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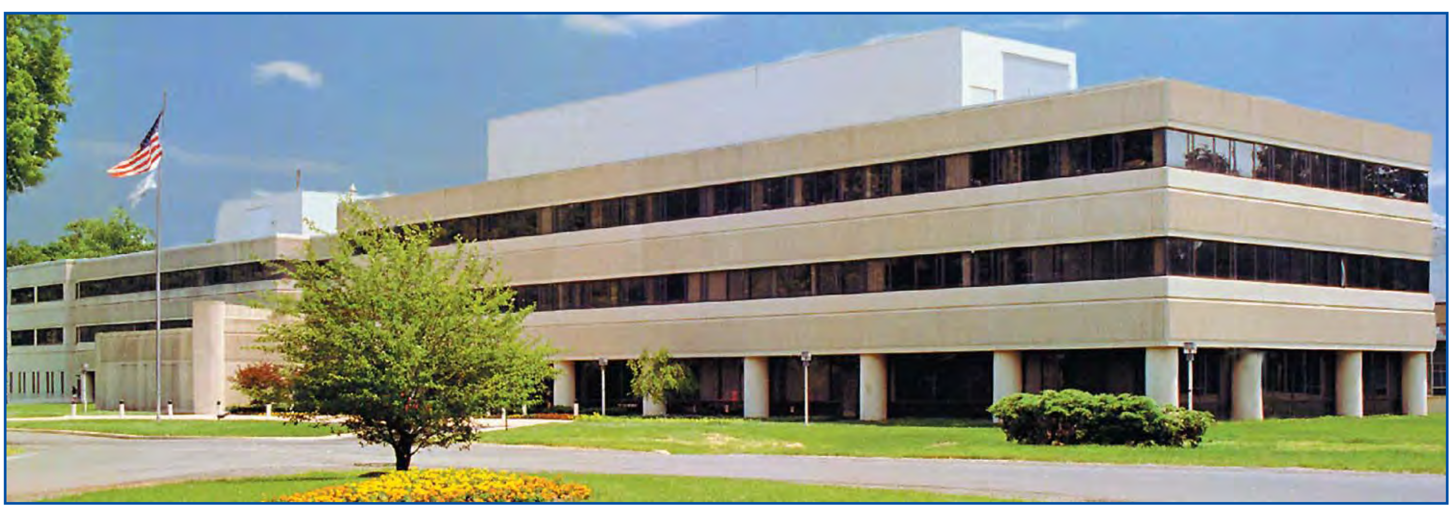

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NCSX Toroidal Field Coil Design

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***Abstract*—The National Compact Stellarator Experiment (NCSX) is an experimental device whose design and construction is underway at the Department of Energy's Princeton Plasma Physics Laboratory (PPPL). The primary coil systems for the NCSX device consist of the twisted plasma shaping Modular Coils, the Poloidal Field Coils, and the Toroidal Field (TF) Coils. The TF Coils are D shaped coils wound from hollow copper conductor and vacuum impregnated with a glass-epoxy resin system. There are 18 identical, equally spaced TF coils providing 1/R field at the plasma. They operate within a cryostat and are cooled by LN2 nominally to 80K. Wedge shaped castings are assembled to the inboard face of these coils so that inward radial loads are reacted via the nesting of each of the coils against their adjacent partners. This paper outlines the TF Coil design methodology, reviews the analysis results and summarizes how the design and analysis support the design requirements**

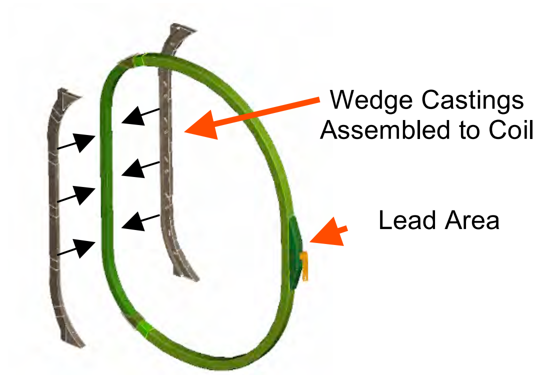
Keywords-Toroidal Field Coil, TF, conductor, NCSX

I. OVERVIEW

The NCSX TF coils are wound from solid copper conductor extruded with a cooling hole and insulated with glass-epoxy and Kapton. The winding pack consists of 12 turns with the conductors arranged 3 by 4. They operate at 80K, cooled by liquid nitrogen, and are electrically connected in series. The D shaped TF Coil's front leg reacts inward radial loads by wedging into the adjacent TF coils. Stainless steel "wedge" castings are adhered to the forward face of the TF coils to transfer these inward loads. The nominal TF coil parameters, conductor dimensions, current rating, and details are described in Table 1 TF Coil Parameters. A diagram showing the assembly of the forward wedge castings is pictured in Figure 1, TF Coil Assembly.

TABLE 1 TF COIL PARAMETERS

Parameter	Unit	Value
Number of TF coils		18
Number of turns per coil		12
Maximum toroidal field at 1.4 m	T	±0.5
Conductor Length	m	107.7
Bundle height	mm	100.8
Bundle width	mm	99.8
Conductor height	mm	18.0
Conductor width	mm	24.5
Cooling hole diameter	mm	8.0
Conductor area	mm2	392
Max current	kA	16



Figur e 1 TF Coil Assembly

II. DESIGN DESCRIPTION

A. *Winding Pack Insulation Scheme*

The TF Coil utilizes a robust insulation scheme to maximize reliability and decrease the chance of electrical breakdown. The TF Coils see a total of 4,000 volts across all 18 coils in series. After applying safety factors this applied overall voltage leads to a turn to turn voltage standoff design requirement of 560 volts and a design voltage standoff to ground of 20.2 KV. The use of both Kapton tape and glass insulation in the turn to turn layers provides a robust voltage standoff of 23 KV turn to turn and between 23 KV and 45 KV (depending on the location on the coil) to ground.

The original insulation scheme included Kapton tape cowound with the glass insulation. Early finite element analysis of the TF Coil found that while stresses were low due to operating loads there was the potential for cracking the turn to turn insulation as the winding pack cools to liquid nitrogen temperatures and contracts. Due to differing coefficients of expansion between the copper and the insulation normal forces manifest themselves separating the glass from the copper surface. Figure 2 (left panel) shows schematically how this thermal mismatch creates high stress in the corners. Testing showed that adhesion of the glass epoxy system to the copper conductor even when various primers were used was inadequate. Figure 2 (right panel) shows a typical copper test sample used to test adhesion at cryogenic temperatures. The insulation scheme was redesigned with the Kapton tape applied directly to the conductor. Analysis showed that by releasing the insulation from the conductor thermal stresses were relieved. Subsequent analysis proved that the stiffness of the coil was still adequate to resist global electromagnetic loads.

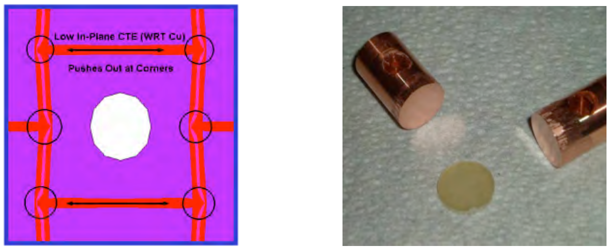


Figure 2 Insulation Contraction & Adhesion Test Sample

B. Wedged Coil Configuration

The TF coils rely on a wedged forward configuration to react inward radial loads. The original TF design incorporated a wider winding pack cross section and had the profile machined into a wedged cross section. While this design had some advantages it also required the machining and re-insulation of the insulated conductor. In the final NCSX assembly the TF Coil is trapped making future repairs very difficult. This makes reliability a primary requirement for the TF Coils. The manufacturing process in which the coil is cut and reinsulated introduced the increased risk of contamination of the dielectric layers. The cross section was redesigned to be a simple rectangular cross section. Separate wedge castings are applied to either side of the coil to obtain the required cross section. This simpler “low tech” solution decreases the risk of latent imperfections causing a TF failure during NCSX operations. Figure 3 shows a cross section of the wedged geometry including the 3 x 4 winding pack and the wedge castings.

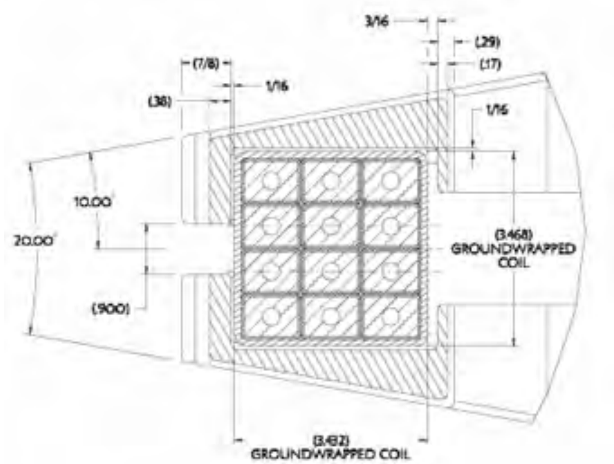


FIGURE 3   TF COIL CROSS SECTION WITH WEDGE CASTING

C. Coil Support Structure

The coil support structure (Figure 4) provides an integrated shell for accurately locating and supporting the TF coils. The structure consists of segmented upper and lower shelf assemblies. The castings have pockets that receive the horizontal legs of the TF coils to provide lateral support for out-of-plane loads. Pads are provided where the lower shelf attaches to the machine base assembly for gravity support; the similar pads on the upper shelf are used for hoisting and rigging during assembly. The upper and lower pads restrain out of plane motion but allow radial growth. Upper and lower cross supports have mounts which fasten to the TF Coil and can be positioned vertically using a jack screw arrangement to achieve the required vertical location within the specified tolerance. Analysis revealed that restraining vertical motion while resulting in higher thermal stresses during temperature excursions led to significantly lower stresses under electromagnetic loading. The TF Coil structure fastens to the modular coil assembly (not shown) which connects the upper and lower shelves. The outboard top and bottom pads (shown in purple) allow for toroidal adjustment.

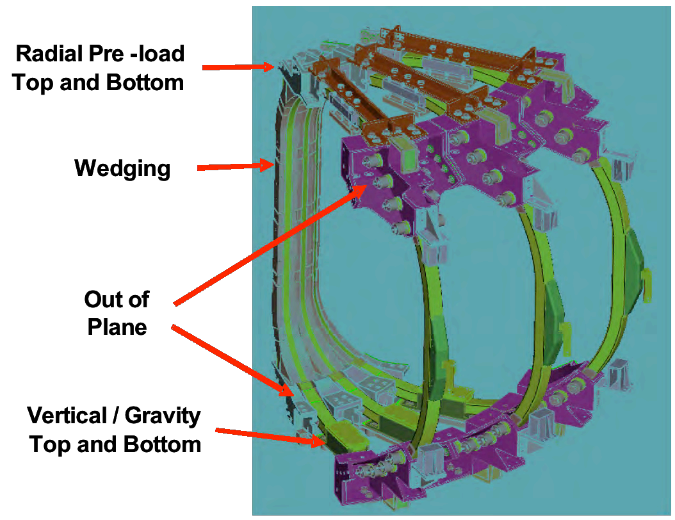


Figure 4   TF Coil Structural Support

Analysis has indicated that at some time points during a TF pulse as the TF Coil current ramps up and interacts with high Modular Coil fields an unstable outward radial load is applied to the TF Coil. In an early design this load was reacted by applying a inboard radial preload on the back side of the TF coil. Further evaluation showed that TF coils stresses were significantly lower if the radial preload was applied at the leading edge of the coil where it can restrain the coil directly. Figure 5 shows the bottom front edge of the wedge casting locked forward by the pre-load stud.

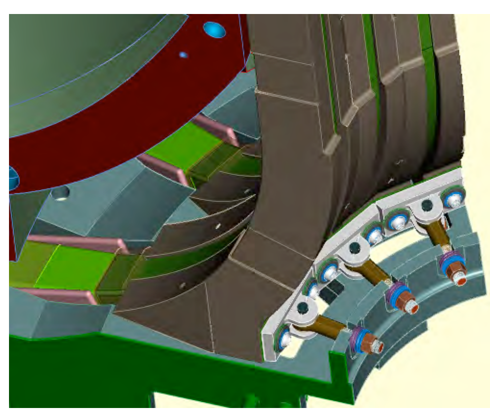


FIGURE 5   RADIAL PRELOAD STUD

III. ANALYSIS

A. Analysis Approach

The TF coils act in concert with the Modular Coils and the Poloidal Field Coils under several required operating scenarios. The modeling of the complete system and various combinations of current profiles is complex and time consuming. To maximize efficiency a combination of simple and more complex models were used to first identify the worst case operating conditions and then to derive accurate deflection and stress results for those conditions. For the coarse evaluation a "Global" coil model (see Figure 6) was created incorporating all coil sets and structure.

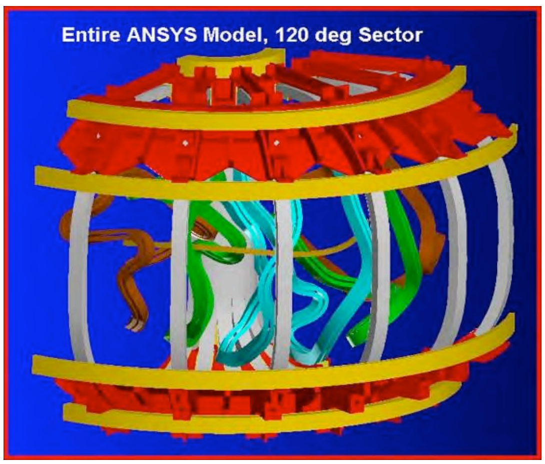


FIGURE 6 "GLOBAL FEA COIL MODEL

The required operating scenarios were examined using the Global model and worst case operating requirements were identified. This model used smeared winding pack properties. To achieve more accurate local stress results a detailed finer mesh model was required. For this a "Hybrid" model was created. The hybrid model meshed one TF coil assembly with the high stress area broken down to the level of conductor and insulation (see Figure 7).

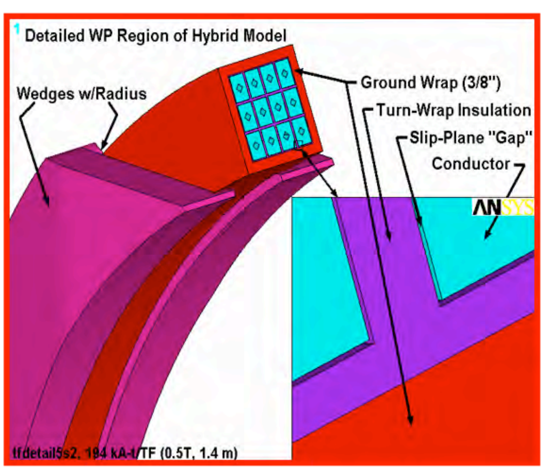


FIGURE 7 "HYBRID" FEA COIL MODEL

Various derivations of these models were necessary to examine local effects such as loads required to prevent de-wedging, thermal growth effects, and coil deflection as they effect plasma perturbations. Additional models were created to evaluate the lead stem area.

B. Lead Stem Design / Analysis

Preliminary design of the lead stem area had the coil leads being bent directly out of the winding pack and support by G11 and glass epoxy fillers. This approach was meant to simplify the design and reduce the overall number of conductor brazes. When analyzed the stresses at the bend in the conductor exceeded design allowables (see Figure 8 left panel). This was primarily the result of applying the Kapton insulation directly to the conductor and not taking any credit for the shear strength of that interface. To resolve this issue a lead spur was added. Cut from a solid plate of copper and gun drilled to provide the cooling hole the lead spur has a more robust cross section to react the bending moments. (see Figure 8 right panel).

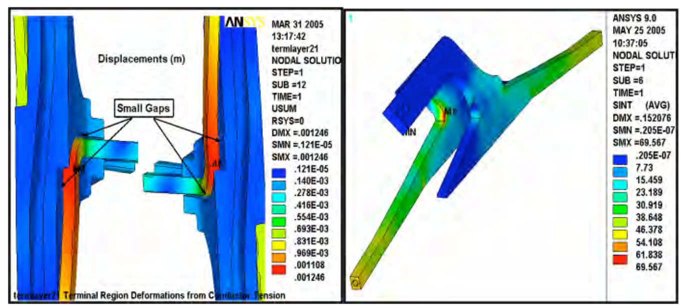


FIGURE 8 LEAD STEM ANALYSIS

This lead spur is brazed to the conductor ends and built into the coil assembly with interlocking G11 blocks before the entire assembly is vacuum impregnated with epoxy. The G11 blocks grab the opposing lead spurs and transfer the electromagnetic loads in shear across from one lead to the other eliminating the reliance on the shear strength of the epoxy glass interface (see

Figure **9**). The resulting design significantly lowered stresses in both the conductor and the insulation.

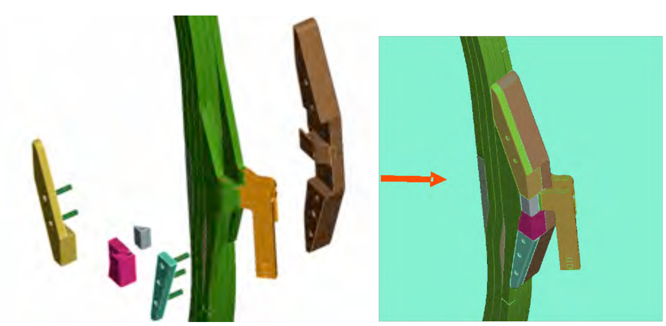


FIGURE 9 LEAD SPUR ASSEMBLY

C. Cooling Analysis

Cooling is achieved using forced flow LN2 with a prescribed inlet temperature of 80 K. A transient analysis was performed to determine the thermal response of the TF Coils to a maximum required pulse (0.5 Tesla TF field). The peak conductor temperature rise was 8.5 ^{o}K for a 16.2 kA peak current with a 1.64 second equivalent square wave. The thermal recovery time was roughly 720 seconds providing a margin of 180 seconds for the stipulated duty cycle of 900 seconds (15 minute rep. rate). This performance was obtained with a 60psi pressure drop across the coil resulting in a flow of 1.6 GPM per TF coil.

IV. Prototype Testing

To validate the design and analysis of the insulation scheme and winding pack a prototype testing program was undertaken at ORNL. The testing had two goals. The first goal was to compare the stiffness of the coil calculated in the analysis to the stiffness of a scale prototype and validate the finite element analysis results. The second goal was to demonstrate that the design was resilient enough to survive fatigue testing both mechanically and electrically.

A. Prototype Bar and Test Setup

The prototype bar was fabricated from copper bars machined to the proper cross-section. The bars were wrapped in Kapton tape and S-Glass mimicking the TF Coil insulation design. Arranged in a 3x4 by 42 inch long pattern the conductor assembly was ground wrapped with 3/8 inches of glass. The ends of each conductor were extended with G10 plugs with the turn to turn insulation wrapped over these plugs. This allowed for high voltage testing of the assembly after completion without arcing at the ends. The entire assembly was then vacuum impregnated using CTD 101K epoxy, the same method proposed for the TF coil (see Figure 10)

Figure 10 Prototype Bar In Test Fixture

A 3 point bending load train was constructed for testing the TF Coil prototype bar. Figure 11 shows the general setup of the loading scenario. An MTS tensile testing machine was used as the pulling apparatus. The test beams were suspended from four rods that connect to an I-beam which was placed atop the MTS machine. Five LVDTs were placed along the length of the testing beam to measure the deflection at the ends quarter points and the middle of the span

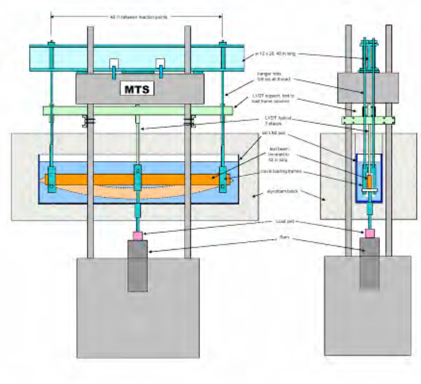


Figure 11 Test Equipment

B. Prototype Test Results and Evaluation

Two TF Coil beam specimens were tested for approximately 140,000 and 260,000 cycles for beams 1 and 2 respectively. Both survived and did not experience a critical fracture during the fatigue loading. Both beams were tested at room temperature and at cryogenic liquid nitrogen temperatures (-193 C). The loads chosen for the testing were based on an FEA analysis of the test bar that determined the loading required to induce a stress equivalent to that of the actual TF coil under its highest loading scenario. The fatigue testing of the bars corresponded to two times life at stress as well as a one times life at two times stress demonstrating that the winding pack design meets the project fatigue criteria. The results of the test demonstrated that the winding pack design met the required criteria. The stiffness of the winding pack fell within the expected calculated range and after fatigue cycling did not degrade. Subsequent high voltage electrical testing of the winding pack demonstrated that fatigue cycling did not damage the dielectric standoff capability of the ground wrap and the turn to turn insulation validating the winding pack design.

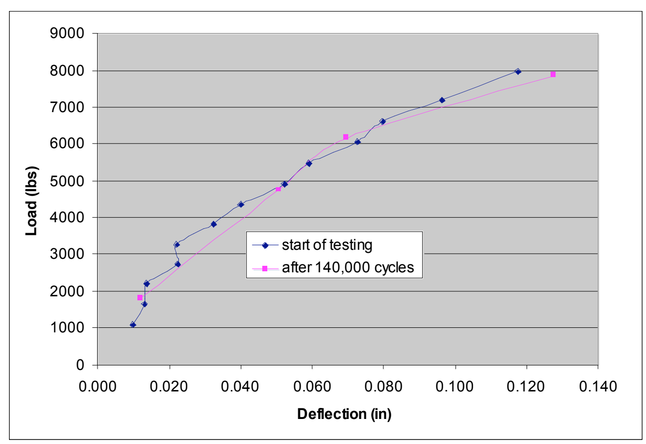


Figure 12 Load vs Deflection Before and After Cycling

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