legs and the plasma shielding. Epoxy filled fiberglass bearing pads serve to transmit the load from the cold coil case to the warm support elements.

Tracing the load support functions in more detail the outboard magnet legs transit their load through epoxy filled fiberglass bearing blocks to the outboard structural support. Although the major fraction of this load is transmitted directly to the foundation, reaction loads are produced at the upper and lower collar pin connection joints. The vertical component of this reaction, as well as the vertical load on the upper collar, is reacted at the tension post through the retaining ring. The horizontal loads acting on the upper collar are transferred to a continuous epoxy filled, fiberglass ring as a tension and compression loading. A similar reaction occurs at the lower collar. The inner vertical magnet leg transmits its load to the bucking column which serves as an integral bucking column and torque ring cylinder. The out-of-plane torque loads are transmitted directly to the cold inner torque cylinder consisting of the coil cases (wedges being used to eliminate clearances) bucking cylinder and upper and lower torque plates and through epoxy filled fiberglass pads to the warm outer torque cylinder. The torque loads are then reacted by the concerted action of the inner and outer torque cylinders, positive interconnection and transmitted of loads between the cylinders being affected by high thermal resistance bearing pad-shear pin connectors.

A summary of the coil conductor and coil case stresses is presented in Figure 5. As indicated on the figure, it was necessary to add plate member bridges to the inboard horizontal legs to reduce moment effects on the otherwise unsupported joint regions. As can be seen, conductor tensile stress levels are all below 4600 psi. The elements of the in-plane load support structure were all fully stressed. This was achieved by reducing the structural area incrementally until the material was stressed to its allowable level. Figure 6 shows the finite element model used for the in-plane structure evaluations. Also shown on the figure are the nodal loadings (10^6 lb) and some resultant nodal displacements. Under full load the structure exhibits a radially outward maximum deflection of 1.18 in. at the centerline of the outboard vertical leg and an upward maximum vertical deflection of 1.4 in. at the centerline of the upper inboard horizontal leg. The stresses in the torque structure were all below allowable levels, the member sizes being chosen to limit deflections.

Conclusions

The design study proved the feasibility of resisting the magnetic loadings with a demountable support structure which is extraneous to the superconducting coil. The resulting magent system, although estimated to be higher in cost than a continuous coil, incorporates a means for complete coil replacement in a time scale commensurate with conventional nuclear power plant repairs and without the dismantling of the toroidal blanket and plasma shell systems. A possible assembly sequence for the entire machine is shown in Figure 7. Alternately, only a signle magnet coil could be removed and reinstalled in this manner. To be sure this entire support system concept is dependent on the assumption of conductor joint slippage, the feasibility of which can only be proven by test.

References

[1] HSIEH, S.Y., et al., "The DEALS Magnet Concept and Its Applications to High Density, High Field Tokamak Systems", Presented to the 7th Symposium on Engineering Problems of Fusion Research, Knoxville, TN (October, 1977).

[2] POWELL, J.R., et al., "DEALS: A Demountable Externally Anchored Low Stress Superconducting Magnet System for Fusion Reactors", BNL 50616 (January, 1977).

[3] POWELL, J.R., et al., "A Niobium-Tin DEALS Toroidal Magnet System for a High Field Ignition Test Reactor", BNL 50802 (December, 1977).

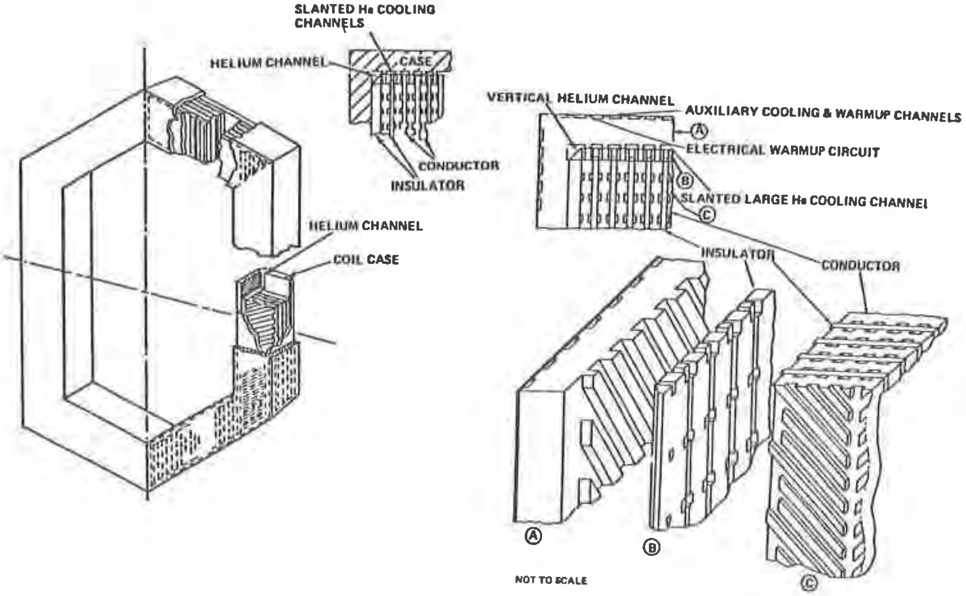


Fig. 1 COIL COOLING SCHEMATIC

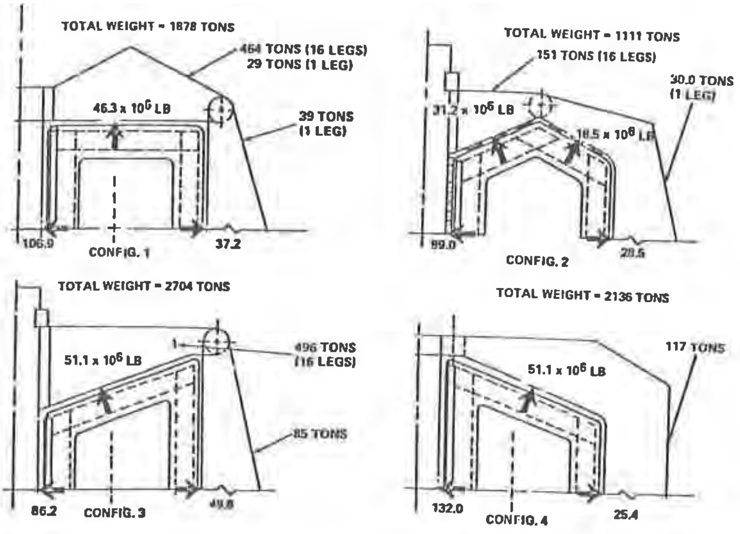


Fig. 2 INPLANE STRUCTURAL SUPPORT OPTIONS

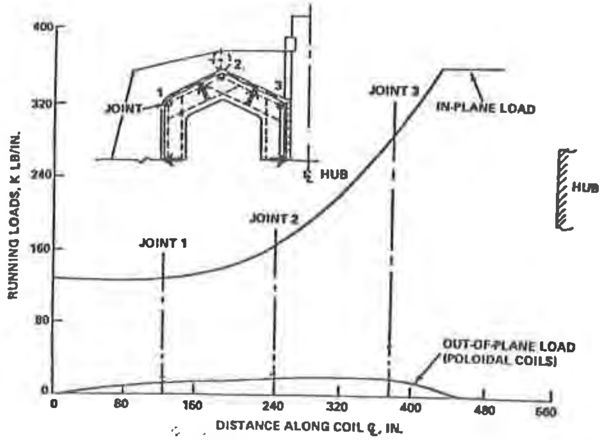


Fig. 3 IN-PLANE/OUT-OF-PLANE FORCES

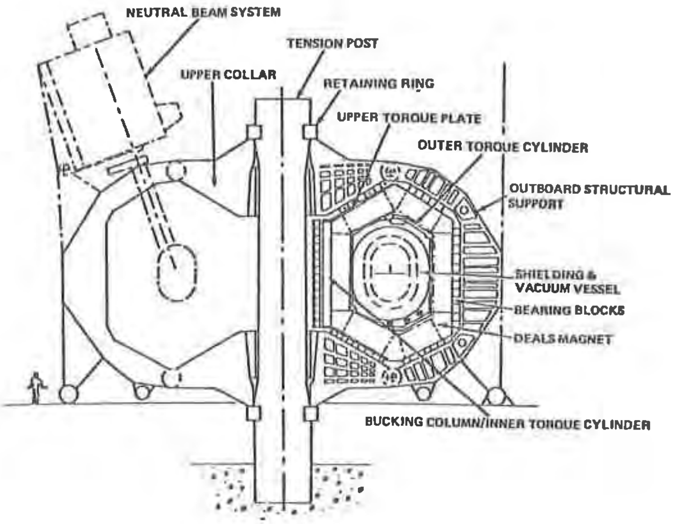
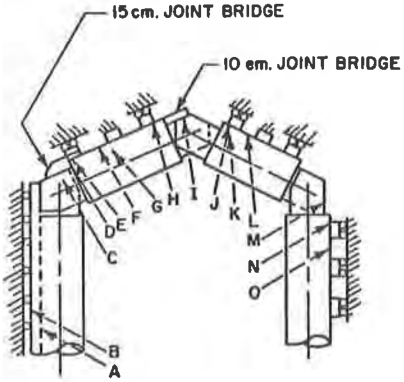


Fig. 4 BASELINE CONFIGURATION



LOCATION	MATERIAL	STRESS, psi
A	Cu	-17,100
B	SS	-18,200
C	Cu	2,600
D	Cu	-20,100
E	SS	-47,200
F	SS	14,500
G	Cu	4,600
H	SS	-24,500
I	Cu	2,400
J	SS	-38,000
K	Cu	-23,600
L	SS	8,000
M	Cu	1,650
N	SS	-22,800
O	SS	6,500

Fig. 5 COIL STRESS SUMMARY

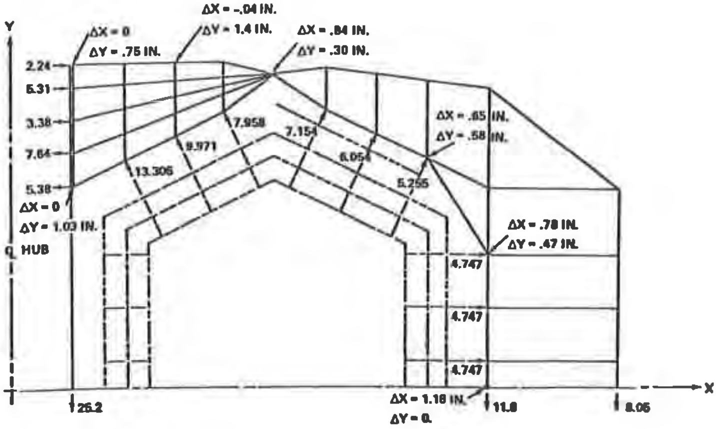


Fig. 6 FINITE ELEMENT MODEL – INPLANE LOADING (10^6 LB)

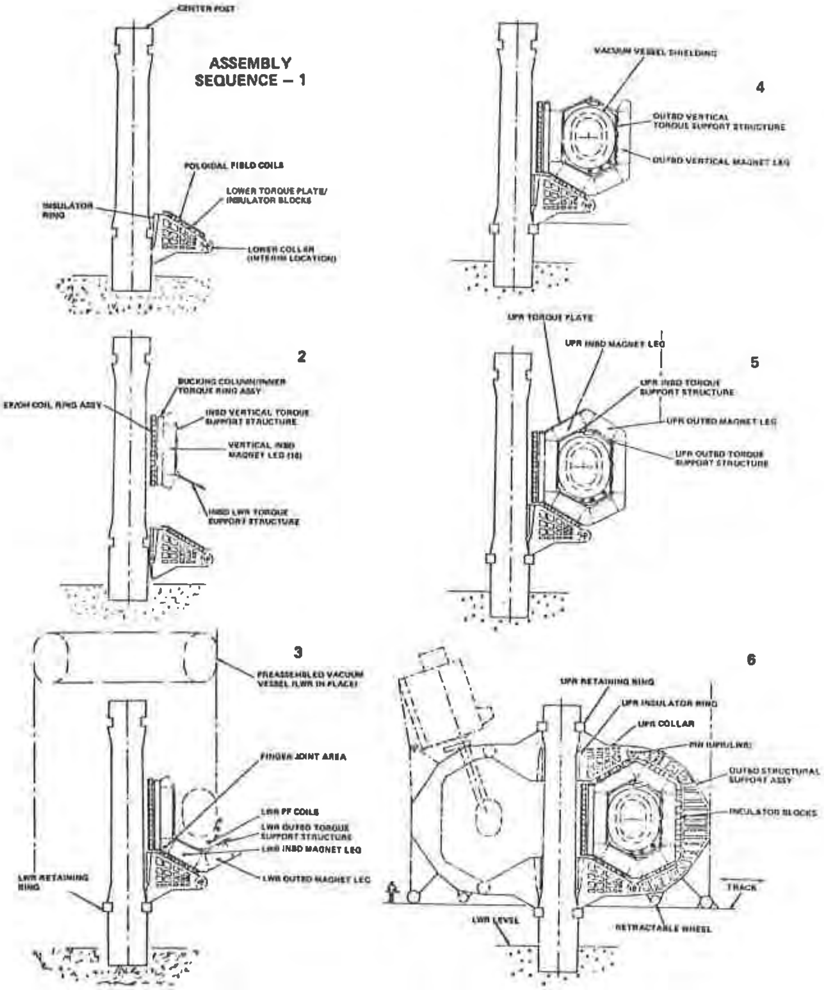


Fig. 7 TOTAL ASSEMBLY SEQUENCE I TO 6