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**Conceptual Design of the LCP Coil
Support Structure**

P. S. Litherland

OAK RIDGE NATIONAL LABORATORY
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P. S. Litherland

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ABSTRACT

The goal of the Large Coil Program (LCP) is to produce and test large (2.5-m $\times$ 3.5-m bore) superconducting toroidal field (TF) coils. The coil support structure is to provide a structural environment similar to that of future tokamaks. The structure must also be adaptable to different configurations of one to six test coils.

Several alternative concepts were considered before a satisfactory conceptual design was chosen. The selected design incorporates a central bucking post and two external torque rings. Using anticipated loading conditions, major structural members were sized. A finite element stress analysis was performed on the structure for various coil arrangements.

SUMMARY

The LCP test requirements resulted in a coil support design which accommodates up to six test coils and is mounted to a structure capable of resisting coil interactions. This paper will discuss the steps leading to the present LCP coil support structure design, details on selected structural components, and the basic assembly sequence.

BASIC REQUIREMENTS

The general requirement for the support structure was that it be capable of restraining loads resulting from configurations of a one-coil to a six-coil torus.¹ Other basic requirements were:

1. To accurately compare coil designs, the coil to support structure interfaces were constrained to be structurally and thermally identical.
2. The structural system must be easy to assemble and disassemble with a maximum coil installation turnaround time of one month.
3. The structure must provide a 5 K conductive surface at coil interfaces.
4. The structural cooldown time must be five days maximum.
5. The structure must be compatible with D-shaped pure tension coil.
6. The structure must be capable of operating in 10^{-5} torr vacuum.

7. The structure must provide means for a set of water-cooled vertical pulse field coils to be supported in the bore of any TF coil.
8. The structure must provide a minimum of interference with magnetic fields of the TF and vertical field (VF) coils.
9. The structure must provide thermal isolation between 5 K coil interfaces and room temperature.
10. Fabrication and erection of structural components must be consistent with existing practices and with readily available materials (i.e., coils are to be tested, not structural components).
11. Each coil must be as structurally independent as possible so that individual coil characteristics can be measured.

ALTERNATIVES CONSIDERED

With these requirements, four different support schemes were considered. The alternatives are described below and shown graphically in Fig. 1.

1. Modular Compartment — Each coil reacts structural and thermal loads to its own independent support module which is mounted to ground. No contact is made between coils.
2. Intercoil Spacers — Centering and out-of-plane loads are resisted by large beam weldments between coils.
3. Tension Frame — Each coil is restrained by a system of pure tension members, which in turn would be attached to an exterior loading ring.
4. Bucking Post/Torque Beam (BP/TB) — Centering loads are resisted by a central post and out-of-plane loads by a tongue and groove joint between the post and coil and by beam weldments between the coils.

Table 1 is a scoresheet of how the alternatives compare to one another and how well they satisfy requirements of the experiment.

The conclusion of the study was the selection of alternative 4 (BP/TB) as the LCP support scheme. One factor which weighed heavily in selecting the BP/TB scheme was that the development of the D-shaped pure tension coil assumes uniform support along the flat nose region of the coil; it was the only scheme which did.

a. Coil module

b. Intercoil spacers

c. Tension frame

d. Bucking post/torque rings

Fig. 1. Support scheme alternatives.

Table 1. Alternative comparison scoresheet

Criteria	F^a	Coil module		Intercoil spacers		Tension frame		Bucking post torque ring	
		C^b	$C \times F^c$	C^b	$C \times F^c$	C^b	$C \times F^c$	C^b	$C \times F^c$
Ease of assembly	5	1	5	3	15	2	10	4	20
Ease of fabrication	5	1	5	4	20	3	15	4	20
Versatility	8	4	32	2	16	1	8	3	24
Structural loads in conductor	5	4	20	2	10	3	15	3	15
Compatibility with D-coil	10	1	10	1	10	1	10	4	40
Similarity to future systems	9	2	18	4	36	1	9	3	27
Structural mass	7	1	7	4	28	2	14	4	28
Structural coolant demand	7	1	7	4	28	2	14	4	28
Forces transmitted to ground	3	1	3	3	9	2	6	4	12
Coil removal/assembly time	8	4	32	2	16	1	8	3	24
Coolant piping complexity	5	3	15	4	20	1	5	3	15
Coil cost	7	1	7	3	21	2	14	4	28
Support structure cost	7	4	28	2	14	2	14	2	14
Pulse coil system complexity	5	1	5	4	20	2	10	4	20
Coil-ground thermal isolation	5	1	5	3	15	4	20	3	15
FINAL COMPARISON (highest product is best)			199		278		172		330

^a F = weight factor given to each criteria - 1 through 10 with 10 being most important.

^b C = rating of each alternative against the criteria being considered - 1 through 4 with 4 being most desirable.

^c $C \times F$ = product giving a comparison between alternatives which includes importance of criteria being considered.

GENERAL STRUCTURAL DESCRIPTION

The structure was designed to support the gravity and magnetic loads of the TF and VF coils. The magnetic loads acting on the TF coils are:

1. centering forces due to the net resultant of in-plane forces,
2. out-of-plane forces due to nonsymmetric currents in the toroidal array, and
3. overturning moment as a result of out-of-plane loads caused by pulsed vertical field.

Using magnetics codes and hand calculations, preliminary magnetic loads were derived. The direction and magnitude of these forces are described in Fig. 2.

The basic magnetic force acting on the pulse coil (P-coil) system is an overturning moment which results from the energized VF coils attempting to align with the toroidal field. It is equal and opposite to the overturning moment on the TF coil. Initial sizing and design of structural components were based on these loads. Figures 3 and 4 show the conceptual design with a full six-coil torus.

The TF coil structure consists of a rigid central bucking post and two external torque rings. The bucking post resists the toroidal coil centering forces and also carries a portion of the out-of-plane loads. This is accomplished through a tongue and groove joint which connects the coil to the post and runs the full length of the post. The torque rings resist the out-of-plane forces and overturning moments at the outside of the torus.

The P-coil structure consists of a torque ring which runs through the bore of the TF coils. This ring in turn is supported by spokes from the top and bottom of the bucking post.

All structural components are designed for off-site fabrication and are within a 50-ton weight limitation of the facility handling equipment.

Centering force — worst case of in-plane centering force of an individual TF coil, 5.56×10^7 N

Out-of-plane fault load — worst case of out-of-plane load caused by a single faulted TF coil, 8.7×10^6 N

Out-of-plane forces causing overturning moment — worst case of overturning moment in an individual TF coil, 5.3×10^6 MN-m

Fig. 2. Applied magnetic loads.

Fig. 3. LCP plan and section views.

Fig. 4. LCP with a six-coil torus.

MATERIALS FOR STRUCTURAL COMPONENTS

Materials were chosen for structural components specifically to meet the following requirements; they (1) are nonmagnetic, (2) have comparatively low thermal conductivity, (3) are weldable, (4) have known properties at cryogenic temperatures, (5) are readily available to metal fabricators, and (6) are typical of materials proposed for future tokamak structures.

All welded structural components, excluding P-coil support spokes and fasteners, are constructed of 304L stainless steel. The bucking post will be a forging of 304 stainless steel. Fasteners will be made of 21-6-9 stainless steel as well as the P-coil support spokes and end fittings. This higher strength steel was chosen to allow for a small cross section in the spokes to reduce heat conduction to the 4 K bucking post. Table 2 outlines yield and established working stresses for the materials used. Table 3 provides a reference of basic statistics on each structural component. Each component is individually discussed in greater detail in the following paragraphs.

COMPONENT DESCRIPTION

BUCKING POST

The bucking post is a forging of 304 series stainless steel. The post has a hexagonal cross section over its entire length. Each TF coil bears against one of these six faces and transmits the centering force of the coil to the post. A portion of the out-of-plane forces is carried by a groove which runs the full length of each of the six faces. A matching tongue running the full length of each coil nose fits into the post groove and provides support against the out-of-plane forces. The TF coils are rigidly attached to the top and bottom of the post with a bolted connection.

Several materials were considered for the bucking post. Aluminum and stainless steel were determined to be the two most likely choices.

Table 2. Allowable stresses

Material	Temperature (K)	Yield σ (N/M ²)	Allowable working σ (N/M ²)	Factor of safety
304L SST	300	1.7×10^8	1.3×10^8	1.3
	77	2.8×10^8	1.7×10^8	1.6
	4	3.8×10^8	2.1×10^8	1.8
21-6-9 SST	297	7.0×10^8	4.1×10^8	1.68
	77	1.5×10^9	4.1×10^8	3.65
	20	1.7×10^9	4.1×10^8	4.02

Table 3. Structural component description

Member	Weight (N)	Material	Construction	Maximum combined stress under load (N/M ²)
Bucking post	3.56×10^5	304 SST	forged	1.24×10^8
TF torque ring segment	2.2×10^4 each	304L SST	welded	1.70×10^8
P-coil torque ring segment	2.7×10^4 each	304L SST	welded	1.70×10^8
Spider base	1.1×10^5	304L SST	welded	1.70×10^8
P-coil support spokes	1560 each	21-6-9 SST	bar stock	4.14×10^8

Concrete cased in stainless steel plate was considered. However, a survey of low temperature concrete properties yielded little useful information below -250°F .

A survey of the aluminum industry concluded that no U.S. aluminum forging facility was capable of forging to the size required. There did exist the capability to cast the post in aluminum; however, only 41 MPa yield strength could be guaranteed in this large size aluminum casting.

Low temperature properties of 304 stainless steel were readily available from several sources; a forging industry survey located at least two facilities capable of forging and machining a piece as large as the bucking post in 304 stainless.

Although a built-up, welded plate post was considered, the cost of preparing and welding the many large plates required exceeded the cost of a one-piece forging. Final machining costs were the same for both alternatives.

With all TF coils equally energized, but without pulsed fields, the post is loaded by only the radial centering forces of each coil. In addition as each energized coil tends to expand, its vertical expansion is resisted by the bolted post connections. This causes an overall axial tension in the post of 21 MPa combined with the centering compression that results in a maximum combined stress in this case of 48 MPa. This axial tension effect in the post reinforces the coil nose and reduces axial tension in the nose region. For example, with all six coils energized with 80% current, the axial stress in each TF coil nose is reduced 15% by being attached to the top and bottom of the bucking post.

During operation with five coils at 100% design current, the post is loaded by the centering forces of all but the de-energized coil and some out-of-plane forces of four of the coils. Due to these nonsymmetrical loads, the post experiences a bending moment, and the combined maximum stress is 69 MPa. During operation with a pulsed field, the post is also loaded by the overturning moment of the coil acting at the tongue-and-groove joint. The maximum combined stress is 124 MPa in this case.

The post will be cooled with liquid helium which runs through coolant holes in the interior of the post. These holes run the full length of the post and will be drilled after forging.

TF COIL TORQUE RINGS

The two TF coil torque rings are designed to resist the out-of-plane loads and the overturning moment of the TF coils. Each ring is built up of six ring segments which span between the test coils. The end of each ring segment is attached to the TF coils with a bolted flange. Each segment is a welded box beam of 304L stainless steel whose hollow interior will serve as a coolant passage for liquid helium to maintain structural temperature within specified limits. The worst combined stress in the torque ring is 172 MPa.

BASE STRUCTURE

The entire weight of the toroidal and P-coil systems is supported by a six-legged base. The base contains a central socket and flange into which the bucking post is attached. The base legs serve as long thermal paths which aid in isolating the helium-cooled bucking post from 80 K pads on the vacuum enclosure floor. Each leg is a box type section which provides its own coolant passage. The end of each leg rests on an expansion roller, which in turn, rests on the vacuum enclosure floor. These expansion rollers allow each leg to contract and expand radially during cooldown and warmup. Each roller is restrained to move only in the radial direction; therefore with six feet, the entire test stand assembly is restrained horizontally while still allowing the individual legs to move radially.

Under the full load of six TF coils and a P-coil experimental assembly, the frame has a maximum combined stress of 172 MPa and deflects 0.8 cm downward at its center.

P-COIL SYSTEM

The P-coil support structure has three major components: a torque ring, torque ring support spokes, and the bucking post. The P-coil torque ring is a segmented ring connecting the three pulse coils. The complete ring is composed of three beam segments and three P-coil assemblies. The entire ring is supported by twelve 4-in.-diam spokes that conduct 2 W to the 4 K bucking post. These spokes support the ring from the top and bottom of

the bucking post and provide a long thermal path between the P-coil system and the helium-cooled bucking post.

The principal load acting on the P-coil torque ring is the overturning moment from one pulse coil.² Since the pulse coil is a part of the ring, the entire ring tends to overturn. This overturning effect is counteracted by the spokes which restrain the ring in its original horizontal plane.

SCOPE OF STRUCTURAL ANALYSIS

In addition to design calculations, a detailed finite element analysis has been performed by Systems Development Corporation³ on the entire structural system. This analysis has generally confirmed that stress levels below the established working stresses are possible in all components. Figure 5 illustrates the finite elemental model used in the analysis of the toroidal coil support system.

SUPPORT STRUCTURE ASSEMBLY PROCEDURE

The assembly of the structural support system begins by leveling the base on the floor of the vacuum enclosure. The base bears on the enclosure floor through six expansion rollers and should not require further adjustments or removal.

The bucking post is lowered into a socket in the center of the base frame. A flange on the lower end of the post is shimmed snug and bolted to the mating surface on the top of the base. To provide for stability of the post during further assembly of the experiment, temporary guy rods are attached between the top of the post and the legs of the base. The structure is now ready to accept the TF coils.

A TF coil is lowered into place by overhead crane and set on temporary jacks on the enclosure floor. These jacks will support and adjust the coil while the coil is being aligned. The coil nose tongue is shimmed into the bucking post vertical groove to provide full bearing along the sides of the tongue-and-groove joint. The coil is then rigidly attached to the bucking post with bolted angle brackets at the top and bottom of the post. All six coils will be set into place in this manner.

Fig. 5. Finite Element Stress Model.

The torque ring sections are lowered into place between coils, shimmed snug, and bolted to each other through holes in the coils. The shims will provide a full bearing surface between the coil and torque ring and align the bolt holes. This completes the assembly of the basic TF coil structure.

The P-coil structural system is designed to be assembled and disassembled without affecting the TF coil system. The three P-coils are set into the bore of the TF coils and secured to temporary support columns. The P-coil torque ring sections are set between P-coils, shimmed snug, and bolted to the P-coils. The P-coil support spokes are attached with pin and clevis joints between the P-coil torque ring and the top and bottom of the bucking post. A final set of spokes is added between the torque ring and the support legs of the base and act as guys for the bucking post. This completes the assembly of the major structural components to support the TF and P-coils. The temporary jacks under the TF coils and the temporary bucking post guys are then removed.

CONCLUSION

This support scheme was developed as the conceptual design for supporting the LCP coils. Further design and analysis will be necessary on each individual component to ensure desirable thermal and structural behavior under all loading conditions.

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