MASTERSTRUCTURE DESIGN OF THE WESTINGHOUSE
SUPERCONDUCTING MAGNET FOR THE LARGE COIL PROGRAM¹

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ability.**ABSTRACT**

In the on-going development of superconducting toroidal field coils for tokamak reactors, the Large Coil Program (LCP) managed by Union Carbide Corporation will include the design, fabrication and testing of large superconducting coils to determine their feasibility for use in the magnetic fusion energy effort. Structural analysis of the large coil is essential to ensure adequate safety in the test coil design and confidence in the scalability of the design. This paper will discuss the action of tensile and shear loads on the various materials used in the coil. These loads are of magnetic and thermal origin.

MAGNET DESCRIPTION

The materials chosen for the magnet are: 2219-T87 aluminum for the structural plates, A-286 stainless steel for the through bolts and a conductor composed of a stranded, cabled Nb₃Sn superconductor encased in a 304L stainless jacket.

The forced flow conductor is composed of 486 copper clad Nb₃Sn strands of 0.029 inch diameter. Each of the strands are insulated and compacted into the jacket to provide strand support, maintain conductor dimensions and contain the helium used as the conductor coolant.

Conductor support is provided by a distributed structure that encases each conductor group in a plate. After assembly each conductor group is completely surrounded by structural material which provides positive restraint of forces in all directions. The conductor strain is limited by the aluminum plates.⁴ This strain is to be no higher than .2% under normal operation to ensure safety against destructive tension and to not decrease the critical current in the conductor filaments. The assembled structure is composed of 28 plates in parallel, each one machined to accept from five to twenty turns of conductor. Figure 1 illustrates the aluminum structural support concept with a winding arrangement utilizing four slots to hold twenty turns of conductor. The plates are split about the horizontal axis of the coil to provide ease in manufacturing, assembly, and scalability to a full size reactor coil.

Magnet assembly is achieved by winding the conductor in each aluminum plate and sandwiching the wound pancakes together. Stainless steel bolts are used to consolidate the split plates into a structurally rigid body.

LOADING DUE TO MAGNETIC FIELDS

Loading seen by the coil during its specified 10 year life will consist of varying conditions and cycles. These loading conditions are described by a primary and nine extended operating cases. The operating conditions are based on the current distribution within the array of six coils listed in Table 1.

Fig. 1. Modular Concept for Westinghouse Coil

Table 1
Coil Current Distribution²

Test Condition	Percent of Design Current in Coils					
	1	2	3	4	5	6
Primary	100	80	80	80	80	80
Extended #1	126	0	0	126	0	0
2	121	0	121	0	121	0
3	100	100	100	100	100	100
4	110	80	80	80	80	80
5	100	100	100	100	100	0
6	110	80	80	80	80	0
7	100	80	80	80	80	0
8	100	80	80	0	80	80
9	100	0	0	0	0	0

Magnetic field strength requirements for the magnet mandate a peak field level of 8 tesla in the winding. Specifications for extended test operation require that the magnet be capable of operation at field levels in excess of 8 tesla. Toroidal field induced coil loading is caused by the interaction of current in the conductors and the magnetic field produced by the coil array. The direction of the load is radially outward from the coil center across the four groups of five conductors as shown in Fig. 2.

Poiodal field induced coil loading is a reaction caused by the coil current interacting with an imposed pulse field with a peak magnitude of .14 tesla and .1 tesla perpendicular to and parallel to the conductor, respectively. Loading on this coil will act in

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such a manner as to cause a twist about the coil array centerline. Distribution of the poloidal load on the coil is shown in Fig. 3 where the loading is normal to the plane of the coil.

Fig. 2. Toroidal Field Distribution

Loading in the extended cases will consist of the same cycle characteristics as that on the primary operation. The average magnitude of the pulse field will be .2 tesla instead of .1 tesla.

Fig. 3. Poloidal Field Distribution

LOADING DUE TO THERMAL CONDITIONS

The thermal transient loading of the coil is based on the variation in the thermal properties of the various materials. For the cooldown and warmup processes the temperatures of the various materials are kept the same. Loading of the conductor and structure is then a function of the difference in their thermal expansion coefficients between 4 and 300°K.

TOROIDAL AND POLOIDAL FIELD STRESS ANALYSIS

A finite element computer analysis defined in the WECAN³ computer code was used on the primary and extended operating conditions. The superconducting toroidal field coil winding section geometry shown in Fig. 4, was approximated by two ellipses and by a straight leg in the computer program PDYNODE⁴.

The homogeneous conductor/structure analysis used assumed that the coil finite elements are a group of parallel and series materials resulting in a composite modulus based on the areas of the various members. Input of the toroidal and poloidal forces on the coil model give coil deflections for each node and principal composite coil stresses for each element. To obtain the stress on the conductor and structure the composite stress must be multiplied by the ratio of the conductor or structure modulus to the composite

modulus. Referring to Fig. 4 the maximum stresses are found in the coil where $\theta = 45^\circ$.

The 26 plates which form the coil are of a modular design. This modular design is shown in Fig. 5 which shows the orientation of the splits. The splits are spaced about the horizontal centerline of the inner and outer leg ($\theta = 0$ in Fig. 4) with six rows of bolts between them. Looking at three consecutive plates, the first will be split below the centerline, the second on and the third above the centerline. The tensile plate stresses are treated as a uniformly distributed load across the plates. At a split, half the uniform load per plate will be added to the adjacent plate. Half of the load being transferred will be taken by the first row of bolts, thirty percent by the second and twenty percent by the third row. This load is due to tension in the coil plus a bending moment which can be added vectorially. The highest bearing stresses occur in bolts adjacent to the split above the centerline on the outer leg.

Fig. 4. Coil Geometry

The toroidal field creates a radial load in each of the conductors. This load must be restrained by the slot teeth as illustrated in Fig. 6. Since the force on a conductor decreases as its distance from the coil center increases, the highest loaded slot tooth will be the innermost one. Magnetic fields crossing the current in each strand create an average force per conductor which when added vectorially yields the total load exerted on the tooth.

Fig. 5. Split Locations

Fig. 6. Radial Loading on Slot Teeth

UNSYMMETRICAL FIELD STRESS ANALYSIS

Unsymmetrical loading is defined when coil #1 is affected by coils #2 and #3 operating at different design currents as in extended case #5. Unsymmetrical loading was analyzed using Castigliano's theorem for a curved beam, with boundary conditions applied to model the actual coil response. These boundaries are: 1) beam deflection equivalent to the support spring deflection; 2) slope of the beam deflection about the coil's horizontal centerline must be 0 due to the symmetric out of plane loading about the coil's centerline. The maximum stresses are found at $\phi = 45^\circ$ of Fig. 4.

THERMAL STRESS ANALYSIS

Loading of the conductor and structure is proportional to the difference in their thermal coefficients. It is assumed that the aluminum structure with the internal conductor windings are two beams rigidly connected. The length of these beams are based on the mean circumference of the D-shaped coil. In cooldown, the aluminum is trying to contract more than the conductor, causing tensile stresses in the aluminum. Obviously the final length of the two members must be the same so that the final load in each member is also equal and the stresses are then found by knowing the cross sectional areas.

Thermal warmup stresses are calculated in the same manner as in the cooldown analysis. However the aluminum structure is trying to expand more than the conductor which produces a tensile force on the conductor causing compressive stresses in the aluminum structure.

The maximum cooldown and warmup conductor and structure stresses occur at 4°K when the absolute difference between thermal expansion rates is greatest.

Based on the arrangement of the five conductors in one slot the thermal loads at 4°K on the slot teeth are found by summing the radial stresses induced by circumferential contraction along with the "shrink fit stresses" created by the greater radial contraction of a tooth in relation to the five conductors.

RESULTS

Tables 2 and 3 list the stresses for the primary, extended and unsymmetrical loaded coil array operating cases. Values shown in these tables are maximum values at 4°K obtained for the particular analysis and under the worse operating cases.

In order to adequately determine the integrity of the coil design, the total equivalent stress seen within the coil structure must be determined. The coil geometry and loading are such that the three dimensional form of the Von Mises' criterion must be used. The equivalent stress must not exceed the maximum allowable structure stress. Substitution of the proper toroidal, poloidal and thermal tensile stresses along with bending and shear stresses on the slot teeth at 4°K will then give the maximum equivalent stress for each operating case.

Primary Operation - 45,950 psi
Extended Operation - 53,264 psi
Unsymmetrical Operation - 55,841 psi

Table 2
Primary Coil Stresses (psi)

	Toroidal	Poloidal	Thermal
Aluminum Structure	10,284	3,364	8,789
Conductor (% strain)	.07	.0099	-.11
Bearing at the Bolts	16,870	2,077	21,677
Slot Tooth Bending	11,107	--	14,913
Slot Tooth Shear	4,230	--	6,920
Allowable Aluminum	47,933	47,933	--
Allowable Conductor (% strain)	20	20	20

Extended Coil Stresses (psi)

	Toroidal (Case #4)	Poloidal (Case #1)	Thermal
Aluminum Structure	12,083	8,477	8,789
Conductor (% strain)	.082	.024	-.11
Bearing at the Bolts	19,890	5,236	21,677
Slot Tooth Bending	12,848	--	14,913
Slot Tooth Shear	4,393	--	6,920
Allowable Aluminum	68,305	68,305	68,305
Allowable Conductor (% strain)	.40	.40	.40

Table 3
Unsymmetrical (Case #5) Coil Stresses (psi)

	Toroidal	Poloidal	Unsymmetrical	Thermal
Aluminum Structure	12,083	8,727	7,725	8,789
Conductor (% strain)	.082	.024	.062	-.11
Bearing at the Bolts	19,890	5,236	21,390	21,275
Slot Tooth Bending	10,444	--	--	14,913
Slot Tooth Shear	3,977	--	--	6,920
Allowable Aluminum	68,305	68,305	68,305	68,305
Allowable Conductor (% strain)	.40	.40	.40	.40

It is apparent that the magnetically and thermally induced loads under primary and extended operating conditions are within design limits in the Westinghouse LCP design. Toroidal, poloidal and unsymmetrical magnetic stresses when combined with cryogenic thermal stresses yield acceptable equivalent stresses with an adequate safety level maintained in the toroidal field coil.

REFERENCES

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