Princeton Plasma Physics Laboratory

PPPL-5126

NSTX U Construction Related (Title III) Analysis Issues

Peter H. Titus, L. Dudek, M. Smith, A.Brooks

July 2015

PRINCETON PLASMA PHYSICS LABORATORY

Prepared for the U.S. Department of Energy under Contract DE-AC02-09CH11466.

NSTX U Construction Related (Title III) Analysis Issues

Peter H. Titus, L. Dudek, M. Smith, A.Brooks

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

The NSTX Upgrade is currently under construction and is scheduled to start operations early in2016. Upgrade designs were analyzed and qualified prior to the beginning of construction, but many issues arose during manufacture and assembly that required adjustments in design and analysis of components. Some designs relied on testing that occurred after final design when the actual material and processes were selected by vendors or in-house shops. Design of some components, like the bus bars was deferred until field run interferences could be identified. Some components used materials that did not meet original specifications. New materials or processes had to be found and components sometimes needed requalification. Cognizant Engineers (COG;s) and analysts worked closely to work out resolution of issues and perform redesign and reanalysis. Revisions to calculations were prepared and filed Some significant items addressed in the Title III effort are selected for more detailed discussion.

I. INTRODUCTION

The NSTX Upgrade is completing construction and is scheduled to start operations early in 2015.The Upgrade project status was discussed in another paper at this conference [1] Upgrade designs were analyzed and qualified prior to the beginning of construction, but many issues arose during manufacture and assembly that required adjustments in designs and analyses of components. Some designs relied on testing that occurred after final design when the actual material and processes were selected by vendors or in-house shops. Design of some components, like the bus bars was deferred until field run interferences could be identified. Some components used materials that did not meet original specifications. New materials or processes had to be found and components sometimes needed requalification. Major items addressed in the Title III effort are shown in figure 1 These included connections between the TF flex and outer TF legs, PF 4 and 5 support details that interfered with diagnostics, small ports re-positioned because of the structural reinforcements in the vessel,. passive plates interference with diagnostics, small port penetration of the vessel for diagnostic re-positioning, PF1c mandrel and heat shield design, fitting RWM coils around the larger modified vessel ports, among other issues

II EXAMPLES
II.A PF1c Mandrel Outer Shell and CHI Heat Loads

The PF1c case forms one of the boundaries of the CHI gap. The gap, shown in figure 2, can be exposed to plasma radiation and particle flux. Potentially heat flux can be applied to tiles in the gap and to the PF1c case. An outer shell of the PF1c mandrel was used for the coil VPI and was sealed with O ring seals.

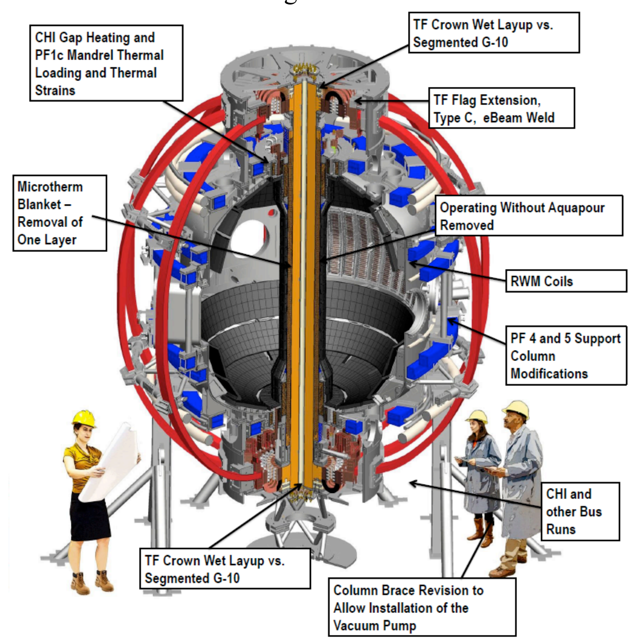

Fig. 1. NSTX Upgrade Machine with Title III Issues Noted

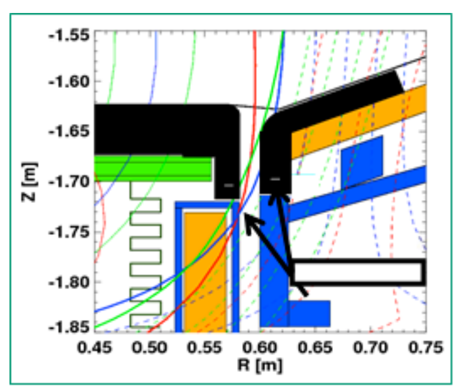

Fig. 2. Possible Flux Lines Intercepting the (lower) PF1c Case

The O ring seals were replaced with a vacuum seal that is the vacuum boundary for the plasma chamber. Thus the integrity of this seal weld is an important component in the reliable operation of NSTX-U. The outer shell of the mandrel is loaded by coil thermal motions and Lorentz forces shown in figure 3. In addition the shell can see heating from the plasma, A thermal shield was recommended for the CHI gap to protect the mandrel shell, but time and budget constraints dictated omission of the shield. A thermocouple near the corner of the case was added. This is shown in figure 4 along with the Silicon band that assists centering of the coil when it expands away from the inner mandrel surface. A best effort assessment of the heat loads and mandrel shell stresses dictate restriction of operations that have heat loads that enter the CHI gap [3]. The PF1c mandrel outer shell closure weld design details evolved based on analysis and benchtop welding tests performed to find weld details with good fatigue life and limited heating of the coil epoxy.

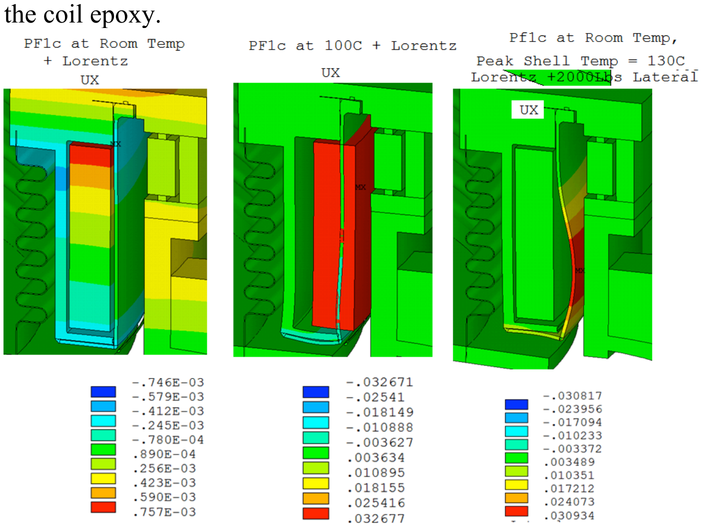

Fig. 3 PF1c (Upper) Exaggerated Displacement

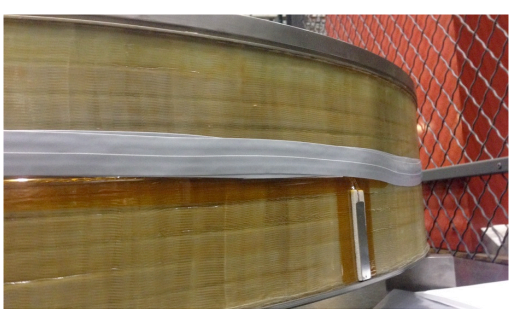

Fig. 4 PF1c coil with Silicon rubber centering band and thermocouple.

II.B PF 4 and 5 Support Column Modifications

During installation of the columns, interferences were found with the diagnostic components that could be remedied with small changes in positions of the columns. Both radial and toroidal shifts were considered. The radial shift was taken by a little extra bending of the support column.

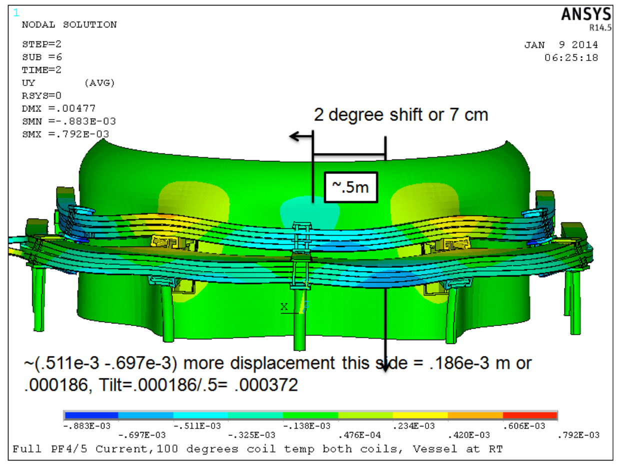

Fig. 5. PF 4 and 5 Supports with a Toroidal Shift

To evaluate the toroidal shift, a 2 degree or 7cm shift was modeled [4]. The concern is that the asymmetry in the load on either side of the sliding mechanism might cock or bind the sliding dovetail. The rotation of the dovetail due to the rotation of the coil with an uneven support caused dovetail displacements less than the clearance of the sliding "foot" it its slot.

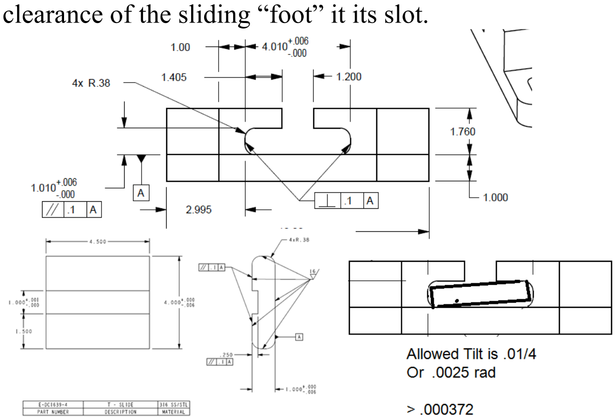

Fig. 6. Geometry of the PF 4 and 5 Dovetail sliding supports and estimate of Locking angle

II.C TF Flag Support Fingers

The finger details provide support for the outer TF flag connections. They are cyclically loaded as the TF and PF fields are pulsed. The finger details were intended to be machined from a solid. The finger material specified was originally Inconel 718. This is expensive both in terms of material and in the machining costs. It was proposed to weld the finger tabs and then finish machine where needed. Lastly, a final heat treat was done to restore the strength of the 718. The original analysis model and files, were queried and the stresses in the local areas of the fingers, where welds are proposed, could be investigated. There were high stresses at the radii at the roots of the tabs. They had been machined radii but in the new design, the radii became fillet welds over full penetration welds. These were smoothed to an acceptable radius.

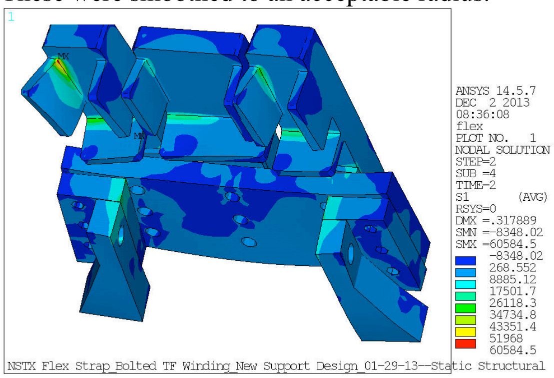

Fig. 7. TF Flex Connector Plates Support Fingers

II.D. TF Flag and Extension Welds

These extensions and adaptors are loaded by Lorentz loads from the TF flex strap and from the currents within the extensions themselves.

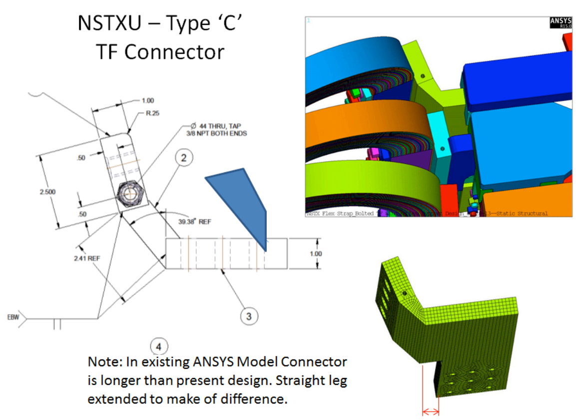

Fig. 8. Type "C" Connector with the Double Bend, Type A and B have Single Bends

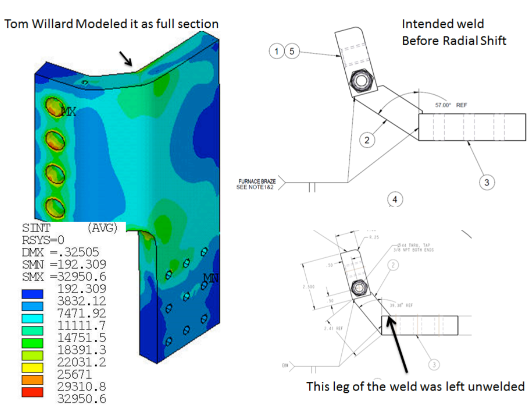

Fig. 9. Type "C" Connector Original Analysis (Left) and eBeam Weld Details (Right)

Because of the offset geometries needed to connect the straps to their corresponding outer legs, the loads on the extensions are complicated and include twisting moments as well as bending moments. The stresses in the electron beam welded joints in connectors 'A', 'B' and 'C' are estimated for the current design based on the analysis by Tom Willard and sub models by A. Brooks. The "A" and "B" connectors were found to be within allowables.

The 'C' connector joint had a partial weld specified which left a large effective crack at the back side of the weld.

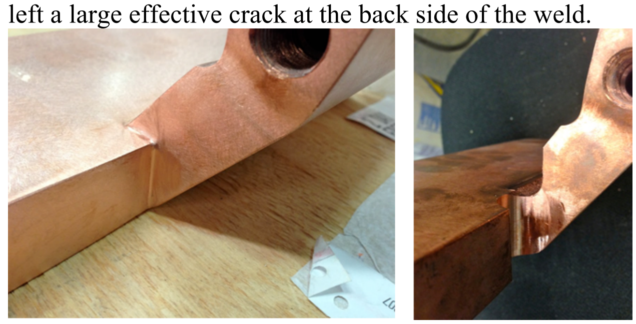

Fig. 10. Machined relief at the back side of the e beam welds in the type "C" connector

This was machined away to leave a smooth surface, but left a minimum section that does not satisfy the full life requirement for the part. The life is estimated as 2000 full power shots. . Miners Rule calculations based on the first year TF shot spectrum show a usage factor well below 1.0. For full operational parameters, "C" connector will either be replaced with a part with a full section and full section welds or reanalyzed. The present analysis is based on a conservative estimate of the R value. A better estimate of the R value could lead to an extended life for the type "C" Conductor. While replacement of connector type "C" is recommended. The existing connector might be qualified by a fracture mechanics assessment. This could be done during the first year of operation.

II.E. TF Crown Wet Layup vs. Segmented G-10

The epoxy wet-layup, planned for the crown, was tested and found inadequate.

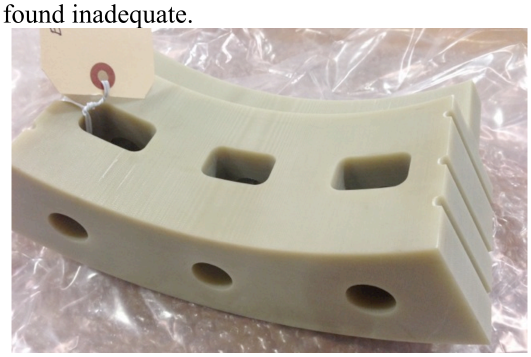

Figure 11 Crown Segment Machined from High Pressure Laminate

The wet wound layup was intended to align the strong reinforcement direction of the cloth in the direction needed to take the torsional shear. The wound version of the collar was replaced by a segmented collar.

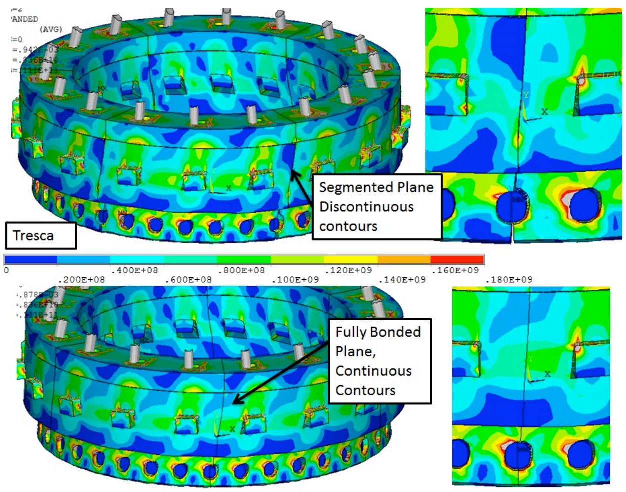

Fig. 12. Analysis of the Segmented Crown /Collar

The segmented crown pieces are machined from 6 pieces which have flat reinforced planes but are aligned on tangents to provide strength close to the intended toroidal shear carrying capacity. Analysis of the crown with a possible separation at the segment parting plan still showed acceptable stresses at the pin holes and clamp blocks.

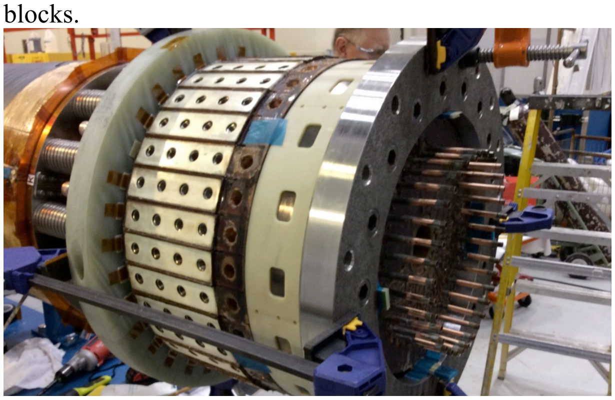

Fig. 13 Installed segmented G-10 Crown/Collar

II.F. RWM Coils

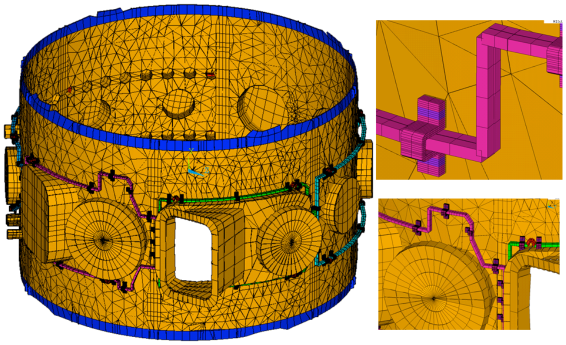

Fig. 14. RWM Coils Fitted Around the New Neutral Beam Port

The external resistive wall mode coils (RWM) were installed in the original NSTX and there is a substantial design analysis and review history prior to NSTX upgrade . Geometric changes were required for the upgrade. Ports were extensively modified to accommodate the new neutral beam, and the RWM coil detailed re-design was deferred until most of the new components and diagnostics were installed. One important target conservatism in the original design was to size components for 5 kA operation. The objective of the re-analysis is to estimate and assess the stresses in the RWM Coils, and their supports for upgrade loads. George Labik originally designed the clamps and coils with hand calculations that had sufficient conservatism to envelope the upgrade Lorentz loads. The coils were intended to be supported every ~20 inches by G-10 lined steel clamps. Details of the support positions and types of supports are shown in drawing E-DC1329, Shell Coils General Arrangement Bays A-L, [5] The finite element model of the coils showed excessive stresses at a few points where the spans were longer that the original design intent. Flexes that allow thermal expansion also reduce fixity and constraint such that some regions displaced due to torsion. A few locations required added clamps to reduce bending stress or excessive deformation.

II.G. CHI and other Coil Bus Runs

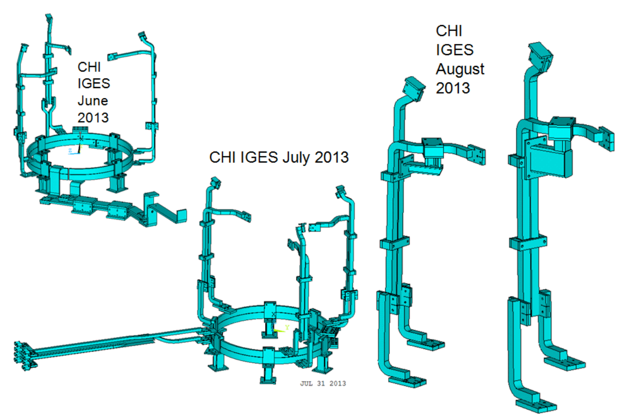

Fig. 15. Evolution of CHI Bus Bar Designs

CHI stands for Coaxial Helicity Injection. It is a system used for start up in a spherical tokamak The inner core of the vessel is electrically isolated from the outer vessel structure. Current flows from the inner vessel to the outer vessel through a gap near the inner divertor tiles. The bus bars carry this current. The CHI systems is also used in the bakeout, but the limiting load occurs during a disruption in which the halo currents flow in the high toroidal field region, close to the OH and PF fields.

Integrally connected to the bus bars are the CHI rods that run vertically and connect with the centerstack casing flange. Final qualification of bus bar runs was done close to the end of the NSTX Upgrade construction to accommodate as-built and as installed conditions.

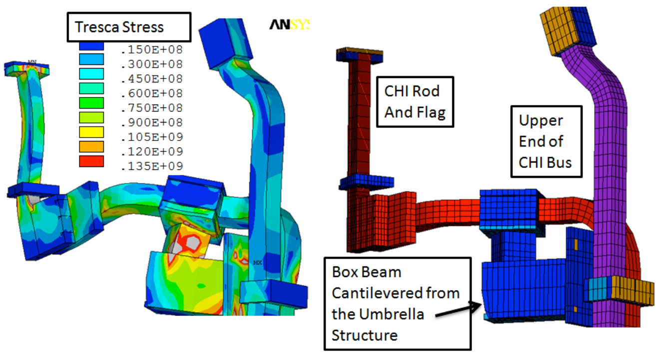

Fig. 16. Upper portion of one of three branches of the CHI system, showing the box beam support

Three branches of the CHI bus extend from a watercooled ring bus up to the inner and outer vessel connections. Halo currents crossing the TF field produce a large Lorentz force necessitating the box beam support cantilevered off the umbrella structure. These components are in a highly congested area and further fit-up and interference modifications are expected.

II.H TF Interaction Without Aquapour Removal

A water soluble material called Aquapour, was intended to create a gap between the TF and the OH, which was wound onto the TF coil. The VPI penetrated the Aquapour and it could not be removed. With the Aquapour left in the annular gap between the NSTX-U TF and OH, the coils could frictionally interact. Experience attempting to remove the material indicates that it is fairly strong. It is assumed that the slip plane measured during heating tests in the last couple of weeks is at the Teflon sheet surrounding the Aquapour. The tall narrow geometry of the coils provides a large cylindrical frictional surface for traction and relatively small cross sections to resist the frictional forces. The main difficulty arises from a cold OH and a warm TF. This can produce axial (vertical) tensile stresses in the OH as the TF expands radially and develops frictional loads and expands vertically which will tend to stretch the OH. The OH winding pack is not designed to take substantial axial (vertical) tension. If the OH is maintained at a higher temperature than the TF throughout the shot, significant frictional forces will not develop. When energized, the OH expands slightly and relieves the radial pressure between the TF and OH, and thus relieves the frictional connection.

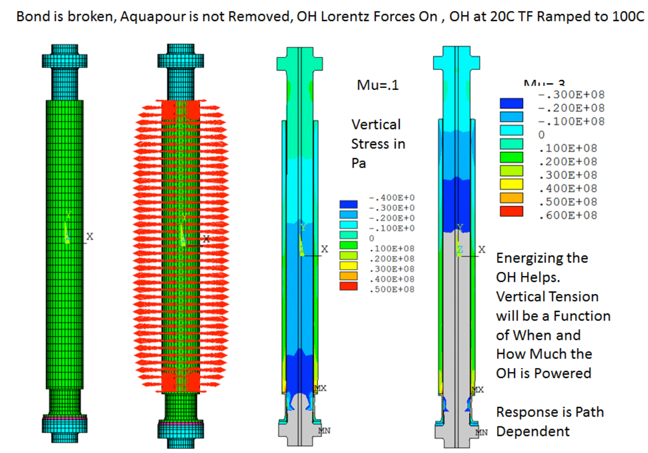

Fig. 17. Simulation with Adverse TF and OH Temperatures

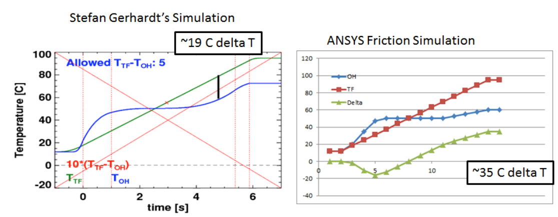

Fig. 18. TF and OH temperatures for a Typical Shot

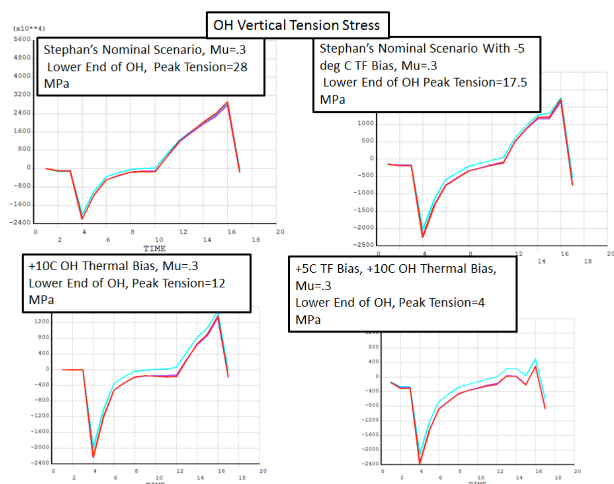

Fig. 19 OH Vertical Stresses for Various Temperature biases

Based on a number of analyses, roughly one MPa of tension in the OH developed for each degree of TF temperature above the OH temperature. Figure 19 shows investigations of TF and OH temperature biases intended to minimize the frictional interaction of the coils. Scenarios have been developed that maintain a OH temperature above the TF temperature. In some cases preheat of the OH will be needed – especially for non-inductive experiments. For future full performance long pulse inductively driven scenarios, a higher allowable OH temperature would be a help. The current coil temperature limits are set at 100C. The CTD 425 epoxy system used for the Upgrade coils, is capable of retaining adequate strength at temperatures above 110 C. Creep behavior is being tested to ensure the preload is retained at higher temperatures.

II.I TF Removal of one layer of Microtherm Insulation

One of the major milestones in the Upgrade construction is the process of slipping the centerstack casing over the centerstack coil assembly. During this operation the casing “snagged” on the insulation between the coils and casing. Lips and irregularities in the inside of the casing were removed. This was not enough and one layer of the microtherm insulation had to be removed. Reducing the Microtherm insulation between the Centerstack casing and OH from 6 mm to 3 mm allowed final assembly of the casing over the centerstack. It is predicted tol drive the temperature of the groundwrap insulation up another 5 C or so. We have already driven it up because of the AquaPour fix of running the coils 10 C hotter. That puts the G10 at 121 C (our comfort level is 120 C since the glass transition temperature is 130 C), We can argue that it is still OK. A bigger concern is the fault scenario during bakeout when we must assume that cooling to the OH is lost. If nothing is done, the OH would eventually be driven close to the bakeout temperature of 350 C. However we have time to react. With the 6 mm Microtherm we had over 3 hours to reestablish cooling flow. With 3 mm, we have just under 1 hour. Service water connections exist that will allow establishment of cooling water flow in case of a system failure.

III. CONCLUSIONS

A number of modifications were required to support construction of NSTX Upgrade. Calculations completed prior to initiation of construction formed the basis for evaluating the acceptability of the modifications. Many minor geometric adjustments were required by interferences with diagnostics and field run components. Bus bar runs were intentionally left until the later part of the construction. Fabrication difficulties required some revisions of the design and material selection. The G-10 TF segmented crown is in this category. More significant changes were required by the difficulty in removing the aquapour. Having a substantial analytic, and test qualification basis for the initial design facilitated the construction and allowed timely support of construction changes.

ACKNOWLEDGMENTS

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

REFERENCES

1. NSTX Upgrade for Establishing Physics and Technology Basis for FNSF, Masayuki Ono (PPPL), ANS Topical on Fusion Engineering, Sept 2014 Anaheim California
2. NSTX (NATIONAL SPHERICAL TORUS EXPERIMENT) STRUCTURAL DESIGN CRITERIA NSTX-CRIT-0001-01 February 2010 I. ZATZ, EDITOR
3. NSTX Upgrade Analysis of the PF1c Mandrel/Case CHI Gap Thermal Response, Including the Proposed Thermal Shield Design NSTXU-CALC-133-15-0 December, 2014
4. " NSTX Upgrade Analysis of Existing and Upgrade PF4/5 Coils and Supports – With Alternating Columns.NSTXU-CALC-12-05-01 December 2011
5. drawing E-DC1329, Shell Coils General Arrangement Bays A-L,

Princeton Plasma Physics Laboratory
Office of Reports and Publications

Managed by
Princeton University

under contract with the
U.S. Department of Energy
(DE-AC02-09CH11466)

P.O. Box 451, Princeton, NJ 08543
Phone: 609-243-2245
Fax: 609-243-2751

E-mail: publications@pppl.gov

Website: http://www.pppl.gov