PPPL- 4806

PPPL- 4806

TF Inner Leg Space Allocation for Pilot Plant Design Studies+

Peter H. Titus and Ali Zolfaghari

September, 2012

Princeton Plasma Physics Laboratory
Report Disclaimers

Full Legal Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Trademark Disclaimer

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors.

PPPL Report Availability

Princeton Plasma Physics Laboratory:

http://www.pppl.gov/techreports.cfm

Office of Scientific and Technical Information (OSTI):

http://www.osti.gov/bridge

Related Links:

U.S. Department of Energy

Office of Scientific and Technical Information

Fusion Links

TF INNER LEG SPACE ALLOCATION FOR PILOT PLANT DESIGN STUDIES+

Peter H. Titus, Ali Zolfaghari

Princeton Plasma Physics Laboratory, Princeton, NJ 08543-0451 USA
ptitus@pppl.gov

A critical design feature of any tokamak is the space taken up by the inner leg of the toroidal field (TF) coil. The radial build needed for the TF inner leg, along with shield thickness , size of the central solenoid and plasma minor radius set the major radius of the machine. The cost of the tokamak core roughly scales with the cube of the major radius. Small reductions in the TF build can have a big impact on the overall cost of the reactor.

The cross section of the TF inner leg must structurally support the centering force and that portion of the vertical separating force that is not supported by the outer structures. In this paper, the TF inner leg equatorial plane cross sections are considered. Out-of-Plane (OOP) forces must also be supported, but these are largest away from the equatorial plane, in the inner upper and lower corners and outboard sections of the TF coil. OOP forces are taken by structures that are not closely coupled with the radial build of the central column at the equatorial plane. The "Vertical Access AT Pilot Plant" currently under consideration at PPPL is used as a starting point for the structural, field and current requirements. Other TF structural concepts are considered. Most are drawn from existing designs such as ITER's circular conduits in radial plates bearing on a heavy nose section, and TPX's square conduits in a case, Each of these concepts can rely on full wedging, or partial wedging. Vaulted TF coils are considered as are those with some component of bucking against a central solenoid or bucking post. With the expectation that the pilot plant will be a steady state machine, a static stress criteria is used for all the concepts. The coils are assumed to be superconducting, with the superconductor not contributing to the structural strength. Limit analysis is employed to assess the degree of conservatism in the static criteria as it is applied to a linear elastic stress analysis. TF concepts, and in particular the PPPL AT PILOT plate concept are evaluated based on amount of space needed for structure and the amount of space left for superconductor.

I. INTRODUCTION

A critical design feature of any tokamak is the space taken up by the inner leg of the toroidal field (TF) coil. The radial build needed for the TF inner leg, along with shield thickness , size of the central solenoid and plasma minor radius set the major radius of the machine. The cost of the tokamak core roughly scales with the cube of the major radius. Small reductions in the TF build can have a big impact on the overall cost of the reactor.

The cross section of the TF inner leg must structurally support the centering force and that portion of the vertical separating force that is not supported by the outer structures. In this paper, the TF inner leg equatorial plane cross sections are considered. Out-of-Plane (OOP) forces must also be supported, but these are largest away from the equatorial plane, in the inner upper and lower corners and outboard sections of the TF coil. OOP forces are taken by structures that are not closely coupled with the radial build of the central column at the equatorial plane. The "Vertical Access AT Pilot Plant" currently under consideration at PPPL is used as a starting point for the field and current requirements. Figure 1 shows the TF coil and structure proposed for the PPPL Pilot plant concept. Results for two analysis models are presented in this paper. A 3D model of a 30 degree sector was built from the CAD model (right in figure 1) of the coil and structure. The 3D model uses a "smeared" property winding pack. A 2D model is also used to investigate the details of the conductor and winding pack cross sections.

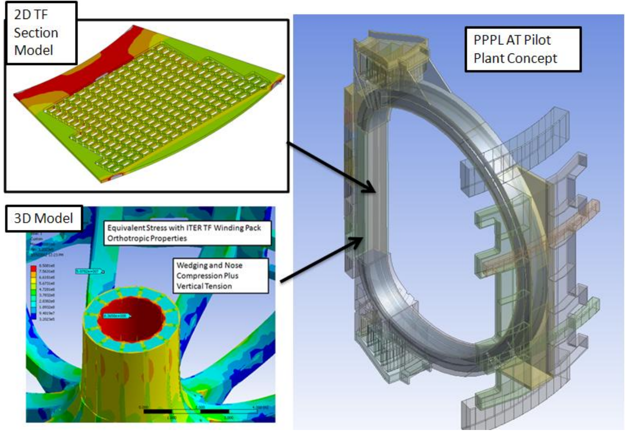


Fig. 1. Results for 2D and 3D models of the PPPL AT Pilot Plant Considered in this Paper.

Other TF structural concepts are considered. Most are drawn from existing designs such as operating and proposed copper tokamaks, and proposed superconducting reactors. ITER's TF employs circular conduits in radial plates bearing on a heavy nose section. , TPX and KSTAR use square conduits in a case. The PPPL AT concept uses a cased rectangular cable in conduit conductor (CICC) with a heavy nose section that supports most of the wedging or vaulted stress. Each of these concepts can rely on full wedging, or partial wedging. Vaulted TF coils are considered as are those with some component of bucking against a central solenoid or bucking post.

With the expectation that the pilot plant will be a steady state machine, a static stress criteria is used for all the concepts. The coils are assumed to be superconducting, with the superconductor not contributing to the structural strength. Static criteria are usually based on linear elastic analysis and the allowables are compared with stress components that are identified with types of loading. Characterization of stresses from a complicated finite element geometry requires judgment and understanding of how loads are being carried, and what portions of the structures are carrying them. Limit analysis is used to help in understanding the margin in a proposed design. A more accurate assessment of the margin allows a re-optimization of space allocated to structure and superconductor.

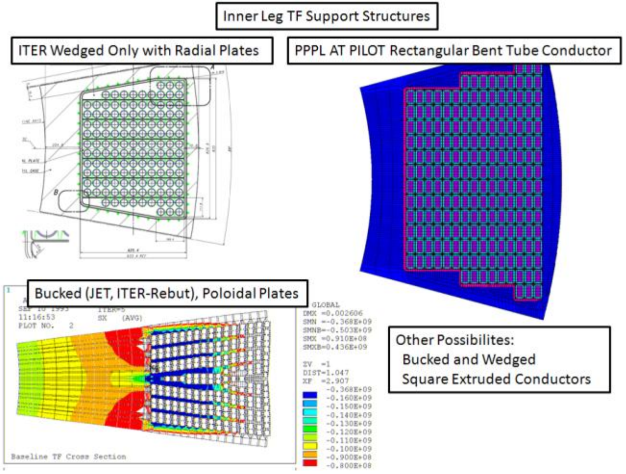


Fig. 2. Two ITER Concepts and the AT PILOT Concept

II. TF BASICS

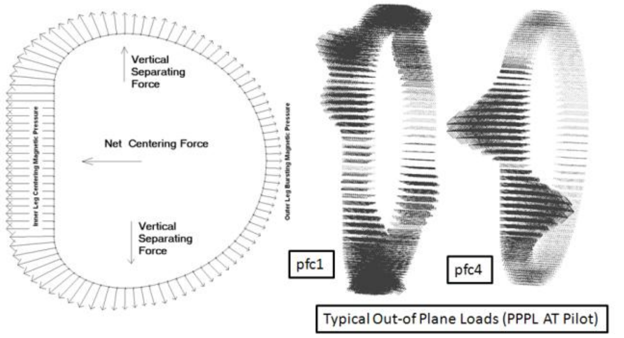


Fig. 3. Loads on a Tokamak TF Coil.

Loads on the TF coil result from the cross product of the toroidal field and currents in the coil. outward Lorentz loads result. They are analogous to a bursting pressure in a pressure vessel. The toroidal field and thus the local magnetic pressure is proportional to 1/r inside the bore of the TF coils. Magnetic pressures at the top and bottom of the coil integrate to vertical separating forces. The inner leg magnetic pressure integrates to a centering force on the inner leg. Loads on the left in figure 1 are considered "in-plane" loads. There are out-of-plane loads as well that result from the interaction between the TF currents and PF fields. For the discussions in this paper, these are the primary loads. Bursting pressures and net centering loads have analogs in mechanical design codes such as the ASME boiler and pressure vessel codes.

III DISCUSSION OF ALLOWABLES

For a Pilot plant or DEMO it is assumed that some form of steady state current drive will be achieved. A practical reactor cannot be pulsed, or at least it would have to have extremely long pulses. For coil design, this means that the failure mechanism will not be fatigue. For ITER and other near term experimental reactors, fatigue life limits the design. The ITER Magnet Criteria[3] is constructed around the expectation that cyclic loading will dominate the stress evaluation.

Without fatigue driving the design, then static stress limits will govern. These are built off of a primary membrane allowable which in fusion magnet codes is taken as the lesser of 2/3 yield or 1/2 ultimate[2,3] . The 1/2 ultimate replaces 1/3 ultimate in the ASME code, and this relaxation of criteria comes with some additional considerations of the ductility of the conductor material and how much the conductor is required to support loads.

For the inner leg of a TF coil, the stress in the coil case and/or winding derives from the compressive force from the magnetic pressure and the bursting tension from the vertical separating force. Equivalent stresses, Tresca and Von Mises which are compared with the allowable stress,are a function of the difference between stress components.

The amount of vertical tension supported by the inner leg is determined by the stiffness of the outer structures. In a constant tension D TF coil, the tension in the whole winding is constant and is is a function of the radial positions of the inner and outer legs of the TF - assuming the winding and the case stiffnesses is the same around the perimeter of the coil. Typically the outer structures are heavier components intended to support the out-of plane loads while allowing access to first wall and blanket components. If structures are selected that preferentially distribute the vertical separating force to the outer structures, then the primary loading in the inner leg can be considered only the centering load. This approach is employed in C-Mod and in FDF which use joints to allow the horizontal legs to move vertically. The vertical loads from the horizontal legs are then transferred to large covers and external shell structures. A jointed approach is challenging for normal conductors, but it also is being considered for VULCAN which uses high temperature superconductors.

FIRE was reactor concept that did not use joints, but much of the vertical separating force was distributed to the outer structures. This was augmented with a preload ring that afforded some initial vertical compression. The IGNITOR external ring is sized and positioned to introduce more vertical preload compression by a "pinching" action on the external support forging. Preload systems are difficult to implement ion copper machines because the thermal expansion from the resistive heat-up can overload the preloaded inner leg in compression - especially at the end of a pulse where the bursting tension is lost. Superconducting machines (with good quench protection) do not have significant thermal expansion during operation.

The goal then is to restrict the primary loading of the inner leg to be the compressively supported centering force, reduce the tensile part, and thus reduce the equivalent stress.

IV. STRUCTURAL CONCEPTS

III.A. Inner Leg Centering Force Concepts

Wedged (ITER, FIRE)
The TF inner legs form a "vault" or keystone wedged segments to resist the centering load

Bucked: (JET, Early Rebut era ITER)
In this concept the inner leg bears against a central solenoid and/or a bucking cylinder. This usually has better TF stresses because it supports the magnetic pressure without the wedged R/t multiplier.

Bucked and Wedged: (IGNITOR)
In this concept the compressive stresses are lower because two directions are used to resist the inner leg -

The downside for a bucked configuration is that it is tough to support OOP loads and the TF will twist the CS For the bucked and wedged configuration, fit-up is an issue, and it is uncertain much wedges and how much bucks.

III.B.Vertical Separating Force Concepts

Use of Heavy External Structures:

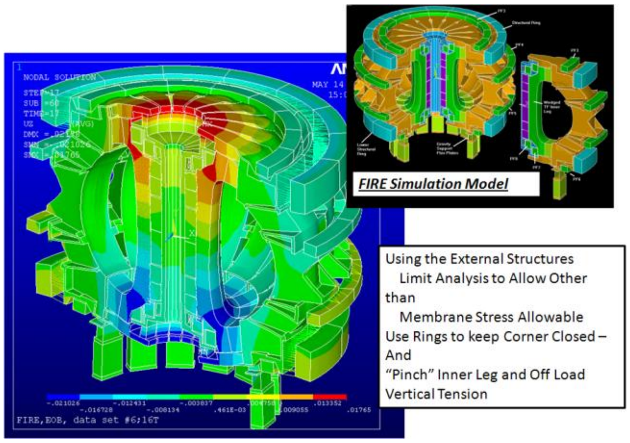
Use of TF Compressive Preload:
This offsets the tensile stress from the bursting pressure - and reduces the difference between the tensile stress and any compressive component from bucking or wedging

Sliding Joints:
This is intended to off-load the inner legs of most of the vertical separating force, but this requires sliding joints which are difficult to cool in copper magnets and are very difficult for superconducting systems.

V LIMIT ANALYSIS

Structural codes like ASME require the analyst to characterize stresses into their functional significance. Primary membrane stresses are those stresses that resist (for a pressure vessel) a bursting load, and must be compared with primary membrane allowables. Bending stresses are those that must resist bending collapse and are compared with bending stress allowables. It is often difficult to characterize stresses in a finite element result. One approach is to process a section, linearizing the stress distribution and identifying the average as the membrane and the linear components as bending, plus membrane, and the deviation from linear distribution ass the discontinuity or secondary stress. This approach requires a lot of judgement with a good understanding of how the loads are being supported. An alternative is to perform a limit load analysis and investigate how much lmargin is in the strucdture with respect to its design loads. This is discussed in the NSTX structural criteria:

"An exception to this elastic analysis approach can be when the nature of the structure and its loading make it difficult to decompose the stresses into the above mentioned categories. In such an instance, a detailed, non-linear analysis that accounts for elastic-plastic behavior, frictional sliding and large displacement shall be used to determine the limit load on the structure [Ref. 12]. The limit load is that load which represents the onset of a failure to satisfy the Normal operating condition as described in Section I-2.6. The safety factor of limit load divided by the normal load shall be greater than 2.0."



Using the External Structures
Limit Analysis to Allow Other than
Membrane Stress Allowable
Use Rings to keep Corner Closed – And
"Pinch" Inner Leg and Off Load Vertical Tension

Fig. 4. FIRE Structural Analysis

This procedure in the NSTX criteria is derived from work done for FIRE, in which the vertical separating forces were taken primarily by the outboard structures and as the limit loading was approached the inner leg shed load to the stiffer outer structures

VI 3D ANALYSIS OF PPPL AT PILOT PLANT

The TF structure of the AT PILOT plant design being studied at PPPL, was analyzed using MAXWELL for the field and force calculation and then transferred to WORKBENCH for structural analysis. The analysis included in-plane TF loads. a 30-degree slice of the reactor with one TF coil is modeled. Cyclic symmetry is applied. The TF current is = 10MA per leg PF &OH Currents were provided by C. Kessel from a TSC code analysis

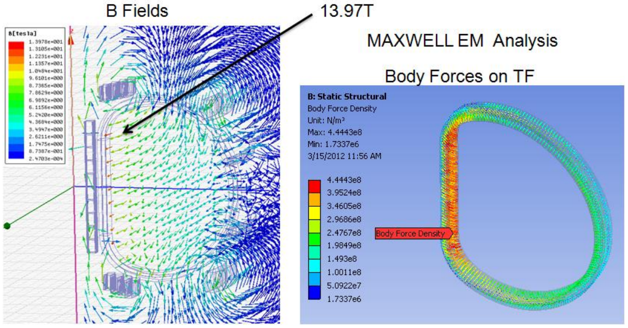


Fig. 5. MAXWELL Field and Force Results

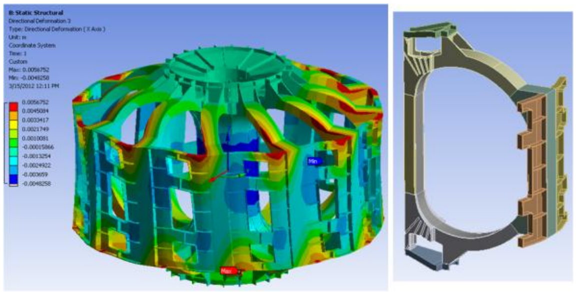


Fig. 6. OOP Displacements

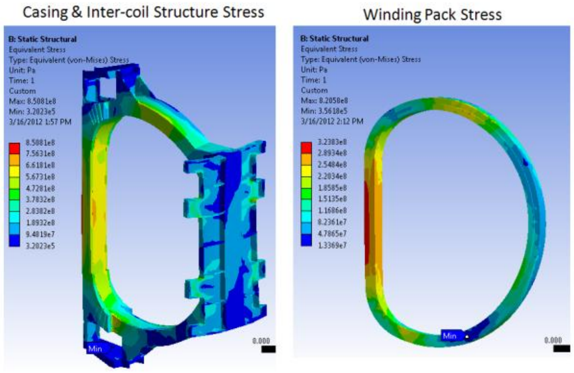
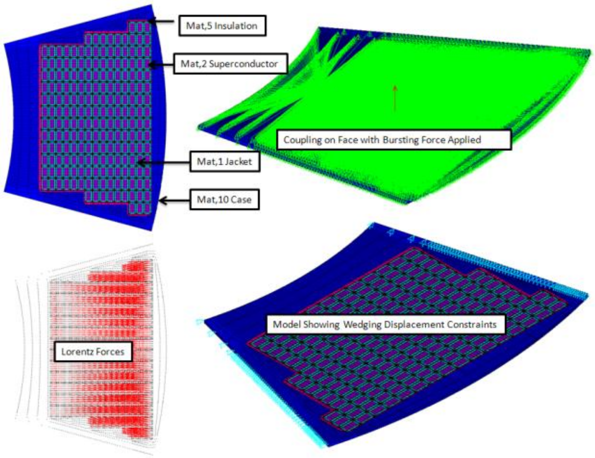


Fig. 7. Case and Winding Pack Stresses from the 3D Model

VII 2D ANALYSIS OF INNER LEG TF CROSS SECTION

VII.A. Modeling



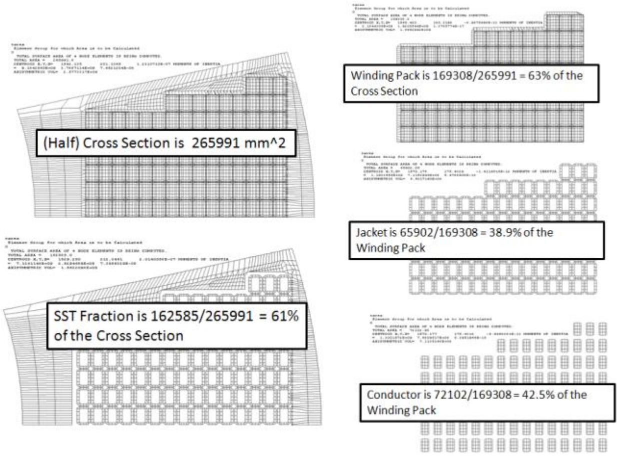


Fig. 8. Area Percentages in the TF Cross Section Considered In this Study

VII.A. Wedged Results

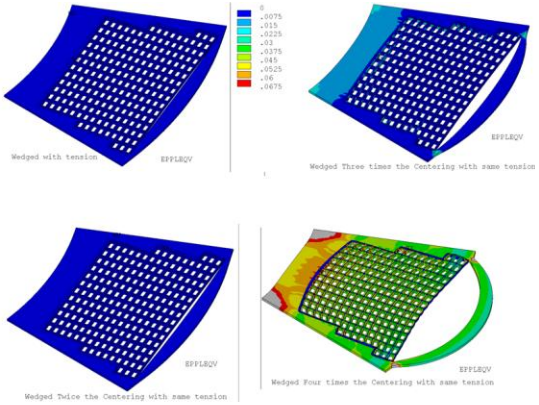


Fig. 9. Displacement Results

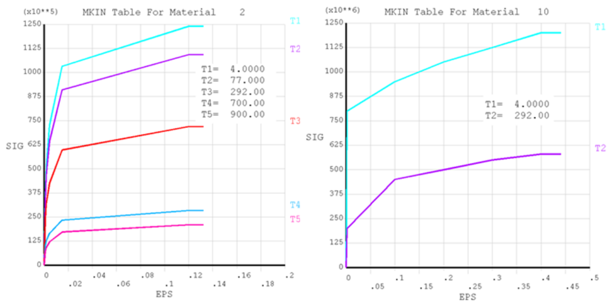


Fig. 10 Stress Strain Curves Used in the Limit Analyses

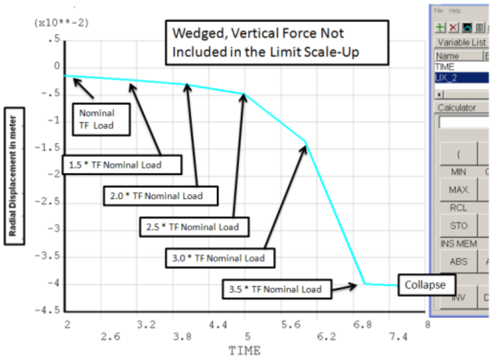


Fig. 11. Radial Displacement vs. Load Factor for a Wedged Configuration in which only the Centering Force is Scaled

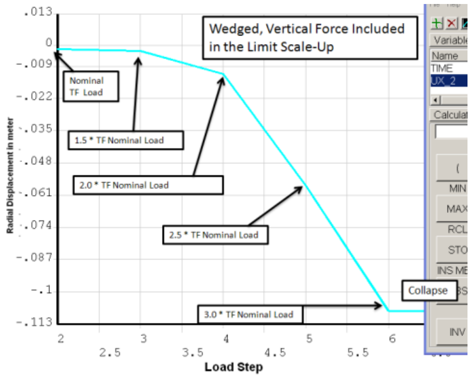


Fig. 12. Radial Displacement vs. Load Factor for a Wedged Configuration in which the Vertical and Centering Forces are Scaled.

VII.C. Bucked Results

The bucked option was modeled with simple radial restraints at the nose, modeling an infinitely stiff bucking cylinder. The result is that the inner leg cross section has a very high limit load. The collapse mode of a bucked configuration would actually be the collapse of the bucking cylinder or central solenoid.

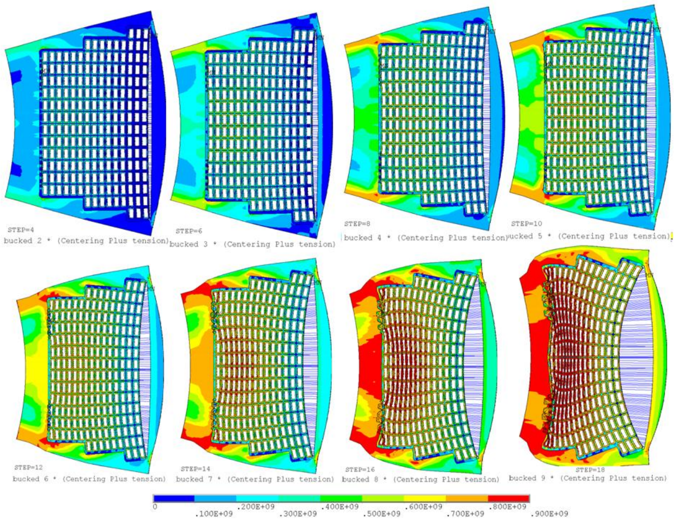


Fig. 13. Von Mises Stress and exaggerated displacecment plot (DSCALE,1,20) vs. Load Factor for a Bucked Configuration in which the Vertical and Centering Forces are Scaled

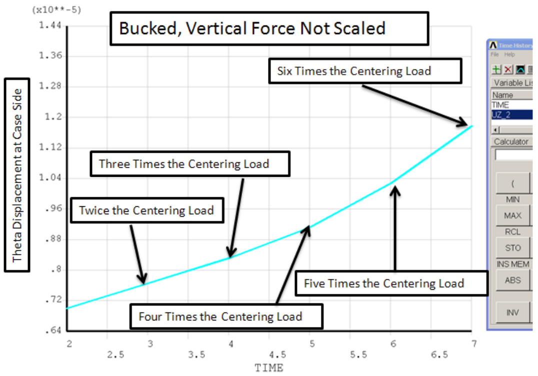


Fig. 14. Toroidal Displacement vs. Load Factor for a Bucked Configuration in which the Vertical and Centering Forces are Not Scaled

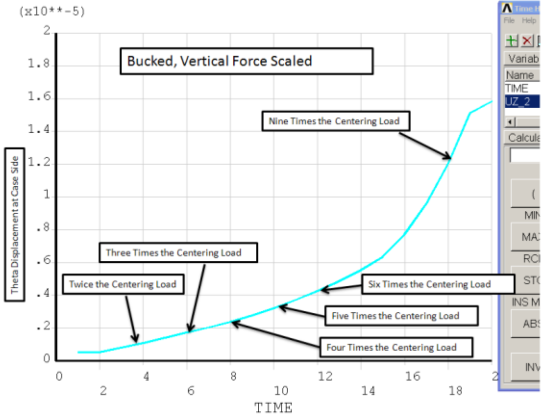


Fig. 14. Toroidal Displacement vs. Load Factor for a Bucked Configuration in which the Vertical and Centering Forces are Scaled

TABLE I. LIMIT ANALYSIS LOAD FACTORS

	Only Centering Force Scaled	Centering and Bursting Force Scaled
Bucked	>6	>9.5
Wedged	3.5 to 4	3

In all cases the cross section satisfies the required factor of safety of 2.0. The nose thickness was sized based on the 2/3 yield stress limit, but based on a limit analysis the thickness of the nose section could be reduced, and if some care is taken to have the outer structures take most of the vertical separating load, the nose section could be reduced still further.

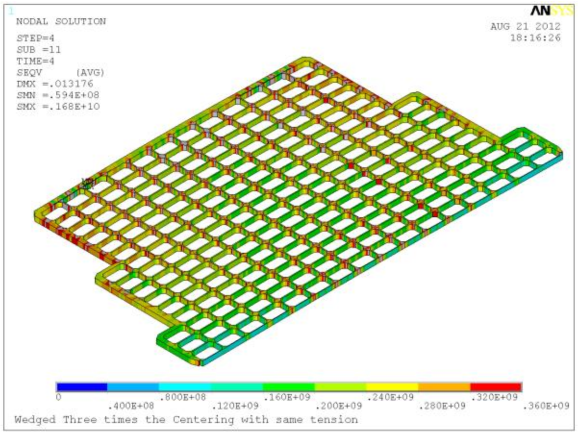


Fig. 14. Insulation Stress at 3.0 Times the Nominal TF Centering Force.

To rigorously address the proposed criteria, the point at which the coil would be assumed to fail should address behavior other than just structural collapse. If the insulation is stressed beyond it's strength, then coil failure would be defined by an electrical failure resulting from breakage of the insulation. The 2D model was checked at the load factor of 3.0 and most everywhere the stress is below 340 MPa. There are some local spikes that are higher but these result from finite element modeling anomalies and very localized crushing and shear bond failures that would not effect the insulation boundary.

TABLE II. INSULATION STRENGTHS[4]

	@4 degK	@292 degK
Comp.Strength	Normal to	Fiber
G-10CR	749	420 Mpa
Tensile	Strength	(Warp)
G-10CR	862	415 MPa
Tensile	Strength	(Fill)
G-10CR	496	257 MPa

VIII. CONCLUSIONS

The static stress criteria applied to the inner leg of the TF coil of a PILOT or DEMO reactor concept has a significant effect on the reactor sizing. Relaxation of fatigue criteria for non cyclically loaded coils allows higher stresses but the static criteria based on a margin against failure must be retained. Use of limit analysis allows the coil sizing to be based on a margin against structural collapse or failure of the functional requirements of the coil.

Use of heavy external support structures to support most of the vertical separating force allows the primary load to be the compressively supported inner leg centering force. For the primary stress in the inner leg cross section the membrane allowable stress based on 2/3 of yield stress or 1/2 ultimate is recommended. Limit analysis is encouraged to demonstrate a margin of 2 against failure mechanisms identified for the coil Limit analysis applied to the PPPL AT PILOT TF Inner leg cross section

ACKNOWLEDGMENTS

*This work is supported by US DOE Contract No. DE-AC02-09CH11466

REFERENCES

1. COMPARISON OF OPTIONS FOR A PILOT PLANT FUSION NUCLEAR MISSION, T. Brown et. al., This Conference
2. NSTX (NATIONAL SPHERICAL TORUS EXPERIMENT) STRUCTURAL DESIGN CRITERIA NSTX-CRIT-0001-01 February 2010 I. ZATZ, EDITOR
3. "Magnet Structural Design Criteria Part 1: Main Structural Components and Welds" IDM UID 2FMHHS. C. Jong, A. Alekseev, N. Mitchell.
4. "Mechanical, Electrical and Thermal Characterization of G10CR and G11CR Glass Cloth/Epoxy Laminates Between Room Temperature and 4 deg. K", M.B. Kasen et al , National Bureau of Standards, Boulder Colorado

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2245
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov