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DESIGN OF A SUPERCONDUCTING 20 MJ INDUCTION HEATING COIL*

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SUMMARY

A pancake-wound, low-loss, superconducting, induction-heating coil has been designed to demonstrate the feasibility of superconducting poloidal system for the Tokamak reactors, to provide confidence in application of superconductivity to actual reactors, and to provide the opportunity to solve specific engineering problems to support the fusion pulsed coil program. The coil is designed to store 20 MJ at 50 kA. The superconductor material is NbTi for a 7.5 tesla maximum field. The coil is designed to survive at least 100,000 cycles of full bipolar half cycle sinusoidal operation from +7.5 tesla to -7.5 tesla fields in one second. The coil is natural convection immersion-cooled at 4.5° K in liquid helium bath. The design demonstrates confidence in an advanced design, low-loss, cryostable conductor, along with safety, reliability and the operating life of the coil of more than 100,000 cycles. The total energy loss during a full bipolar pulse will be approximately 0.3% of the stored energy. The analysis shows that the coil design will meet or exceed all of the performance requirements. The key design features of the coil include modular construction, no superconductor joints at I.D. transition, independent cooling of individual pancakes, and scalability to ETF size ohmic heating system. The results of structural and thermal analyses are presented.

INTRODUCTION

A study[1] was completed by the Westinghouse Electric Corporation in 1978 for LASL to demonstrate the feasibilities of a superconducting induction heating coil for the Tokamak poloidal field systems. The results of this study were presented at the 8th Symposium on Engineering Problems of Fusion Research in November 1979. Since the completion of the study the Westinghouse Electric Corporation has completed the detailed design and analysis of the 20 MJ coil. This paper presents the results of the detailed design and analyses[2] of the 20 MJ superconducting induction heating coil.

OBJECTIVES

The following design criteria are consistent with the objectives of the program.

- Long lifetime integrity and reliability normally associated with the electrical utility industry.
  - Mechanical ruggedness and firmness that will not change over the lifetime of the Tokamak machine (greater than 10^5 cycles).
  - Tough insulation that will not degradate over the operating lifetime of the Tokamak machine.
- Lowest possible losses but consistent with above approach.
- Manufacturability.
- Design concept scalable to an ETF size system.

The specified magnet performance requirements and operating environment are summarized below.(2)

- The coil is to store 20 MJ ± 3% of energy at full normal operating current.
- The maximum magnetic field for normal operating current is to be 7.5 tesla on the superconductor.
- The normal operating current is to be 50 kA.
- The nominal maximum voltage across the coil terminals is expected to be 10 kV for fast energy transfer.
- The coil will be natural convection immersion-cooled (Pool Bath) at 4.5 K in liquid helium.
- The coil is to be capable of operating 100,000 cycles of full bipolar (one bipolar cycle is repeated at mode every 10 seconds), without degrading its performance.
- The full bipolar mode will be a half-cycle sinusoidal operation from +7.5 T to -7.5 T fields in one second.

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- The testing of the coil will include both discharge into resistive load for L/R = 0.5 second exponential decay time constant, and a full bipolar field and current reversal operation.

- The coil is not to go normal during testing.

- The coil is to be cryostable with the ability to recover to the superconducting state of one complete turn of the conductor continuously carrying full normal current in the highest field region and which has been driven normal from an energy disturbance which raises the temperature of the individual superconducting strands at the middle of the normal turn to 25 K.

COIL DESCRIPTION

The major coil parameters are shown in Table 1. The coil is of spirally wrapped, pancake wound configuration. The wide-flat cabled conductor[3], shown in Figure 1, is wound on individual coil formers in a clockwise and counterclockwise configuration for alternate pancakes. The coil is made up of eight spiral-wound pancakes as shown in Figure 2. To eliminate the need for internal electrical joints the pancakes are wound in pairs with consecutive pancakes alternating between clockwise and counterclockwise rotation. The coil support structure is made up of segmented G-10CR plates located between pancakes.

TABLE 1
20 MJ COIL PARAMETERS

PEAK FIELD	7.5 TESLA
TYPE OF CONDUCTOR	WIDE FLAT CABLE OF SUBCABLES
COOLING	POOL BOIL AT 4.5°K
WINDING	PANCAKE
CURRENT	50 kA
CONDUCTOR WIDTH	1.532 cm
CONDUCTOR THICKNESS	12.48 cm
CONDUCTOR CURRENT DENSITY	2615 A/cm²
COIL HEIGHT	140.48 cm
COIL BORE	80 cm
COIL O.D.	147.54 cm
TURNS/PANCAKE	25
NUMBER OF PANCAKES	8
COIL OVERALL CURRENT DENSITY	1678 A/cm²
INDUCTANCE (FLUX LINKAGE METHOD)	18.24 mH
STORED ENERGY AT 50 kA	20.3 MJ

These plates are supported by an internal cylinder made up of the individual pancake winding formers and a segmented external cylinder as shown in Figure 2. G-10CR bolts (12 at the I.D. and 32 at the O.D.) are used to hold the coil together and provide sufficient bolting force to maintain contact between coil members under load.

A railroad-tie-like spacer made from G-10CR strips glued to two pieces of glass tape forms the axial helium flow channels. The spacers are 0.25 inch wide and 0.06 inch thick, with a 0.125 inch space between them. The spacer is secured to the former at the I.D. with a small G-10CR screw and is co-wound with the conductor. At the 12th turn on the midplane of the coil a 0.25 inch thick 304 L (30% to 40%) cold rolled strap is added for structural support. The strap will bear against a steel insert in the plate to reduce the bearing load on the G-10CR plates. The strap has tapered ends to provide a smooth transition in this area. It has a 0.5 inch radius at the top and bottom as well as radii at the tapered ends to reduce stress concentration. This strap will transmit a portion of the axial forces through the coil. The strap is made 0.020 inch over the conductor size to allow for plate deflection, therefore, greatly reducing the axial load to be carried by the conductor.

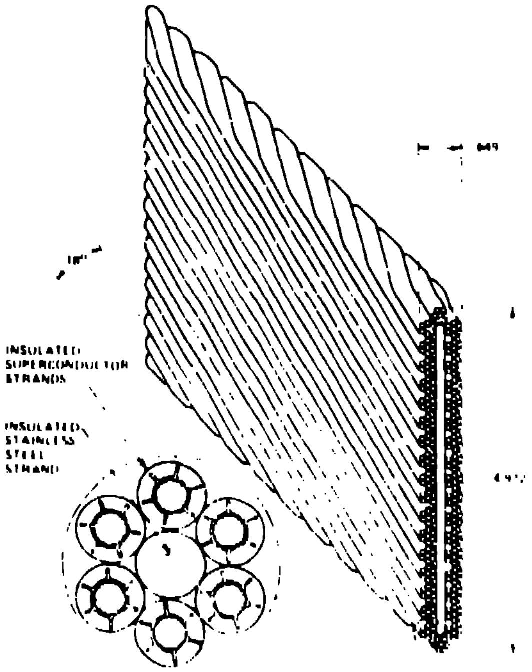

FIGURE 1 20 MJ SUPERCONDUCTING CABLE

The G-10CR axial support members provide separation between pancakes. In addition, the plates support the coil axial loads and transmit them to the inner and outer support cylinders. A portion of the axial load is also transmitted through the mid-plane support strap. This construction prevents an accumulation of axial forces on the conductors which could be detrimental. Because the mandrel is located inside the conductor, the axial load would bear against the strand if it was transmitted through the conductors. The ribbon spacers (railroad-tie-like spacers) are too small (0.060 inch thick) to provide much support for the axial loading. The conductor, however, must transmit its own load to the plates which can be considerable (600 pounds/inch or more). In addition, this method of axial support provides for the lowest conductor motion, because there is no accumulation of forces. There are two different size plates, 3-inch and 2-inch. The 3-inch plate provides support to the outermost pancakes, since these have the highest axial loads (1.5×10^6 pounds each, or approximately 50% of total load).

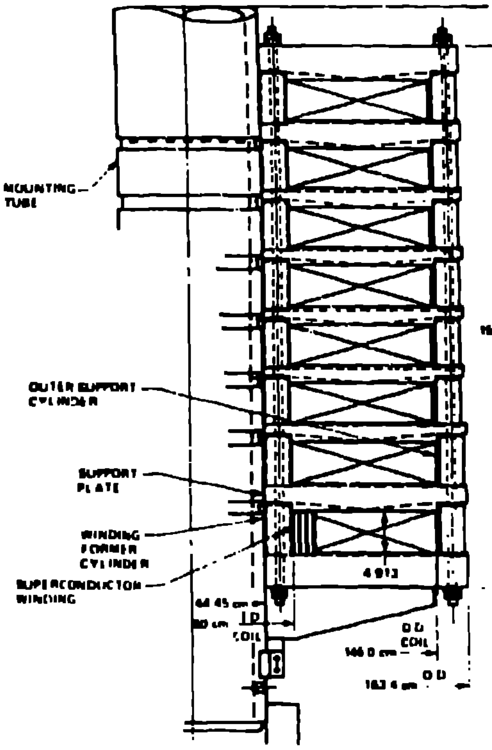

FIGURE 2 CROSS-SECTIONAL VIEW OF THE 20 MJ COIL

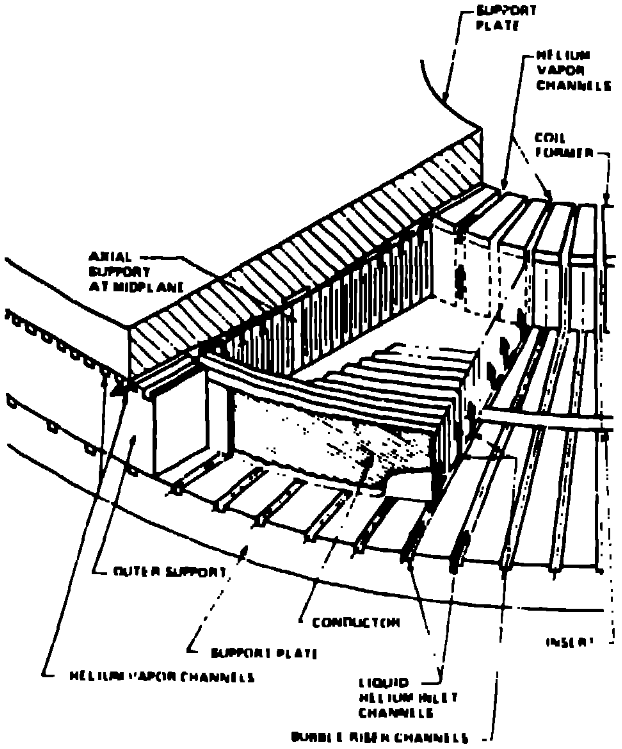

FIGURE 3 ONE PANCAKE ASSEMBLY SHOWING COOLANT FLOW PATTERN

The axial plates between pancakes are in four segments with an overlap area. The top portion of each plate has grooves machined every 2^0 which are 0.125 inch wide by 0.060 inch deep for helium inlets. The bottom of each plate has helium outlet channels spaced 2^0 at the I.D. and 1^0 at the O.D. which are machined at a 5^0 slope from the centerline. The sloped channels enable the helium bubbles to exit from each pancake with sufficient velocity. At the mid-plane of each plate, a groove is machined for the steel inserts. There are sixteen inserts per plate. Between each insert there is a 0.125 inch spacer, which is undersized to provide ventilation in the region. The width of the insert region was determined by the tolerances, and the criteria that the strap must bear on the inserts. The pancake assembly is shown in Figure 3.

The radial support is provided by the stainless steel conductor mandrel of Nitronic 40. Attachment members are also provided at the coil I.D. and O.D. of Nitronic 40. The pancakes are designed to be self-supporting so each pancake is radially supported individually by the coil former and conductor mandrel.

CONDUCTOR DESIGN AND PERFORMANCE

The first step in the conductor design was to select the pancake-wound wide flat cable approach. It was immediately clear that the surface for heat transfer from the conductor for stability should be increased as far as possible, within the limits of (1) preserving adequate channel size for bubble clearance, and (2) limiting the number of cable elements to that which can be handled with conventional cabling machinery. At the same time, a maximum coil current density and packing density would be achieved by (1) maximizing the conductor width to minimize the number of pancake coils overall and (2) minimizing the conductor thickness to pack in as many turns as possible.

To accommodate these considerations, the conductor core which supports the coil hoop load was made as thin as possible through the use of a high-strength Nitronic 40 stainless steel. The number of subcables was eventually set at 36, the maximum number accommodated by conventional cabling machinery. With the cable geometry thus established, the ultimate dimensions of the cable would depend upon the selection of the smallest subcable strands possible, within the constraint that the operating current of 50,000 amperes be achieved with the assurance of recovery from a fully-normalized long section of conductor.

The fully-normal I^2R heat transfer for stability was conservatively but realistically chosen at 0.26 Watts/cm^2 (from the unoccluded 2/3 of the strand surface). Similarly, a 0.71 level of operating current relative to the critical current at 7.5 Tesla and 4.5 K was selected. The total AC loss for a one-second pulse of the coil from -7.5 T to +7.5 T is 0.31%[3] of the 20 MJoule stored energy when coil is operating alone, and the loss is 0.32% when coil is operating in a stack. This loss is marginally [illegible] the 0.3% of 20 MJoule target of this program for the coil operating in a stack (as allowed with [illegible] approval) for copper matrix superconductors, in accordance with the program specifications.

The 20 MJ cable is shown in the isometric sketch of Figure 1. The conductor is a wide flat cable of [illegible] subcables wrapped around an insulated stainless steel central strap or mandrel. Each subcable consists of six Omega (polyester amide-imide) film-insulated superconductor strands around a similarly insulated stainless steel core strand. A description of component materials, parameters and dimensions of the cable and subcable are provided in Table 2. A description of the superconductor strand is provided in Table [illegible].

TABLE 2
CONDUCTOR DESIGN AND PERFORMANCE

PERFORMANCE	
Operating Current I_{op}	50 000 Amperes
I_{op}/I_c at 4.5K, 7.5T	0.71
Jop (Circumscribed Conductor Area t x w)	2 615 Amps/cm^2
Fully-normal Heat Transfer from 2/3 of Strand Surface	0.26 Watts/cm^2
OVERALL CABLE DISCRIPTION	
Conductor Length	720 meters
Cable Dimensions	1.532 cm x 12.480 cm
Configuration	Cable of Subcables
Number of Subcables N	36
Mandrel Core Material	Nitronic 40
Mandrel Core Dimensions t x w	0.211 cm x 11.164 cm
Mandrel Dimensions including Insulation t x w	0.257 cm x 11.210 cm
Cable Pitch Angle ϕ	18 Degrees
Cable Pitch Length and Sense 4L	73 cm (plus angle)
SUBCABLE DESCRIPTION	
Configuration	Cable Around A Core
Number of Nb Ti Strands n	6
Subcable Diameter with Insulation $2r_{SC}$	0.6374 cm
Core Strand Diameter with Insulation	0.2238
Pitch Length and Sense	4.670 cm (plus Angle)
Core Strand Material	304 Stainless Steel
Core Strand Diameter Uninsulated $2r_c$	0.2187 cm
Insulation on Core Strands	Omega (Polyester Amide Imide)
Core Strand Insulation Thickness	0.0025 cm

TABLE 3
FINAL STRAND DESIGN

ITEM	VALUE
METALLIC RADIUS* r_s	1.020 mm (0.0402")
WITH INSULATION, r_i	1.034 mm (0.0407")
INSULATION TYPE	OMEGA (POLYESTER AMIDE IMIDE)
INSULATION THICKNESS	0.014 mm (0.0006")
FILAMENT REGION r_f	0.600 mm (0.0236")
FIN THICKNESS t_f	0.064 mm (0.0025")
COPPER SHELL Δr	0.104 mm (0.0041")
STRAND TWIST, L_s	7.72 mm (0.304")
Cu OUTER AREA	1.803 mm^2 (55%)
Cu CORE AREA	0.611 mm^2 (19%)
Cu TOTAL AREA	2.414 mm^2 (74%)
90 Cu 10 Ni AREA	0.335 mm^2 (10%)
Nb Ti AREA	0.520 mm^2 (16%)
METAL WITHIN r_s	3.269 mm^2 (100%)
FILAMENT SIZE d	22.1 μm
NO OF FILAMENTS N_f	1,356
RRR Cu BETWEEN FILAMENTS[1]	90
RRR Cu ELSEWHERE[1]	125
ρ_r, Cu Ni	17 x 10^{-8} Ωm
HELIUM WITHIN CONDUCTOR ENVELOPE	43%
FULLY NORMAL HEAT FROM 2/3 SURFACE	0.26 WATTS/cm^2

[1] 273 K TO 4.2 K

TABLE 3 (CONT'D)
FINAL CONDUCTOR DESIGN AND PERFORMANCE

SUBCABLE DESCRIPTION (CONT'D)	
Nb Ti STRAND OVERALL DIAMETER $2r_i$	0.2068 cm
Nb Ti STRAND INSULATION	OMEGA (POLYESTER AMIDE IMIDE)
Nb Ti STRAND INSULATION THICKNESS	0.0014 cm

THERMOHYDRAULIC DESIGN

It is generally recognized that an efficient method of cooling magnets is immersion or bath cooling. For the pulsed magnet applications, bath cooling is particularly advantageous because it produces the maximum heat capacity per unit volume for storage and subsequent removal of pulsed losses. Pool cooling systems scale to larger size coils very well if proper attention is given to vapor diversion from the magnet interior to prevent vapor accumulation. The operational chararcteristics of the coil must be viewed in light of the coil's ability to meet the design requirements during normal cyclic operation. For the specific case of thermal design, these requirements translate into maintaining adequate conductor cooling. Insurance of conductor cooling margin is contingent on providing satisfactory vapor venting and liquid helium inventory.

The 20 MJ coil is a induction heating NbTi magnet cooled by saturated liquid helium at 4.5 K. The magnetic field changes sinusoidally from +7.5T to -7.5T in 1 second; stays constant at -7.5T for 10 seconds, changes from -7.5T to +7.5T in 1 second and stays constant for 10 seconds to start another cycle.

During the bipolar pulse, 0.31% of the energy stored in the magnet (62 kJ) is dissipated as heat losses to be transferred to the helium in the magnet. The losses depend on both space and time. The inner turns have higher magnetic field and consequently higher losses with a maximum of 0.5 Joules/cm^3 in the innermost turn. For bipolar pulse the power loss has a distribution of $q_m \cos^2 \theta$ where $q_m = 1.0$ W/cm^3 and θ is the time in seconds. The conductor behavior during a bipolar pulse is shown in Figure 4.

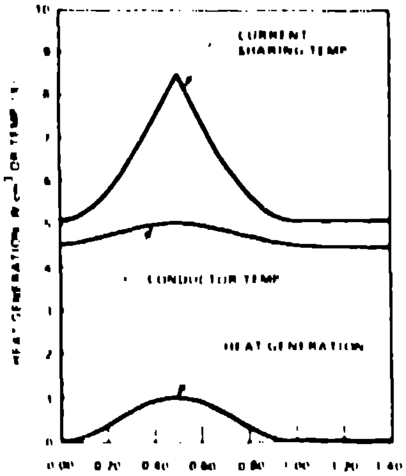

FIGURE 4 CONDUCTOR BEHAVIOR DURING A BIPOLAR PULSE

The heat generation and heat removal curves are shown in Figure 5. At a conductor temperature of 25 K or more, the heat removal is higher than the heat generation and the conductor recovers to the temperature where the heat generation and the removal are equal. Based on the equal area criteria of Maddock, James and Norris[4], the conductor recovers to the superconducting state by the end effects since the area under the heat removal curve is more than the area under the heat generation curve as can be seen from Figure 5.

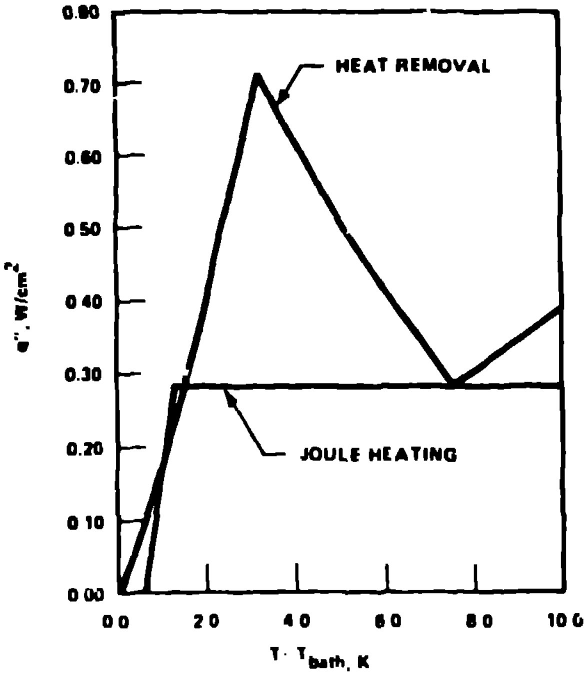

FIGURE 5 20 MJ CONDUCTOR STABILITY

STRUCTURAL ANALYSIS

The structural design considers the conductor forces, the conductor motion, and the conductor cooling.

The design is based on prestressing the superconductor by applying a preload (10,000 lb) during winding because of the difference in thermal contraction between superconductor assembly and the coil former during cooldown. The following structural design criteria was applied:

- The maximum strain in the NbTi superconductor was limited to [illegible].
- The primary stress intensity in the structure was less than 2/3 material yield stress (metallic components) or 40% of the ultimate strength (nonmetallic components).
- The maximum stress theory was used for composite structures.
- The maximum shear theory was used for metallic structure.

The analytical methods used for the 20 MJ were a computer program for stress analysis of nonhomogeneous solenoids (STANSOL), a general purpose finite element code (WECAN), and appropriate hand calculations.

The STANSOL model was used to calculate winding stresses due to preloads, thermal, and magnetic loads. STANSOL considers the coil to be an axisymmetric, multilayered composite with arbitrary distribution of layer thickness and material properties. The materials can be anisotropic. Applied loads include winding preload, differential temperature, electromagnetic body forces, internal pressure and external pressure. References 5 and 6 provide the theoretical basis for the program.

The model was also run to simulate the maximum gradient possible during the cooldown.

The mechanical properties of the conductor were obtained by two means. The radial modulus was determined by ratioing values obtained from a sample conductor which was tested in compression. The hoop modulus was calculated by considering the modulus proportional to the copper-superconductor area modulus product. In addition, the calculations were repeated assuming the hoop modulus to be low. In general, the stresses are higher when the conductor strands carry no load and these are reported in this paper.

The STANSOL model was used to calculate the amount of preload necessary to maintain the winding pack in a state of radial compression. This preload was from 8,000 to 10,000 lbs.

The resulting stresses for each load case has been calculated. Figures 6 shows the conductor mandrel stress under two load conditions. These cases represent the load which exists when the current in the coil is on (preload-magnetic-thermal) and off (preload-thermal). The difference in the levels indicate the change in stress state during pulsing. As can be observed from the curves, the maximum hoop stress in the conductor mandrel is approximately 40,000 psi. This is well within the limits.

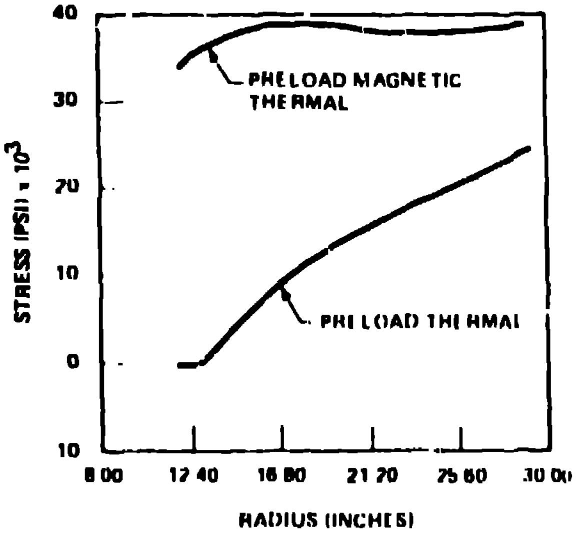

FIGURE 6 CONDUCTOR MANDREL HOOP STRESS

Since there is a difference in tension in each turn of the winding, shear stresses are carried throughout the pancake. These shear stresses were computed by the method given in Reference 6, and are plotted in Figure 7. It was concluded that with 10,000 lb winding tension, no separation of the radial turns will occur during magnetic loading. By comparing the shear load which must be transmitted to that available from the radial pressure and using even a modest friction factor (<0.1) sufficient radial load exists to maintain radial tightness. This also minimizes losses from mechanical hysteresis.

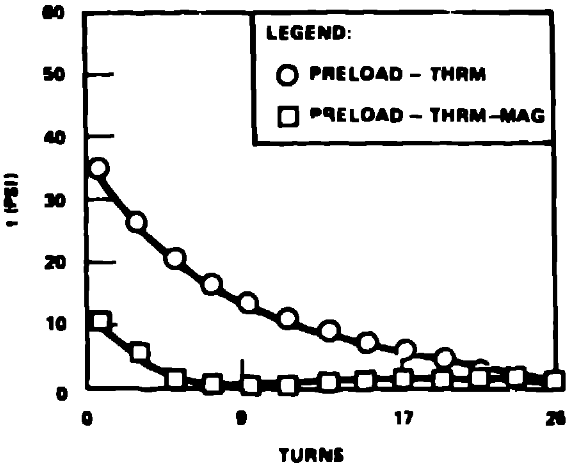

FIGURE 7 SHEAR STRESS IN THE WINDING DURING OPERATION

The displacement of the winding pack has also been calculated and is shown in Figure 8 for the two load cases. The difference between the two curves indicates the displacement the winding undergoes during pulsing. This is approximately 0.02 inches at the outer diameter and 0.025 inches at the inner surface. This is considered small in view of the forces involved, i.e. 2,000 lb/in. radial force at the I.D.

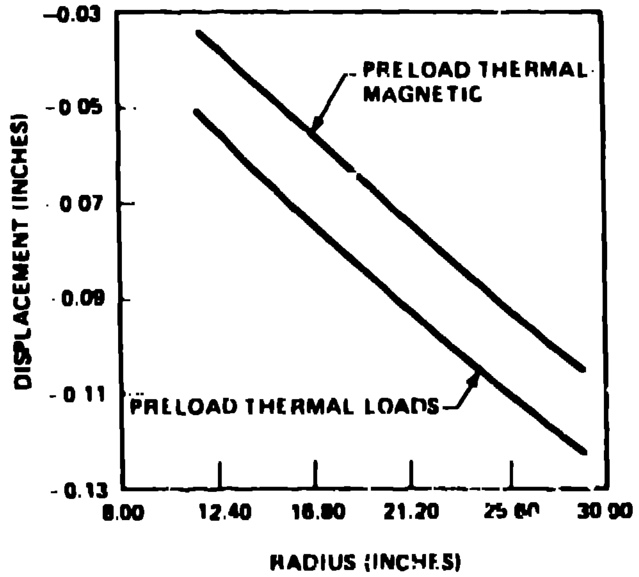

FIGURE 8 WINDING DISPLACEMENT

The stresses in the 20 MJ structure were calculated using the axisymmetric finite element model (Reference 8). Constant strain quadrilaterals were used in the model. The ventilation channels destroy the axisymmetric nature of the plates and cylinders, therefore, at these locations plane stress elements were used. The model contained 2,114 finite elements and 2,373 nodal points. The finite element model was primarily used to analyze stresses and deflections due to axial forces. The radial loads were added for completeness. The model was also used to finalize the necessary bolting pressures, by requiring that all the cylinder-plate interfaces be in axial compression when the magnetic loads were applied. The total axial loads per plate are given in Table 4.

TABLE 4 AXIAL LOADING

PLATE	DIST FROM CENTERLINE (INCHES)	LOAD (POUNDS)
1	3.46	-13[illegible]
2	10.37	-438 240
3	17.28	-801 187
4	25.19	-1 450 406

TOTAL LOAD SYMMETRIC ABOUT COIL CENTERLINE - 2 921 471 LB

The results of the analysis indicated that the stresses are acceptable. Maximum stresses in the G-10CR plates is approximately 10,000 psi. The central support strap is compressed to -50,000 psi.

The coil is capable of operating 100,000 cycles in a full bipolar mode with a 10 second hold time without degrading its performance. During this operation, the coil is subjected to stresses in the stainless steel mandrel, coil former and axial support plates, both mean and alternating. The Goodman diagram was used to calculate the effect of mean stresses on fatigue life.

Linear fracture mechanics analysis were also performed to develop inspection criteria to assure that no defects will propagate to failure during the operating lifetime. Several flaw types were analyzed and a maximum initial flaw size of .04[illegible] inches determined for the mandrel. Critical flaw sizes were in the range of 1.5 inches.

CONCLUSIONS

The overall coil design meets or exceeds all the performance requirements. The design also provides the confidence in application of superconductivity to Tokamak reactors. The structural analysis shows that enough structure is provided to withstand the Lorentz force and the design concept minimizes the conductor motion during coil energization. The design is scalable to an ETF size ohmic heating system because of modular construction and other design features, such as independent cooling of individual pancakes and the conductor support concept.

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