NSTX Upgrade

Bake-Out Evaluations

NSTXU-CALC-10-04-00

~~NSTXU-CALC-133-15-0~~

April 2016

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Conclusion (Specify whether or not the purpose of the calculation was accomplished.)

The range of issues listed above has been evaluated and input has been provided to the Bake-Out Procedure D-NSTX-OP-G-156 [11]. These include mechanical thermal expansion behaviors that have been affected by the structural reinforcements and changes necessitated by the upgrade. Heat balance calculations have been updated for the mechanical support of the new centerstack. Addition of the inner PF coils has affected the ability to properly heat the neighboring divertor tiles during bake-out. Heating the divertor tiles, particularly near the PF1b mandrel/case, can raise the temperature of the PF1b insulation beyond the capacity of the CTD-425. Structural and electrical tests on the winding packs have been performed at 225 and 250C and these are included in this calculation. The allowed temperature for an extended operating time is 225C for no mechanical or Lorentz force conditions like bake-out. Heat balance calculations are included that address heating/cooling flow temperatures in PF1b, as well as vessel, passive plate heating and cooling and centerstack Ohmic heating.

After considering many alternatives, a system that provides modest heating of PF1b is used to raise the local divertor tile temperatures as much as possible without damage to the coil insulation. This was a best effort solution and modifications are proposed for future bake-outs that should improve the inner divertor tile temperatures.

PF1b should be initially run at 70C during the bake-out. The new thermal control system is capable of going up to 110C. In the September 2015 bake-out, 100C temperature was authorized and 90 C operation was achieved. This probably degraded the G-10 shim inside the CTD-425 ground wrap but the remaining CTD-425 turn to turn insulation should retain its required properties. The PF1b heating system has been disconnected and different methods of heating the inner divertor tiles are being developed that don't require high epoxy temperatures in PF1b.

Cognizant Engineer's printed name, signature, and date

Mark Cropper Mark B. Cropper 8/18/16

I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct.

Checker's printed name, signature, and date

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NSTX Upgrade

Bake-Out Evaluations

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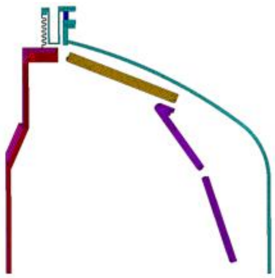
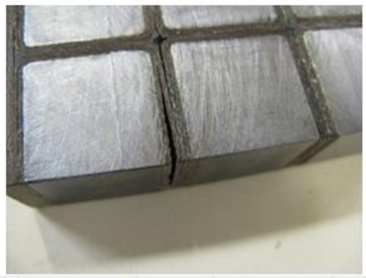
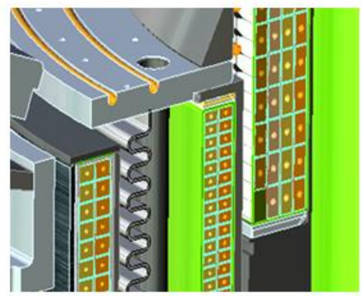
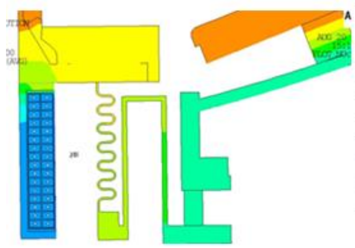
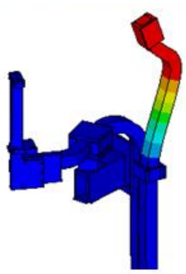
April 2016






Prepared by P. Titus	Reviewed by I. Zatz
Section 8.0 Prepared by S. Gerhardt	Reviewed by P. Titus
Section 9.0, 10.0 and 14.0 Prepared by A. Brooks	Reviewed by P. Titus
Section 11.1 to ,11.4 Stephan Jurczynski	Reviewed by P. Titus

PPPL Calculation Form

Calculation # **NSTXU-CALC-12-01-01** Revision # **00** ____ WP #, **1672**
(ENG-032)

Purpose of Calculation: (Define why the calculation is being performed.)

The purpose of this calculation is to evaluate bake-out strategies for NSTX upgrade that will produce acceptable temperatures at the tile surfaces, i.e., temperatures approaching 350 degrees, and not damage insulation or structural components,
A number of evaluations are included in this calculation:

Strategies to increase temperatures at the tile surfaces without damage to coil insulation. PF1b and the OH are of particular interest

Evaluation of the new PF1b water heating/cooling system and the effects of running the PF1b coil at an elevated temperature.

Documentation of insulation tests to support selecting a temperature limit for the PF1ab insulation

Limiting the Casing – to PF1b Mandrel weld stress

Limiting the Ceramic Break O ring seal temperatures

Possibilities of using the horizontal divertor flange and/or the vertical casing shell cooling tubes to heat the divertor tiles

Necessity for loosening the CHI bus bar supports

Necessity for loosening the TF truss connections

Necessity for loosening the PF 4 and 5 support columns

Necessity for disconnecting the inner PF coil power connections

Missing insulation on the Bay J-K cap

The calculations of record that previously considered bake-out are from Art Brooks, Larry Dudek[2], Ali Zolfaghari, Andrei Khodak, and Len Myatt and these are cross referenced appropriately.

References (List any source of design information including computer program titles and revision levels.)

These are included in the body of the calculation, in section 6.3

Assumptions (Identify all assumptions made as part of this calculation.)

The number of planned equilibria that use the full PF1b current is limited. This is shown in figure 6.6-1. For design and analysis it will be assumed that each normal operating pulse heat the coil to 100C.

Calculation (Calculation is either documented here or attached)

These are included in the body of the following document

Conclusion (Specify whether or not the purpose of the calculation was accomplished.)

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Cognizant Engineer's printed name, signature, and date

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I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct.

Checker's printed name, signature, and date

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2.0 Table of Contents

3.0 Revision Status Table

Rev 0	Initial Issue

4.0 Executive Summary

This calculation reports on a collection of analyses relating to the bake-out behavior of NSTX Upgrade. It includes the heat balance analysis that predicts temperatures and heat fluxes at various tile locations, structures and coils connected to the vessel. In addition, bake-out analyses performed throughout calculations qualifying NSTX Upgrade, are collected and referenced or models from the calculations are exercised with bake-out temperature distributions. The goal of this effort was to support the content of the NSTX-U bake-out procedure, D-NSTX-OP-G-156 [11]. Some mechanical components needed to be loosened to allow for thermal growth of the vessel. Simulations used to identify these components are described.

The goal of the bake-out is to raise the temperature of the graphite tiles to a sufficiently high temperature over a sufficiently long time to eliminate any volatiles that will contaminate the plasma during operation. Higher temperatures substantially reduce the required time for the bake-out to feasible time scales. Inner divertor coils PF1a, b and c were added or enlarged in the Upgrade to facilitate divertor shape experiments. This places the coils close to the inner divertor tiles and introduces a conflict in the bake-out requirements. The divertor tiles should be heated to 350C but the insulation in the nearby coils, particularly PF1b must be maintained below the temperature that would damage the epoxy systems used in the coil. A successful bake-out was conducted in September 2015, but the inner divertor tiles did not reach the desired 350C temperature. Predicted temperatures of the PF1b insulation ground wrap were kept below that allowed to avoid electrical failure. As of February 2016, NSTX-U has operated successfully but has not operated with the strike point on the inner divertor, and the quality of the bake-out with respect to the inner divertor tiles is not yet known. Plans for thermally isolating the inner divertor tiles from the PF1b case are being pursued. This includes testing of thin insulating material to replace Grafoil under the divertor tiles.

4.1 Cross Reference to Other Bake-Out Structural Requirements:

Input to the bake-out procedure [11] was collected by Neway Atnafu and appears in the table below. In addition to these items, a large number of diagnostics require special attention. The needs of these pieces of equipment were collected by Atiba Brereton and are documented in a separate spreadsheet and procedure.

Pre-Requisite to Bakeout of the NSTX-U		
Water Systems		
No.	**Type**	**Description**
1	Upper and Lower Inboard Diverters (IBD)	Disconnect the IBDs from the water systems
2	Inner 3 Layers of the OH Coils which are OH-7 (O-P), OH-1 (K-L), OH-2 (M-N), OH-3 (I-J), OH-4 (G-H) and OH-5 (C-D)	Turn off water supply valves for the inner 3 layers of the OH Coils
3	Upper and Lower CS Casing	Disconnect the upper and lower CS Casing from the water systems
Coil Supports		
4	TF Coil Support to VV Clevis	Loosen the rods between the TF coil supports and the VV clevis Pins at the TF outer leg clamp can be replaced with temporary ½ inch bolts to allow clearance for vessel growth
5	ALL (old modified) PF4 & PF5 Column Supports	Loosen column between upper PF4/5 coil clamps and Lower PF4/5 coil clamps. Clamps on the new columns that are not attached to the vessel do not need to be loosened
	PF 4 and 5 terminals and bus connection	Loosen the Phenolic block clamps on the flex

	between the upper and lower coils	cables, and loosen the G-10 blocks supporting the bus connection between upper and lower coils to allow possible radial and vertical motion with the vessel grow
	Coil Sliding supports	Scribe or mark with aluminum tape the initial locations of the slide blocks to allow checking that the slides return to nominal positions after the bake-out
	Umbrella sliding feet.	Scribe or mark with aluminum tape the initial locations of the slide blocks to allow checking that the slides return to nominal positions after the bake-out
	Main Machine Column Slides	Scribe or mark with aluminum tape the initial locations of the slide blocks to allow checking that the slides return to nominal positions after the bake-out
Bus Bar Supports		
6	Lower CHI bus bar supports at the lower umbrella.	Loosen CHI upper clamp support of the Lower CHI bus connected to the Umbrellas. Loosening the upper clamp provides enough flex length of the 2 inch square bus to allow the vessel growth
	Upper CHI Bus Bake-out Jumper	These connections are flexible enough as-is

4.2 Monitoring Sliding Supports During the Bake-Out

There are a few places where proper sliding of the coil supports needs to be verified. This includes PF2, 3, 4, and 5 support pads umbrella structure feet and the main support columns. Aluminum tapes were applied to locations at the slides where they would be deformed or crumpled as the slide grows. After the bake-out, the tapes and slides were inspected to make sure the slides have returned to their pre-bake-out positions, which they did (see section 8.0).

4.3 Protecting the OH from Tensile Strains

Removal of one layer of the Microtherm insulation adds heating to the outer layer of the OH during bake-out. This increases the outer layer temperature vs. the inner layers causing the cooler inner layers to develop axial tension, and the outer layers axial compression. In section 14.0 of this calculation, the effects of the loss of microtherm is discussed in terms of the time required to recover from a loss of coolant (the OH would gradually reach the 350C casing bake-out temperature). A. Brooks assessed the loss of the microtherm layer and simulated cooling only the outer layer of the OH - rather than feeding 12C water to all layers, and there is some advantage to this to keep the temperature/strain gradients down. Around September 10, 2015, the cooling in the inner layers was restored at a reduced rate because the outer layer was approaching 90C.

4.4 PF1b Epoxy Temperature Limits

For the bake-out, and allowed temperature for the CTD 425 system has been set at 200C. This is based on communications with CTD, and a few tests performed in Steve Jurczynski's lab.

There are a number of areas around the machine that require adherence to temperature limits. CTD-425 Epoxy qualifications included measurements up to 125 C and 110 C was qualified for normal service in the OH. During bake-out, the machine has the vessel internals heated to 350C and the vessel is limited to 150C. Assessments of epoxy temperatures were needed to assess the natural gradients from the heating/cooling systems to the coils and for variations in the calibrations of the thermocouples. This is discussed in section 9.1. The coils are normally protected by running cooling water through them during the bake-out, but to raise the temperature of the inner divertor tiles, PF1b will be "cooled" with warmer water, and this raises the possibility of local temperatures of the epoxy beyond that expected for normal operation. CTD was contacted to verify that the chemistry of CTD-425 can survive a high temp. The answer was in the affirmative up to 300C but the electrical performance and the post heat mechanical performance were not quantified. Consequently, tests were performed to assess the survivability of the epoxy system used for the new inner PF coils.

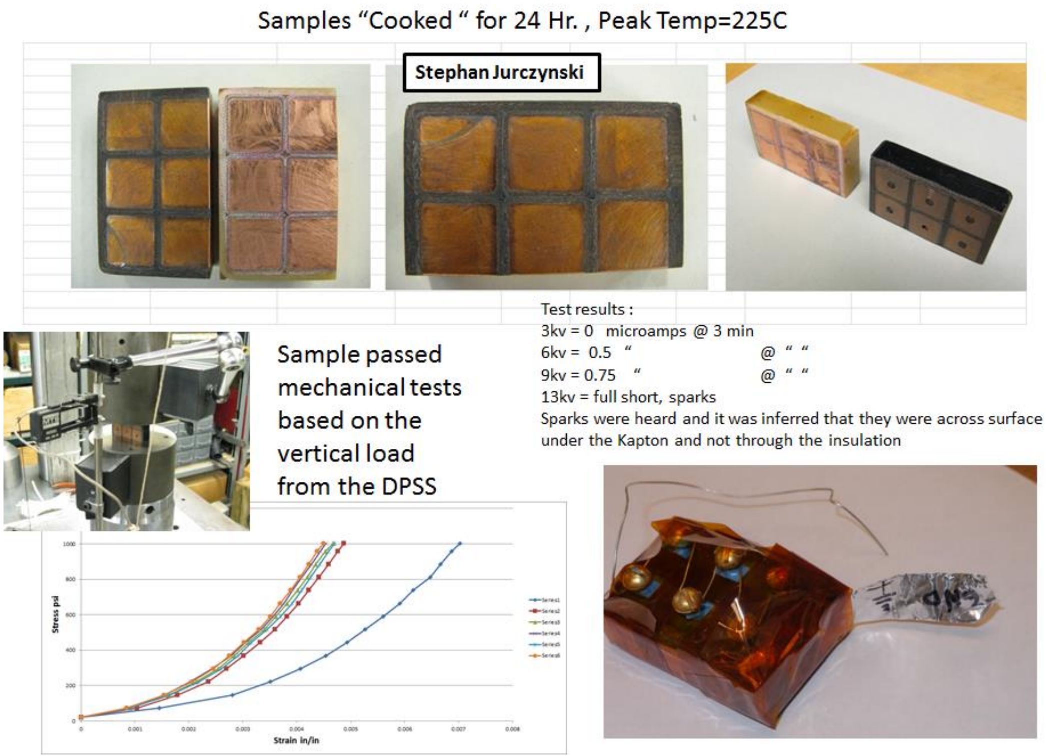


Figure 4.4-1 Testing of the CTD 425/Kapton System for Elevated Temperature Survival

Structural and electrical tests on the winding packs at 225 and 250C were performed. During operation, PF1b sees a max vertical load of 84182 lbs. This produces an average compressive stress of 84182/15.758/2/3.1416/1.332 = 638 psi. Samples were mechanically tested after baking and then electrically tested as shown in figure 4.4-1.

Sample	Test Config.	Test Time	3kv (μamps)	6kv (μamps)	9kv (μamps)	13kv (μamps)	Comments
PF1B Sample. baked 24 hours @ 225C in air	Turn to Ground Wrap	3 min.	0	0.5	0.75	Full Short, sparks	
PF1B Sample. baked 24 hours @ 225C in air	Turn to Turn	3 min.	2	5	10	14*	* Shorted after 2 minutes
PF1B Sample. baked 24 hours @ 250C in air	Turn to Ground Wrap	3 min.	1	3	arcing @ 8.5 kv	not tested	

Figure 4.4-2 Electrical Test Results

At 225°C for 24 hrs, the samples passed the mechanical and electrical requirements. At 250° C, the sample passed electrical tests up to 8.5kV but the electrical behavior was clearly degraded by the extra 25 degrees C. Mechanically it took the load, but the cracking looked scary and 250° C was considered too risky. The tests summarized in figure 4.4-2 were re-done at a longer time interval than 24 hrs to better represent the bake-out condition.

From the Design Point Spread Sheet (DPSS), the PF1b coil operates at 2026 V. The voltage per turn is 63.3V. The DPSS specifies 13103 V as the hipot voltage. The area of concern is at the top of the lower coil and at the bottom of the upper coil. These locations are midway between the applied voltage at the terminals. The largest voltage possible in service at the insulation that will be thermally challenged will be 1013V and a 2*E+1 voltage criteria would set the test limit to be 3 kV. The 13 kV was specified to be consistent with the DPSS, but for the materials tests, voltage increments of 3, 6, 9, and 13kV for 3 minutes each were specified to be able to evaluate the lower service voltage.

Another epoxy that might be affected by the elevated temperaures of bake-out is the Hysol binder in the bands that were added to the inner PF coils, mid-height, to provide a bearing surface against the outer shells that provide centering alignment of the PF coils. This is addressed in section 11.2.

4.5 Heat Balance Calculations and Achieving Desired Divertor Tile Temperature

The goal of the bake-out is to raise the temperature of the graphite tiles to a sufficiently high temperature over a sufficiently long time to eliminate any volatiles that will contaminate the plasma during operation. The need for a contaminate free plasma begins with start-up in which the initial plasma breakdown requires a specific density of Hydrogen or Deuterium gas and minimal amounts of heavier atoms, particularly water and oxygen. Figure 4.5-1 is intended to emphasize the advantages of getting the tiles to 300 to 350 degrees C. The higher temperatures substantially reduces the required time for the bake-out to feasible time scales.

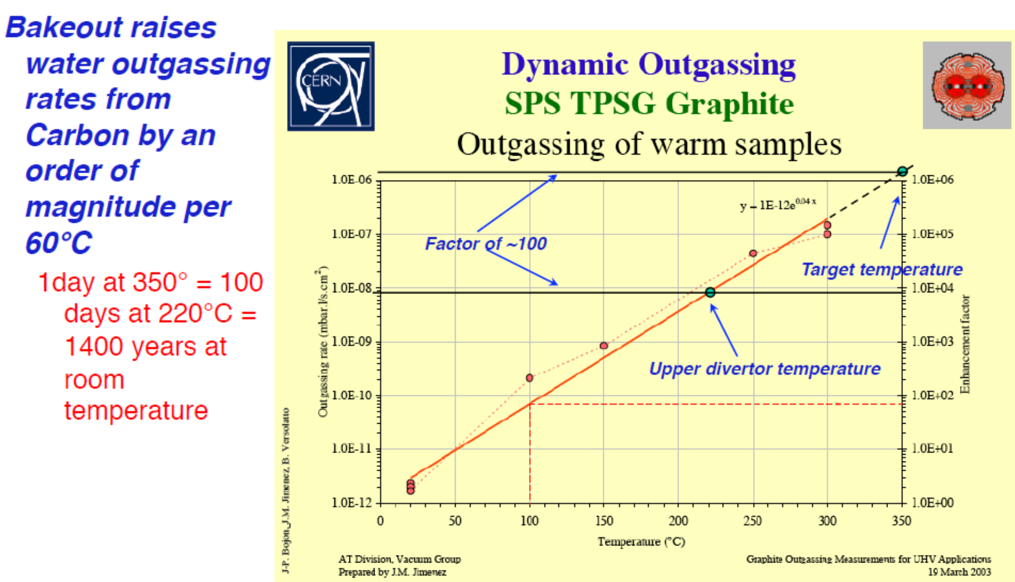


Figure 4.5-1 Slide from Dennis Mueller's Operators Class Showing the Temperature Sensitivity of the Bake-Out Out-Gassing.

The main monitors of adequate temperatures of vessel internal components are the thermocouples arrayed inside the vessel and in various heating systems. Unfortunately, there are a few temperature sensitive components that limit the ability to get the vessel internals up to temperature. A heat balance analysis [6] was developed to predict operating temperatures and size cooling systems. This same modeling is used to assess the bake-out. The analysis had the advantage of a "Mini-Bake" in April 2015 to provide a benchmark for the modeling of the heat balance. This is described in section 9.1. It was not a full bake-out and did not reach the temperatures needed for experimental operations but it was sufficient for the CD-4 plasma and was a useful check on the modeling parameters.

For normal plasma operations, the inner divertor areas are of particular concern because the tile support flange is connected to the PF1b mandrel. Since this is an area that has strong plasma interactions, it is important that it be baked out at a high temperature, but the proximity of PF1b makes this difficult.

Problems Associated with Elevating the Bake-Out Temperature of the Divertor Tiles:

- PF1b Ground wrap temperature
- PF1b G-10 winding shim between the ground wrap and the turns.
- PF1b turn to turn insulation temperature
- Excessive temperatures in the PF1b Hysol centering band
  (Epoxy limits are discussed in section 4.4 and in more detail in section 11.0)
- PF1b to Casing weld Shear Stress
- Higher temperature in the OH due to the loss of one layer of Microtherm Insulation
- Higher temperature differentials in the OH layers due to higher heat gain resulting from the removal of the Microtherm insulation.
- Maintaining acceptable temperatures in the O ring seal

This is an extensive but not all inclusive list. More aspects of the problem are discussed in the remainder of the calculation. There are a few strategies for improving the temperature of the inner divertor tiles.

“Knobs to Turn”

- Raise the temperature of the cooling water in PF1b
- Emissivity – Remove uncertainty
- Actively heat the horizontal divertor flange of the casing with hot Helium gas
- Actively heat the vertical inner Divertor Casing Shell – on the air side
- Increase the temperature of the secondary passive plates by routing the Helium gas to the secondary passive plates first
- Add insulation in the area below the inner PF coils
- Add air circulation in the area below the inner PF coils (Maybe to limit the O ring temperature)

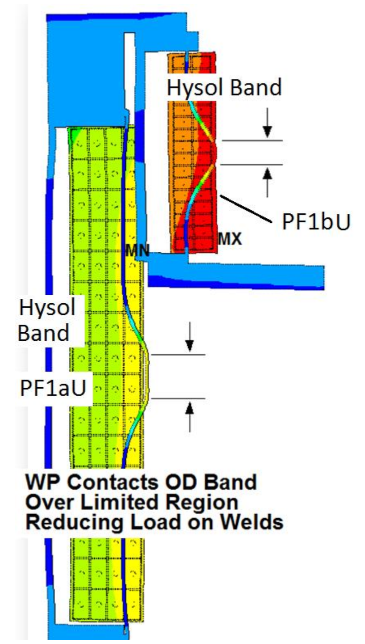


Figure 4.5-2 Excerpt from NSTXU-CALC-133-01-01[9]. Showing HYSOL band

One task that was accomplished was to install bakeout compatible connection tubes/hoses which are accessible from outside the umbrella structure for the vertical and horizontal divertor sections. However, these actually were not used (see sections 13.1 and 13.2). Actively heating the horizontal divertor flange had to be abandoned because the tubes are copper and are limited to low pressure at the desired operating temperature and were found to leak anyway. Additionally, the copper tubes were laid in a groove with an end loop with no allowance to accommodate the thermal expansion differential between the Inconel 625 and copper tubing. Outside the vacuum space, higher temperature compatible feed tubes tubes were installed [18]. This modification would have enabled the divertor tiles to be heated to the desired temperature of 350°C – or something lower based on the refrigerator pressure rating. However, a leak was discovered in the upper horizontal divertor cooling tube which precluded the use of helium-based heating. The present plan is not to actively heat the upper divertor tile sections. The copper tubes used in the Centerstack casing inboard vertical divertor shell could be used but would have to be operated at a pressure lower than 200 psi if they are supplied with 350C gas and the temperature differential between the shell and tube will have to be limited. As of the September 2015 bake, this was not used.

Care is not only needed to protect the PF1b ground wrap. The calculations indicate that the PF1b coil being cooled at 12 °C while aggressively heating the inner divertor flange will cause an unacceptable level of stress on welds attaching the PF1b coil to the horizontal divertor plate. This is discussed in more detail in sections 4.6 and 10.0. Keeping the PF1b cooling temperature at 12°C will also cause the divertor tile temperature to be well below the required 300 °C. The suggested remedy was to use 150°C water for the PF1b coil cooling which solves the weld stress issue while increasing the divertor tile temperature to 300°C. In order to make this elevated temperature operation for the PF1b coil possible, a new set of cooling water hoses must be replaced while the area is available for the hose replacement. The replacement of the PF1b hoses is pursued presently at high priority.

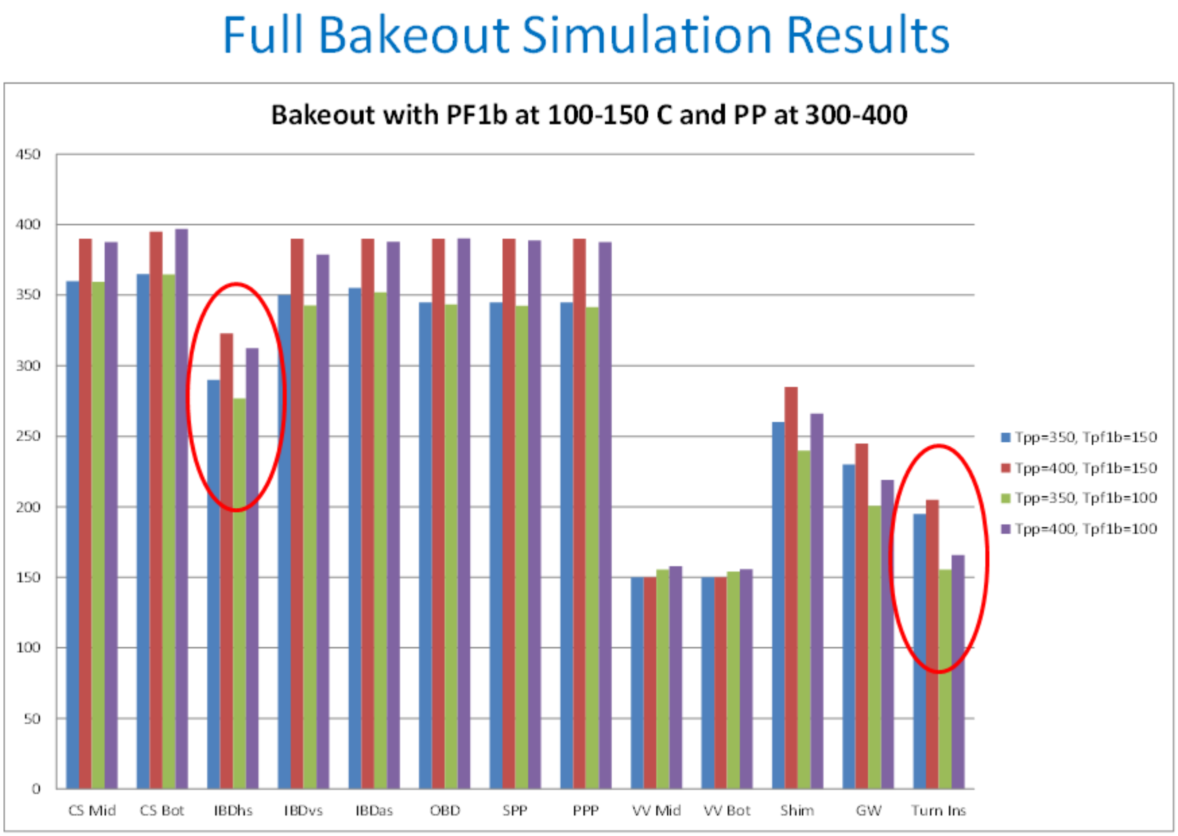


Figure 4.5-3 Temperatures at Various Points in the Model for a Few Passive Plate and PF1b Temperatures

Figure 4.5-3 represents temperatures predicted with control of the PF1b temperature and the best estimates of the heat transfer – both radiation and conduction during the bake-out. In this plot, the Shim and GW (Ground wall) should be switched, as they were switched during manufacture. Everson-Tesla requested that the G-10 spacer or shim be put inside the coil ground wrap, which was done. The bake-out procedure was written to start the PF1 heater control circuit to 70C with the option of allowing an increase if approved by the project engineer. An approval was requested for 100C based on an expectation that the G-10 shim would be ruined. This left the G-10 as possibly conducting and the turn to turn insulation left to support the applied voltage. As discussed in section 4.4, from the Design Point Spread Sheet (DPSS), the PF1b coil operates at 2026 V. The voltage per turn is 63.3V. The DPSS specifies 13103 V as the highpot voltage. The area of concern is at the top of the lower coil and at the bottom of the upper coil. These locations are midway between the applied voltage at the terminals. The largest voltage possible in service at the insulation that will be thermally challenged will be 63.3V turn to turn and 1013V to ground midway in the total number of coil turns.

The Bake-out task included efforts to find the right combination of cooling and heating of various components in the divertor area.

	Case	Description	IBDhs Tile Temp	G-10 PF1b Coil Shim Temp	PF1b Ground Wrap Temp	PF1b Conductor Insulation
Near Term	1	No Heating or cooling of IBD, OBD, PP or VV	205	180	135	80
	2	PP & OBD He Heating Turned On	290	240	180	110
	3	VV Heating/Cooling at 150 C turned on	260	225	162	95
	4	IBD Heating at 350 C	325	280	200	120
Long Term	5	No IBD Heating, Grafoil Removed from Tile	265	215	160	95
	6	Radiation Shield added behind IBDhs Tile	270	225	165	100
	7a	Heat Leakage to PF1a at 40 included	240	200	148	87
	7b	Repeat assuming no conduction between Tiles	310	125	95	60
	8a	Radiation Shield added behind IBDvs Tiles also	325	80	60	40
	8b	Repeat assuming no conduction between Tiles	315	80	60	40
Near Term (Modified Assumptions)	9	Starting with (4) above, contact resistance and conduction thru weld	325	270	195	115
	10	Contact resistance artificially increased to see impact. Still conduction thru weld	330	113	105	65

Figure 4.5-4 Some Suggested Options To Improve the Temperature of the Inner Divertor Tiles

The most attractive option was to run 100 to 150C water through PF1b. Care was needed to make sure the temperatures in the PF1b insulation system would not be damaged by the increased temperatures.

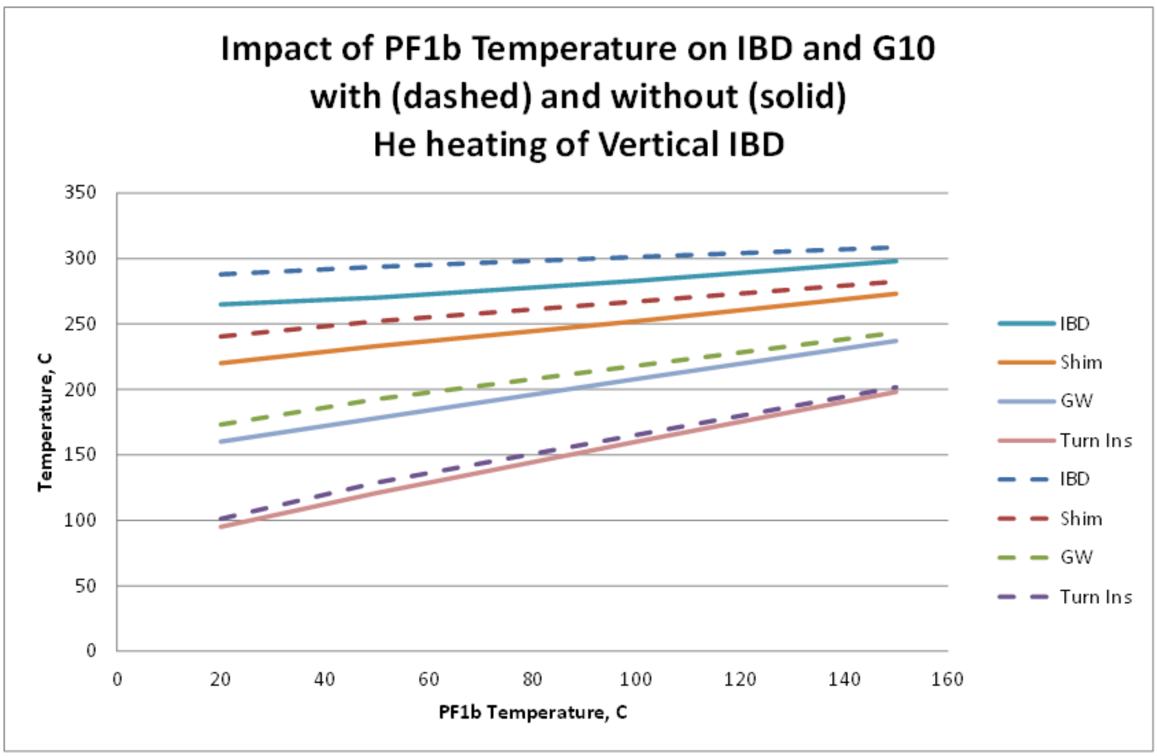


Figure 4.5-4 In Board Divertor and G-10 Shim (Actually the Ground Wrap) Temperature vs. PF1b Temperature

Increased PF1b temperatures can get us close to 300C on the divertor tiles (with some analysis uncertainty). We would retain an option to run low pressure air or helium in the inboard divertor and vertical divertor cooling pipes. The system implemented to heat, rather than cool, water flowing through PF1b is described in section 17.2 of the calculation. This has included installation of a small heat exchanger, active temperature control, and hose replacement to allow PF1b to run at 150C.

So far, much of the analysis and test needed to support a preferred approach is in place or in process. Hoses are being installed. The water and gas systems to support the new cooling/heating have been designed and purchased. One conclusion of this calculation and of the bake-out experience is that a new way of raising the divertor tile temperatures is needed. Insulating the tile is being investigated. Radiation from the passive plates and centerstack will heat the tile if there is minimal heat leakage to the divertor flange/PF1b Mandrel. The tech request to measure conductivity of various insulators to be used under the inner divertor is included in Appendix D and photos of the rig are shown below in Figure 4.5-4.

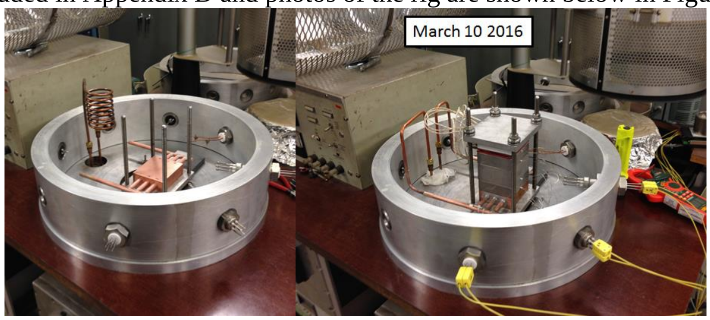


Figure 4.5-4 Inner Divertor Tile Insulation Test Rig

4.6 Analysis of PF1b mandrel to casing weld

This weld is a major structural element that supports the centerstack casing, OH and PF1a, and B. It resists coil electromagnetic launching loads and lateral loads during a disruption. Reference [20] addresses the adequacy of the casing weld for other than bake-out loads. No degradation of this weld can be tolerated during the bake-out. The detailed analysis of this weld is presented in section 10.0. Simply, this weld transmits the shear load between the hot centerstack casing and colder PF1b mandrel and support structures which connect to the pedestal. Section 10.0 assesses the weld stress and plastic strain expected to occur during bake-out with the allowed temperature distributions chosen to limit the temperatures of the PF1b insulation system to those acceptable for the epoxy system.

4.7 Terminal Bus bar Connections for the Inner PF Coils

Section 16.0 of this calculation presents a verbal argument that bake-out displacements are acceptable based on qualified normal operation differential motions and expected coil cooling during bake-out.

The extra radial motion of the hotter PF1b coil is less than a mm. The peak PF1b coil temp from the design point spreadsheet is 43C. The mandrel is assumed to be 30C for normal operation. This is the basis for the outer centering steel shells. If we allow the coils to go to 150C for bake-out, the mandrel temperature should be close to this and should not stress the centering shells beyond nominal design. The outer bus supports are on the PF2 support clamp and remain at 20C even during bake-out. So, with 150C PF1bL, the stress due to differential motion of coil and bus support will go up, but during bakeout there is no Lorentz force or joule heat. The upper PF1b support has a rubber clamp that allows 8mm relative vertical displacement and should allow the extra <1 mm displacement. The calculations of record are from A. Brooks, A. Khodak, A. Zolfaghari, and Len Myatt and would have to be cross referenced.

4.8 PF4/5 Column Bake-Out Behavior.

In rev 4 of the bake-out procedure, there isn’t a reference to the PF 4/5 columns. Loosening the columns should have been a requirement in the original NSTX bake-out procedure. Technicians responsible for the bake-out have said that the columns were loosened in the past. This has been included in the latest revision of the bake-out procedure [11].

At six upper locations and six lower locations, brackets connect to the vessel to support PF4 and 5. The upper and lower pairs of these coils are in series and have large attractive loads that required adding columns between theses brackets. The original NSTX columns were undersized, and the Upgrade has had stronger columns fitted. During Bake-out, the vessel is at a higher temperature than these supports and columns. At the original PF4/5 support locations, the new columns need to be disconnected to allow differential thermal growth. These heavier columns have a flange in the middle of the column, and the bolts should be loosened at least to allow 1/8 inch growth. Also, an additional six new columns have been added between PF4/5 U&L that don't connect to the vessel. These do not need to be loosened because the coils flex to accommodate the vessel growth. Analysis has been performed (Section 21) to determine if they could be left un-loosened.

There are two locations where the PF4/5 slide supports are locked and fixed to the vessel. These are near the terminals. This makes the terminals fixed to the vessel and the terminal supports (at the bus tower?) will fight the vessel growth - the terminal supports need to be loosened. George Labik's special column near the Thompson scattering system at Bay L, Figure 4.7-1 will have to be loosened as well.

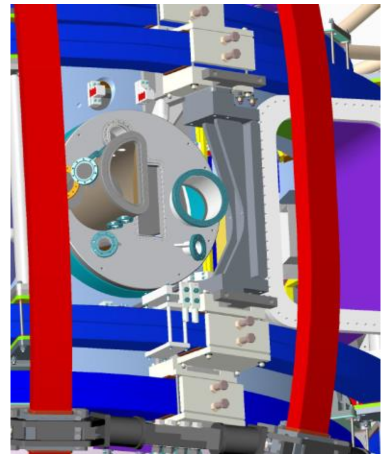


Figure 4.7-1 Bay L Special Column

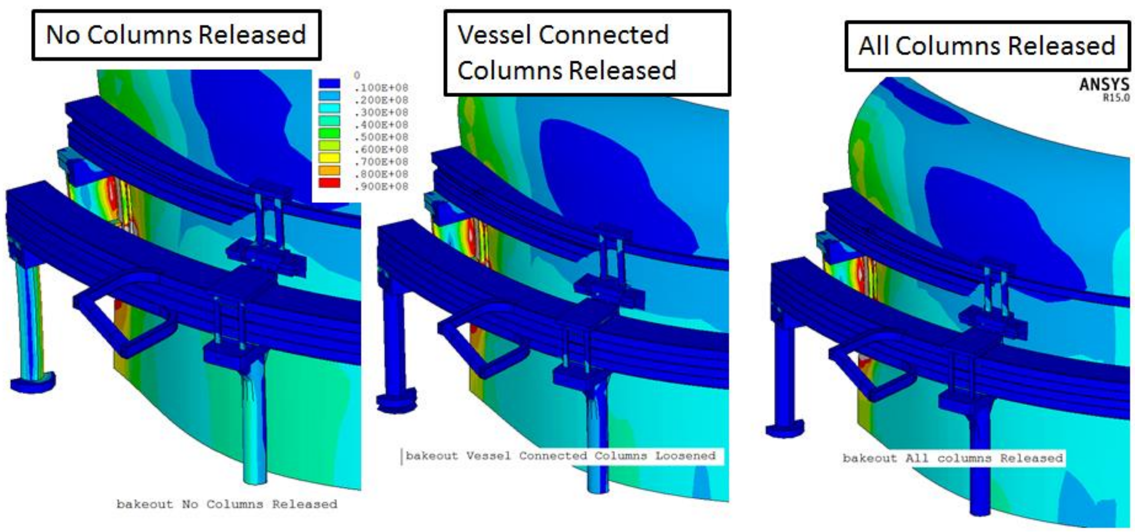


Figure 4.7-2 Comparison of stresses for various column connections

Stress analysis doesn't show a significant difference between the column restraint cases. Part of the vessel stress shown in figure 4.7-2 is the result of the cold clevis on the hot vessel shell. Stresses from the column tensile load superimposed on the thermal stresses on the vessel, add to stresses locally above yield and potentially plastically deform. A more appropriate caution is that if and when the stresses in the vessel shell go above yield, the bracket area would take the deformed shape imposed by the cooler columns. This is the basis for releasing the columns to allow the vessel shape to be retained.

4.9 TF Truss Connections

In the bake-out procedure [11], the instruction to disconnect the "coil turnbuckles" was included in section 5.8. This was changed to "TF coil support truss links or turnbuckles". During the September 2015 Bake-Out, the clevis pins at the TF clamp were removed and temporarily replaced with ½ inch bolts to hold the pieces loosely in place. Thermal stresses at the clevis block welded to the shell dominate, rather than the mechanical stresses that result from thermal growth of the larger components. Thermal stresses can be close to yield and similar to the PF 4 and 5 supports. The disconnection of the truss elements is needed to avoid deforming the shell near the clevis to shell attachment. This is discussed in section 22.0.

4.10 Bay J, K Cap Insulation

The original vessel insulation was replaced for the bakeout. Altered components and added structures were reviewed for insulation consistent with the original insulation approaches used on NSTX. The new Bay J-K cap had not been insulated and this was corrected just prior to the Sept 2015 bakeout. This is discussed in section 23.0.

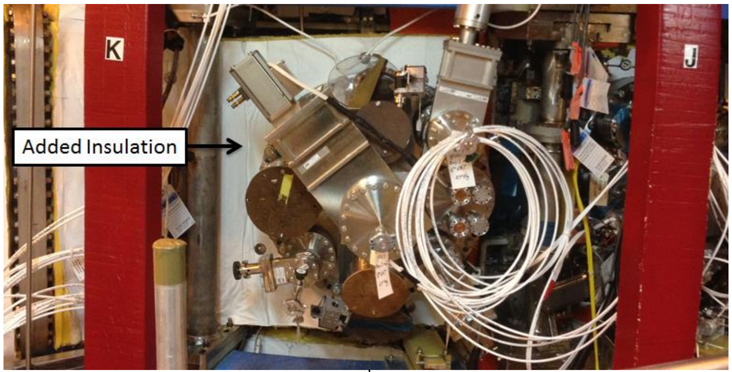


Figure 4.10-1 Photo taken Sept 4th 2015

4.11 CHI Bus Bar Clamp Loosening

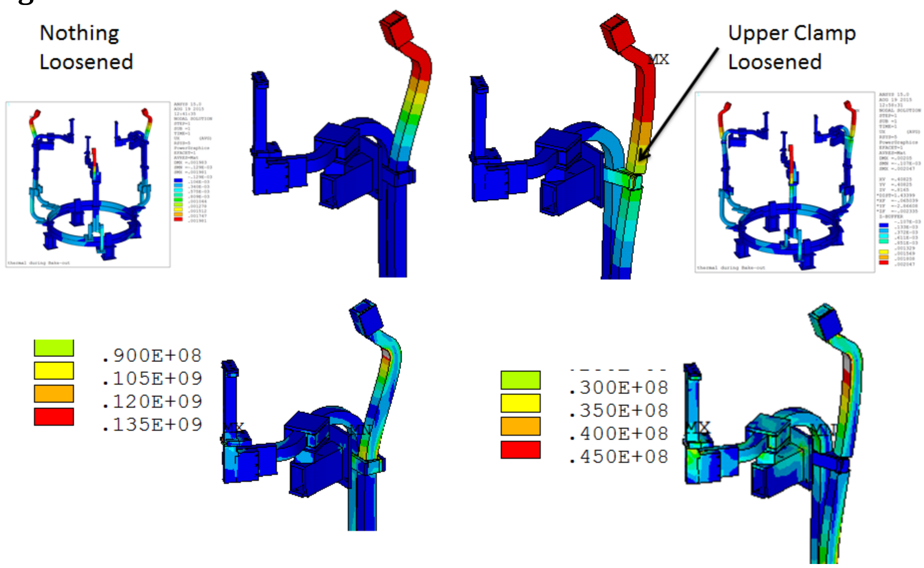


Figure 4.11-1 Stress and Displacement Results With and Without Loosening the Upper Clamp

The CHI bus connection to the CS through the CHI bars was analyzed in calculation #NSTXU-CALC-54-0 [13] for the bake-out condition and is OK. The CHI Bus connection to the outer vessel will grow with the vessel. The analysis, assumed all the end points were fixed. The model was modified with ~2mm radial growth of the vessel imposed on the CHI vessel Lug. The stresses are qualifiable with more modeling of the bolted connection and braze joint. If the upper clamps on the outside of the umbrella structure are loosened the stresses drop substantially. It should be easy enough to do this and have less disturbance of the CHI vessel electrical connection. This should be enough to adequately off-load the vessel lugs.

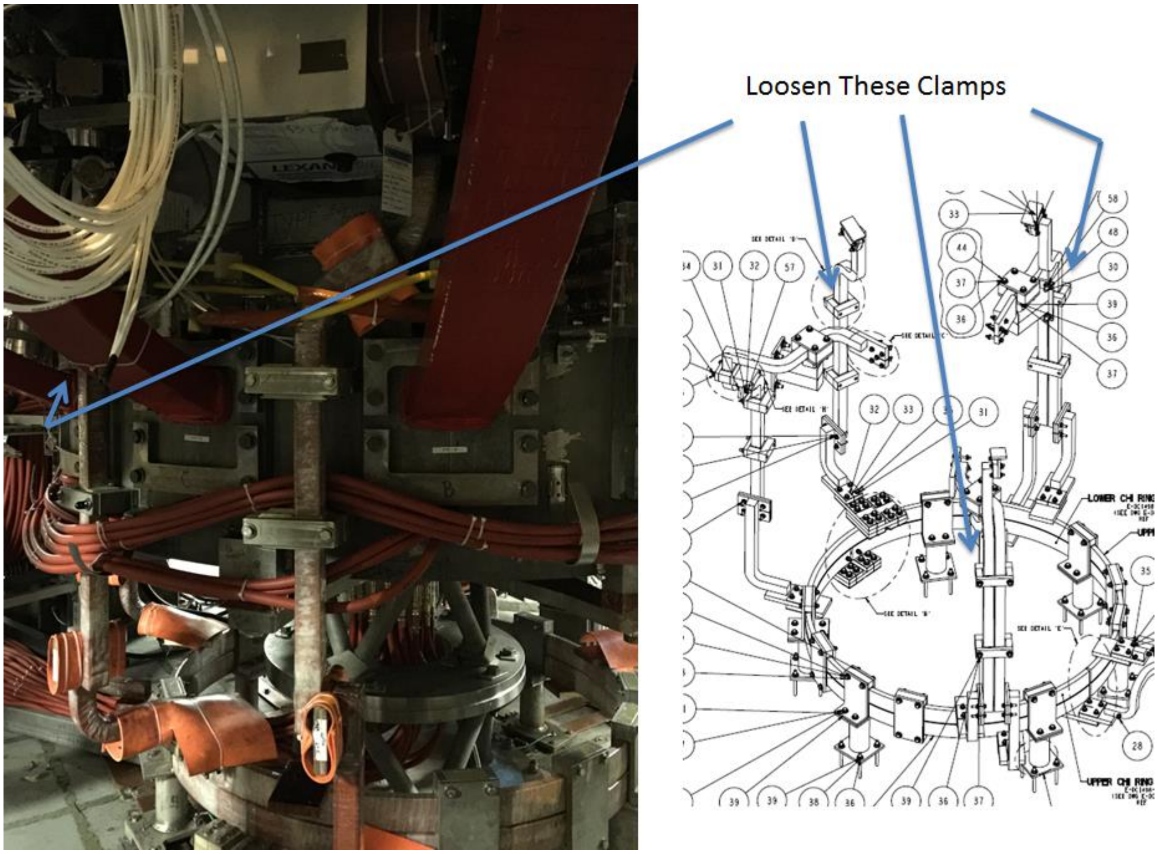


Figure 4.11-2

The new PF2/3 terminal reinforcements are of two types. Brackets have been added that connect the two terminals to cancel the local loads at the leads. These don't connect the PF2/3 coils or terminals to the vessel. The second type of reinforcement is a G-10 clamp that supports the flex cables. Neway Atnafu will define the load path of these supports. If they are tied to the vessel, they will need to be loosened.

4.12 Differential expansion of the Copper Cooling tubes in the Inner Divertor flange

The hose feeding coolant to the inner divertor cooling tubes was replaced to allow the horizontal divertor flange to be heated with Helium gas. Qualification of the piping and tubing for the higher temperature Helium gas was made moot by the discovery of a vacuum leak in the upper cooling tube. The copper refrigerator tubes that were inserted into grooves in the divertor tile support plate are on the vacuum side, and are tightly fit into a “loop” groove that should have had some allowance for expansion of the circumferential length of the loop. It has been confirmed that the design is tight fitting around the full length of the groove. Accumulations of expansions – in the case of He heating and contractions – in the case of flowing cooling water – potentially will concentrate at the end of the tubing loop and potentially will crush it. With compatible temperatures between the flange and tube and just the differential alpha between the copper tubing and the Inconel 625 casing, some deformation of the loop end is likely.

Figure 4.12-1 Divertor Flange Cooling Tube Loop

4.13 Heating the Vertical Section of the Casing Inner Divertor area

Figure 4.13-1 Inner Divertor Vertical Section Cooling Tubes

It might be possible to heat the IBDv vertical section by feeding hot Helium into the tubes intended for cooling of the in-board divertor tiles during normal operation. The cooling tubes are on the air side of the vessel, and are not as much of a danger to operation if they develop small leaks. The temperatures proposed for the divertor shell would be higher than the recommended design limit for the refrigerator tubing. Figure 6.4.2-1 “Copper Refrigerator Tubing Pressure Rating vs. Temperature” shows a drop off in the pressure rating at around 300C. A case could be made for lower pressure operation.

5.0 Digital Coil Protection System.

There is no input to the DCPS planned for bake-out

6.0 Design Input

6.1 Criteria

From the GRD:

"b. All materials utilized within the primary vacuum boundary shall be designed to withstand the anticipated temperatures during plasma operation. Note that the vacuum vessel shall be baked out at a temperature of 150^{o}C, and internal plasma facing components including the CSC, IBD, OBD, and PPs shall be baked out at 350^{o}C. "

The Safety analysis document (SAD) quotes the 350C bake and acknowledges that the input to the helium system must be 420C to get the 350^{o} C tile surfaces. Also the SAD allows temperatures greater than 350C for the centerstack. :

"3.2.3.3.4 Center Stack Casing

The center stack casing is electrically isolated from the outer vacuum vessel and is compatible with operation in high vacuum conditions. Electrical breaks are provided between the vacuum vessel and the center stack casing to support coaxial helicity injection (CHI) during startup. The electrical isolation is rated for 2kV DC CHI operations (upgradable to 4kV), 5kV DC hipot. The center stack casing includes suitable terminals for electrical connections for CHI, and accommodates the passage of a current in the Z direction for the purpose of resistive heating as a source of heat during the bakeout mode. The center stack casing is bakeable to a temperature > 350°C."

Note the ‘greater than’ sign. It can be assumed that a +/- tolerance on the 350C is implied and that 370C would be acceptable, especially on the centerstack casing.

From the bake-out procedure [11]

7.1 Start Taking data immediately after the heating systems are brought on line:

a. Monitor and record Center Stack thermocouple temperatures (TC-CSC), maintain 350° average.

The Safety Certificate (see appendix C) states that the 350C PFC limit and the Vessel 150C limit shall be per OP-G-156, "NSTX Integrated Machine Bake-out Operation". This procedure provides guidance and an interpretation of the 350C limit as being the average of the centerstack thermocouple measurements (section 7.1). Similarly, the 150C limit is the set point on the vessel heating and cooling system. Local temperatures above 150C are allowed, and anything over 175C is to be reported to the ATI.

Clearly, the Safety Certificate is a shorthand version of the more complete bakeout procedure requirements.

Stress Criteria are found in the NSTX Structural Design Criteria Document[3]. Disruption and thermal specifications are outlined in the GRD [7].

6.2 References

[1] NSTX-U Design Point Spreadsheet, **NSTXU-CALC-10-03-00** C. Neumeyer, http://w3.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html
[2] Upgraded Centerstack Bake-out Ohmic Heating, NSTX-U Calculation NSTXU-CAlC-33-01-00 7-9-2009, Larry Dudek, S, Ramakrishnan
[3] NSTX Structural Design Criteria Document, NSTX_DesCrit_IZ_080103.doc I. Zatz
[4] ITER material properties handbook, ITER document No. G 74 MA 15, file code: ITER-AK02-22401.
[5] "Stress Analysis of ATJ Center Stack Tiles and Fasteners" NSTXU-CALC-11-03-01 Revision 1 by Art Brooks
[6] Global Thermal Analysis of Center Stack Heat Balance,NSTXU-CALC-11-01-00 A. Brooks June 1, 2011
[7] NSTX Upgrade General Requirements Document, NSTX_CSU-RQMTS-GRD Revision 6, P. Titus, August 3 2015, Original issue by C. Neumeyer, March 30, 2009
[8] Inductive and Resistive Halo Current s in the NSTX Centerstack, A.Brooks, Calc # NSTX-103-05-00
[9] Inner PF Coils (1a, 1b & 1c), Center Stack Upgrade NSTXU-CALC-133-01-01 March 30, 2012 Rev 0/1 by Len Myatt.
[10] Inner PF Coils (1a, 1b & 1c), Center Stack Upgrade NSTXU-CALC-133-01-02 May, 2014 Rev 2 by Len Myatt. Rev 2 by A Zolfaghari and A Brooks
[11] NSTX Integrated Machine Bakeout Operations, D-NSTX-OP-G-156, Rev 4 Mark Cropper August 28 2015
[12] Microtherm Thermal Insulation Solutions, Product Performance Data, w w w. m i c r o t h e r m g r o u p . c o m Microtherm Inc. 3269 Regal Drive Alcoa, Tennessee 37701 T. (+1) (865) 681 0155 F. (+1) (865) 681 0016 E. sales@microtherm.us
[13] CHI Bus Bar Analysis NSTXU-CALC-54-0 P. Titus, November 21 2013
[14] On Wed, Oct 22, 2014 at 10:31 AM, William Blanchard <wblancha@pppl.gov> wrote: All,
The majority of leaks are on the inside of the can in the 10-7 t-l/sec range. We recommend these be sealed with leak sealer (good to 450 C). There appears to be one leak on the outside corner that will have line of sight to the plasma. S. Vinson is localizing and measuring the leak rate. If it is in the 10-7 range, we recommend using leak sealer for that leak also. Bill Blanchard Joseph Winston
[15] Viton Seal Properties http://www.row-inc.com/techspecs.html
[16]] PF1 Flex Bus Analysis, NSTXU-CALC-55-03-00 June 2016, P. Titus
[17] Analysis of Existing & Upgrade PF4/5 Coils & Supports – With Alternating Columns, NSTXU-CALC-12-05-00, Prepared By: Peter Titus, Reviewed by Irv Zatz, Cognizant Engineer: Mark Smith WBS 1.1.2
[18] Peer Review of the "Installation of Hot Helium Divertor Tubing" Mike Kalish, June 9 2015
[19] Design Review "PF1b Temperature Control During Bake-Out Only" Mike Viola August 11 2015
[20] Centerstack Casing and Lower Skirt Stress Summary, P. Titus, NSTXU-CALC-133-03-0

6.3 Photos and Drawing Excerpts

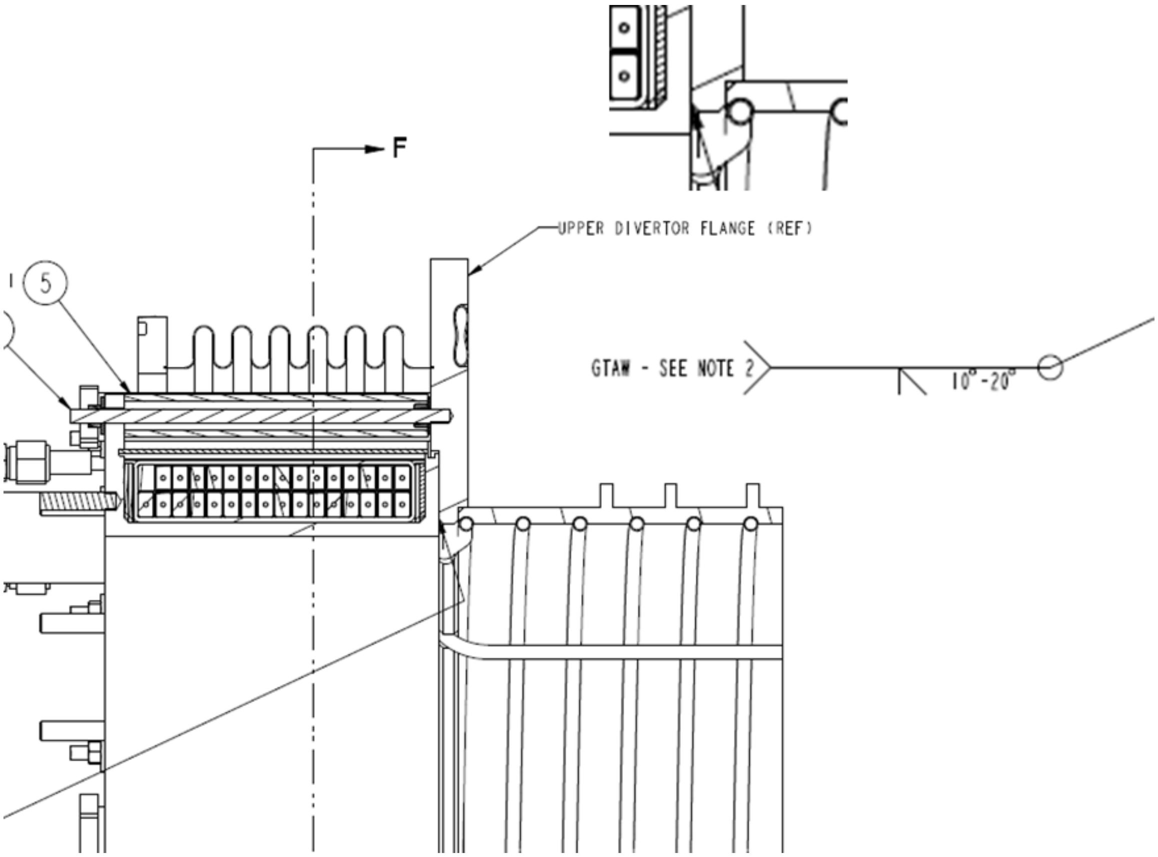


Figure 6.3-1 Divertor Flange Details

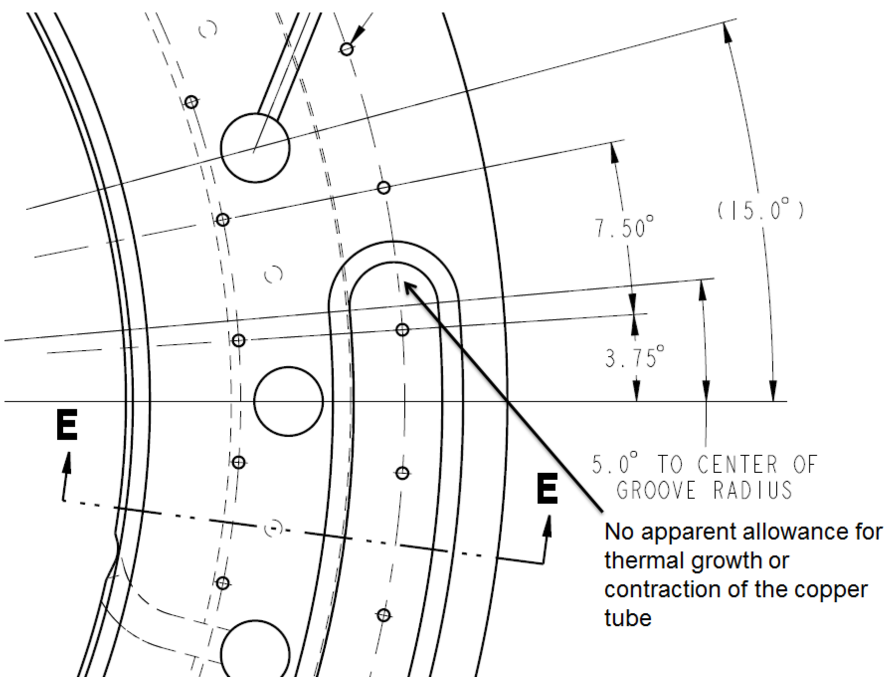


Figure 6.3-2 Divertor Flange Cooling Tube Details

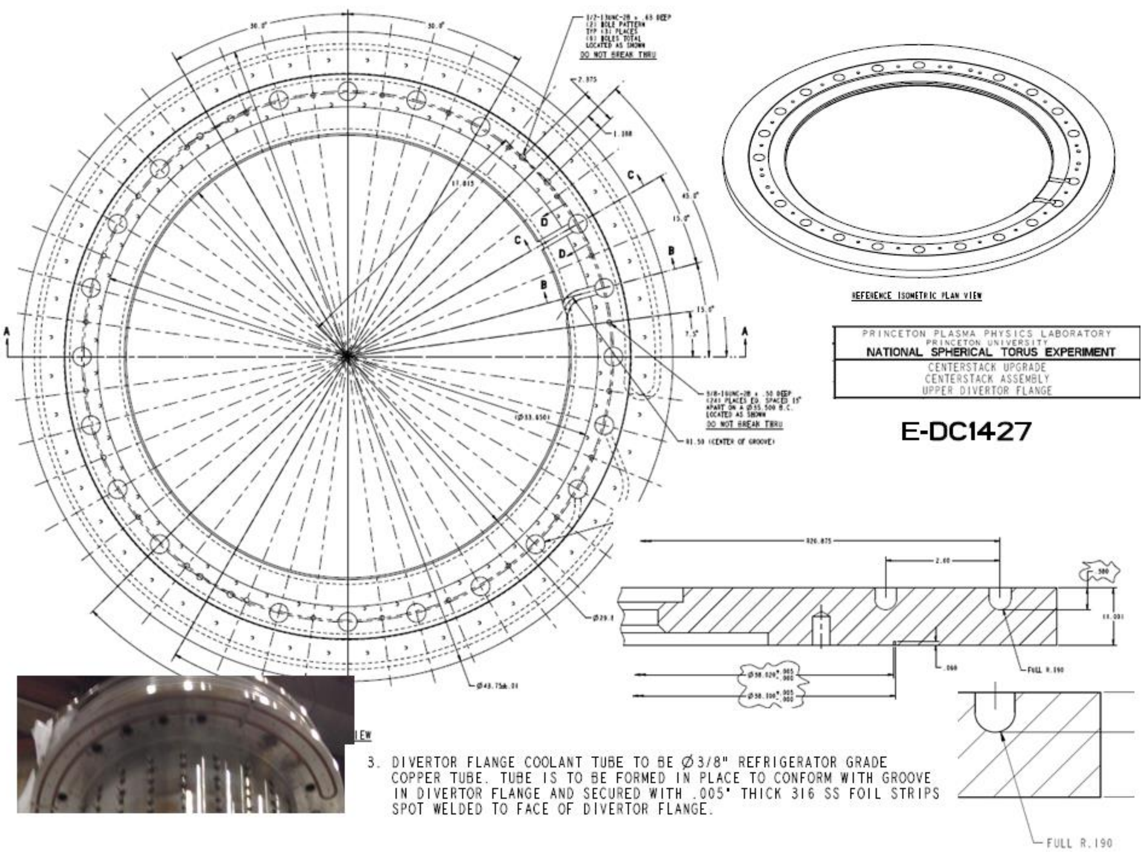


Figure 6.3-3 Divertor Flange Cooling Tube Details

Figure 6.3-4 Centerstack Case Showing upper Inner Divertor Cooling Loop (That Leaks)

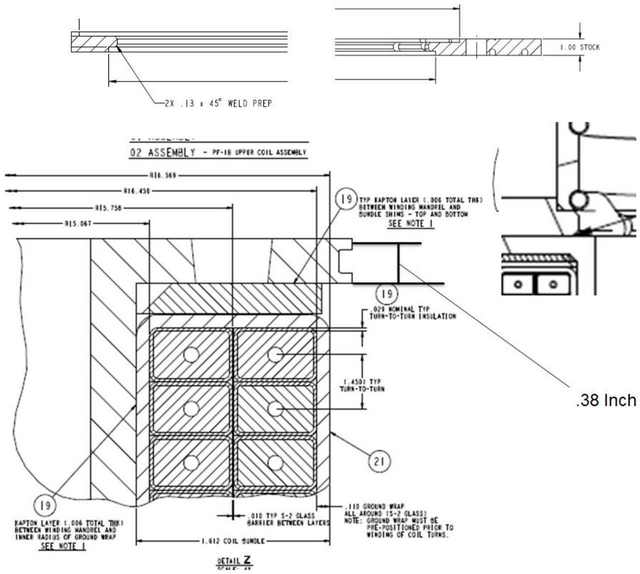


Figure 6.3-5 PF1b Case Details

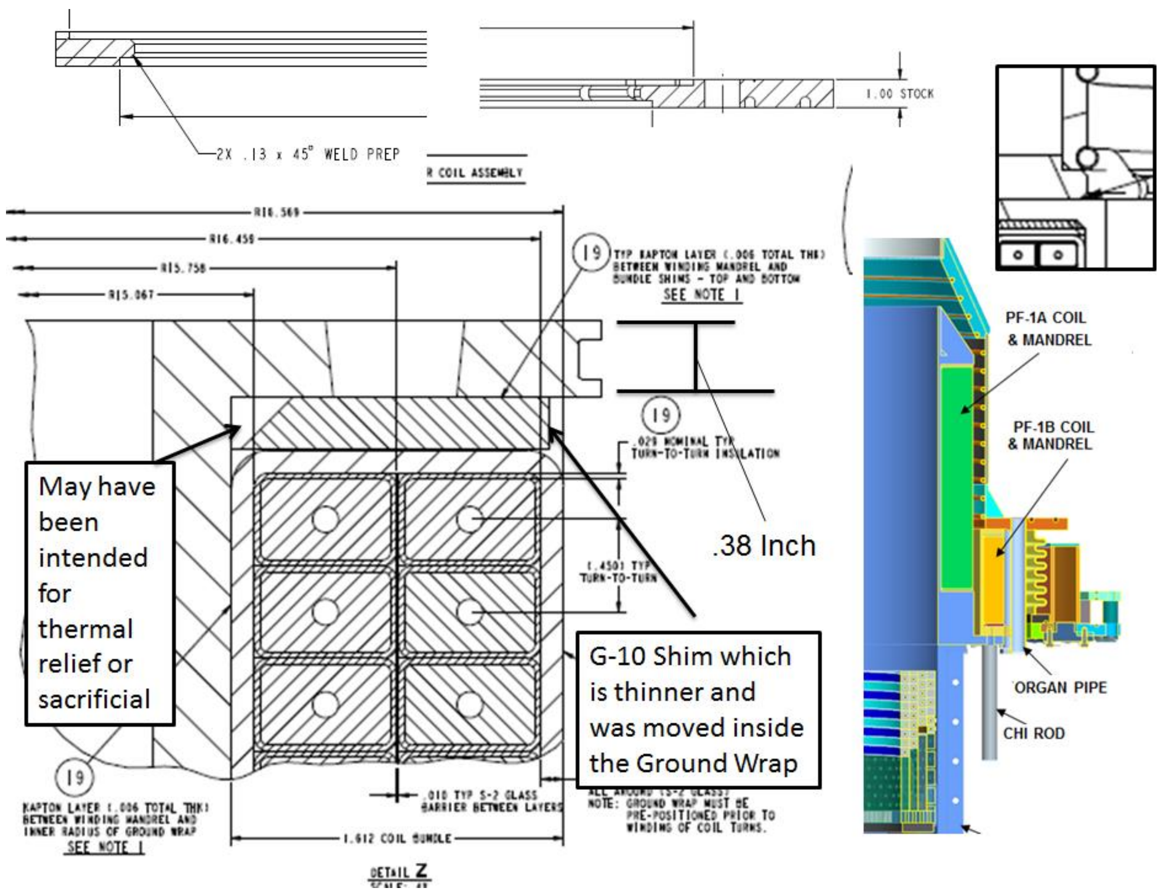


Figure 6.3-6 PF1b Design Details

6.4 Materials and Allowables

6.4.1 Stainless Steel Fatigue Allowable

The fatigue allowables have been collected from a few sources below:

RCC-MR	30000 cycles	483 MPa	70 ksi
NSTX Criteria	30000 cycles	275 MPa	40 ksi
ASME (corrected for R=.1)	30000 cycles	400 MPa	58 ksi
ITER in-vessel Components [18]	1e6 cycles	351 MPa	51ksi

The choice of an S-N allowable is made somewhat moot by the inclusion of fracture mechanics assessments of the expected life of the case welds.

316 Allowables for 30,000 cycles

	R=-1 Strain Controlled Max Stress	R=0 Strain Controlled Max Stress	Strain Controlled Stress Range
ASME/Myatt	340 MPa	410 MPa	410 to 680
NIST/Titus 2 and 20	205 MPa	275 MPa	275 to 410
RCC-MR			483 MPa
ITER In Vessel Criteria			>308 Mpa (308 Mpa is for 1e6 Cycles, Load Controlled)

Table 3.8.2-1 316 Allowable Fatigue Stress – 483 MPa is 70 ksi

Design Life = 30,000 Full Power Pulses, With a factor of 20, The requirement is 600,000 cycles which yields a 420 MPa =60.9ksi, At 30,000 cycles the criteria based on 2*stress yields 550 MPa/2 = 275MPa = 40 ksi

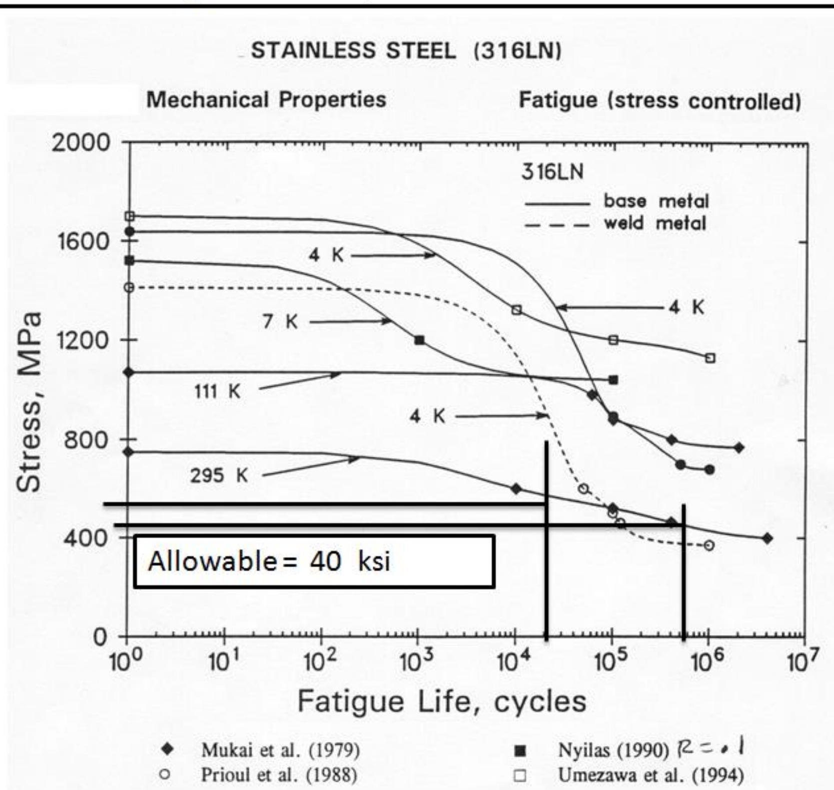


Figure 6.4.1-2 (NIST)

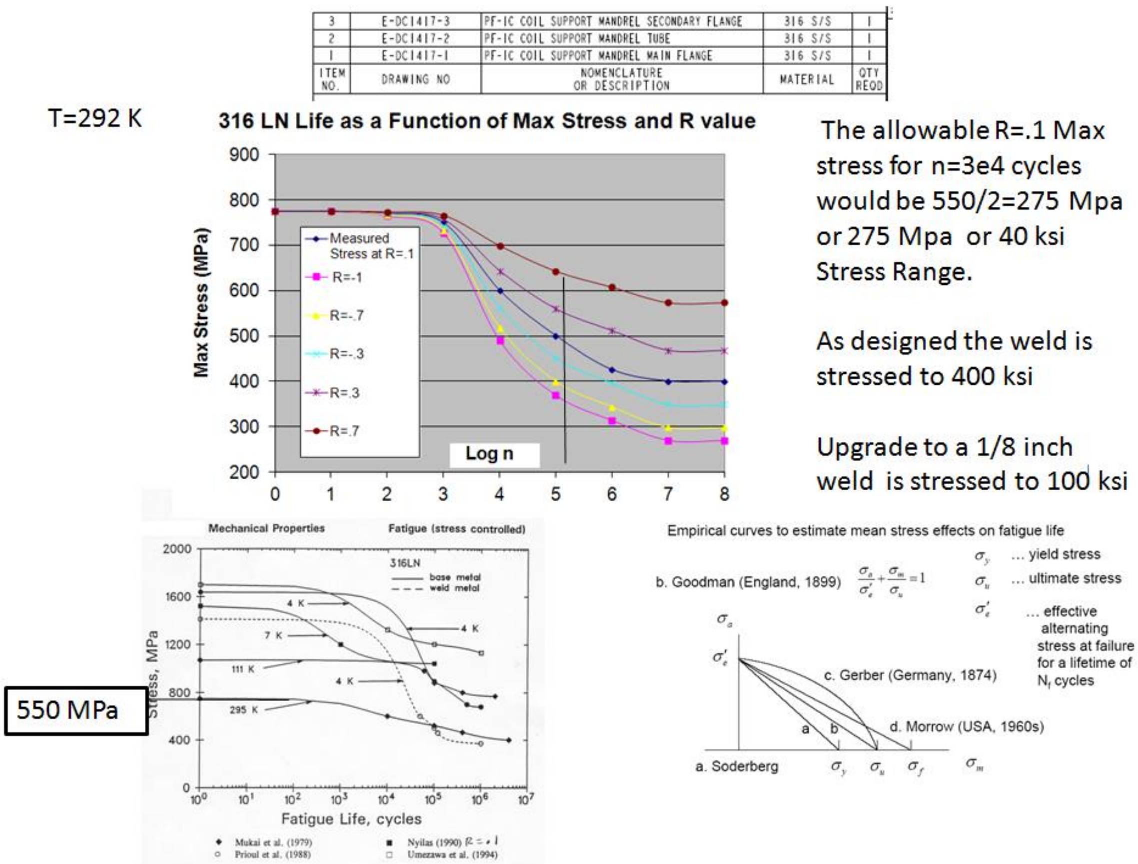


Figure 6.4.1-3 Recommended Strain Range (%) Values from the 316 SST section of [18] (structural Design Criteria for In-Vessel Components, Material Section)

T⇓/N⇒	10^6	10^7	2.10^8	4.10^{11}
20°C	0.190	0.147	0.111	0.107
425°C	0.183	0.140	0.106	0.102
550°C	0.167	0.128	0.097	0.094

Table A.S1.5.5-2: Recommended fatigue design values Stress controlled for N > 10^6.

Figure 6.4.1-4The allowable fatigue stress for 1e6 cycles from [18] is .00190*185e9=351 Mpa, or 51 ksi.

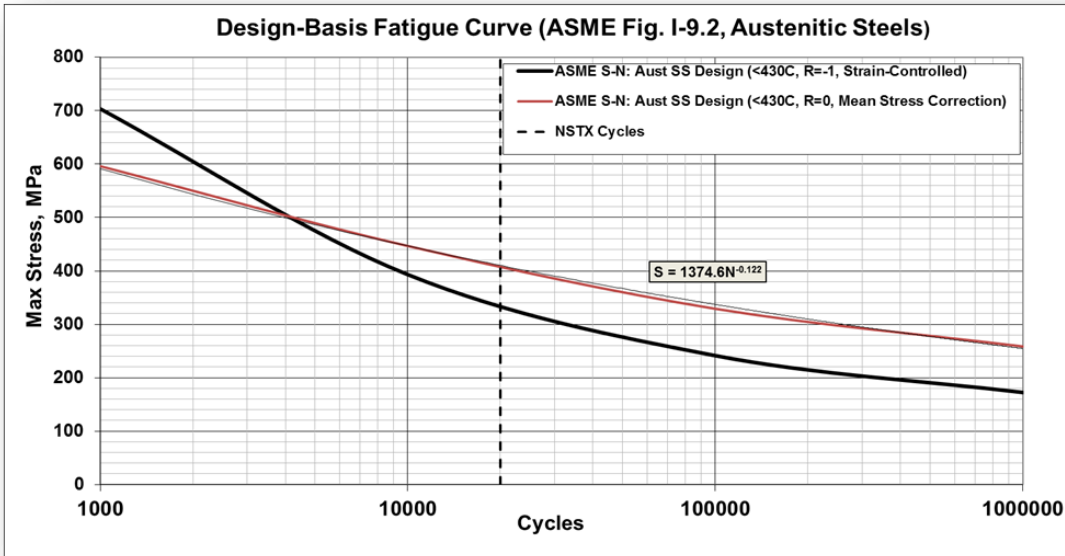


Figure 6.4.1-5 ASME Design SN curve with R=0 Correction by L. Myatt [81]

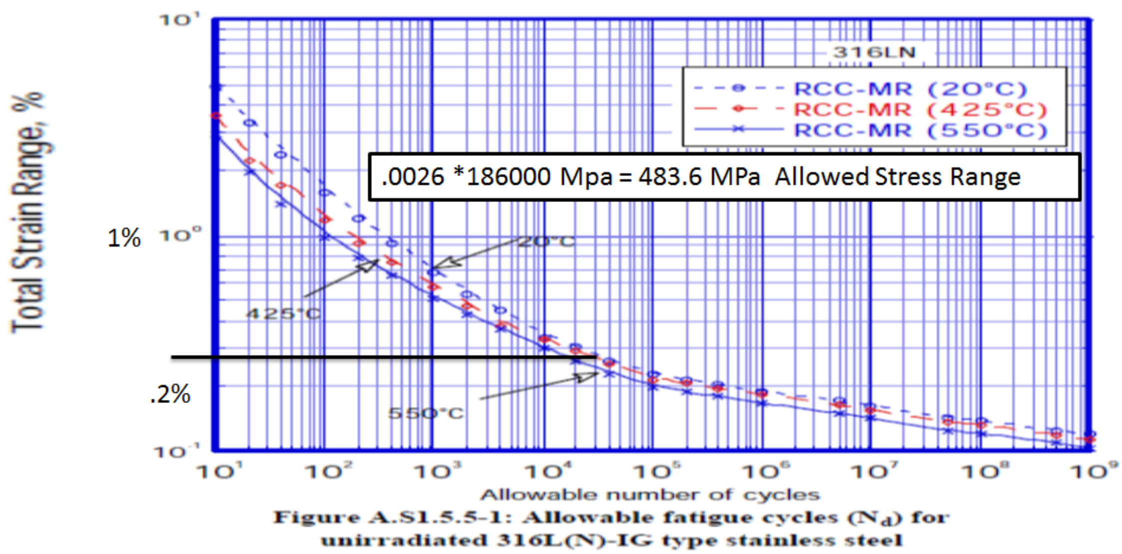
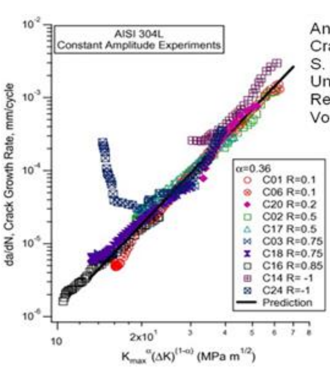


Figure 6.4.1-6 RCC-MR Design Design Fatigue curve Total Strain Range



An Experimental Investigation of Fatigue Crack Growth of Stainless Steel 304L
S. Kalnaus,F.Fan, Y Jiang, A.K. Vasudevan
University of Nevada and Office of Naval Research , International Journal of Fatigue, Volume 31, Issue 5, May 2009

Fig. 10 shows the results by using Eq. (3) for all the constant-amplitude loading experiments with different R-ratios conducted in the current study. For the AISI 304L stainless steel, α was found to be 0.36. Except for the early part of crack growth from the notch, Eq. (3) with α = 0.36 can bring all the crack growth curves together into one master curve. This master curve (thick line in Fig. 10) can be described by using the Paris type power law,

$$da/dN = C_1 k^{n_1} \quad (4)$$

where C_1 and n_1 are material constants. For the 304L alloy, $C_1 = 1.25 \cdot 10^{-10}$ and $n_1 = 3.97$, with da/dN in mm/cycle and k in $MPa\sqrt{m}$.

Table 2. ΔK_{th} values and Paris equation parameters ($da/dN = C(\Delta K)^n$) at different temperatures for $R = 0.1$ (units are $MPa\sqrt{m}$ and m/cycle)

Temperature (°C)	ΔK_{th}	C	n
25	8.2	3.1×10^{-13}	3.3
475	—	6.8×10^{-12}	2.8
500	11.8	6.8×10^{-12}	2.4
600	6.5	5.5×10^{-12}	2.9
700	5.1	2.6×10^{-11}	2.6
800	–	2.4×10^{-12}	5.1

Figure 6.4.1-7 Fracture Mechanics Properties of Stainless Steel

6.4.2 Copper Refrigerator Tubing Properties

Below is some data on the pressure capability of the 3/8" refrigerator tubing. The allowed pressure beyond 200C is dropping off quickly. From the properties for annealed copper at 350C, the allowed pressure would be ~297 psi - differential thermal stresses between copper and Inconel 625 should be minimized, but we might be able to heat the vertical inner divertor section.

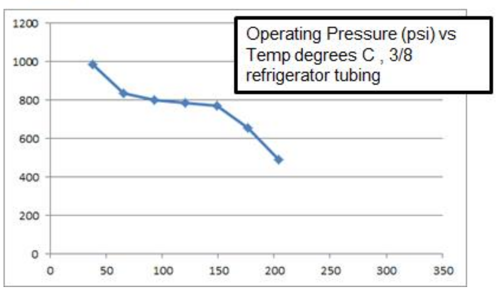
TABLE 2e. Dimensions and Physical Characteristics of Copper Tube: ACR (Air-Conditioning and Refrigeration Field Service) (A= Annealed Temper, D=Drawn Temper)

Nominal or Standard Size, inches		Nominal Dimensions, inches			Calculated Values (based on nominal dimensions)				
		Outside Diameter	Inside Diameter	Wall Thickness	Cross Sectional Area of Bore, sq inches	External Surface, sq ft per linear ft	Internal Surface, sq ft per linear ft	Weight of Tube Only, pounds per linear ft	Contents of Tube, cu ft per linear ft
1/8	A	.125	.065	.030	.00332	.0327	.0170	.0347	.00002
3/16	A	.187	.128	.030	.0129	.0492	.0335	.0575	.00009
1/4	A	.250	.190	.030	.0284	.0655	.0497	.0804	.00020
5/16	A	.312	.248	.032	.0483	.0817	.0649	.109	.00034
3/8 →	A	.375	.311	.032	.076	.0982	.0814	.134	.00053
	D	.375	.315	.030	.078	.0982	.0821	.126	.00054
1/2	A	.500	.436	.032	.149	.131	.114	.182	.00103
	D	.500	.430	.035	.145	.131	.113	.198	.00101

TABLE 3e. Rated Internal Working Pressure for Copper Tube: ACR* (Air Conditioning and Refrigeration Field Service)

Tube Size (OD), in	Annealed							Drawn**						
	COILS													
	S= 6000 psi 100 F	S= 5100 psi 150 F	S= 4900 psi 200 F	S= 4800 psi 250 F	S= 4700 psi 300 F	S= 4000 psi 350 F	S= 3000 psi 400 F	S= 10,300 psi 100 F	S= 10,300 psi 150 F	S= 10,300 psi 200 F	S= 10,300 psi 250 F	S= 10,000 psi 300 F	S= 9,700 psi 350 F	S= 9,400 psi 400 F
1/8	3074	2613	2510	2459	2408	2049	1537	—	—	—	—	—	—	—
3/16	1935	1645	1581	1548	1516	1290	968	—	—	—	—	—	[illegible]	—
1/4	1406	1195	1148	1125	1102	938	703	—	—	—	—	—	[illegible]	—
5/16	1197	1017	977	957	937	798	598	—	—	—	—	[illegible]	[illegible]	—
3/8 →	984	836	803	787	770	656	492	—	—	—	[illegible]	[illegible]	—	—
1/2	727	618	594	581	569	485	363	—	—	[illegible]	[illegible]	—	—	—

MANUFACTURED



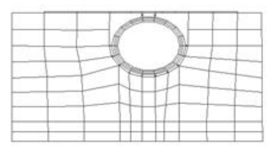
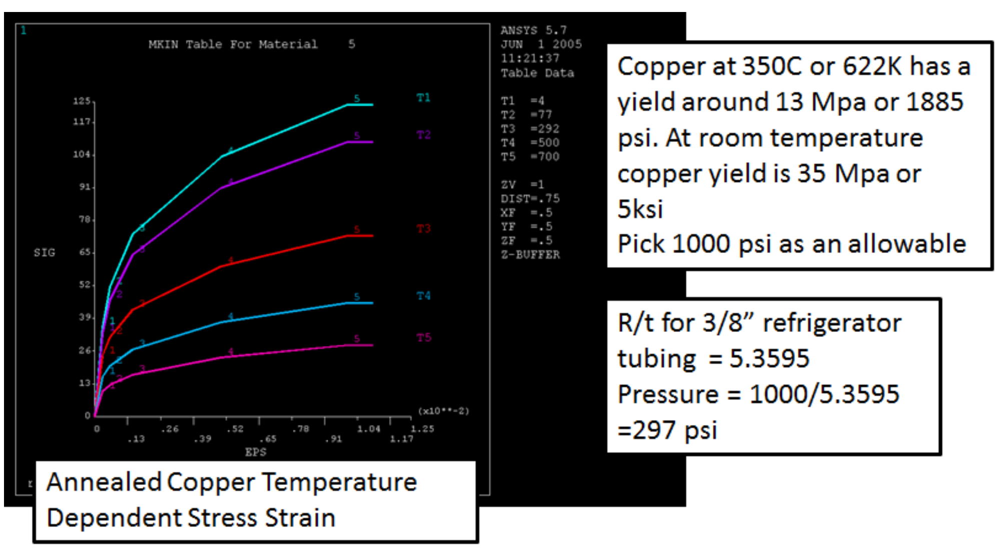


Figure 6.4.2-1 Copper Refrigerator Tubing Pressure Rating vs. Temperature



6.4.3 Viton Seal Temperature Limits

From the Web, reference 15, http://www.row-inc.com/techspecs.html:

Temperature Range

	FEP	PFA
Silicone	-75° to +400°F -60° to +205°C	-75° to +500°F -60° to +260°C
Viton	-15° to +400°F -26° to +205°C	-15° to +400°F -26° to +205°C
EPDM	-65° to +300°F -54° to +150°C	-65° to +300°F -54° to +150°C

6.4.4 G-10 Shim Limits

G-10 Property	G10/FR-4 (MIL-I-24768/2/27-GEE,GEE-F)
Density	.069
Water Absorption	0.05
Hardness (Rockwell M)	109
Tensile with grain (psi)	50,000
Compressive flatwise with grain (psi)	60,000
Flexural flatwise (psi)	65,000
Bonding (psi)	2,600
Maximum Operating Temperature (°C)	
Electrical	
Mechanical	130
	140
Impact Strength	12
Izod edgewise with grain (ft-lb/in)	
Shear flatwise (psi)	20,000

Figure 6.4.4-1 G-10 Properties and Temperature Limits

6.5 Heat Sources

6.5.1 Ohmic Heating

The centerstack is heated by passing 8 kA through the centerstack. The resulting temperature and tile heating is calculated in [2] but this calculation concluded only 3.5 kA was needed. Based on experience, this was increased to 6kA by Raki Ramakrisnan and to 8kA later by Mike Williams. A Brooks used the 8 kA in his heat balance simulations.

6.5.2 Passive Plate Heating

The outer divertor and passive pates can be actively heated with helium gas. Anecdotally, the gas is heated to 400C to 420C and exits the plates around 325C during past bake-outs. Some sections of the plates are at or slightly above the 350C target temperature.

6.5.3 Vessel Heating/Cooling

The vessel is insulated with blankets, and is supplied with 150C water that acts to either heat the vessel or maintain the 150 C temperature as the passive plates and centerstack approach the 350 degree target temperature.

6.6 Design Currents and Lorentz Forces

The only current that needed to be considered during bake-out is the 8kA current running through the centerstack casing.

To assess the need for PF1b, the required currents are plotted below:

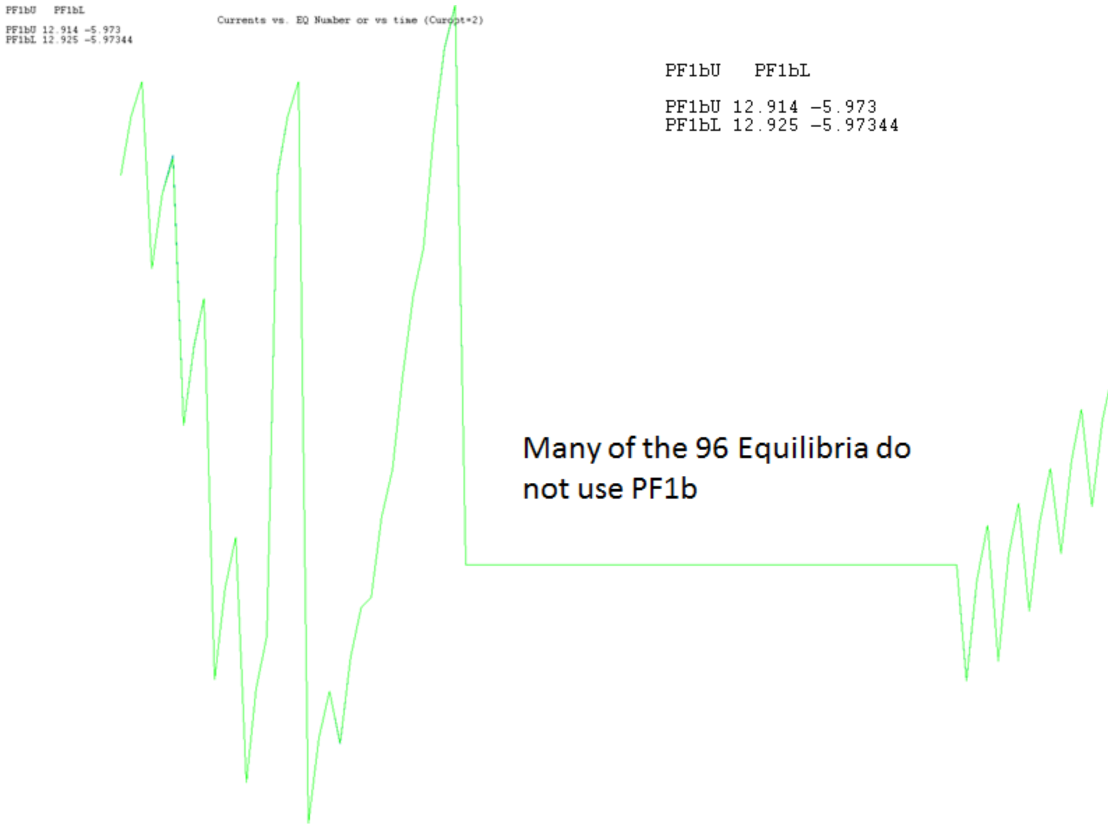


Figure 6.6-1 PF1bUpper and Lower Curretns from the 96 Equilibria

7.0 Models

7.1 Heat Balance Model

A heat balance analysis [6] was developed to predict operating temperatures and size cooling systems. This same modeling is used to assess the bake-out.

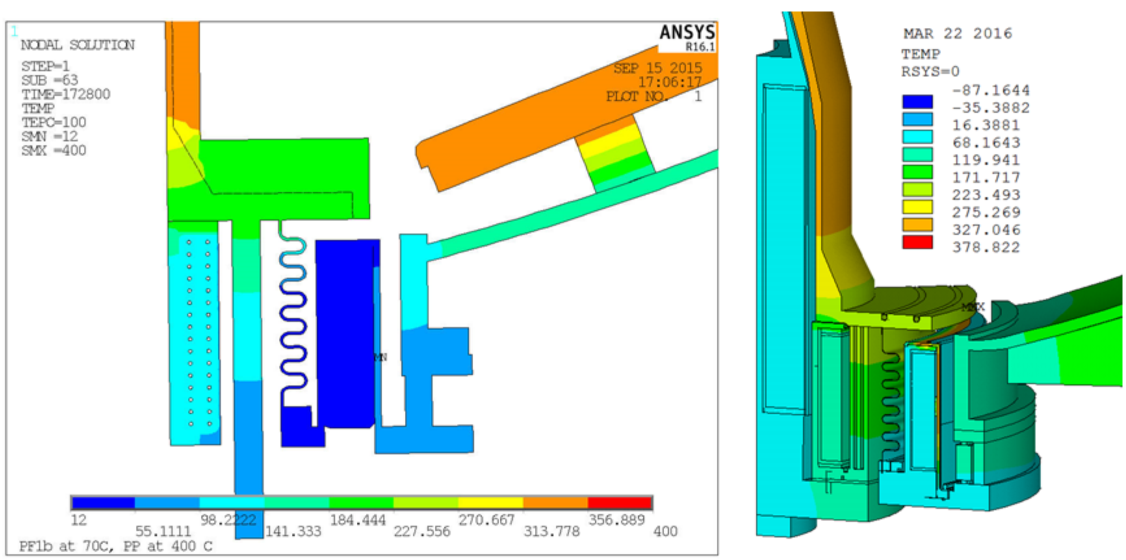


Figure 7.1-1 Detail of Heat Balance Model near the Inner Horizontal Divertor Flange

7.2 PF1b Mandrel to Centerstack Weld

Section 10.0 assesses the weld stress and plastic strain expected to occur during bake-out. The weld is analyzed in two models. One derived from the 2D axisymmetric heat balance model by A. Brooks, and a second model by P. Titus that intends to look more deeply into the stress in the weld and plastic strain at the root of the "crack" formed by the connection of the mandrel flange and centerstack inner divertor flange. The (Titus) structural model is swept from a 2D mesh and includes the concentration due to the intermittent weld.

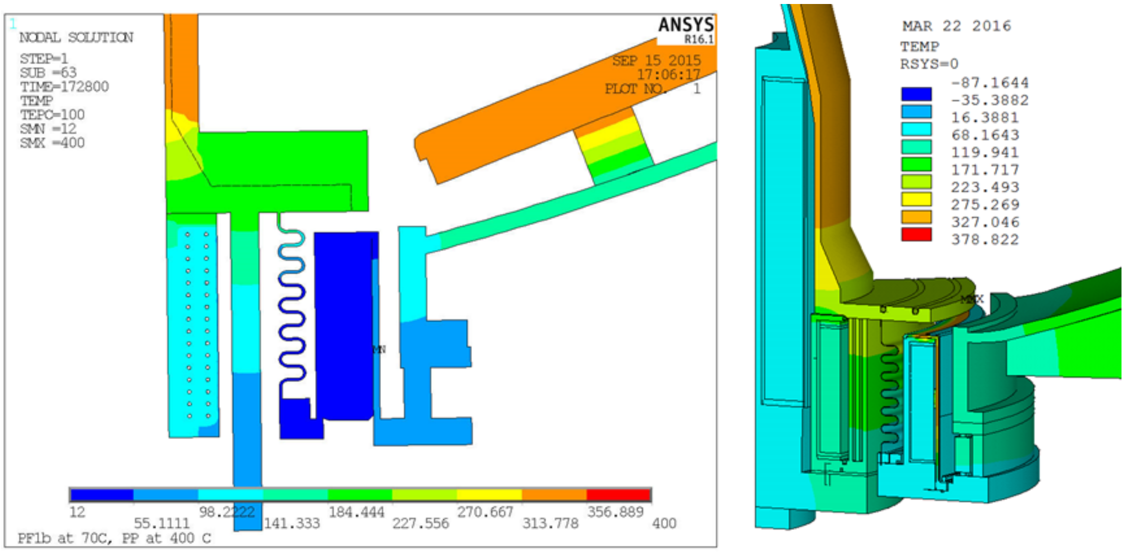


Figure 7.2-1 Inner Horizontal Divertor Flange Thermal Results and as Mapped to (Titus) Weld Stress Model.

7.3 Divertor Flange Cooling Tube Model

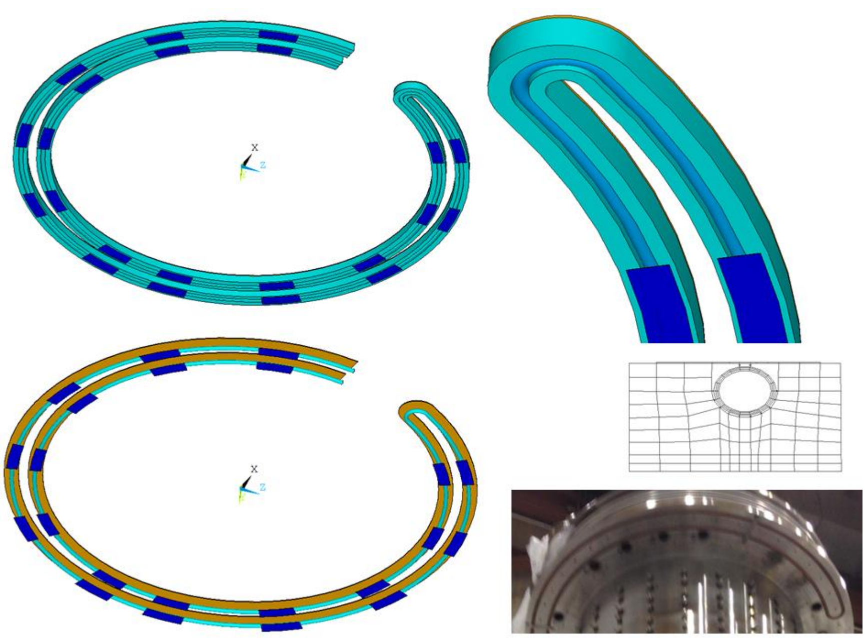


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Figure 7.3-1 Horizontal Divertor Plate Cooling Tube Model

8.0 September-October 2015 Bake-Out Experience

A bake-out was completed in September 29, 2015. Details of the bake-out are in the run copy of the procedure [11] and in summary spreadsheets prepared by Stefan Gerhardt. A post job de-briefing was conducted November 21 2015. Gerhardt's PowerPoint summary is also included in this section.
It met requirements for the initial operating period.

8.1 Documentation of the Bake-Out

This calculation is not intended to document the bake-out results, but there are a few things needing confirmation to support the analysis efforts. Gerhardt's spreadsheets may be found at:
https://docs.google.com/spreadsheets/d/1Yee_sVu_j6y7CWgT_d8lX0Cr9cEomTKGisB_DP0r1QE/edit#gid=395247459

https://docs.google.com/spreadsheets/d/1mD0mYHhXYhQq3Rh2crAGOrHwoONjG4sbLMBiliXlFf8/edit#gid=395247459

Gerhardt's spreadsheets include timelines of the bake-out and note things like the PF1b cooling water temperature revision that is considered in the evaluation of the peak insulation temperature.

9/12/2015	7:15	Started Temperature Ramp
9/12/2015	13:15	raised to 5000 amps total. power supplies tripping, will investigate
9/12/2015	1730	raised to 8000 amps and backing off outer vessel bake
9/12/2015	2207	EM Turned on per Bill Blanchard
9/13/2015	1730	Had an e-stop system shutdown. System back up. Increased water flow to Oh paths.
9/14/2015	1005	degas Micro ion gauge on NB #2drift duct\ could not degas, pressure too high
9/14/2015	1130	increased PF1B inlet temperature
9/14/2015	1215	reducing CSC power to 7000 amps total
9/14/2015	1340	increased PF1B inlet temperature 90 C
9/15/2015	745	use IG-1 NOT IG-2 due to TIV through put leak
9/15/2015	855	raise to 8000 amp. total
9/16/2015	1320	reverse flow of He bakeout system
9/16/2015	2000	Raised Helium Temp inlet from 420 to 430 degress
9/16/2015	2230	Raised Helium Temp inlet from 430 to 450 degress
9/17/2015	325	Do to Diff temp could not make 450
9/17/2015	610	hot helium system tripped
9/17/2015	740	hot helium system up
9/17/2015	900	hot he tripped again. system restored shortly after
9/17/2015	1300	8 deg temp drop on lower IBDH target. no reasonable explanation why. all other temps still increasing
9/17/2015	2207	Dropped Current From 8000 to 7500 Per Mark Cropper (Stefan Gerhardt)
9/18/2015	730	change vessel presure adjustment from 571 to 362
9/18/2015	1800	beginning bakeout rampdown for repairs
9/18/2015	2020	RGA Now in FC and Normal Config
9/19/2015	645	turned on electron multiplier per B. Blanchard. captured RGA data to inpsect possible leak,
9/19/2015	1000	start setting up for leak check

9/23/2015	0:00	starting bake out ramp up
9/23/2015	0:00	Set RGA to Normal Mode Faraday Cup per Bill Blanchard
9/23/2015	1535	large He leak in Bakeout system, ramping down to investigate/repair
9/24/2015	700	
9/24/2015	850	
9/24/2015	1105	rga in normal mode and EM=800
9/24/2015	1130	stop bake out to find helium leaks
9/24/2015	2200	last set of readings going to help work on He Skid
9/26/2015	1200	restart bake out
9/27/2015	157	0157 entire He system shutdown John D got restarted
9/27/2015	308	He System down Cooling Down (Blower?)
9/28/2015	1405	start bake out
9/28/2015	2042	Blower speed reduced after tripping per John D
9/28/2015	2115	Blower speed now @ 1275
9/28/2015	2322	Blower speed now @ 1450
9/29/2015	715	Blower speed now @ 1510
9/29/2015	1922	He system down
9/29/2015	2045	Cooling Down AGAIN

Issues arose with the measured temperatures of the centerstack casing and passive plates. The 350C target temperatures needed to be clarified with respect to the actual local temperatures. The criteria applied is explained in section 6.1 of this calculation. The average temperature of the centerstack casing was to be maintained below 350C and this is demonstrated in one of the screen shots of the thermocouple data below (Figure 8.3-1).

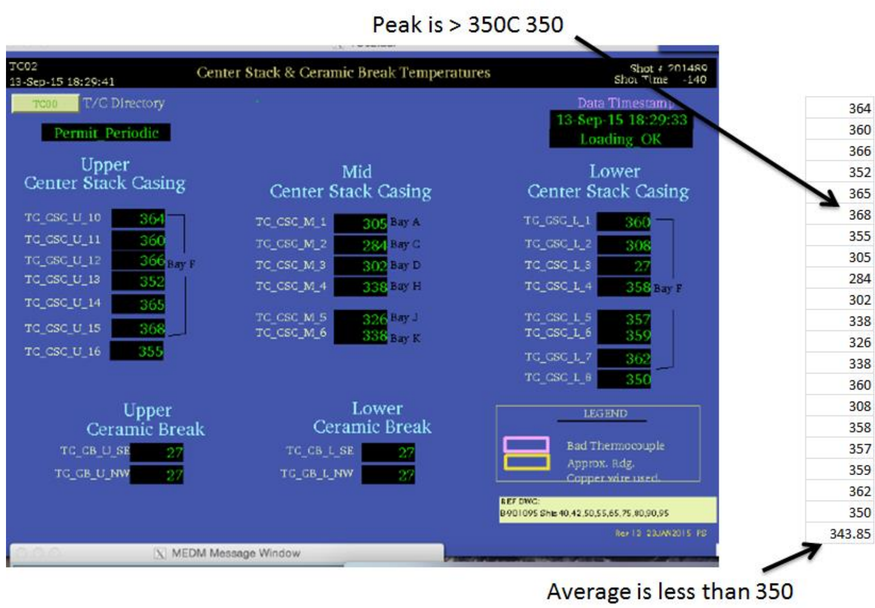


Figure 8.3-1 Typical Thermocouple Monitor Screen, Showing Average Centerstack Temperatures

In an April 12, 2016 personal discussion between Mark Cropper and P. Titus, Mark indicated the fans under the centerstack were turned off, but blowing air was directed at the CHI bus bar to vessel connections because these had discolored.

Consistent with Stefan's concerns, evaluate all the problems and needed with the Helium system. What insulation was added? Was the up-down asymmetry in temperature fixed? understood? Do we have a serviceable pump? spare? Can we fix any of the leaks? What is recommended to improve the temperature distribution?

At least verbally, confirmation that things went back together as intended, was obtained. This included TF truss supports, CHI bus bar supports, PF 4/5 Phenolic block clamps, and PF4/5 column supports.

A verbal report was provided by Scott Gifford that after cooldown, the aluminum tapes on the sliding blocks - PF 4&5, PF 2 and 3, main column slides, and umbrella feet, showed that the sliding supports allowed components to return to their original positions.
The new PF1b heating/cooling system has been disconnected. And the normal cooling has been re-connected.

The status of the horizontal divertor tile flange cooling loops at the bake-out was that both were be isolated and pumped on. PF1b was properly grounded.

8.2 From Stefan Gerhardt's Powerpoint Summary:

Things that went well...

~3 weeks at temperature.
Many tweaks to the system in order to squeeze every last bit of temperature out of it.
Rapid appropriate responses by the bakeout team to problems.
Nice log keeping.
~51 hours of D2 GDC, ~12 hours of He GDC
<u>Essentially achieved the target base pressure</u>
No major diagnostic problems that I know of.
Leaks that opened up were found, and sealed, by meticulous leak checking.

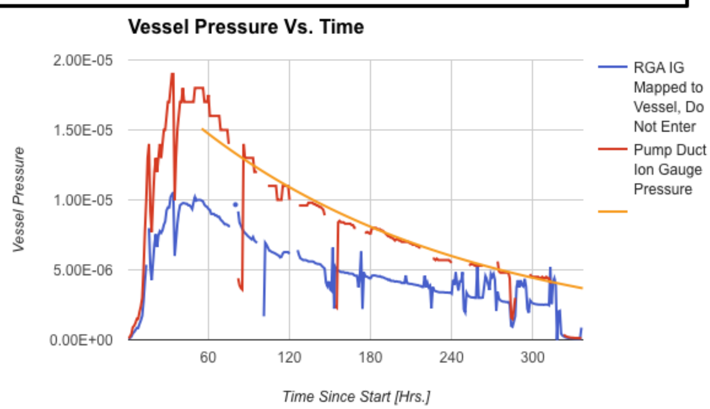
Base Pressure Target was Largely Achieved

Target was 3.5e-6 base pressure at temperature

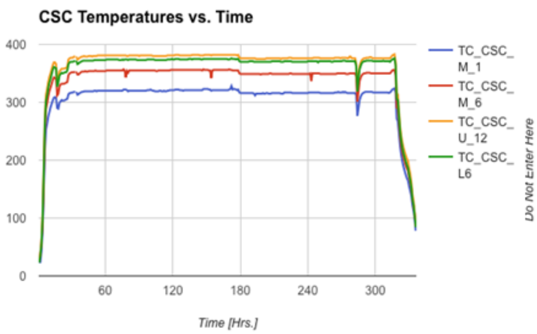
This number based on achieving 5e-6 at full temperature in NSTX for successful plasma operations, and adjusting that number for the new pumping speed. (WB)

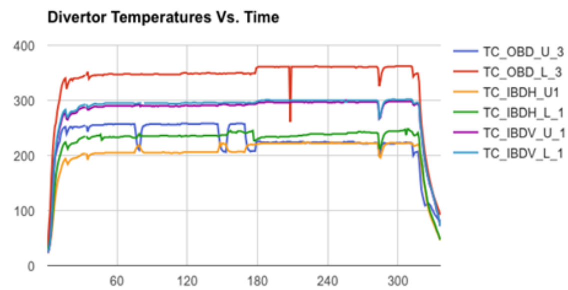
Both the duct ion gauge and IG1 showed a pressure of 4e-6 on the morning of the He system vent.

Ended on 10/20, had been intending to go to 10/23



Temperatures Were Largely Quite Steady





Typical Temperatures

CS Top: 360

CS Mid: 330

CS Bot: 370

Vertical Target Top: 300

Vertical Target Bot: 310

Horizontal Target Top: 222

Horizontal Target Bottom: 235

Outboard Lower: 360

Outboard Upper: 225

PPP Upper: 324 (?)

PPP Lower: 300 (?)

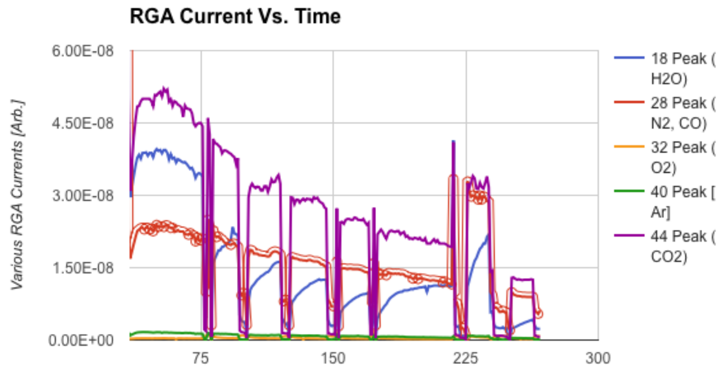
SPP Upper: ???

SPP Lower: 280 (?)

NBPP: 260-300

(October 15, 9:00 AM)

Hydrocarbons Appear to Have Been Dominant; Recovery of Mass 18 After Each GDC



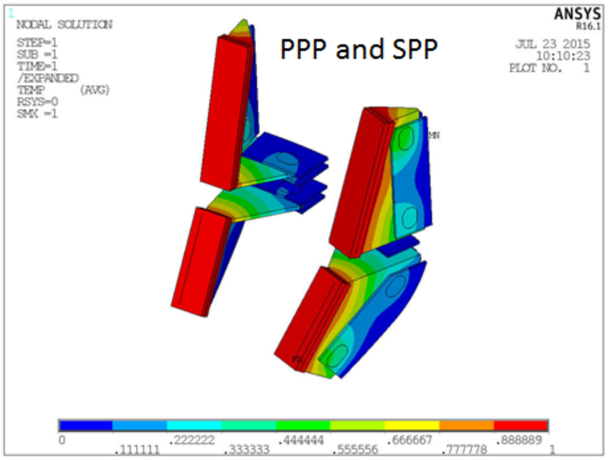
Suggested Improvement Areas

- Higher Temperatures Needed in Key Places
  - Need to improve temperature of inner horizontal targets.
    - Thermal isolation? Would be highly desirable to avoid an active heating solution.
  - Need to make the outer vessel more up-down symmetric
    - Changes to how the He is plumbed? Throttle down some places to increase flow others?
    - Need more total energy input for this?
  - These can be related, since a hotter outer vessel will increase radiation to the horizontal targets?
  - Highly desirable to stop abusing the PF-1b coil.
- Need to improve the legacy TC situation on the outer vessel. It is very difficult to trust many of the measurements.

9. Heat Balance (A. Brooks)

The heat balance calculation employed for the bake-out is an extension of the model used for the heat balance during normal operations. [6] "Global Thermal Analysis of Center Stack Heat Balance", NSTXU-CALC-11-01-00. This simulation employs a 2D axisymmetric ANSYS model of NSTX.

3D Models Created to Determine Equivalent Axisymmetric Conduction



Comparison of Conduction and Radiation between PP and VV

Conduction (ANSYS Model of Supports)			
	Full	15-Apr	
Q/dT per support	1.1239	1.1239	w/C
Number of Support	48	48	
Q/dT, total	53.9472		
Tpp	350	150	C
Tvv	150	25	C
dT	200	125	C
Qcond	10,789	6,743	w
Radiation			
Area	15	15	m2
sigma	5.67E-08	5.67E-08	
Tpp	623	423	K
Tvv	423	298	K
emis	1	1	
Qrad	100,894	20,522	w
Qcond/Qrad	10.7%	32.9%	

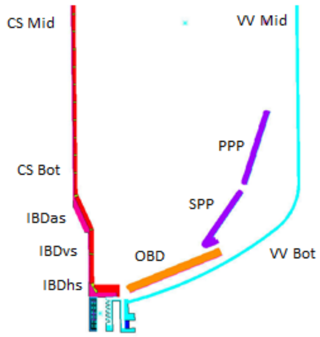
9.1 Mini Bake-out Benchmark

- Initial predictions of the April 15th bake-out over estimated the temperature the IBDhs would reach
  - 127 C predicted, 94 C (max) measured
    - See next figure for more detail

- Assumptions of heat losses from PPP, SPP and OBD found suspect
  - Analysis assumed radiation heat loss primarily thru radiation to VV from back surface
  - This was a reasonable assumption for the components at 350 C but not at the ~150 C without helium heating as during April 15th bake-out
  - At low temperatures, conduction thru supports is not insignificant
  - Also, emissivity values used (.27 from Cu and SS) may be low due to prior darkening of surfaces during operation

- Model modified to include supports with equivalent axisymmetric conduction

Comparison of April 15, 2015 Bakeout with ANSYS Simulations

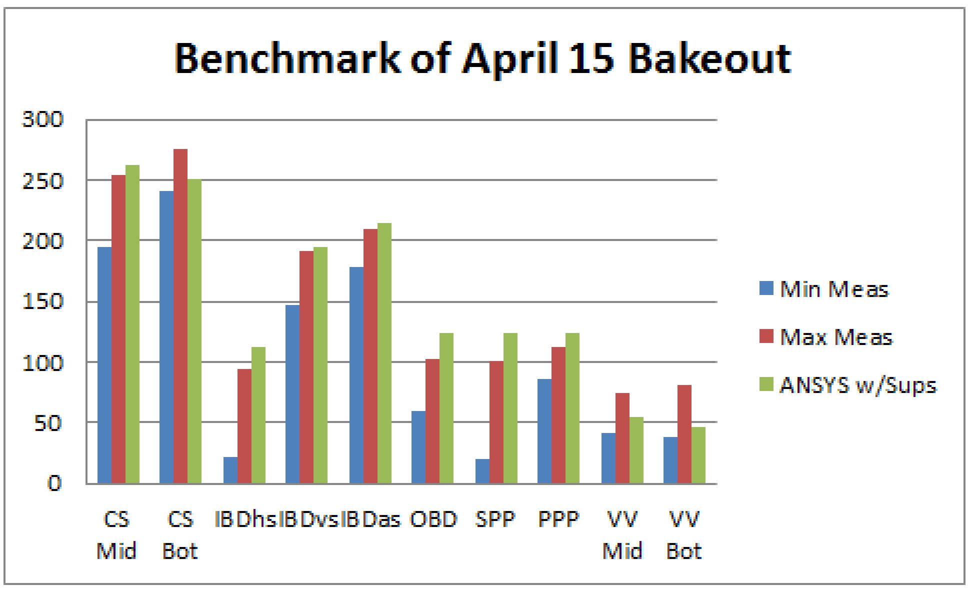


	Measured		ANSYS				
	Min	Max	e=0	e=1	e=.7	e=.7/.27	e=.27
CS Mid	195	254	658	220	255	274	350
CS Bot	241	276	591	207	238	262	325
IBDhs	22	94	207	91	100	127	125
IBDvs	147	192	419	158	180	205	240
IBDas	179	209	546	172	202	227	285
OBD	60	102	25	86	96	150	125
SPP	21	101	25	93	104	158	138
PPP	86	112	25	93	105	162	142
VV Mid	41	74	25	72	70	63	60
VV Bot	39	81	25	49	47	48	43

Reference Emissivities
VV =.27, Tiles=.7

- 8 kA CSC Ohmic Heating
- Radiation Exchange between all surfaces (emissivity varied)
- VV Insulated but not cooled/heated
- PP, IBD, OBD not heated
- Heat Losses thru VV Insulation, OH at 40C & PF1b at 20 C

After adding conducting supports from the PP & OBD to the VV, the agreement is fairly good even without changing the surface emissivities:



9.2 Bakeout with PF1b at 150C

The bakeout has been run with the new supports and keeping PF1b at 150 C. The heat loss would raise the water temperature ~20 C going thru the coil. The resulting temperatures are plotted below for the PP at 350 C and also at 400 C to show the benefit. The turn insulation is about 200 C.

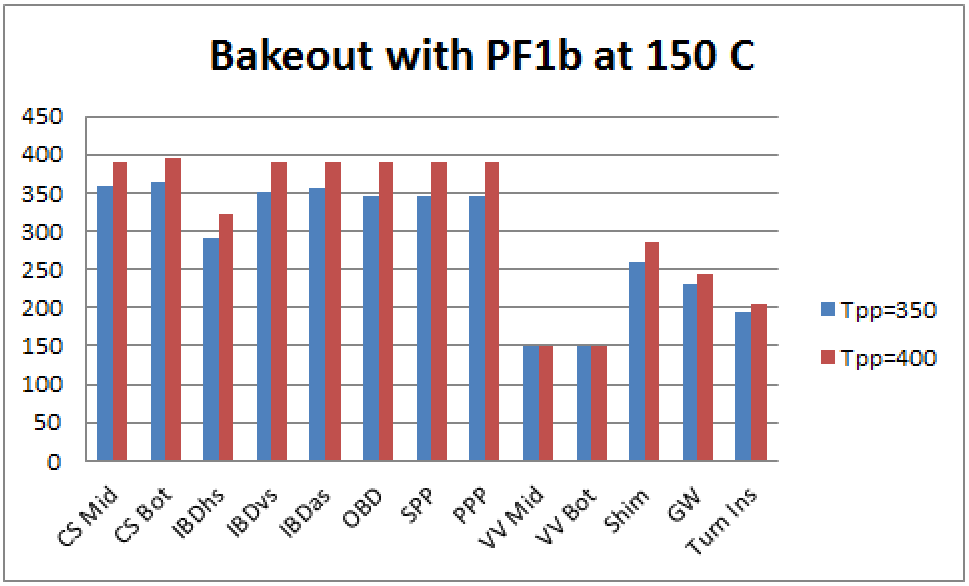


Figure 9.2-1 Bake-Out with PF1b at 150 C for two Passive Plate Temperatures

	Case	Description	IBDhs Tile Temp	G-10 PF1b Coil Shim Temp	PF1b Ground Wrap Temp	PF1b Conductor Insulation
Near Term	1	No Heating or cooling of IBD, OBD, PP or VV	205	180	135	80
	2	PP & OBD He Heating Turned On	290	240	180	110
	3	VV Heating/Cooling at 150 C turned on	260	225	162	95
	4	IBD Heating at 350 C	325	280	200	120
Long Term	5	No IBD Heating, Grafoil Removed from Tile	265	215	160	95
	6	Radiation Shield added behind IBDhs Tile	270	225	165	100
	7a	Heat Leakage to PF1a at 40 included	240	200	148	87
	7b	Repeat assuming no conduction between Tiles	310	125	95	60
	8a	Radiation Shield added behind IBDvs Tiles also	325	80	60	40
	8b	Repeat assuming no conduction between Tiles	315	80	60	40
Near Term (Modified Assumptions)	9	Starting with (4) above, contact resistance and conduction thru weld	325	270	195	115
	10	Contact resistance artificially increased to see impact. Still conduction thru weld	330	113	105	65

Figure 9.2-2 Bake-Out Results for Various Divertor Tile Thermal Connection Options

9.3 Impact of Convection from Tubes and Bolts at IBD Flange

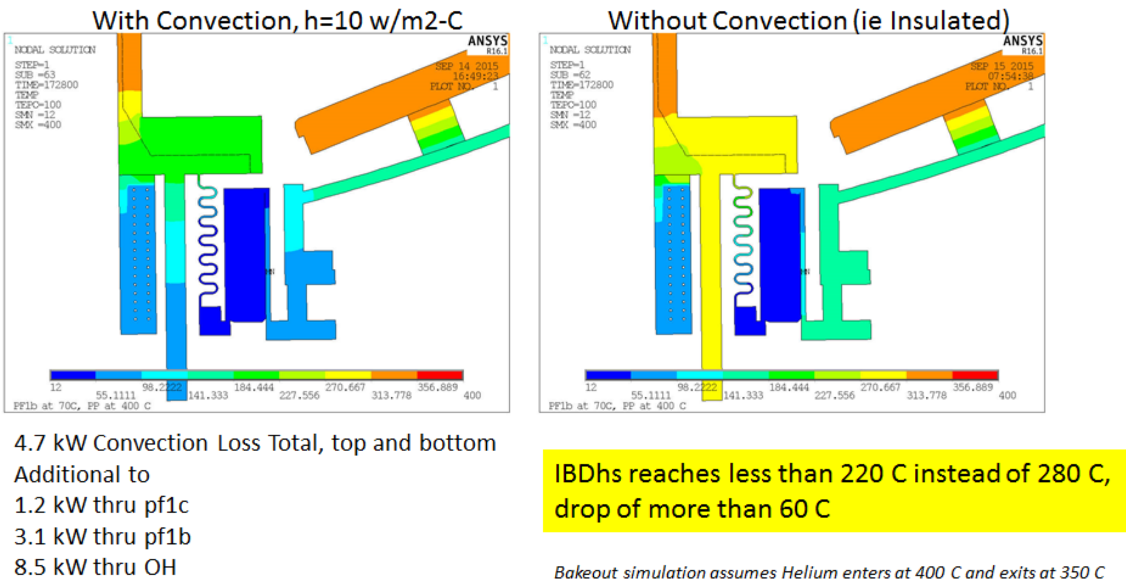


Figure 9.3-1 Effect of Convection and Insulation in the Area Above the Pedestal on Bake-Out Results

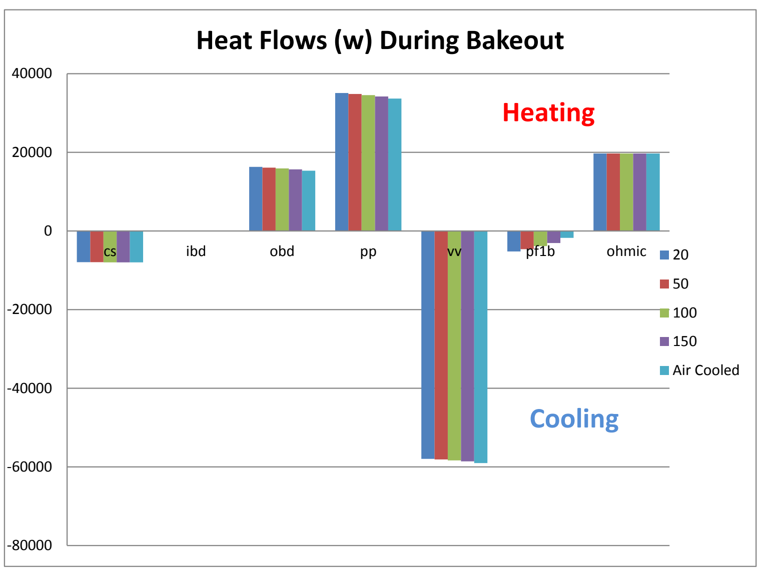


Figure 9.3-2 Heat Flows

10.0 PF1b to Casing Weld

This section assesses the weld stress and plastic strain expected to occur during bake-out. This weld is a major structural element that supports the centerstack casing, OH and PF1a and PF1b. It resists coil electromagnetic launching loads and lateral loads during a disruption. Reference [20] addresses the adequacy of the casing weld for other than bake-out loads. No damage to this weld can be tolerated during the bake-out.

The weld is analyzed in two models. One is derived from the 2D axisymmetric heat balance model by A. Brooks, and a second model by P. Titus that intends to look more deeply into the stress in the weld and plastic strain at the root of the "crack" formed by the connection of the mandrel flange and centerstack inner divertor flange. The (Titus) model includes the concentration due to the intermittent weld.

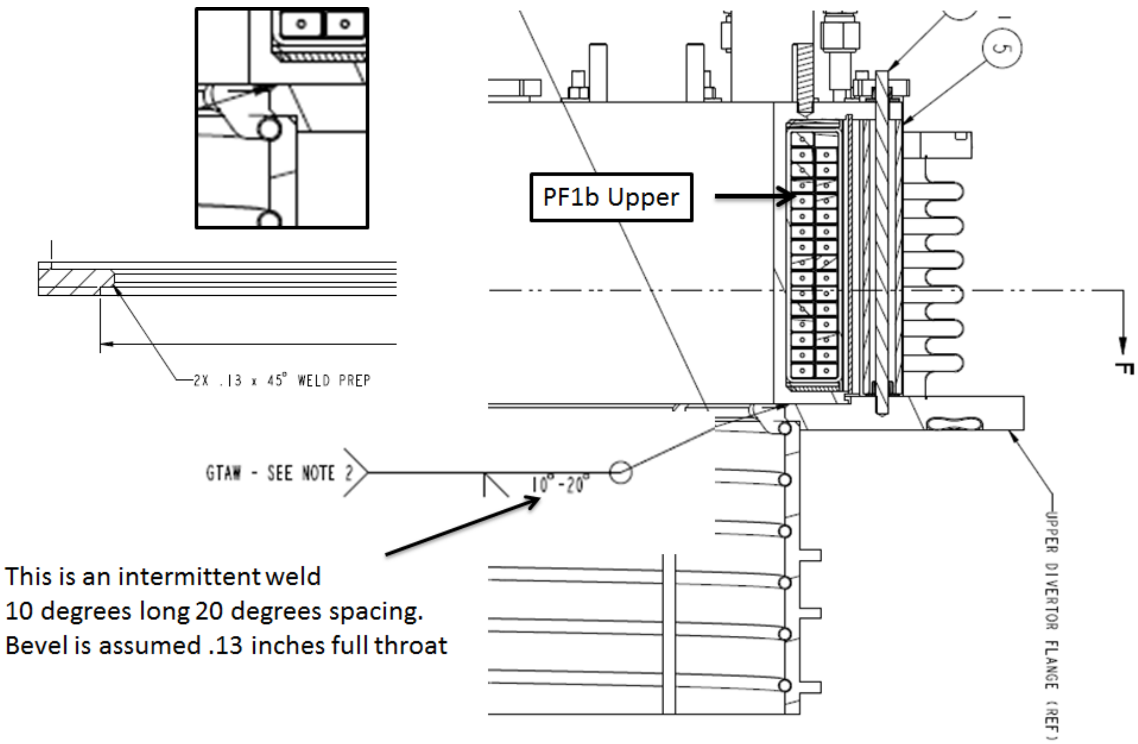


Figure 10.0-1 PF1b Mandrel Weld Details

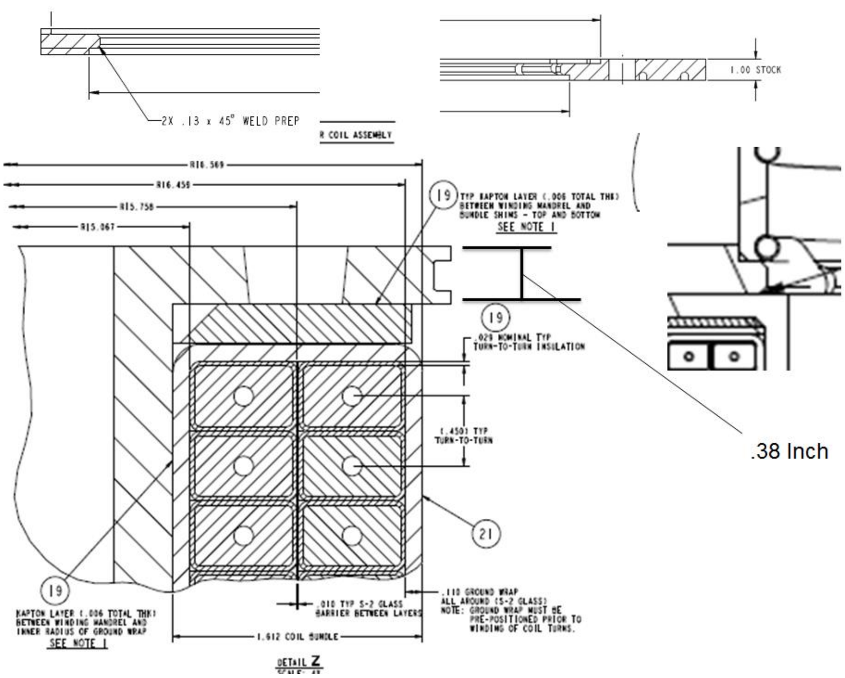


Figure 10.0-2 PF1b Mandrel Weld Details

The (Titus) model includes the concentration due to the intermittent weld. The A. Brooks model includes the weld connection with some adjustment in area and axisymmetric properties to model the fact that the intermittent weld is effectively only 50% of the full circumference of the joint. This weld is a small weld but the diameter is large and produces a significant weld area. The effectiveness of such a small weld was an issue with other structures in NSTX-U and was the subject of a mechanical test shown in Figure 10.0-3.

Figure 10.0-3 1/8 inch fillet weld testing

Tensile Pull Weld Samples

WR#20110329 MTL#351 2011-06-15

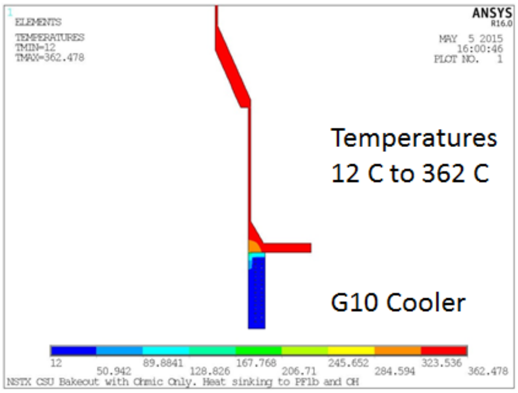
A total of 4 welded samples were tested in tension

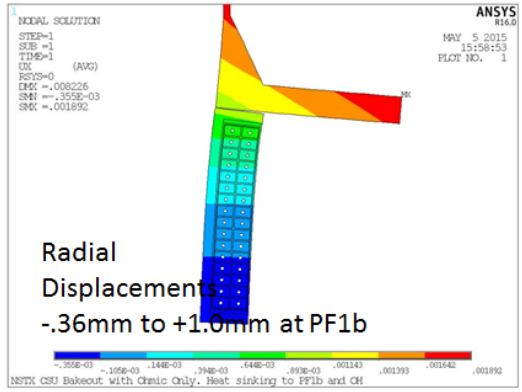
All samples were a 300 series stainless steel, butt welded to a 1” plate using nominal 1/8” fillet welds. The thinner plates were centered on the heavier plate edge and welded with a fillet on each side comprising a welded assembly consisting of two welds across the reduced section. Overall specimen length was 16” with the reduced section straddling the welded zone.

Sample #1 ¼” plate to 1” plate, reduced section 1.425”, rupture 26847lbs force
Sample #2 ¼” plate to 1” plate, reduced section 1.328”, rupture 26113lbs force
Sample #3 ½” plate to 1” plate, reduced section 1.310”, rupture 26194lbs force
Sample #4 ½” plate to 1” plate, reduced section 1.458”, rupture 31851lbs force

Stresses the Samples Survived:
26194 LBS/2/1.375 = 9252 Lbs/inch
26194/2/1.375/.125 = 76200 psi Nominal Average Tension
26194/2/1.375/.125/.707 = 107780 psi Shear on Throat

Shear At Weld from Thermal Growth





723.63MPa is 104949 psi

Weld Shear from Thermal Growth		
Radius	0.381	m
Weld Depth	0.003175	m
Weld Fraction	0.5	
Weld Area	0.0038	m2
Radial Force, 360deg	2.75	MN
Shear	723.63	MPa

Assuming separation of PF1b from Flange (near 0 conductance) produces a larger temperature gradient and higher shear stress

Figure 10.0-4 PF1b Mandrel Weld Stress with a Hot Centerstack Casing and Cold (12C) PF1b

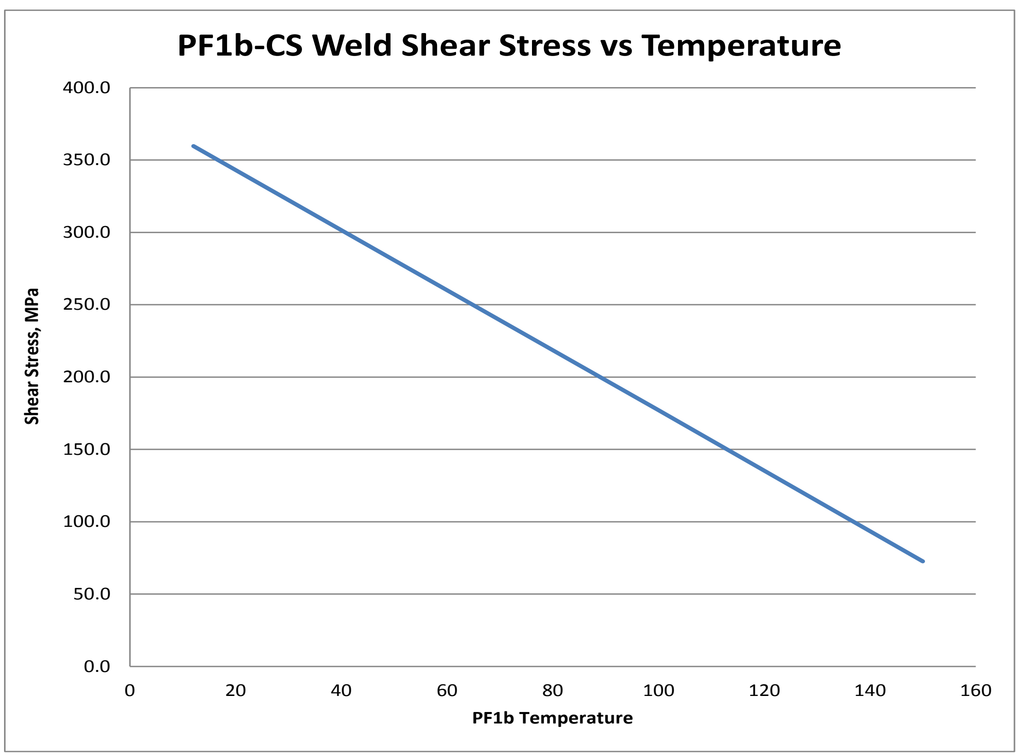
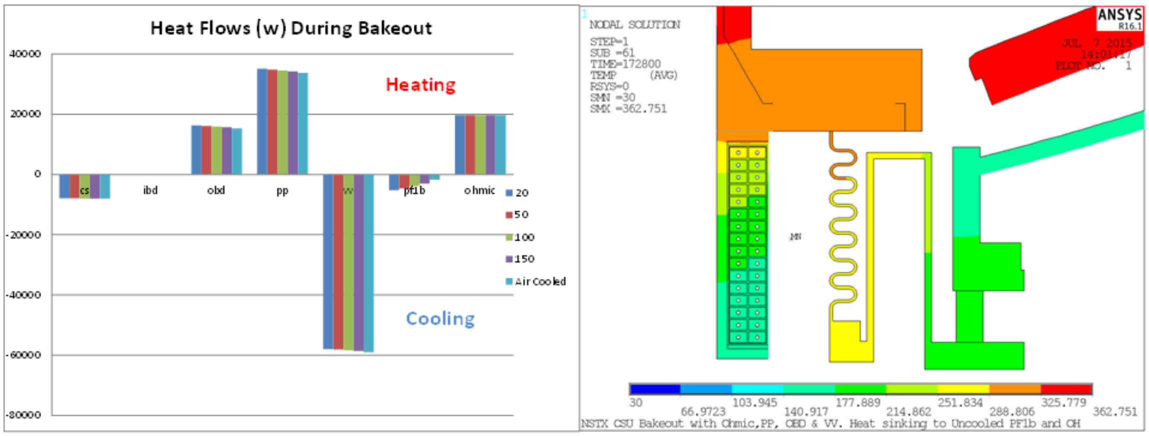


Figure 10.0-5 PF1b Weld Shear Stress vs. Temperature

Heat Balance During Bakeout



Legend: PF1b Temperature

Natural Convection to 30 C Air at OD of PF1b
h_film=10 w/m2-C

If Natural Convection cooling is much less, average pf1b temperature increases driving weld shear stresses more negative. At h_film=0, the temperature rises to 350 C and Weld Shear Stress is -347 MPa

Figure 10.0-6 Heat Balance During Bake-Out

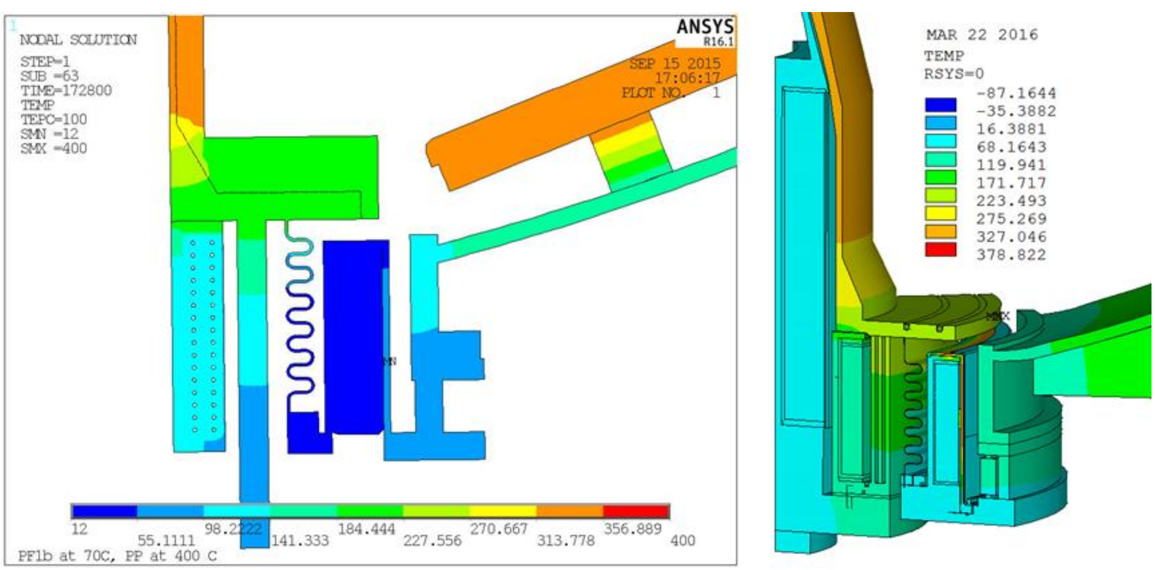


Figure 10.0-7 Temperatures from Art Brook's Simulation (Left) and on P. Titus's Weld Model (Right)

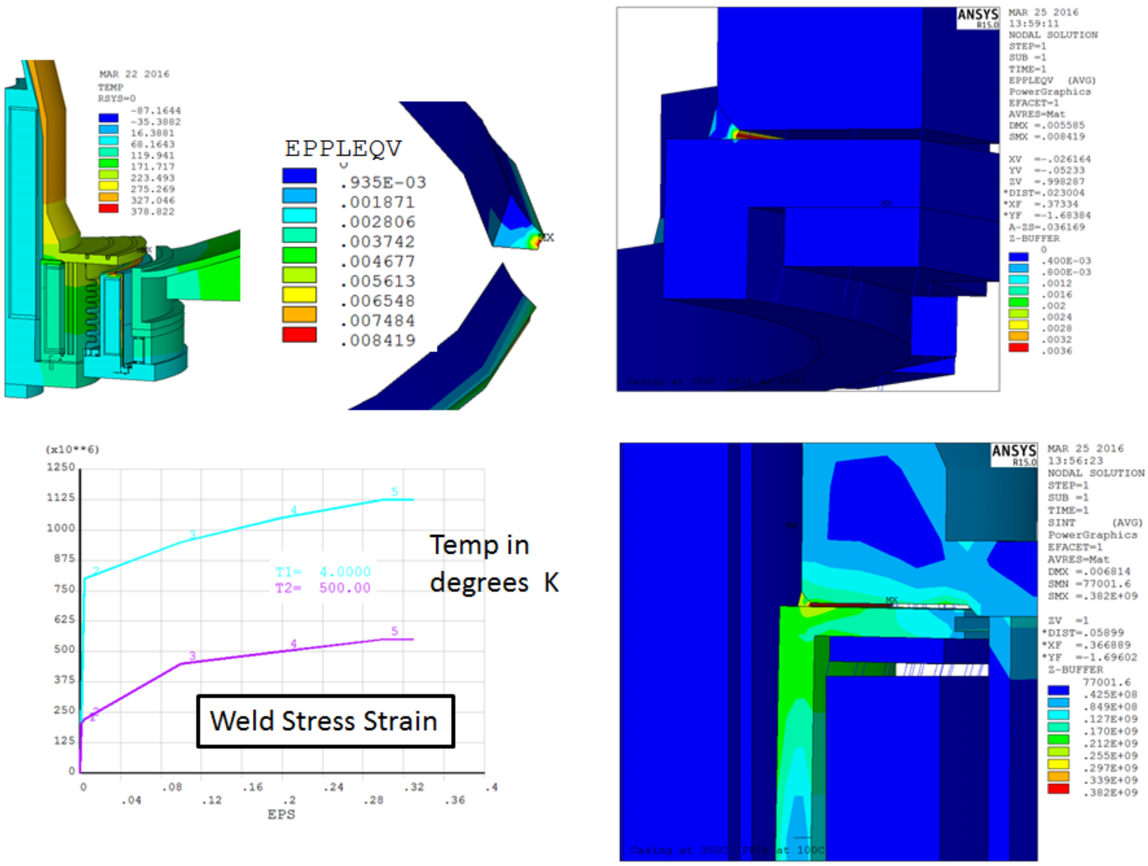


Figure 10.0-8 Weld Stress and Plastic Strain (P Titus Model)

The weld strain is less than 1%. This must survive only a few bake-outs, and once yielded will shake-down .Comparing this the plasticity during weld cooling, and with the ductility in the tests shown inn figure 10.0-3, the welds are judged to be able to survive the bake-out strains.

11.0 PF1b Winding Pack Thermal / Electrical / Mechanical Evaluation

11.1 CTD-425 + Kapton Bake + Mechanical + Electrical Tests

There are a number of areas around the machine that require adherence to temperature limits. CTD-425 Epoxy qualifications included measurements up to 125 C and it was qualified for normal service in the OH. During bake-out the machine is to have the vessel internals heated to 350C and the vessel limited to 150C. Assessments of these temperatures were needed to adjust for the natural gradients from the heating/cooling systems and for variations in the calibrations of the thermocouples. This is discussed in section 6.1. The coils are normally protected by running normal cooling water through them during the bake-out, but to raise the temperature of the inner divertor tiles, PF1b will be "cooled" with warmer water, and this raises the possibility of local temperatures of the epoxy beyond that expected for normal operation. Initial indications of the chemistry of the epoxy provided by CTD indicated that the epoxy does not start to degrade until 300C with a weight loss of 5% at 350C indicating an altered chemistry and likely change in properties. The glass transition temperature of CTD 425 is 175 to 180C and if there was any loading on the insulation during bake-out temperatures in this range, the coil winding could be deformed. CTD's evaluations are included in an email in Appendix A. The insulation system used for the inner PF coils includes interleaved Kapton tape of uncertain high temperature capabilities. Consequently tests were performed to assess the survivability of the epoxy system used for the new inner PF (and OH) coils. Because the insulation system is the same for both the OH and inner PF coils, samples from the OH testing could be used to qualify the PF's for higher temperature bake-out survivability. The criteria is that the insulation must survive the higher temperatures, and then at lower operating temperatures and mechanical loads, base the necessary mechanical and electrical strength requirements.

From the Design Point Spread Sheet (DPSS), the PF1b coil operates at 2026 V. The voltage per turn is 63.3V. The DPSS specifies 13103 V as the highpot voltage. The area of concern is at the top of the lower coil and at the bottom of the upper coil. These locations are midway between the applied voltage at the terminals. The largest voltage possible in service at the insulation that will be thermally challenged will be 1013V and a 2*E+1 voltage criteria would set the test limit to be 3 kV. The 13 kV was specified to be consistent with the DPSS, but voltage increments 3, 6, 9 and 13kV for 3 minutes each were specified to be able to evaluate the lower service voltage.

Sample	Test Config.	Test Time	3kv (µamps)	6kv (µamps)	9kv (µamps)	13kv (µamps)	Comments
PF1B Sample. baked 24 hours @ 225C in air	Turn to Ground Wrap	3 min.	0	0.5	0.75	Full Short, sparks	
PF1B Sample. baked 24 hours @ 225C in air	Turn to Turn	3 min.	2	5	10	14*	* Shorted after 2 minutes
PF1B Sample. baked 24 hours @ 250C in air	Turn to Ground Wrap	3 min.	1	3	arcing @ 8.5 kv	not tested	

It is assumed that the G-10 shim will be cooked and ruined. The turn to turn insulation must stand-off the layer to layer voltage which at the end of the coil is only the turn to turn voltage. If the ground insulation is cooked and ruined, the turn to turn insulation has to take the voltage standoff as “ground wrap”.

11.1.1 Test Results after 225C 24 Hour Bake

The 225C test piece "passed" the mechanical and electrical test. It went to 9kV and then sparked externally, and it is probably a consequence of the flash shield design. We are going ahead with 250C mechanical and electrical tests, and will do better with the flash shield. CTD says the chemistry of the CTD-425 can survive 300C, but they are not accounting for the Kapton and electrical qualification. So, with a successful 250C test, we should be able to heat the divertor flanges to at least 250C or not actively heat or cool them and let them float to no more than 250C.

If active heating is needed, one approach with the tube leak is to flow pure helium through a heater at less than 100 psi and with a controlled delta T so as not to disturb the tube. Then pull a vacuum on it during operation.

[email exchange]:
To simulate Bake-out thermal effects on PF1b, bake a sample mock-up of the PF1b winding to 250 C for 24 hours in air. The normal operating compressive stress applied to the ground wrap is 650 psi. Mechanically test in compression to 1000 psi. Apply Loctite EA 9395 to the exposed metal surface to avoid flash-over and test across the ground wrap to the electrical taps in the conductors in steps of 3, 6, 9 and 13kV for 3 minutes each. These tests should be performed on the remaining sample which is in the material test lab.
Your desired need date is: 7/10/2015

Work Request(s) status can be electronically reviewed by going to http://www-local.pppl.gov/techshop/

Lawrence Dudek <ldudek@pppl.gov>

4:44 PM (16 hours ago)

to me, FRANK, Stephan

Pete,
They closed the original work request so I reopened a new one to perform the second 250C test. See below.

I spoke with Frank Jones about the failure, he said it looked like the part was arcing around the insulation and not through it. They could see sparks jumping from the screws under the kapton to the foil on the edge. I attached two photos, one after the epoxy and screws were installed and one as tested. Probably would have been better to install the screws and the wire first and then covered all of the exposed screws and wire with epoxy. There is only about 3/8" of gap between the edge of the ground foil and the screw head at ground.

Test results as follows:

3kv = 0 microamps @ 3 min

6kv = 0.5 " @ " "

9kv = 0.75 " @ " "

13kv = full short, sparks

Larry

Lawrence E. Dudek
ldudek@pppl.gov

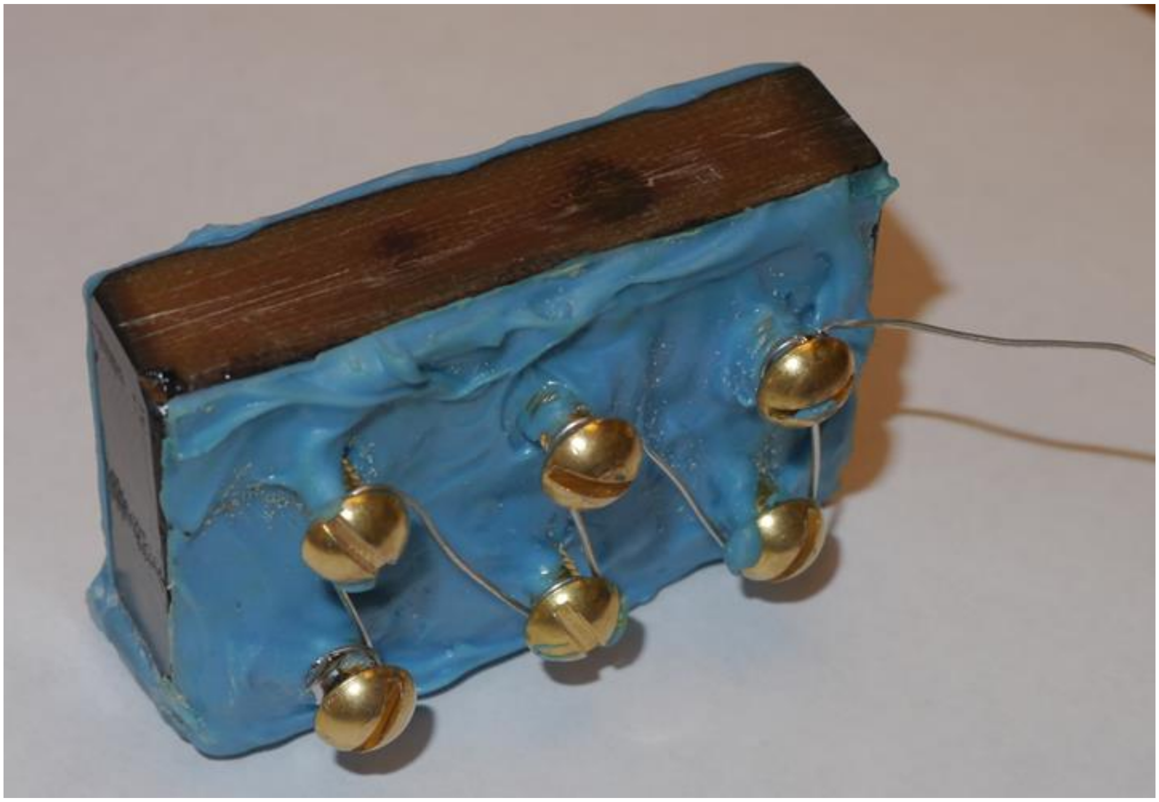


Figure 11.1.1-1 Voltage Stand-off Test Sample With Epoxy Coating to Eliminate Flash-over

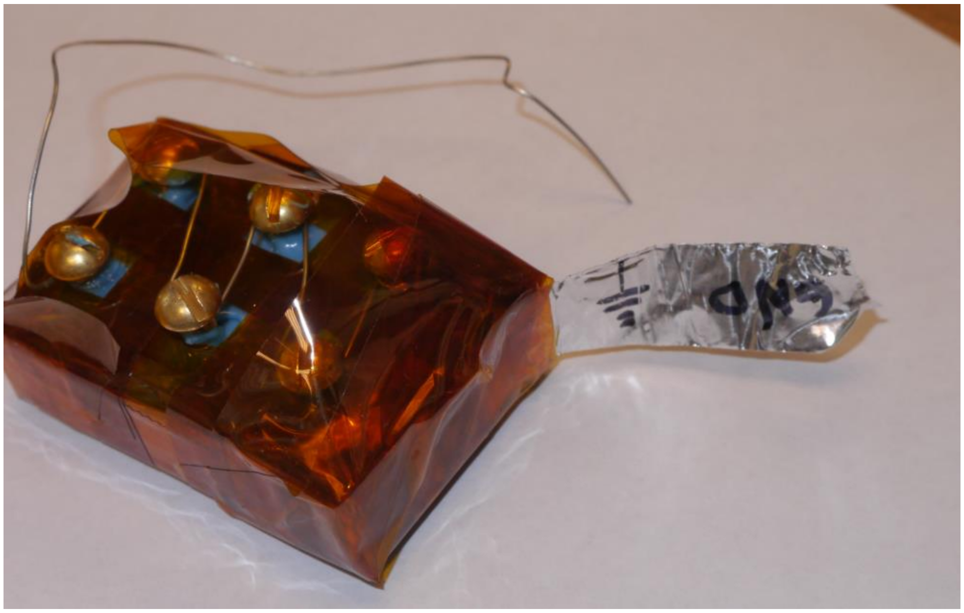
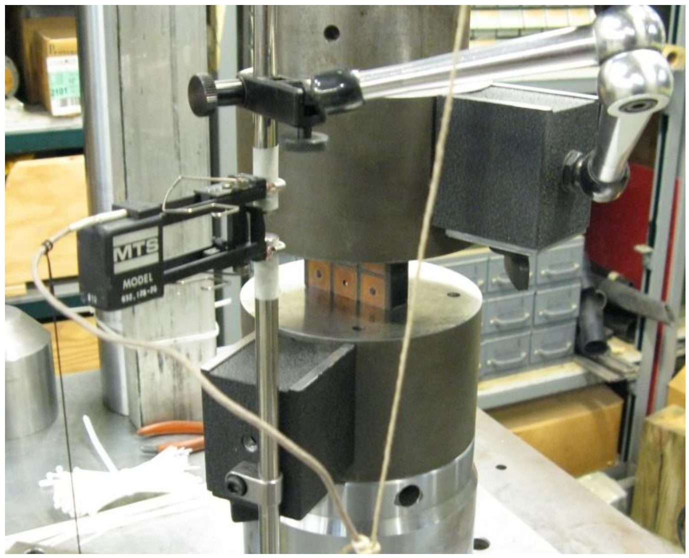


Figure 11.1.1-2

Figure 11.1.1-3-Samples “Cooked “ for 24 Hr. , Peak Temp=225C



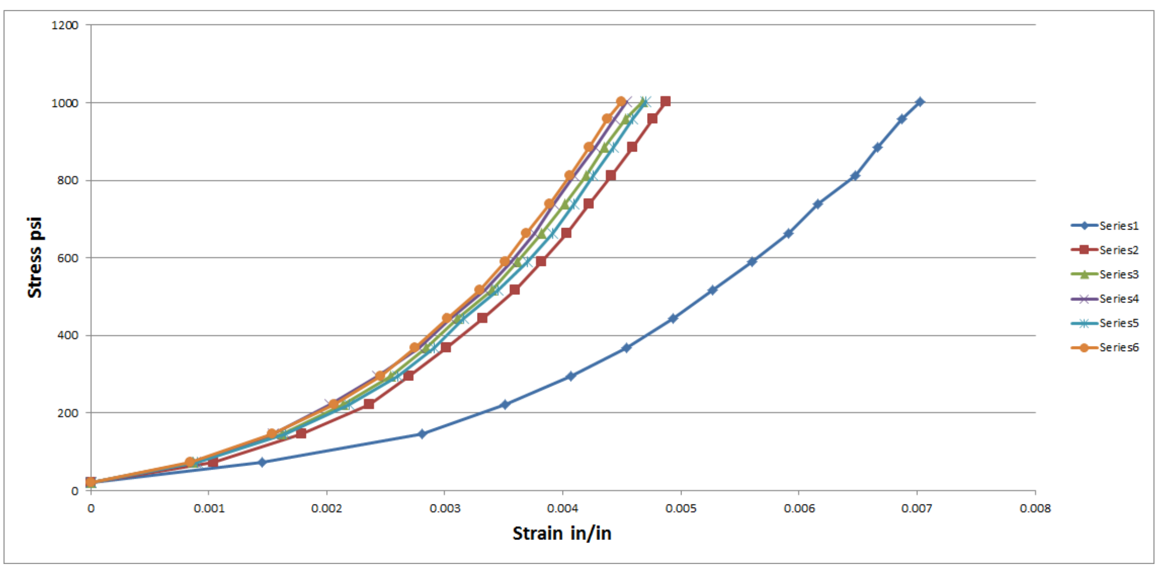


Figure 11.1.1-4 Load deflection of the 225 degree C sample

11.1.2 PF1b Sample Compressive test after 250C 24 hour Air Bake

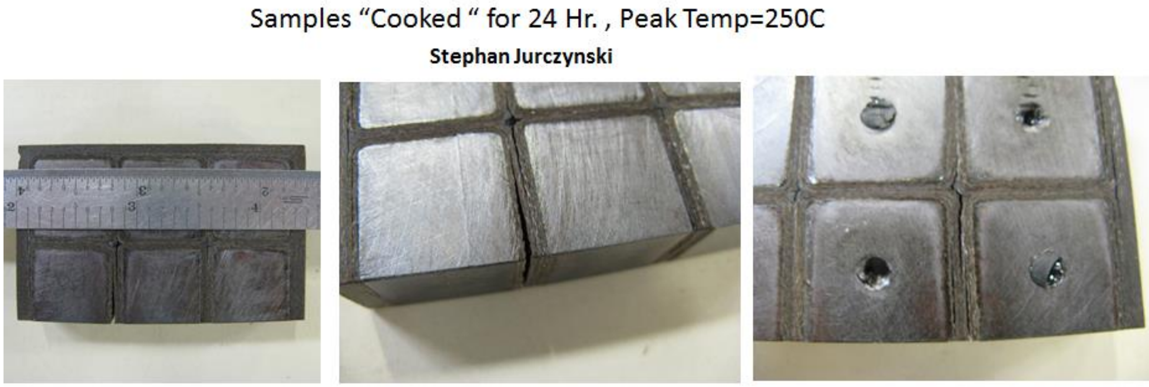


Figure 11.1.2-1 Photos of the 250C sample

Electrical tests passed up to 8.5kV but the electrical behavior was clearly degraded by the extra 25 degrees C. Mechanically it took the load, but the cracking looked scary and 250C was considered too risky.

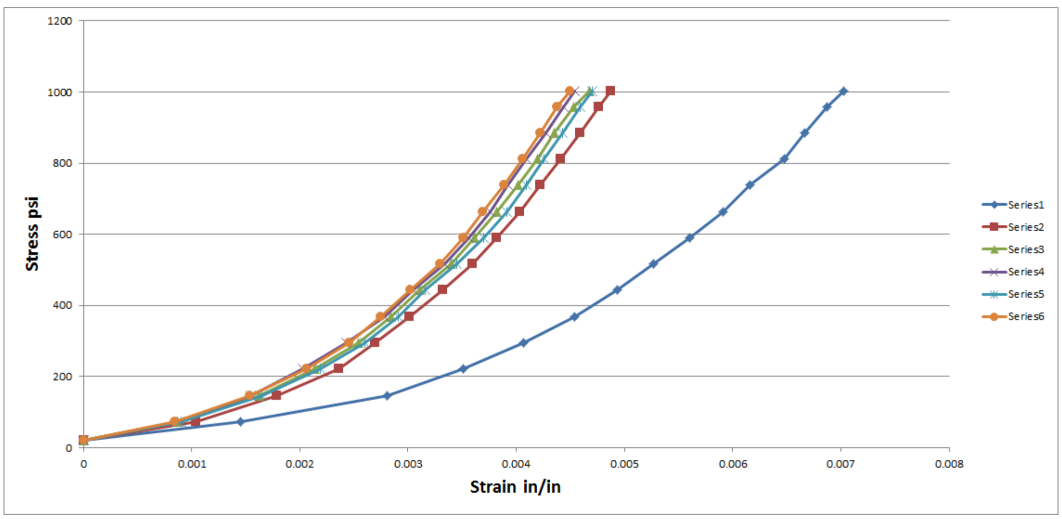


Figure 11.1.2-2 Load deflection of the 250 degree C sample

11.1.3 PF1b Long Term Bake 200C 16 days

Work Request:

20142467 for the Job: "Long Term Bake Out Survival PF1b Insulation System" has been submitted for tech shop review. Your work description is: Cut the sample provided by Larry Dudek in two (as was done in the 24 hr tests). Bake the first sample at 225 degrees C for 2 weeks. Concurrently, bake the second sample at 200C for the same two weeks. This is intended to support the Sept bake-out, so we need baking results by August 31 to support a decision on the allowed temperature of the insulation system. Bake-out should be in air as in the 24 hr tests, and mechanical and electrical tests should be performed as in the 24 hr tests.

Your desired need date is: 09/04/2015

PF1b Sample 1 - Compressive Tests - after 200C 384hr(16 Days) air bake 2015/09/17

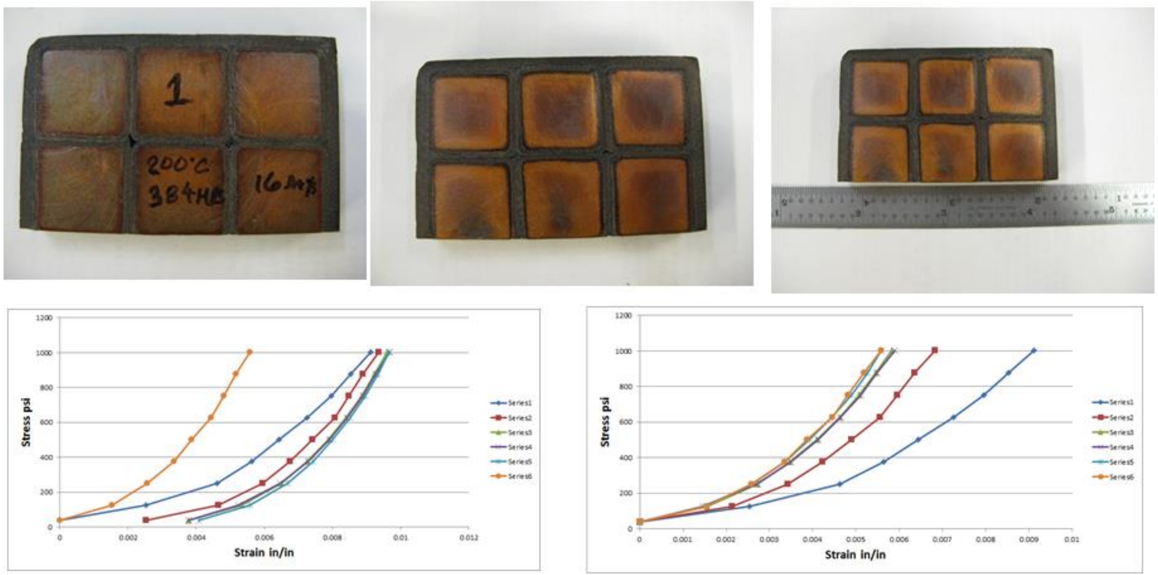


Figure 11.1.3-1 Long Term Bake Results - 16 days total at 200C

In an August 19th phone call, Steve Jurczynski called to let P. Titus know the two tests can't be done concurrently. They chose to start the test at 200C to have a result that would allow some heating of PF1b. After two weeks, we can remove one specimen and run the second for 225 C for as long as we can before a decision needs to be made to support the bake-out. The email transmitting the results is in Appendix C
From a October 14 2015 email from Larry Dudek:

CTD 425 High Temperature Long Term Bake samples.
Hipot Test Results:
Sample 1 - Baked 200c for 16 days in air 3kvdc for 3 min
6kvdc for 3 min 9kvdc " 13kvdc leakage current 1.5 microamps after 3min

11.1.4 PF1b Long Term Bake 200C 16 days + 225 C for 14 Days

PF1b Sample 2 - Compressive Tests - after 2000C 384hr(16 Days) then 2250air bake for 336hr(14 days) 2015/09/17

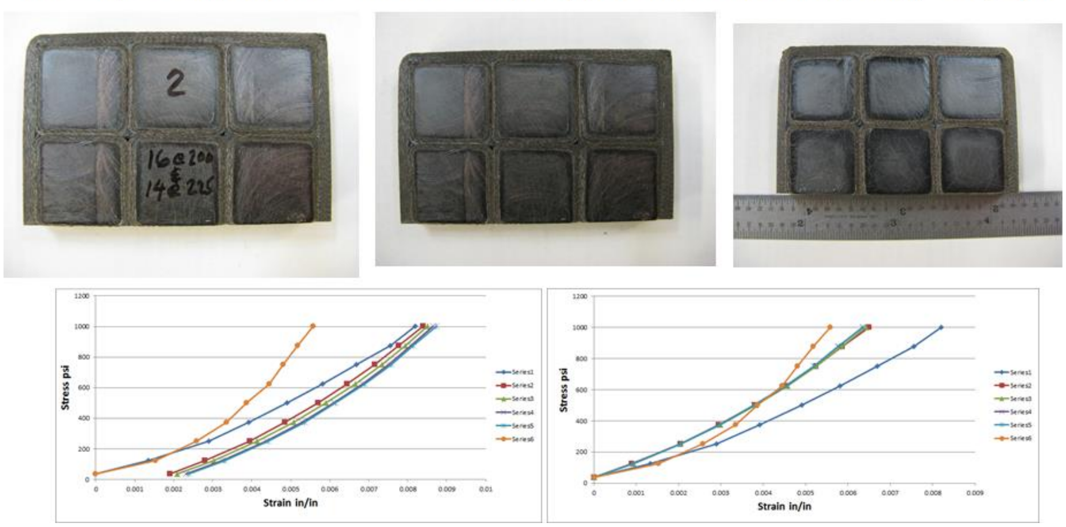


Figure 11.1.4-1 Long Term Bake Results - 30 days total (~half at 200C and half at 223C)

CTD 425 High Temperature Long Term Bake samples.

Hipot Test Results

Sample 2 - Baked 225C for 14 days in air

3kvdc for 3 min	**6kvdc for 3 min**
9kvdc "	**10kvdc arced over**

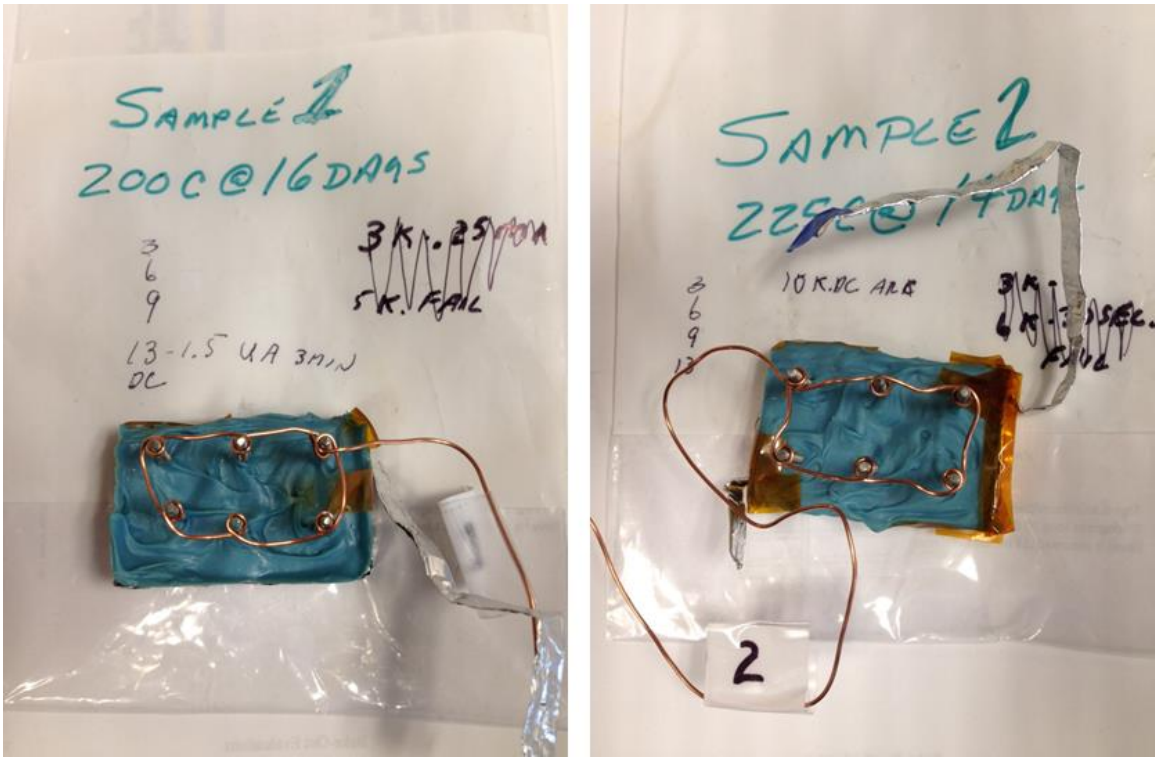


Figure11.1.4-2 Electrical Samples for the Long Term Bake Results 223C

11.2 Hysol Centering Band Bake Tests

In order to get the divertor tiles near 300C, active control of the PF1b water supply is being investigated to maintain the PF1b coil at an elevated temperature. The winding pack epoxy system is being tested separately. The PF1b centering system used a Hysol/glass band wet layup. If PF1b is heated to 70 to 150 degrees C, the Hysol/glass band will have to survive the bake-out and still function to keep the coil centered. As of August 2015, the PF1b temperature will not be allowed to go above 100C and the mechanical tests were not conducted after the Hysol was baked. During bake-out, the coil and mandrel or case will be maintained near the same temperature and the centering system will not be loaded. Only the survivability of the Hysol/Glass needs to be demonstrated. Hysol and glass should be wound in "hand tension" on a cylinder with mold release. A 1/4 inch thickness is sufficient. Sample pieces should then be cut from the ring baked to 150 C for 24 hrs. A baked and an un-baked sample should then be tested in 5 ksi compression at room temperature normal to the glass fabric reinforcing plane. The force-deflection curves should be reported for both. Curved anvils matching the winding mandrel cylinder may be needed.

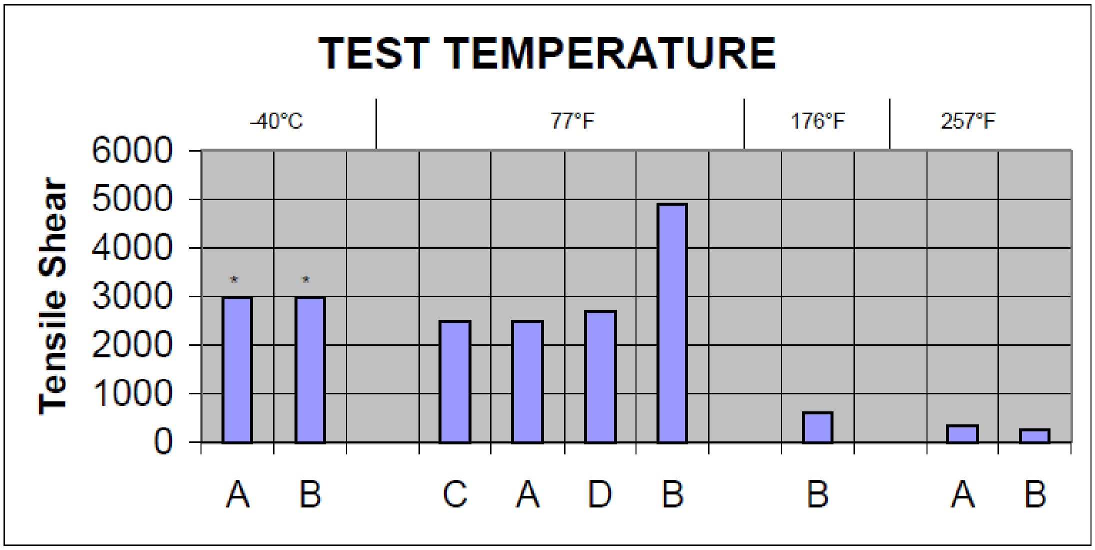


Figure 11.2-1 Hysol Strength vs. Temperature
http://www.chemcenters.com/images/EA9394%20Hysol.pdf)

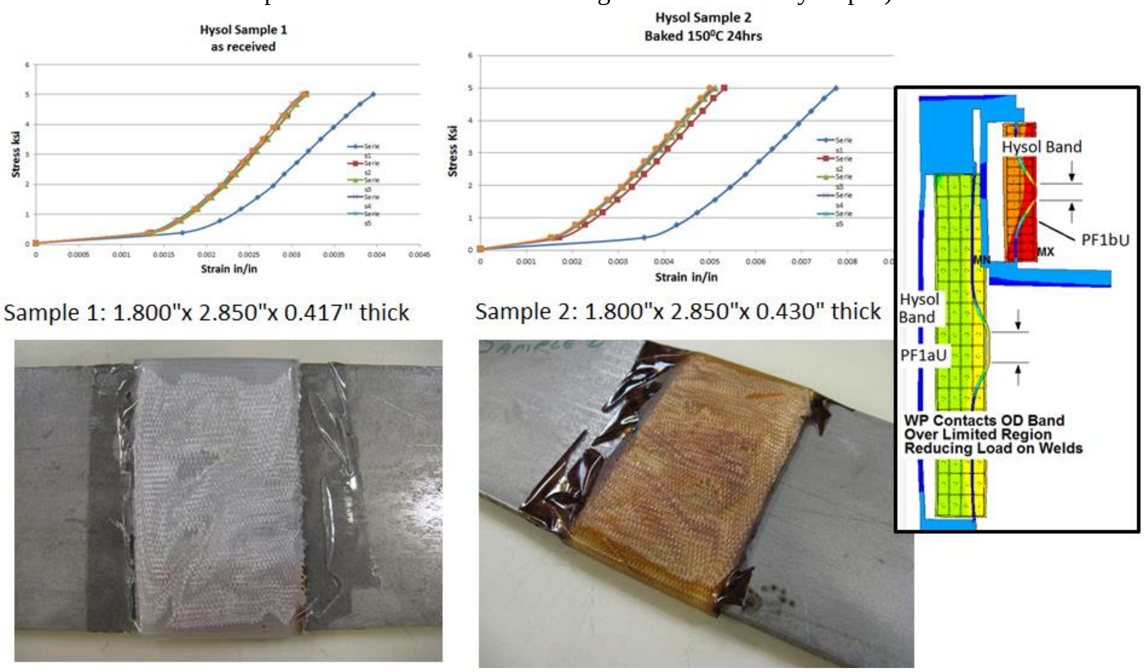


Figure 11.2-2 Compression Test Sample and Results

The mechanical tests on the sample were judged successful for the modest pressures on the centering band, but the excessive temperatures in the PF1b Hysol centering band turned out not to be a an issue. PF1b. was maintained below 100C – We thought we might heat it to 150C.

12.0 Inner Horizontal Divertor Flange Tubing

The copper refrigerator tubes that were inserted into grooves in the divertor tile support plate are on the vacuum side, and are tightly fit into a "loop" groove that should have had some allowance for expansion of the circumferential length of the loop. It has been

Figure 12.0-1 Photo of Divertor Flange Cooling Loop

confirmed that the design is tight fitting around the full length of the groove. Accumulations of expansions – in the case of He heating, and contractions – in the case of flowing cooling water – potentially will concentrate at the end of the tubing loop and potentially will crush it.

The hose feeding coolant to the Inner divertor cooling tubes was replaced to allow the horizontal divertor flange to be heated with Helium gas. Qualification of the piping and tubing for the higher temperature Helium gas was made moot by the discovery of a vacuum leak in the upper cooling tube.

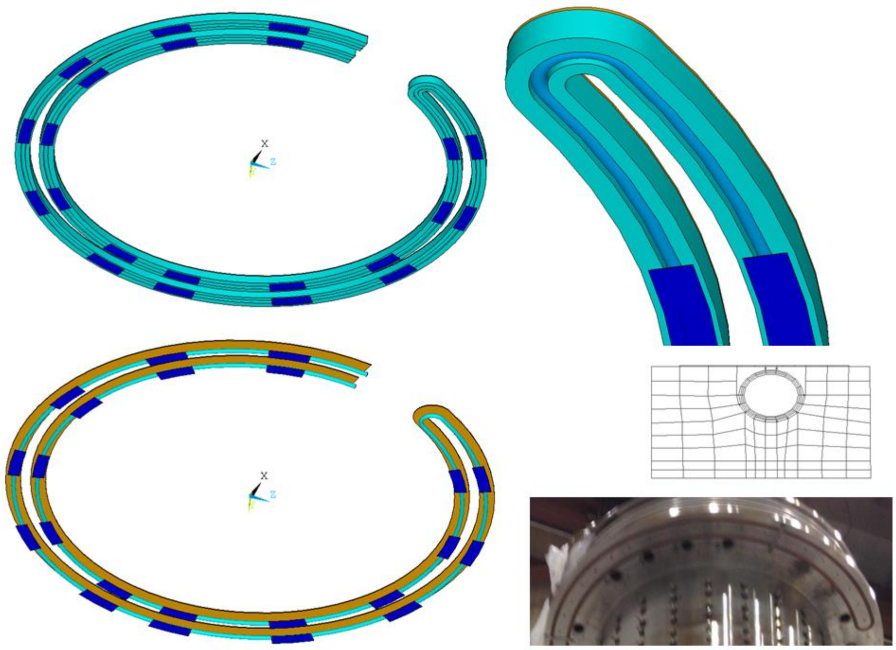


Figure 12.0-2 Inner Divertor Flange Cooling Loop Model

The model was generated by sweeping the 2D cross section of the groove and retaining strip. Point to point gap elements (ANSYS interface 52) were used between the tube and the groove cut in the flange. The retainer strips were formed by selecting strip elements in the regions were strips weren't and deleting those elements.

The temperatures proposed for the divertor flange during bake-out with the helium heating upgrade would have been higher than the recommended design limit for the refrigerator tubing. Figure 6.4.2-1, "Copper Refrigerator Tubing Pressure Rating vs. Temperature", shows a drop off in the pressure rating at around 300C. A case could be made for lower pressure operation if the crushing of the end of the loop and the vacuum leak in the upper tube weren't problems.

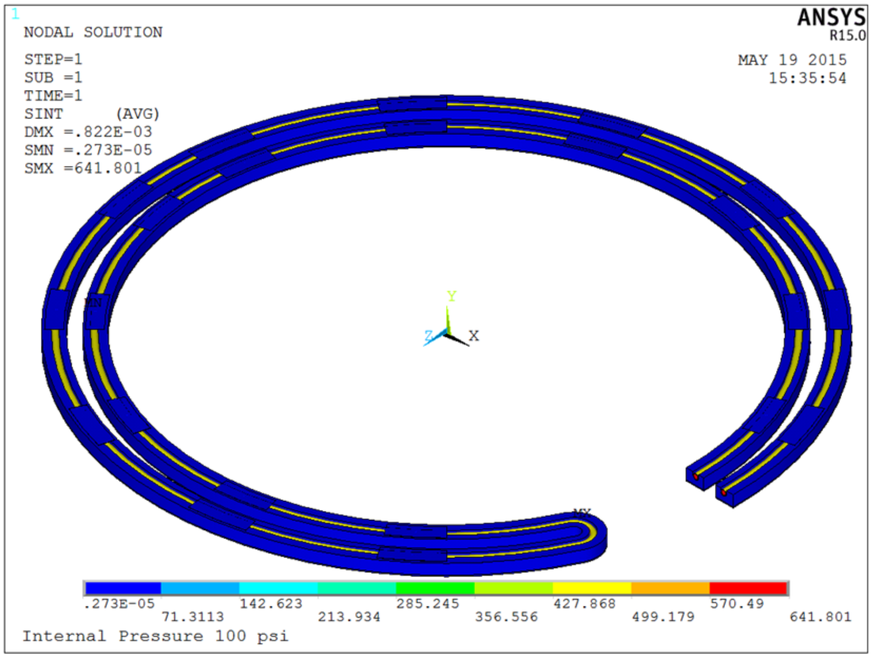


Figure 12.0-3 Horizontal Divertor Plate Cooling Tube Pressure Stress

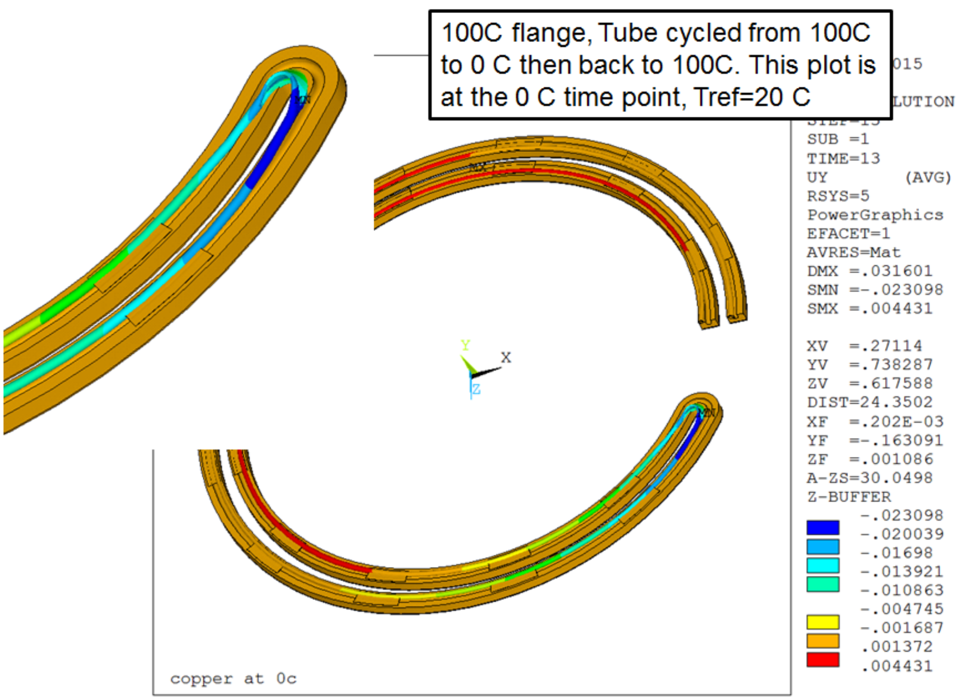


Figure 12.0-4 Horizontal Divertor Plate Cooling Tube End Crush

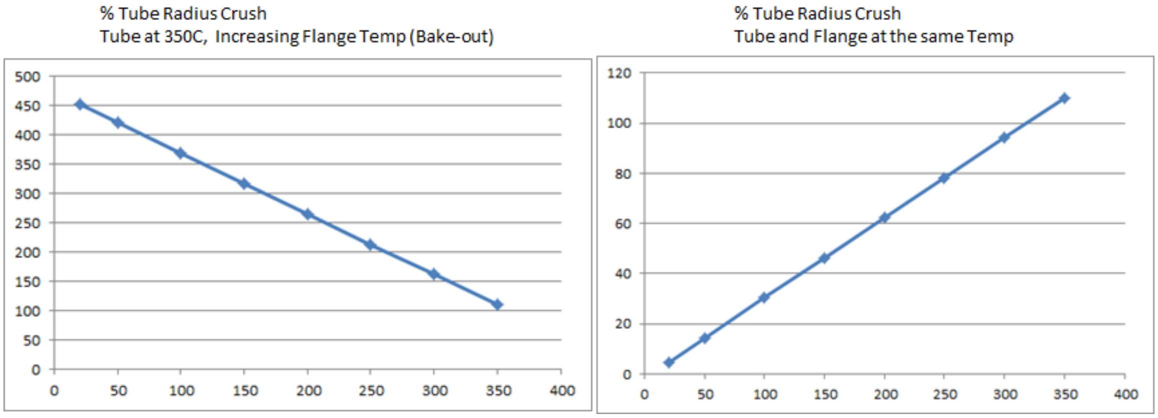


Figure 12.0-5 Horizontal Divertor Plate Cooling Tube End Crush

In Figure 12.0-5, the % crush for the proposed bake-out operation is plotted. The main cause of the end tube crush in the plot at the left is the high temperature of the refrigerator tubing. The % tube crush improves with a warmer divertor flange. The only way using the cooling tube to heat the flange might be acceptable is if the tube and flange temperatures were tracked and maintained at nearly the same temperature. At right, the tube and Inconel 625 flange are assumed to be at the same temperature, but the differential alpha between the copper and flange still produce displacements at the loop end of the cooling tubes. Even if the inner divertor tiles are insulated from the flange and PF1b is not heated, the loop end may still be disturbed. The fact that the tubes survived the September 2015 bake-out is an indication that the tubes should survive future bake-outs.

13.0 Helium Heating/Cooling System
13.1 Proposed for Horizontal In-Board Divertor

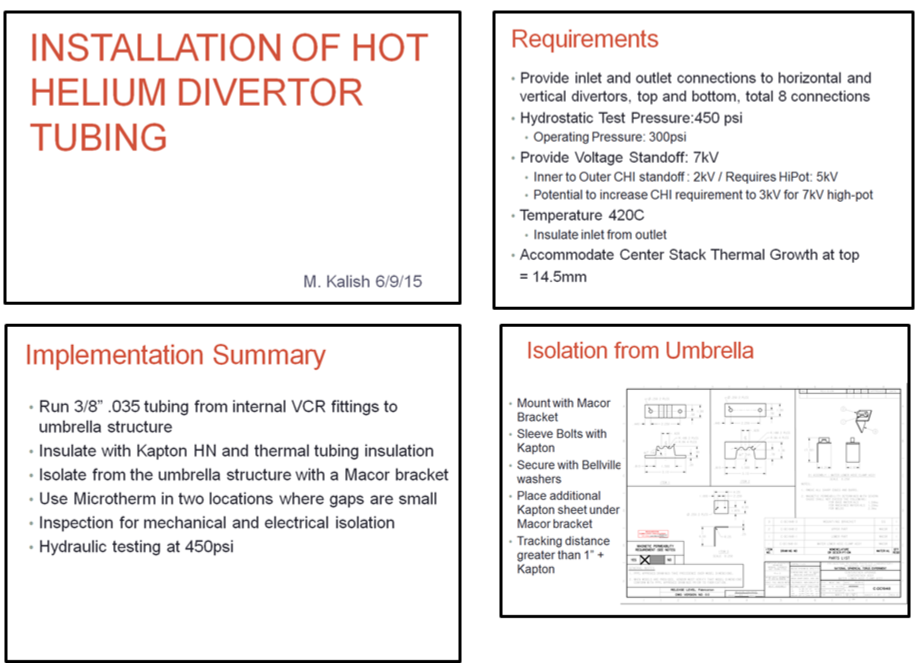


Figure 13.1-1 Excerpts from the Heeling Heating Tubing Peer Review [18]

Hoses feeding the divetor tubes were replaced with high temperature, high pressure metal hoses. This was in anticipation of using the cooling tubes in the divertor flanges as a heat source for the bake-out. This turned out to be not feasible for a couple of reasons. First was raising the temperature of the copper refrigerator tubes beyond around 200 C limited the pressure rating. The pressure rating of the tubing is plotted versus the service temperature in Figure 6.4.2-1 and the allowed pressure is dropping quickly after 200C. This still allowed the tubes to carry some pressure, but the helium system would have had to have a pressure reducer. Additionally, the differential expansion of the cooling tubes and Inconel 625 flange would stress the end loop tightly fitted in the groove. Some expansion could be absorbed, however, the upper tubes were found to have a slow vacuum leak. They passed the hydro, but the vacuum qualification failed. This raised the possibility that we just use the helium system during bake-put and pump the slow leak, then close off the feed during operation. Mike Kalish was concerned about this because:

1: The helium in the bakeout system is not purchased with the sufficiently high purity for operations.
2: The blower can contaminate the helium with oil.

As a consequence, actively heating the divertor tubes with helium was abandoned.

13.2 Proposed for Vertical In-Board Divertor

This option would heat the vertical section of the casing near the divertor with the “cooling” tubes intended for removing the divertor heat. This is still an option with restrictions to improve the stress and pressure rating at temperature of the copper refrigerator tubing.

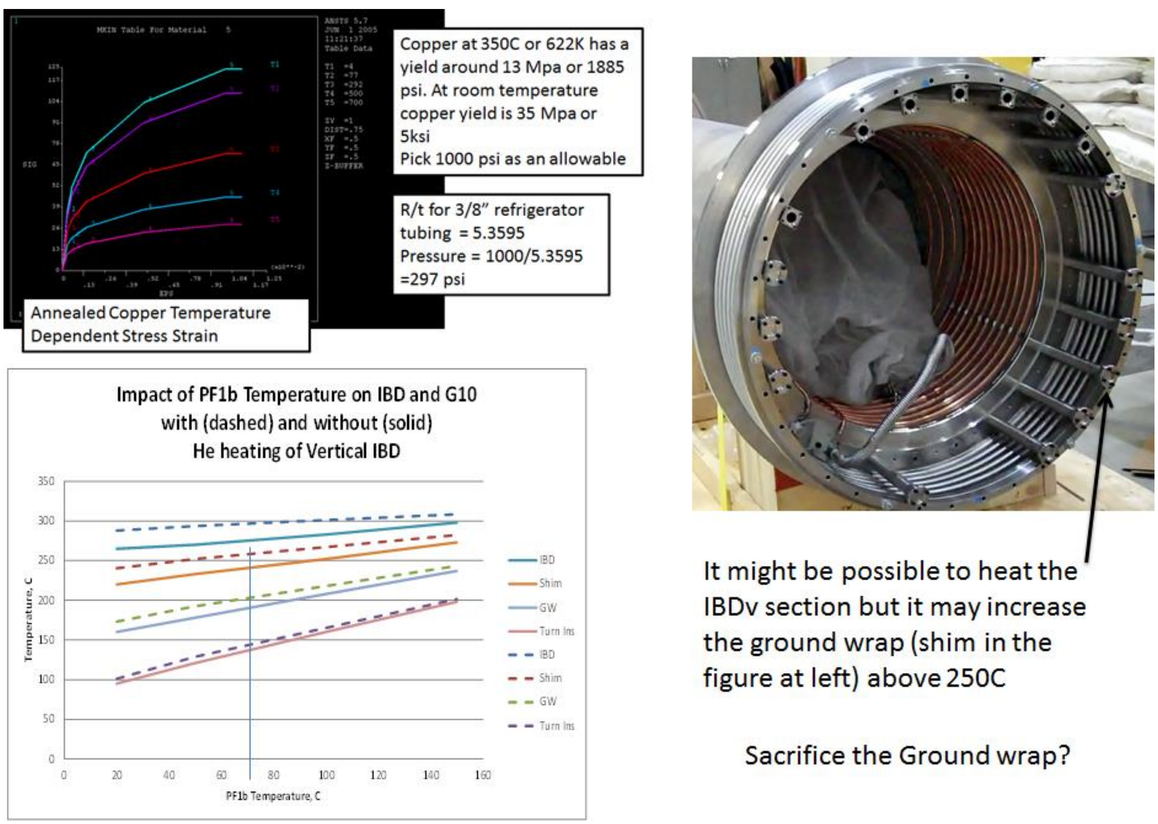


Figure 13.2-1 Effects of Heating the Vertical Section of the Inner Divertor Section of the Centerstack Casing

14.0 Microtherm Layer Removal
14.1 Normal Operating

During assembly of the centerstack, the microtherm insulation snagged on protruding edges of the conical section of the casing as it slipped over the PF1a and b mandrels. Microtherm thermal data is available in [12]. The updated microtherm thickness was included in the heat balance model. The reduced Microtherm insulation thickness between the CS and OH from 6 mm to 3 mm we will drive the temperature of the OH 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.

Normal Operation and Bakeout marginally acceptable with 3 mm Microtherm

	Bakeout		Normal Op		Pre AquaPour
thk_g10, m	0.0039				
thk_mic, m	0.006	0.003	0.006	0.003	0.006
k_mic, w/m-C	0.02				
k_g10, w/m-K	0.3				
T_cs, C	350	350	250	250	250
★T_oh (cu), C	29	43.1	110	110	100
T_g10, C	42.3	67.6	115.8	121.2	106.2
q_g10, w/m2	1025.6	1882.8	447.3	858.9	479.2
q_micro, w/m2	1025.6	1882.8	447.3	858.9	479.2
Q_oh, w	7732.5	14196.1	3372.4	6475.9	3613.3

Heat Balance to Account for Water Heating		
dia	0.0057	m
v	2.1336	m/s
dens	1000	kg/m3
Cp	4186	J/kg-C
area	2.55176E-05	m2
flow	5.44443E-05	m3/s
	0.862954922	gpm
mdotcp	227.9039327	kg/s-C
dT_water	17.0	31.1
Tin	12	12
Tout (ie T_oh)	29.0	43.1
	w/6 mm	w/3 mm

★ *T_oh based on water heat balance -> to right*

Figure 14.1-1 Effect of Reduced Microtherm Thickness

14.2 OH cooling water failure during Bake-Out and time to connect service water.

A significant concern is the fault scenario during bakeout when it must be assumed 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, and the end regions modeled the same as the central region of the OH, there would be just under 1 hour to reestablish cooling flow.

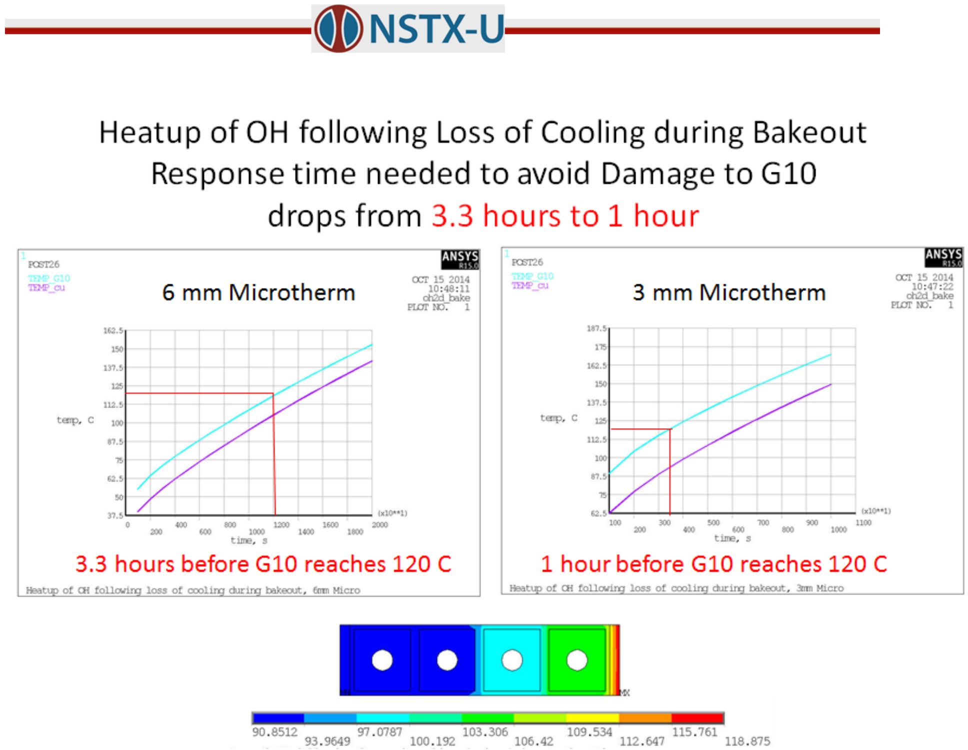


Figure 14.2-1 Time to Reach 120C at the OH Coil Surface During a Loss of Cooling Fault During a Bake-out

14.3 OH Cooling only Outer Layer During Bakeout

With the removal of one layer of Microtherm insulation, the heat flux to the outer layer of the OH goes up during bakeout. This elevates the temperature of the outer layer while the inner 3 layers would have been cooled with 12C water. The thermal strains that would result would be comparable or worse than the thermal strains imposed by the cooling wave. This can be readily avoided by turning off the cooling to the inner layers of the OH. This was implemented in the bake-out procedure [11]. Around September 10, 2015, the cooling in the inner layers was restored at a reduced rate because the outer layer was approaching 90C.

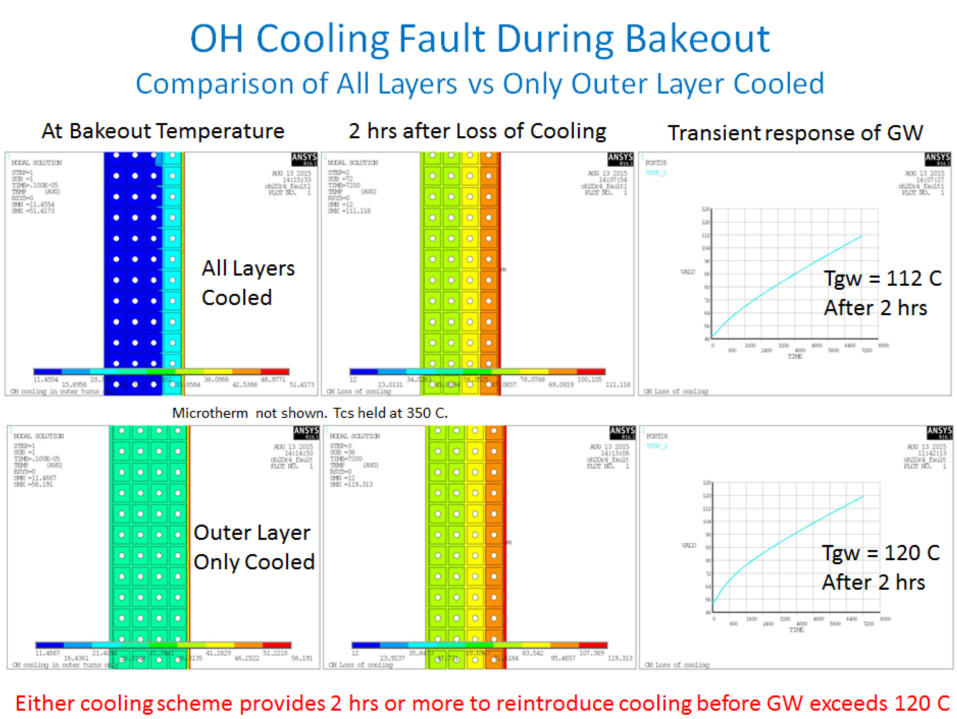


Figure 14.3-1 OH Loss of Cooling Fault During Bake-out

Actively flow water in the outer layer, that is layer 4 of 4. Do not cool the inner 3 layers. This is because the heat flux coming from the casing through the microtherm and through the OH ground wrap is heating only the outer layer of OH conductors. Art Brooks calculates 40C in the outer layer due to the bake out heat flux, and if the 3 layers are cooled, they would be close to 12C, and the resulting thermal strain would be worse than the cooldown strains.

The OH is protected from the bakeout heat at the ends which are covered by PF1a U&L. With this taken into consideration, 2 hrs is allowed to avoid a peak OH surface temperature of 120C.

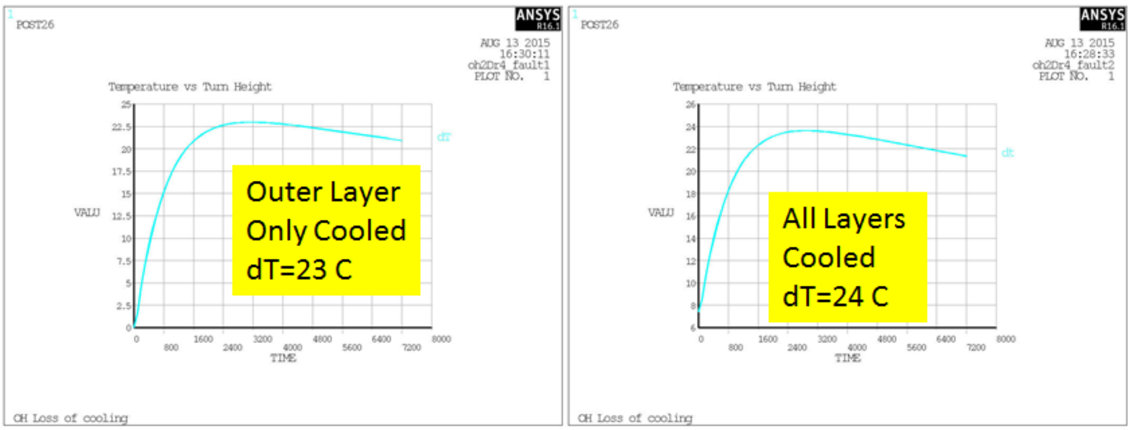


Figure 14.3-2 Peak Temperature Difference between Inner and Outer Layers occur ~ 1 hr after loss of cooling

After only 1 hour, the peak temperature difference between the outer layer and inner layers reaches a peak of 23 degrees C. This would introduce axial tensile strains in the inner turns, and it would be good to avoid as much of this as possible.

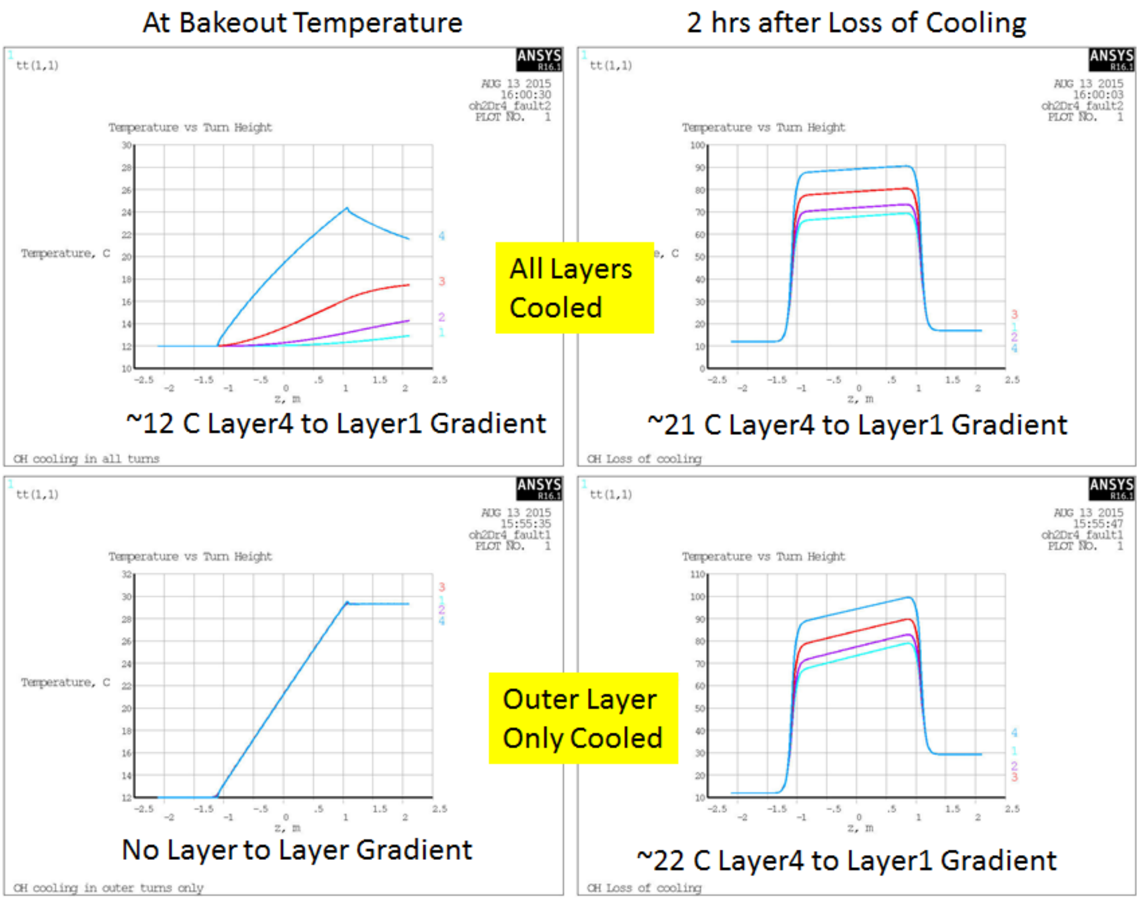


Figure 14.3-3 Comparison of All vs. Outer Layer only Cooling After Loss of Cooling

Both cooling schemes provide 2 hrs or more to re-introduce cooling before the groundwrap exceeds 120 C. Cooling outer turns only eliminates the 12 C layer to layer gradient while increasing the peak conductor temperature from 24.5 C to 29.5 C. During a fault, both schemes develop an inner to outer layer gradient of ~24 C.

The bake-out procedure [11] includes the following instructions/check-offs:

5.54 Close the six supply valves to the inner three OH cooling paths. __________
(OH-1 through OH-5, and OH-7)

CAUTION: The outer layer (the one closest to the center stack casing) must Have cooling water at all times. (OH-6 & OH-8)

NOTE: Each layer has two flow paths.

15.0 Nominal PF1B Behavior

From [9]:

"When unrestrained thermal expansion effects are added to the analysis (PF1a at 85C, PF1b & 1c at 100C), the radial displacements are as shown in the plot on the right. Thermal strains are calculated assuming a 150ºC (zero strain) reference temperature. The relative motion between structure and coil WP are:

- $\Delta r(PF1b) = 0.7$ mm

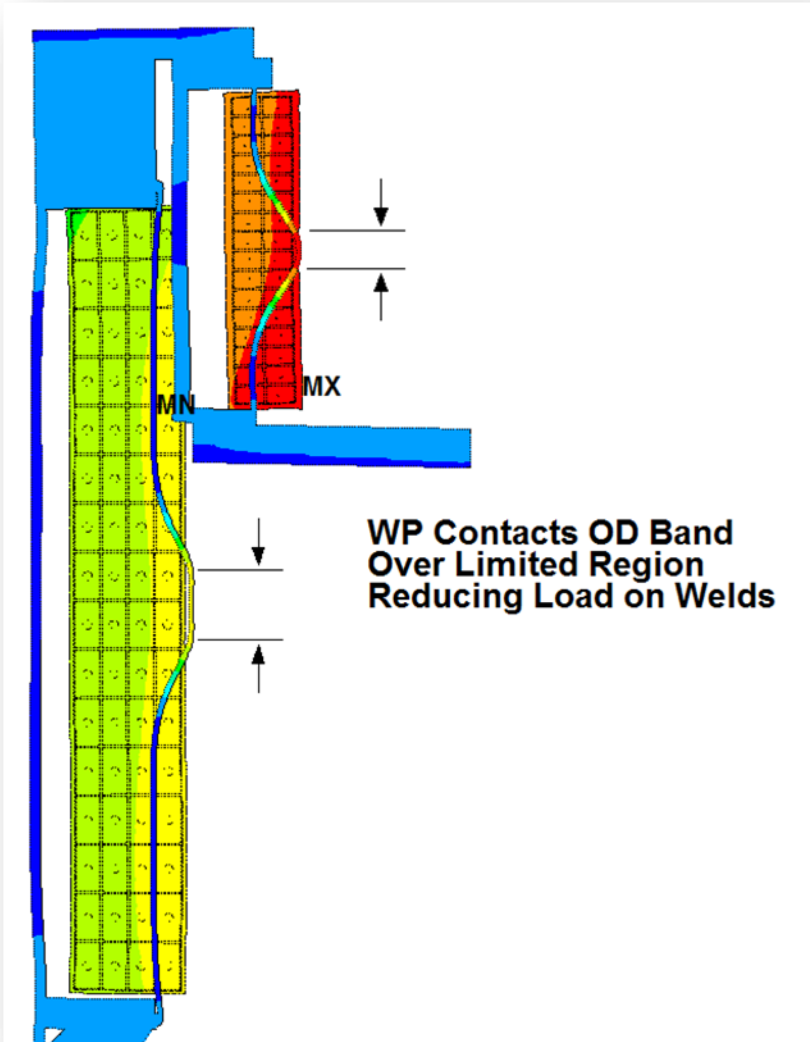


Figure 15.0-1 Deformed Shape of the PF1a and PF1b Coils with their Centering Bands

16.0 PF1a and PF1b to PF2 Support Clamp Bake-Out Bus Motion

Work on this detail of the inner PF coils began by Leonard Myatt and is documented in NSTXU-CALC-133-01-01[9]. The original concept was based on winding the coil on a temporary mandrel then transferring it to a case in which it would be potted. The case was intended to have appropriate flexibility, strength, and adequate corner radii to avoid unacceptable stress concentrations. The thermal excursion of the coil from 12C to 100C produced unacceptable bending strains in the case wall. Introduction of a gap to allow the radial growth then necessitated addition of a centering mechanism to ensure the coil would not shift and add error fields or adversely load the terminal break-outs that were fixed to solid bus bar. The bus bar and terminal bending stress are addressed in rev 2 of [9] prepared by A Zolfaghari [10].

The upper PF1a and b bus bars connect from the coil terminals supported on the top of the casing/mandrel to the clamp on the PF2 coil. During bake-out, the casing expands vertically around 8 mm when heated to 350C. The outer vessel expands about half this when it is heated to 150C during bake-out. The PF2 clamp travels with the top of the vessel. So, the differential motion of the two ends of the bus bar is around 4 mm vertically, which is less than the normal operating case when the casing is heated by plasma operation and the outer vessel remains around 30 to 100C.

The peak PF1b coil temperature from the design point spreadsheet is 43C. The mandrel is assumed at 30C for normal operation. This is the basis for the outer centering steel shells. If PF1b was allowed to go to 150C for bakeout, the mandrel temperature should be close to this and should not stress the centering shells beyond nominal design. In the actual September 2015 bake-out, the PF1b coil only was allowed to go to 90C and the mandrel was close to this in temperature, again not stressing the shells. The outer bus supports are on the PF2 support clamp and remain at 20C even during bakeout. So, with 90 to 150C in PF1bL, the stress due to differential motion of coil and bus support will go up, but during bake-out there is no Lorentz force or joule heat. The upper PF1b support has a rubber clamp that allows 8mm relative vertical displacements and should allow the extra <1 mm displacement.

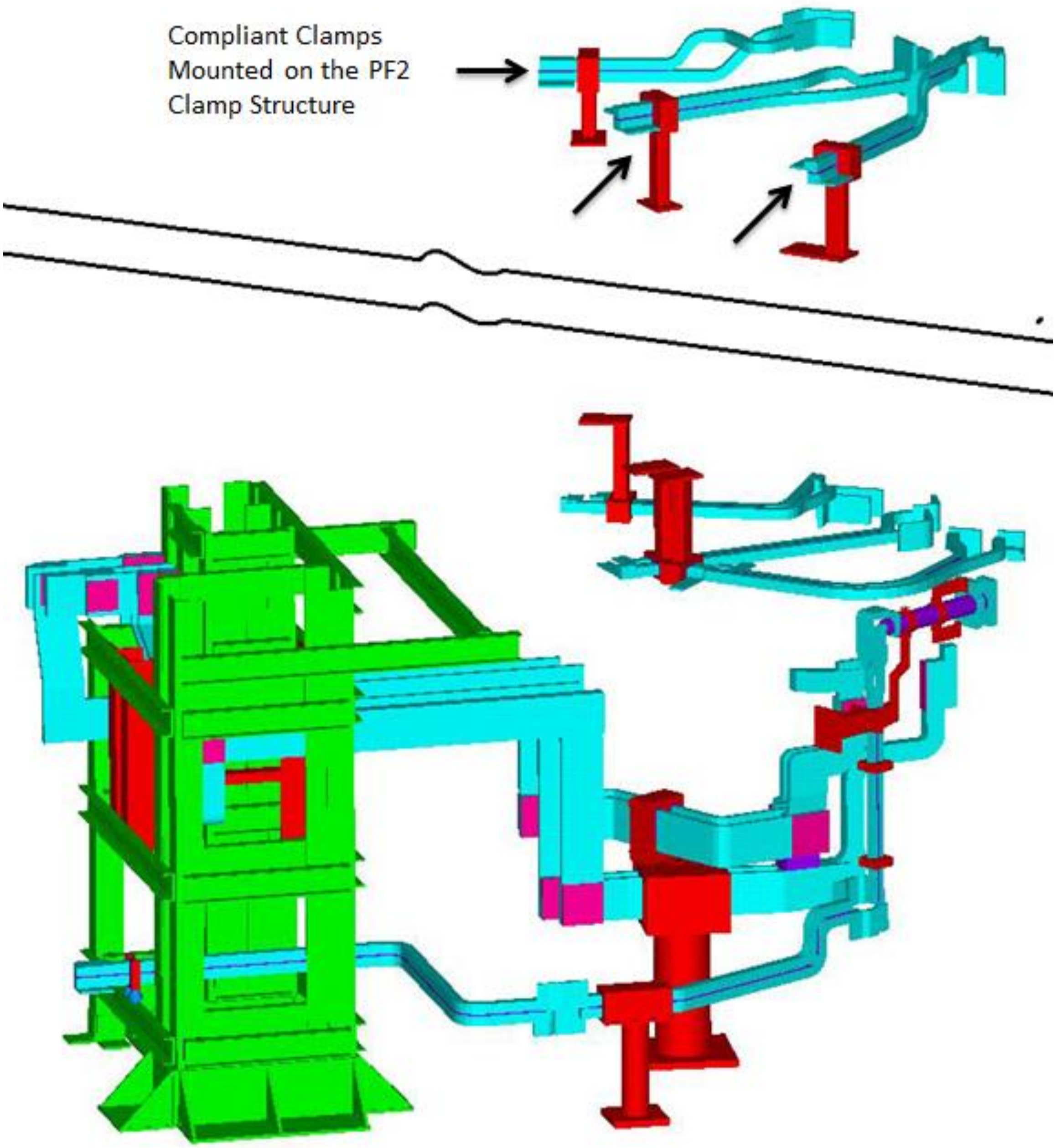


Figure 16.0-1 Upper Inner PF Bus Bar and Lower OH, PF and TF Bus Bar

Radially, during normal operation, PF1a and b are allowed to grow inside their cans from their Joule heat during normal operation. Their terminals are fixed to “tower” supports mounted on the casing flange. The

PF2 coil has minimal Joule heat during normal operation, and is cooled during bake out. It is mounted on slides to especially allow the bake-out motion to occur without stressing the PF2 coil. So, the PF2 end of the bus bars moves radially very little during either normal operation or bake-out. The radial differential motion of the bus bars is basically the radial motion of the casing flange on which the towers are attached. During bake-out, the casing flange on which the terminal towers are mounted is cooled by the PF1a and b coils and is away from the heated side near the inner divertor tiles. The clamps that support the bus bars at the PF2 clamp end have silicon rubber clamps that are mainly intended to accommodate the vertical motion differential, but also will absorb radial differential motions.

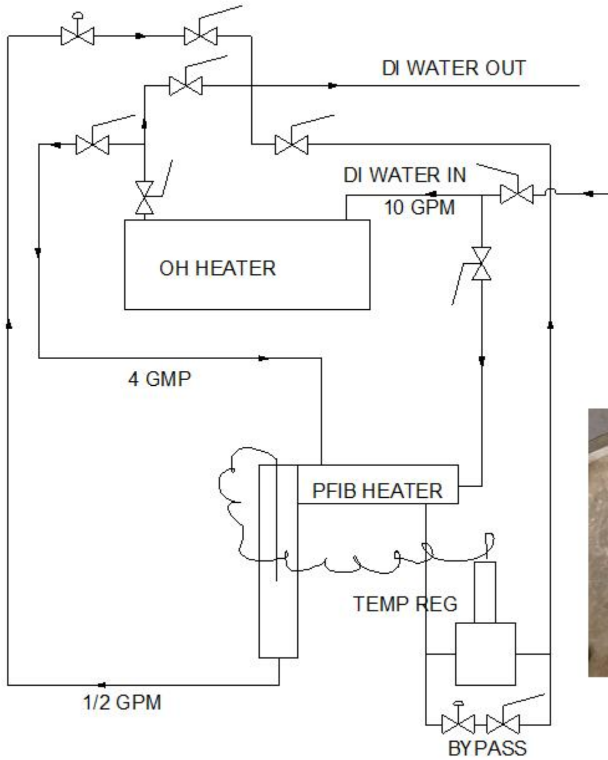
17.0 PF1b Flow System
17.1 PF1b Low Flow Heat Removal Capability

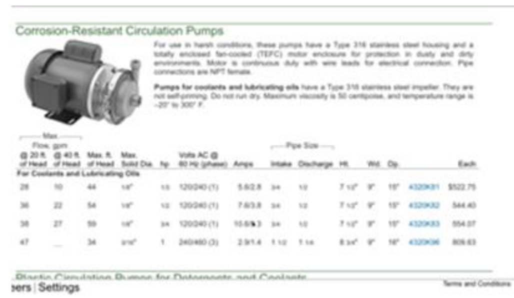
John Desandro measured the following flows in PF1b for low pressure water heating/cooling:

inlet pressure psi	return pressure psi	gpm	measured water ml pm
60	0	.12	460ml
60	40	.042	160ml
100	0	.145	550ml
100	40	.11	450ml
150	0	.19	725ml
150	40	.165	625ml
280	0	.27	1050ml
280	40	.24	930ml

17.2 PF1b Heating System.

The intent of this system is to elevate the PF1b temperature above the normal coil cooling water temperature of 12C. This will elevate the divertor flange temperature a bit and raise the divertor tile temperature a bit. The target was initially 70C, but the bake-out procedure was writtren to allow the temperature to be raised during the bake-out if the tile temperature was too low. This requires a small, thermostatically operated heat-exchanger based system to be designed and installed relatively quickly. Mike Viola was responsible for implementing the system. The photo in the figure below is from the design review that took place August 11, 2015. [19]





Excerpt from D-NSTX-OP-G-156 rev 4 [11]:

2.8 As part of this procedure PF1B shall be heated to maximize the diverter Temperatures.

NOTE: The starting limit for the PF1B inlet Temperature shall be 70 degrees.
This limit can be adjusted per the NSTX Project Engineer once the bake out has reached steady state.

The new thermal control system is capable of going up to 110C. In the September 2015 bake-out, 100C temperature was authorized and 90 C operation was achieved.

This system has been disconnected and different methods of heating the inner divertor tiles are being developed that don't require high epoxy temperatures in PF1b.

18.0 Ceramic Break O Ring Temperature

An O ring seal is used to form the vacuum seal between the inner casing structure and the outer vessel. The operating temperature limit of the Viton seal is 200C.

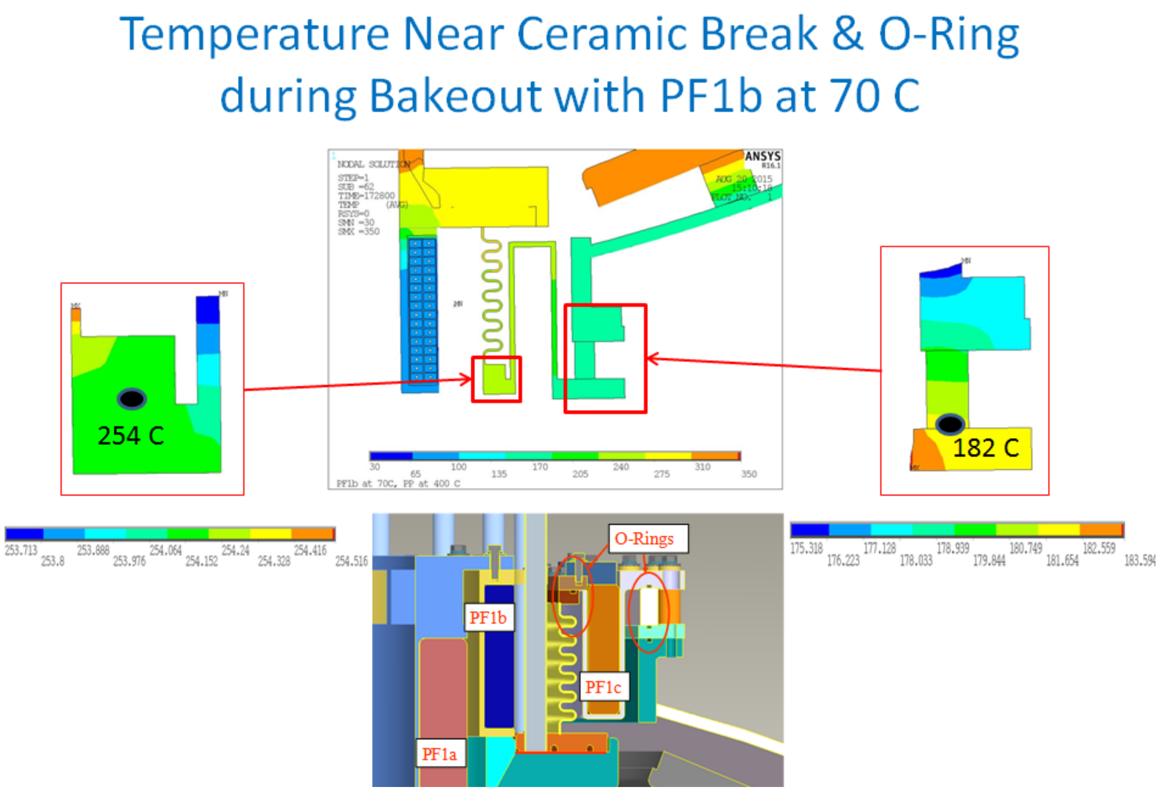


Figure 18.0-1 Temperatures near the ceramic Break and O-Ring

From the web [http://www.row-inc.com/techspecs.html], Viton should be good to 200C. Mike Kalish sent the original NSTX calculations which put the bakeout temperature of the Viton seal at 175C. So NSTXU is a bit higher at 182C.

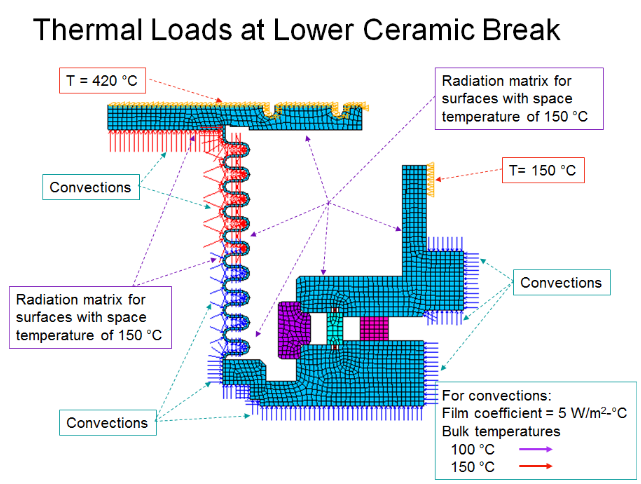


Figure 18.0-2 Original NSTX Ceramic Break Model, Demonstrating that the O-Ring temperatures during bake-out were a concern with the original NSTX design.

The working temperature range for Viton® is considered to be -15 to +**400 degrees** F (-29 to +204 degrees C), but it will take temperatures up to 600 degrees F (316 degrees C) for short periods of time.

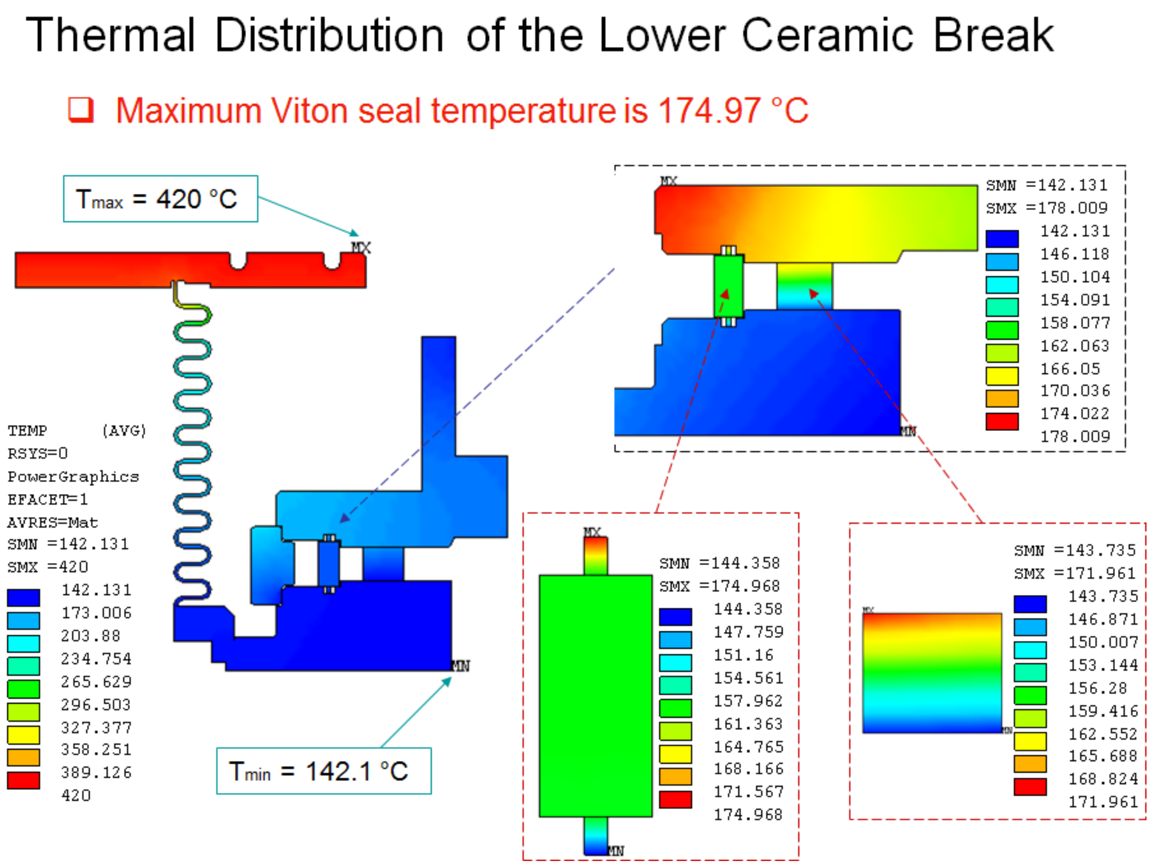


Figure 18.0-3 Original NSTX O-Ring Temperature Analysis

19.0 Inner PF Bus – Disconnect? – or Not?

In the bus bar calculation, NSTX-CALC-55-01, the connections of PF1a, b and c upper and lower are supported at the "tower" terminal supports at one end and the PF 3 sliding clamps at the other. During the bake-out, the temperatures of these support points should be at the coil cooling temperature ~12C and there should be no relative radial motion. Now that PF1b will be maintained at 70C, there will be a little motion, but no more than normal operation for which the coil is allowed to go to 100C. Vertically, the upper bus bars must allow the CS vertical expansion, which also must be accommodated during normal operations. In the calculation, the upper and lower supports for the inner PF's are the same. So there should be no need to disconnect the PF1a, b and c bus bars during bake-out. This was confirmed in [16] -

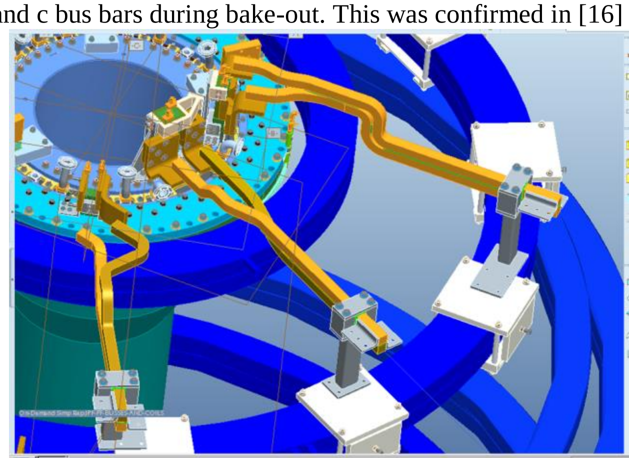


Figure 19.0-1 PF 1,a,b and c Upper Solid Bus Bars (Before Field Modifications Qualified in [16])

20.0 CHI Bus Bar Bake-Out
20.1 Lower CHI Busbar Power Connections

The CHI busbar is an active participant in the bake-out. The current passed through the inner casing is supplied by the CHI bus inner vessel connections. The outer connections at the bottom of the machine are not used during bake-out, but they are potentially loaded by the thermal motion of the vessel. Bake-out calculations were included in calculation #NSTXU-CALC-54-0. [13]

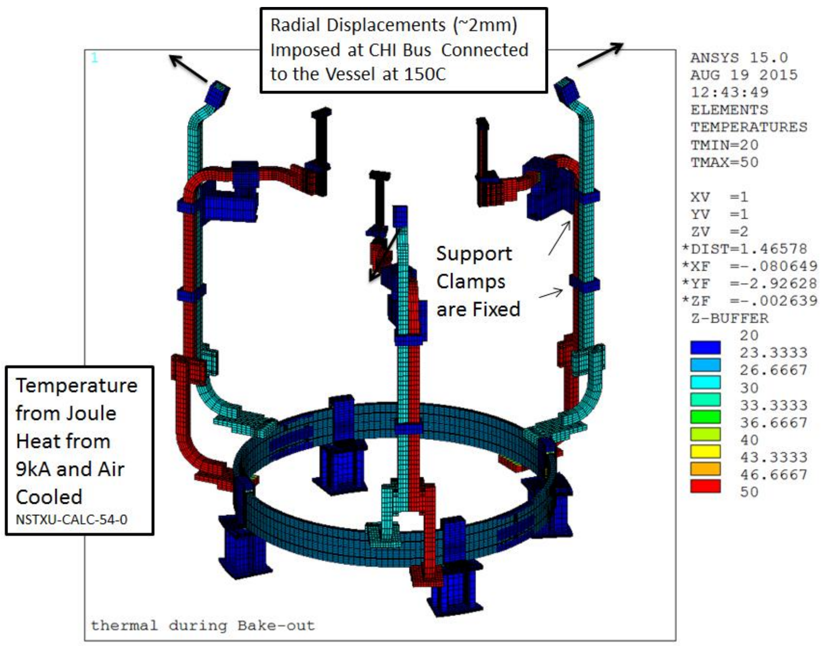


Figure 20.1-1 Lower CHI Bus Bar Model from [13]

The CHI bus connection to the CS through the CHI bars was analyzed in the calculation for the bake-out condition and is deemed OK. The CHI Bus connection to the outer vessel will grow with the vessel. The original analysis assumed all the end points were fixed. The model was re-analyzed with ~2mm radial growth of the vessel imposed on the CHI vessel lug. The stresses are potentially qualifiable with more modeling of the bolted connection and braze joint. If the upper clamps on the outside of the umbrella structure are loosened, the stresses drop substantially.

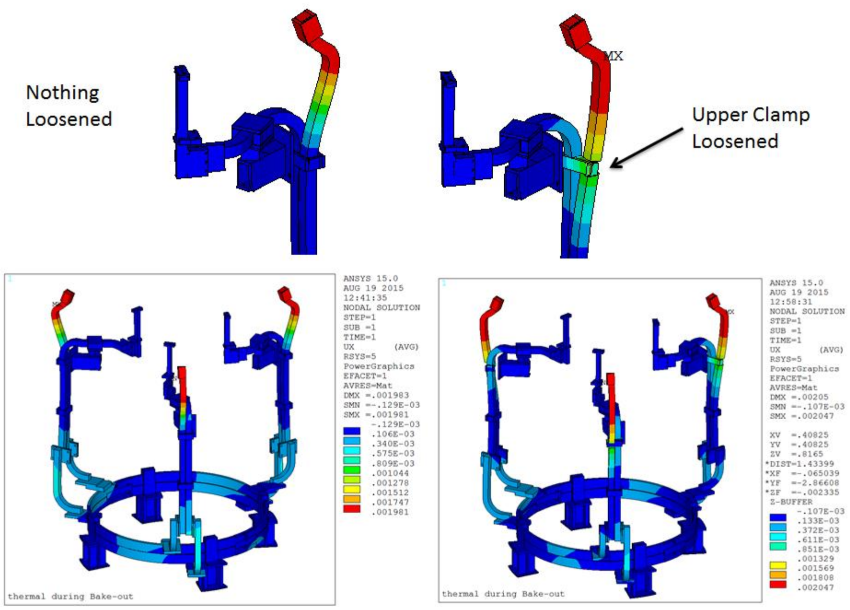


Figure 20.1-2 Lower CHI Bus Bake-Out Analysis

It should be easy enough to do this and have less disturbance of the CHI vessel electrical connection. This should be enough to adequately off-load the vessel lugs.

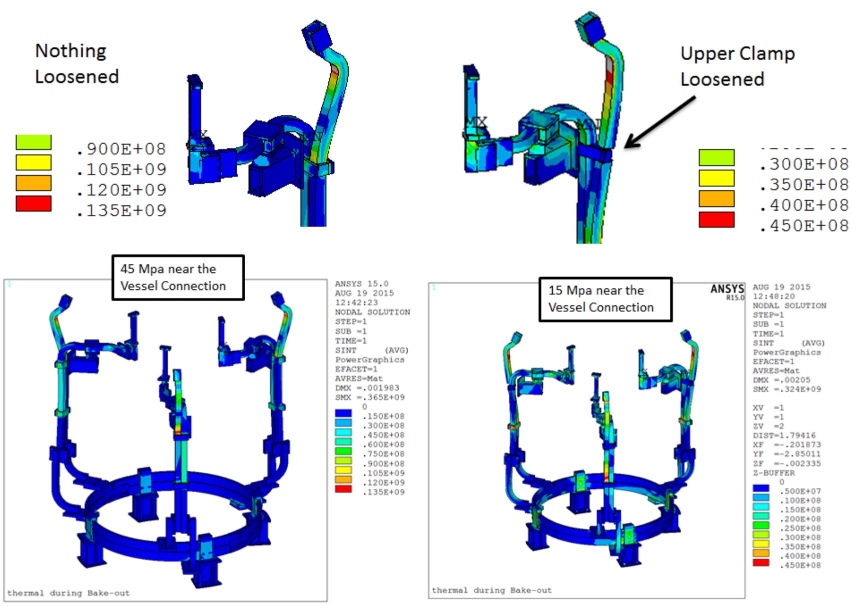


Figure 20.1-3 Lower CHI Bus Bake-Out Analysis

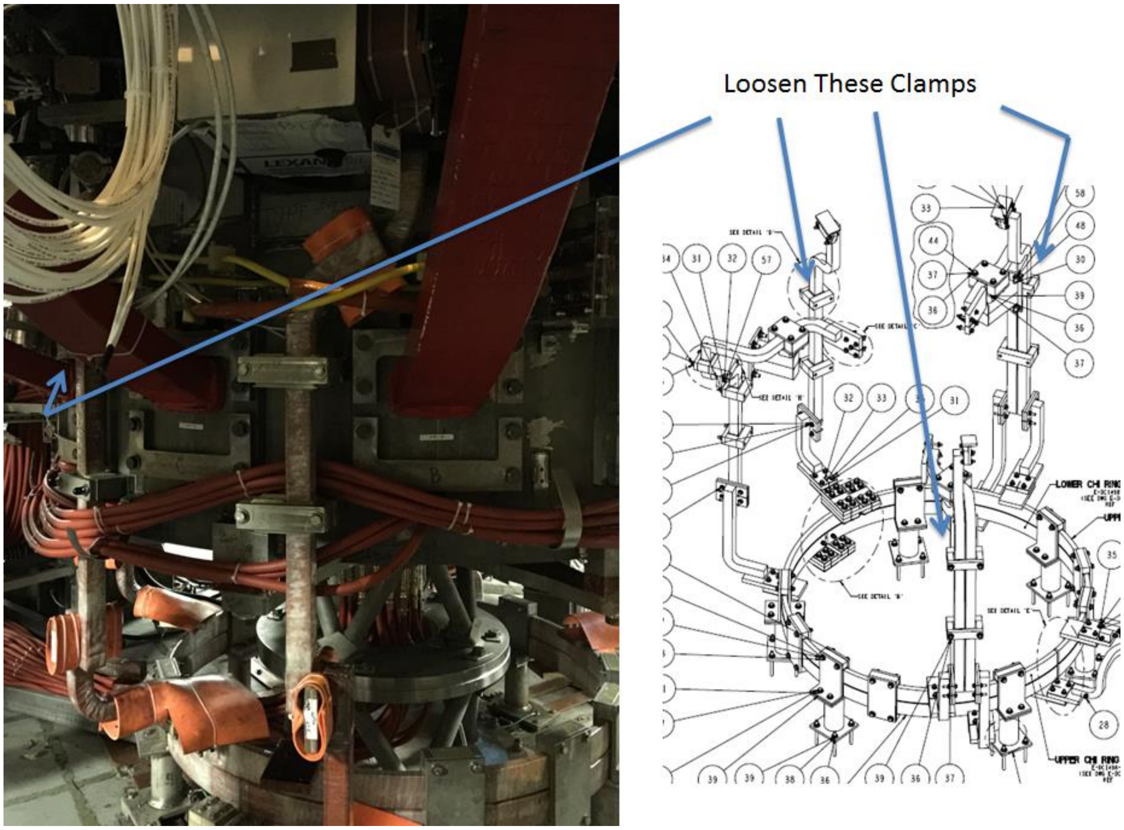


Figure 20.1-4 Lower CHI Bus Bake-Out Analysis, Location of clamps to be loosened

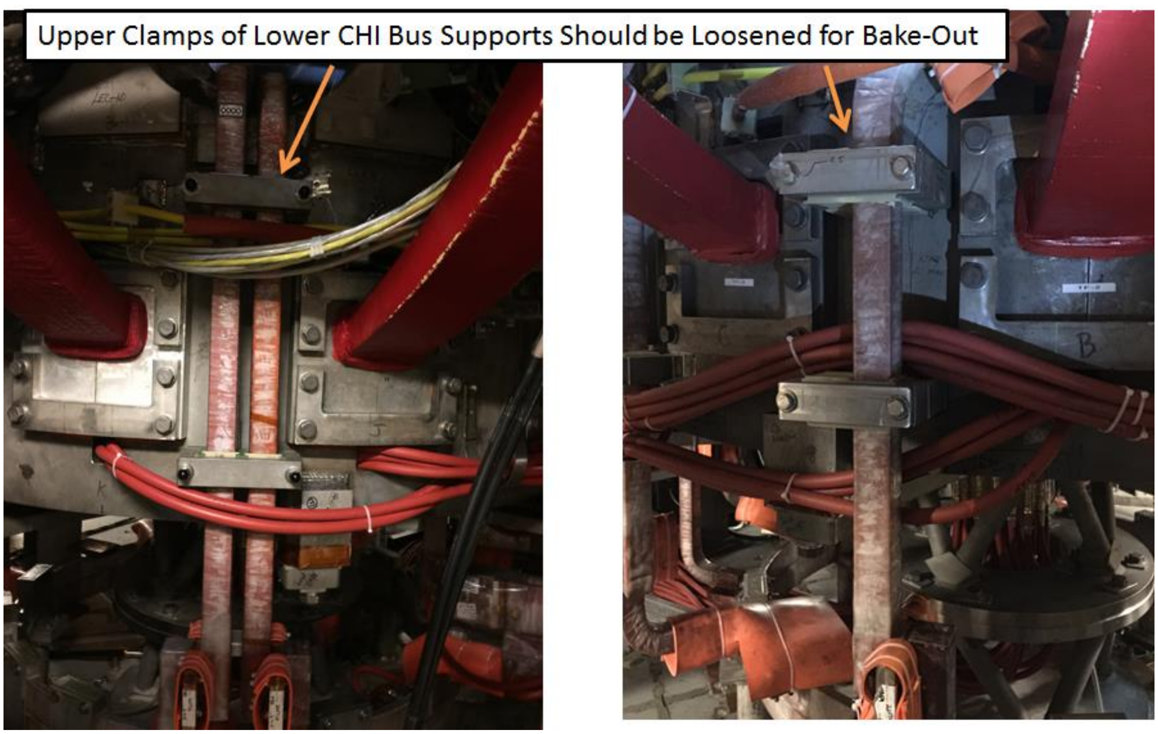


Figure 20.1-5 CHI Bus Bake-Out Analysis , Location of Clamps to be Loosened

It was noted that the CHI bus insulation at the outer vessel connection was discolored. With the vessel at 150 degrees during bake-out, the cause of the CHI leads discoloration is believed to be the combined effects of the vessel elevated temperature and the Joule heating of the connections as they carry the 8kA that is used to heat the centerstack casing.

20.2 Upper CHI Busbar Power Connections

There is adequate flexibility in these connections by compliance of the bus and clamps and by provision of a flex connection bridging the inner and outer vessel.

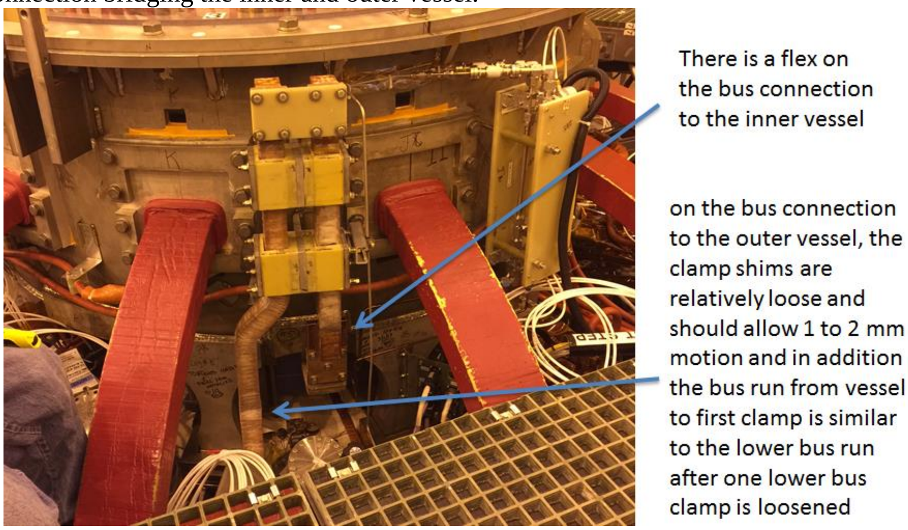


Figure 20.2-1 Upper Jumpers

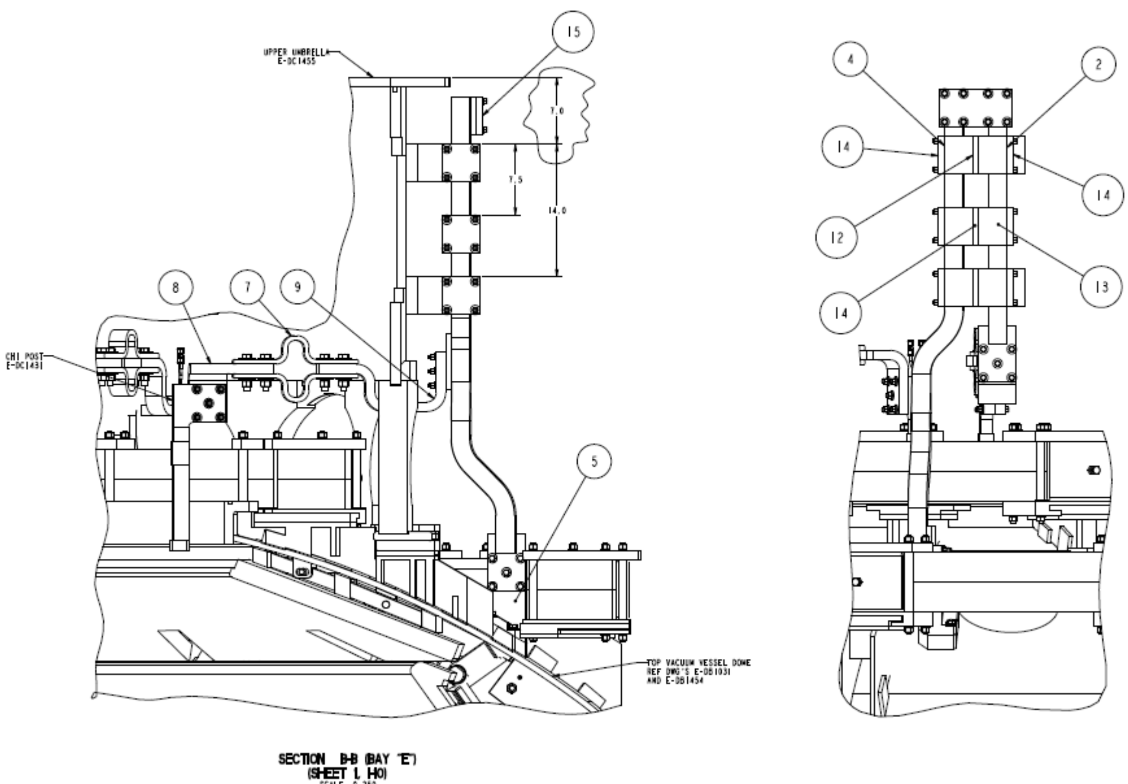


Figure 20.2-2 Upper Jumpers Showing Flex Connections to Relieve Bake-Out Thermal Motions

21.0 PF 4 and 5 Support Columns

At six upper locations and six lower locations, brackets connect to the vessel to support PF4 and 5. The upper and lower pairs of these coils are in series and have large attractive loads that required adding columns between these brackets. The original NSTX columns were undersized, and the Upgrade has had stronger columns fitted. During Bake-out, the vessel is at a higher temperature than these supports and columns. At the original PF4/5 support locations, the new columns need to be disconnected to allow differential thermal growth. These heavier columns have a flange in the middle of the column, and the bolts should be loosened to allow at least 1/8 inch growth. Also, an additional six new columns have been added between PF4/5 U&L that don't connect to the vessel. These do not need to be loosened, because the coils flex to accommodate the vessel growth. Analysis has been performed (Section 21) to determine if they could be left un-loosened.

There are two locations where the PF4/5 slide supports are locked and fixed to the vessel. These are near the terminals. This makes the terminals fixed to the vessel and the terminal supports at the bus tower fight the vessel growth. The terminal supports need to be loosened. A picture of the PF-5L Flex bus support is included in figure 21.0-6. The details of the loosening the terminal clamp were left to the technicians. It is included in the bake-out procedure [11]:

5.12 Loosen the clamps that hold the PF5 connecting buss to the buss tower.

George Labik's special column near the Thompson scattering system will have to be loosened as well.

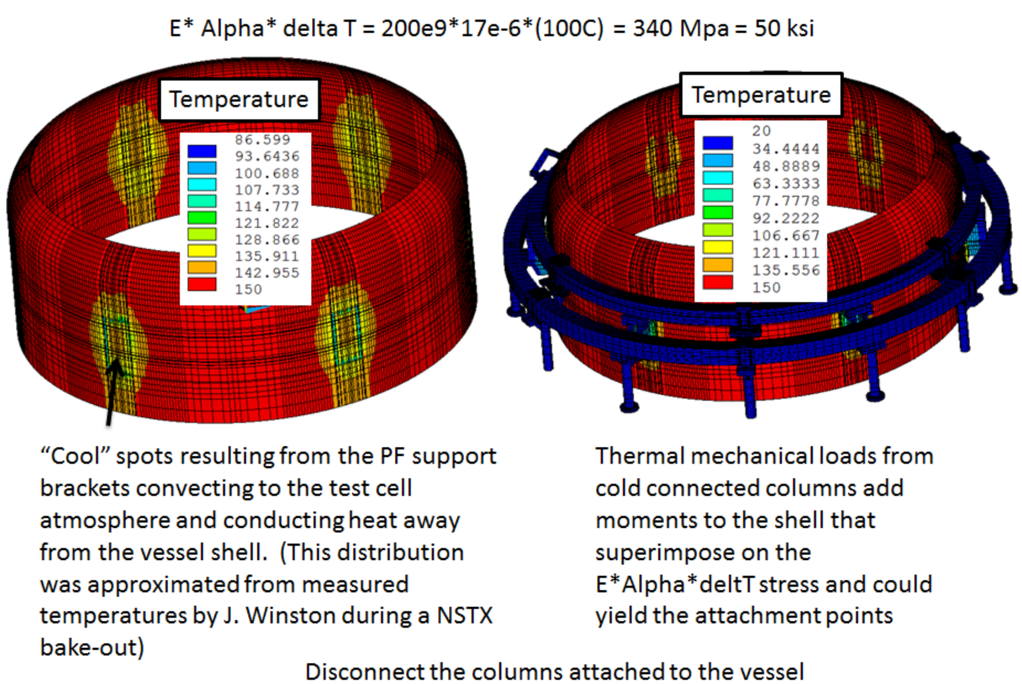


Figure 21.0-1 PF 4 and 5 Support Column Thermal Stress and Recommendation to Loosen the Columns

The measured thermal distribution referred to in the figure 21.0-1 appears in the PF4 and 5 support calculation [17].

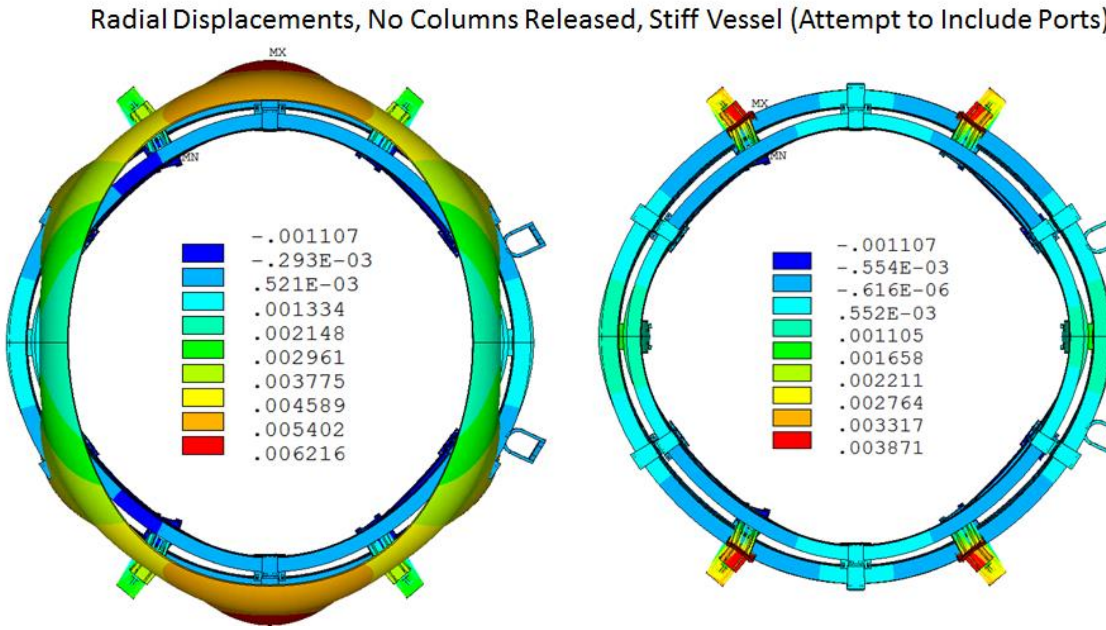


Figure 21.0-2 Radial Displacements, No Columns Released based on a Stiff Vessel.

The slides are important to keep the coils from being stressed by the vessel motions. Aluminum tapes were added at the slides in a manner that would indicate the extent of motion by crimping the tapes. In some instances tapes were applied that would indicate whether the slides had returned to their original pre-bake positions.

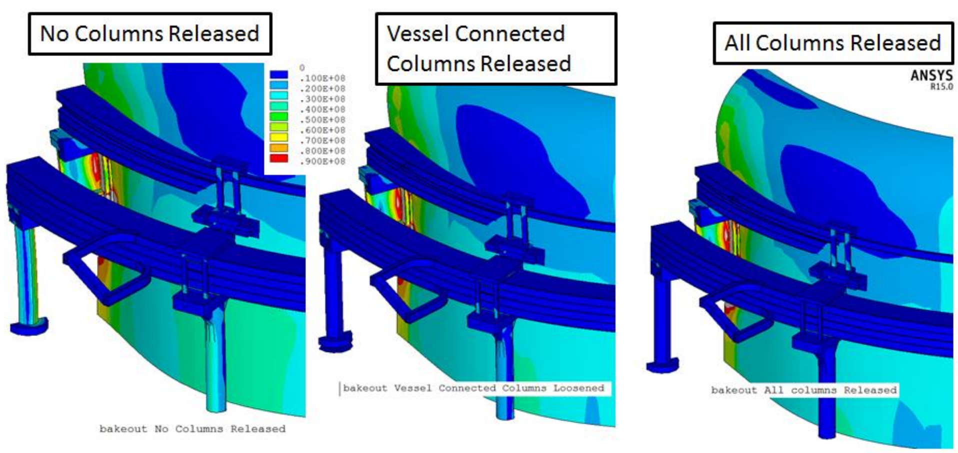


Figure 21.0-3 Comparison of Columns Released vs. Columns Not Released

Stress analysis doesn't show a significant difference between the column restraint cases. Part of the vessel stress shown in Figure 21.0-1 is the result of the cold clevis on the hot vessel shell. Stresses from the column tensile load are superimposed on the thermal stresses. The vessel adds to the stresses where they locally are above yield with the potential to plastically deform. A more appropriate caution is that if and when the stresses in the vessel shell go above yield, the bracket area would take the deformed shape imposed by the cooler columns. This is the basis for releasing the columns to allow the vessel shape to be retained.

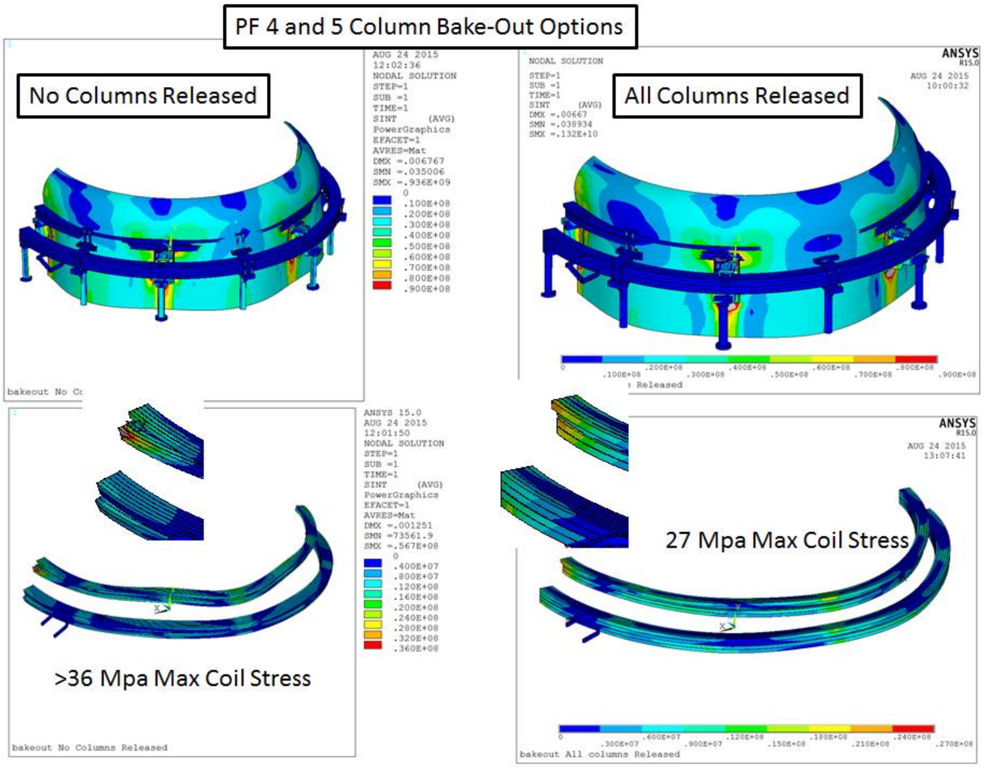


Figure 21.0-4 Coil Stresses for the Cases with Columns Released and Not Released

In figure 21.0-4, the vessel shell stress is dominated by the stress due to the thermal gradient in the shell around the cooler bracket. The contours are chosen to eliminate some of the peak stresses, which are mostly modeling anomalies from the imposed thermal gradient and mesh issues, but there is an improvement in the coil stress.

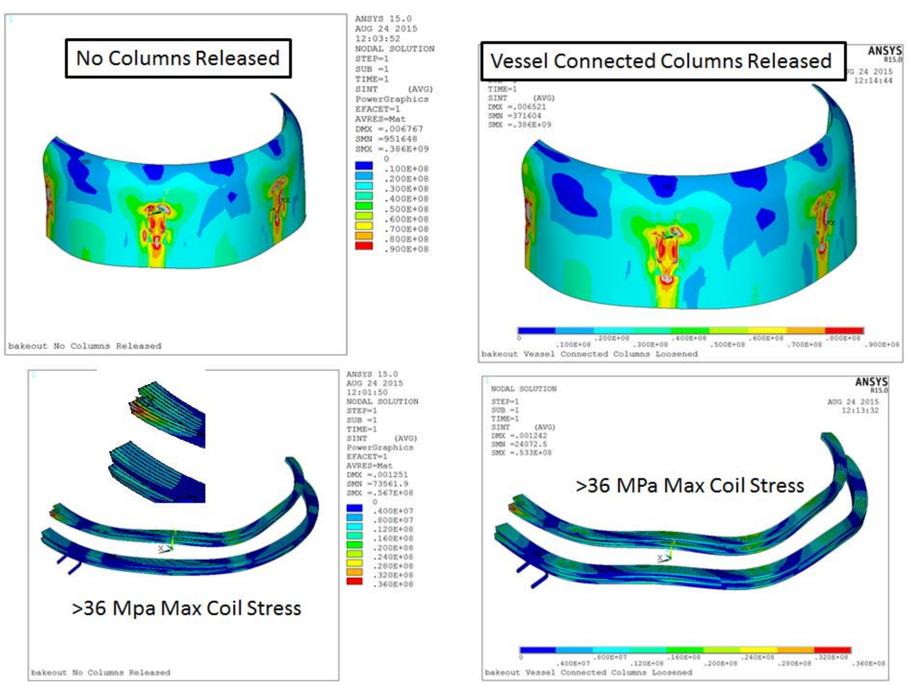


Figure 21.0-5 Coil Stresses for the Cases with Vessel Connected Columns Released and Non Released

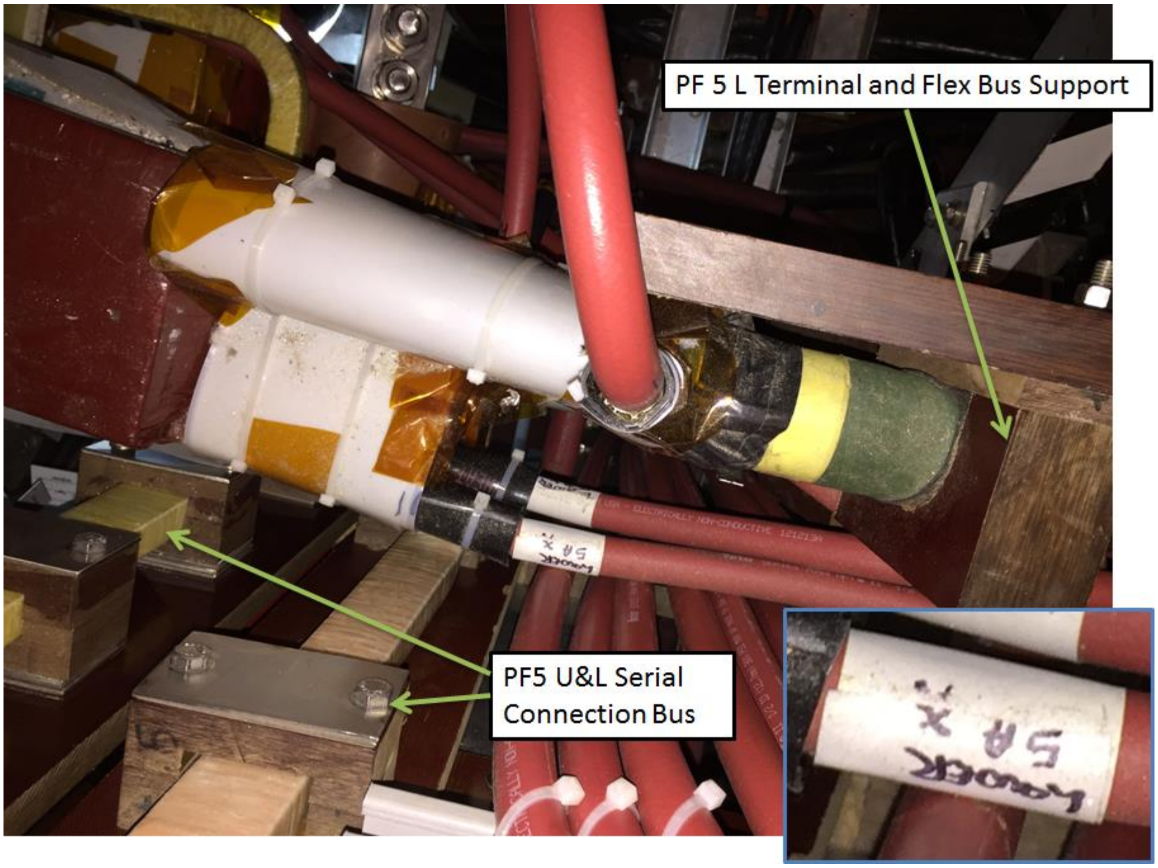


Figure 21.0-6 PF 5L Bus Support and Serial Connection Between Upper and Lower

22.0 TF Truss Behavior – Loosen or Not

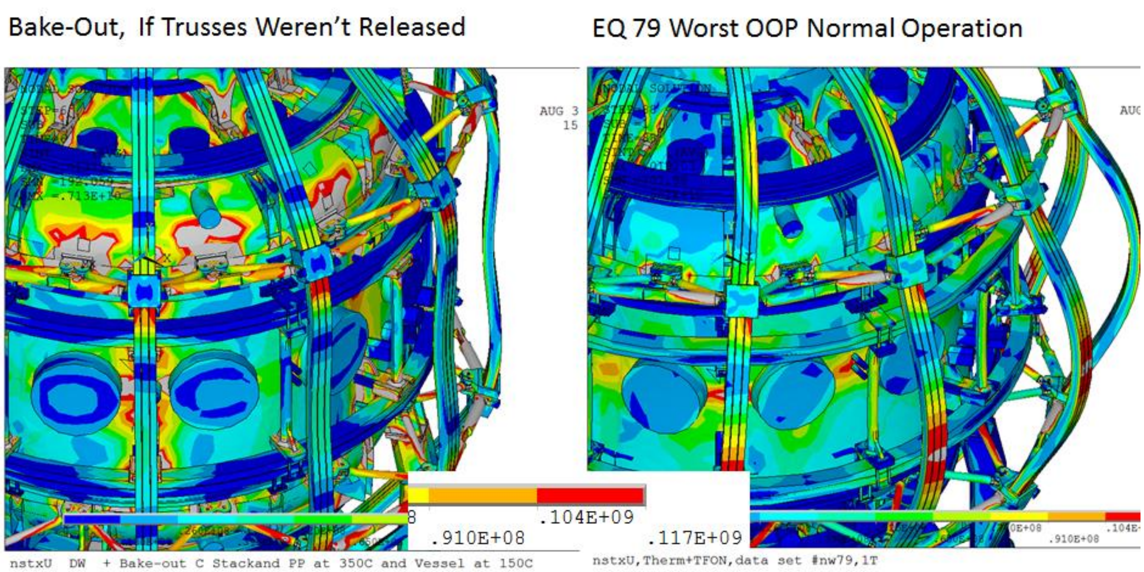


Figure 22.0-1 TF Truss, Peak Contour=117 MPa - Bake-out Compared with Normal Operating Max OOP loading

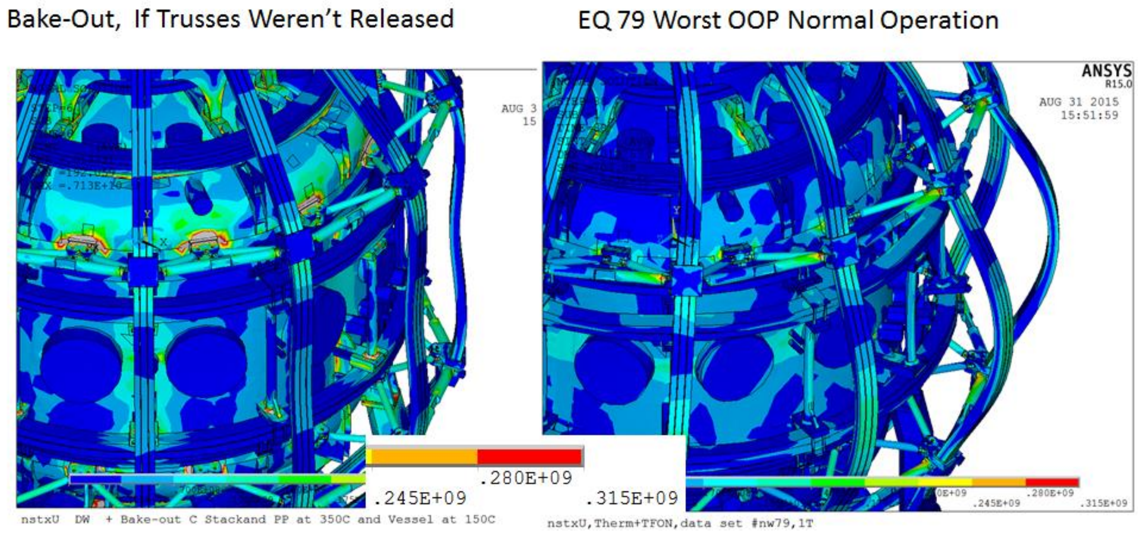


Figure 22.0-2 TF Truss, Peak Contour -= 315 MPa - Bake-out Compared with Normal Operating Max OOP loading

At many locations, individual stresses are comparable with regards to the normal vs. bakeout stress. However, comparing the amount of gray area (larger than the max value chosen for the contour range), the bake-out condition is worse than the largest normal operating condition. TF coil bending is about the same. The biggest effect is in the vessel, and in figure 22.0-2, the local stress at the vessel clevis ID > 315 MPa or 46 ksi which potentially could yield the vessel. Part of the vessel stress shown in the figure is the result of the cold clevis on the hot vessel shell, but if the stresses from the truss compressive load were superimpoosed on the thermal stresses, the vessel could "dent". So the conclusion is to release the trusses during bakeout. The pins at the TF outer leg side of the truss were removed and replaced with ½ inch bolts to retain the shims and washers and allow ease of re-assembly.

23.0 Bay J-K Cap Insulation

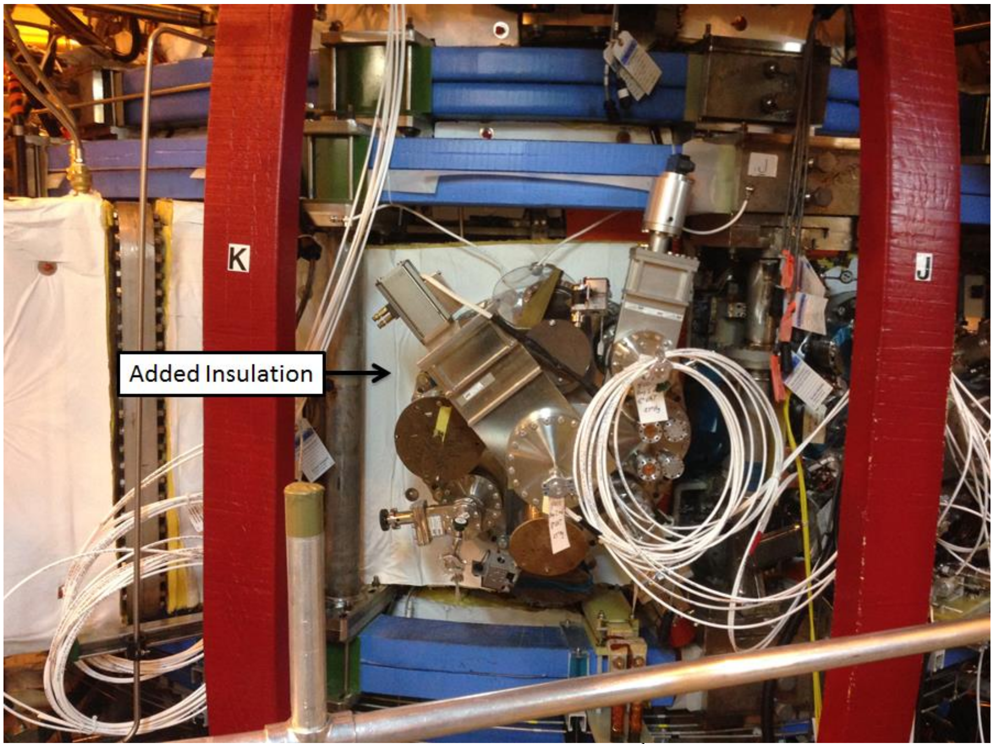


Figure 23.0-1 Photo taken Sept 4th 2015

The original vessel insulation was replaced for the bakeout. Altered components and added structures were reviewed for insulation consistent with the original insulation approaches used on NSTX. The new Bay J-K cap had not been insulated and this was corrected just prior to the Sept 2015 bakeout.

Appendix A

EMAILS

Pat Hipp <Pat.Hipp@ctd-materials.com>
AttachmentsMay 26

To me, Paul, Arthur, Steve, Lawrence
Peter,
Our chemists analyzed the resin characterization results and have come to the following conclusions:
• The TGA analysis shows that CTD-425 does not start to degrade until the temperature exceeds 300°C. The onset of weight loss appears to be around 315°C, with 5% weight loss occuring at approximately 350°C. Thus degradation at the proposed bake-out temperature of 225°C is not expected.
However;
• The glass transition temperature (Tg) of CTD-425 is in the 175-180°C range, so the resin will soften significantly at the 225°C proposed bake-out temperature. It should not flow at that temperature if the recommended cure profile is used because the resin will be highly cross-linked , but if there is any load at all, some deformation could occur since the resin will be in its rubbery state.
The TGA plot that I gave you is attached for your reference.
Best Regards,
Pat

Lawrence Dudek <ldudek@pppl.gov>

4:44 PM (16 hours ago)

to me, FRANK, Stephan
Pete,
They closed the original work request so I reopened a new one to perform the second 250C test. See below.

I spoke with Frank Jones about the failure, he said it looked like the part was arcing around the insulation and not through it. They could see sparks jumping from the screws under the kapton to the foil on the edge. I attached two photos, one after the epoxy and screws were installed and one as tested. Probably would have been better to install the screws and the wire first and then covered all of the exposed screws and wire with epoxy. There is only about 3/8" of gap between the edge of the ground foil and the screw head at ground.

Test results as follows:

3kv = 0 microamps @ 3 min

6kv = 0.5 " @ " "

9kv = 0.75 " @ " "

13kv = full short, sparks

____
Larry

Lawrence E. Dudek
ldudek@pppl.gov

Email to P. Titus, Art Brooks, Larry Dudek from Steve Raftopoulos <sraftopo@pppl.gov>
10/22/14

Peter,
We should take credit for the woven silica fabric.
The butt-lap woven silica is 0.062" thick and its thermal conductivity is ~0.123 [W/(m*K)], which is ~6.5 x microtherm. Note that the thermal conductivity of fused silica fiber is much higher(~50 x microtherm), but as a woven fabric it becomes substantially better. Steve
Steve Raftopoulos <sraftopo@pppl.gov>

Attachments10/14/14

to Arthur, me, Michael, James
Art,
What are the ramifications of removing one of the two microtherm insulating blankets? I believe that the blankets are 3mm in thickness, as opposed to .100" which was the nominal design value.

Attached is a product brochure and MSDS for the Microtherm Blanket. We used the "Microtherm SG Hydrophobic Quilted Panel".

Thanks,
Steve

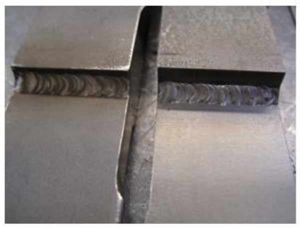
Peter Titus <ptitus@pppl.gov>
Sep 1
to Mark
PF support slide scribing -add the main column support slides. -Peter
On Tue, Sep 1, 2015 at 1:59 PM, Mark Cropper <mcropper@pppl.gov> wrote:
All,
Attached is the bakeout procedure with the changes from this morning:
a. 2.8 Changed to allow higher than 70 degrees PF1B inlet temp
b. 5.8 Changed to a generic step to allow the tech's to disconnect the TF truss links by removing the pin or inserting a 1/2" rod.
c. 5.54 corrected OH flow paths
d. 6.16.1 Added Initial PF1B temp limit.
e. 6.18.d Added Project engineer sign off to change PF1B limit.
f. 6.18.h Added PF1A temp limit.
g. 6.18.i Added PF1C temp limit.
h. 7.1 Added PF1A, B, & C to readings to record on data sheet.
i. 7.8 Step added to verify rogoski functionality.
j. Data Sheet: Added He flow direction, OH lower Temp reading, PF1A and PF1C temp readings, rogoski readings.
The diagnostic sign off is still in the procedure step 5.30.
Let me know if I forgot any thing or if any thing else needs to be added.

Thanks,

Mark

Appendix B
1/8 inch Fillet Weld Tests

1/8 inch Fillets on ¼ inch and greater stock are not accepted by AISC an AWS – But were used on NSTX for PF 2 and 3 Supports. These were qualified by test.



Tensile Pull Weld Samples

WR#20110329 MTL#351 2011-06-15

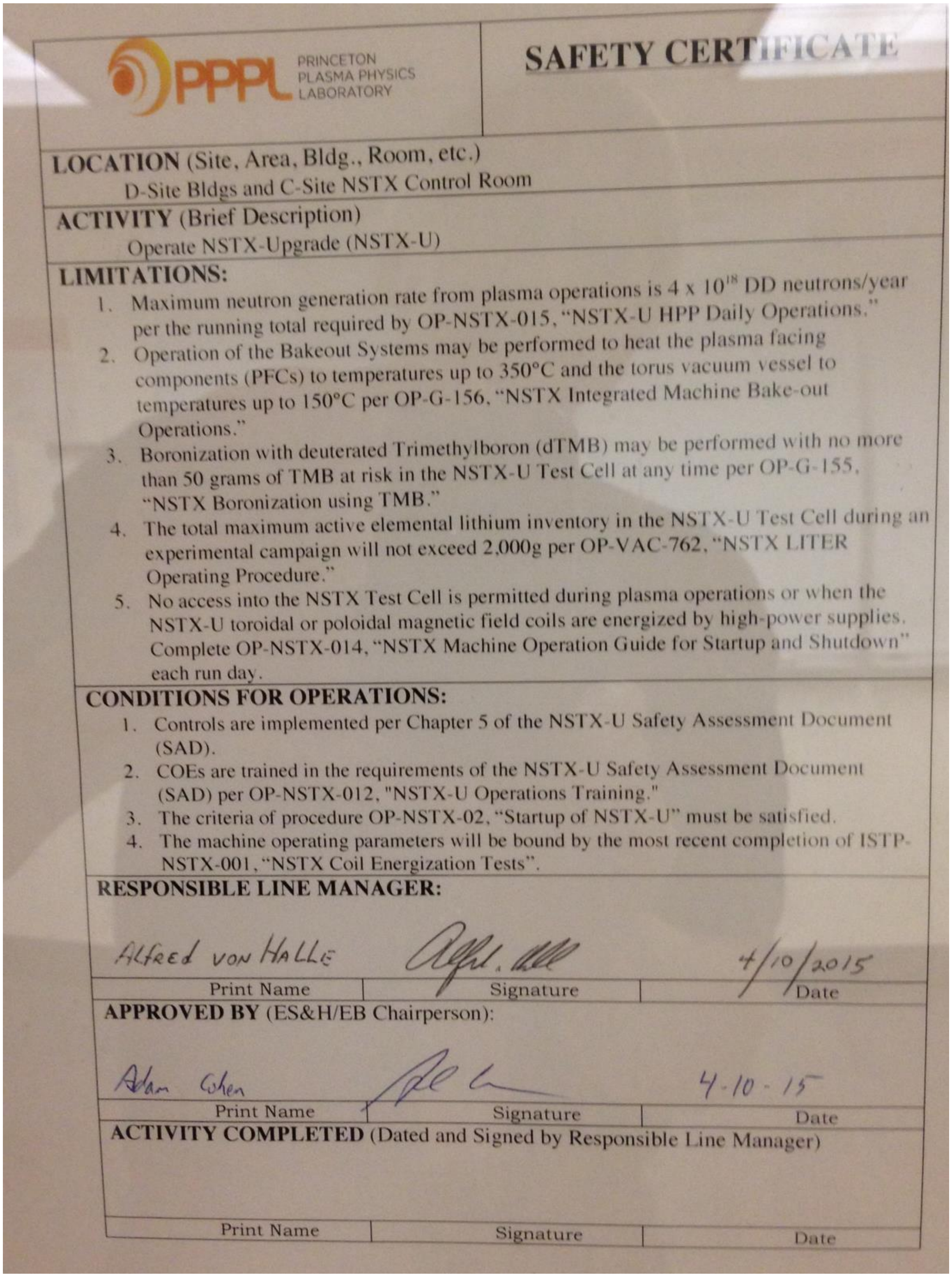
A total of 4 welded samples were tested in tension

All samples were a 300 series stainless steel, butt welded to a 1" plate using nominal 1/8" fillet welds. The thinner plates were centered on the heavier plate edge and welded with a fillet on each side comprising a welded assembly consisting of two welds across the reduced section. Overall specimen length was 16", with the reduced section straddling the welded zone.

Sample #1 ¼" plate to 1" plate, reduced section 1.425", rupture 26847lbs force
Sample #2 ¼" plate to 1" plate, reduced section 1.328", rupture 26113lbs force
Sample #3 ½" plate to 1" plate, reduced section 1.310", rupture 26194lbs force
Sample #4 ½" plate to 1" plate, reduced section 1.458", rupture 31851lbs force

Stresses the Samples Survived:
26194 LBS/2/1.375 = 9252 Lbs/inch
26194/2/1.375/.125 = 76200 psi Nominal Average Tension
26194/2/1.375/.125/.707 = 107780 psi Shear on Throat

Appendix C
Safety Certificate as Posted in the Control Room



PRINCETON PLASMA PHYSICS LABORATORY

SAFETY CERTIFICATE

LOCATION (Site, Area, Bldg., Room, etc.)
D-Site Bldgs and C-Site NSTX Control Room

ACTIVITY (Brief Description)
Operate NSTX-Upgrade (NSTX-U)

LIMITATIONS:

1. Maximum neutron generation rate from plasma operations is 4×10^{18} DD neutrons/year per the running total required by OP-NSTX-015, "NSTX-U HPP Daily Operations."
2. Operation of the Bakeout Systems may be performed to heat the plasma facing components (PFCs) to temperatures up to 350°C and the torus vacuum vessel to temperatures up to 150°C per OP-G-156, "NSTX Integrated Machine Bake-out Operations."
3. Boronization with deuterated Trimethylboron (dTMB) may be performed with no more than 50 grams of TMB at risk in the NSTX-U Test Cell at any time per OP-G-155, "NSTX Boronization using TMB."
4. The total maximum active elemental lithium inventory in the NSTX-U Test Cell during an experimental campaign will not exceed 2,000g per OP-VAC-762, "NSTX LITER Operating Procedure."
5. No access into the NSTX Test Cell is permitted during plasma operations or when the NSTX-U toroidal or poloidal magnetic field coils are energized by high-power supplies. Complete OP-NSTX-014, "NSTX Machine Operation Guide for Startup and Shutdown" each run day.

CONDITIONS FOR OPERATIONS:

1. Controls are implemented per Chapter 5 of the NSTX-U Safety Assessment Document (SAD).
2. COEs are trained in the requirements of the NSTX-U Safety Assessment Document (SAD) per OP-NSTX-012, "NSTX-U Operations Training."
3. The criteria of procedure OP-NSTX-02, "Startup of NSTX-U" must be satisfied.
4. The machine operating parameters will be bound by the most recent completion of ISTP-NSTX-001, "NSTX Coil Energization Tests".

RESPONSIBLE LINE MANAGER:

Print Name	Signature	Date
Alfred von Halle	[signature]	4/10/2015

APPROVED BY (ES&H/EB Chairperson):

Print Name	Signature	Date
Adam Cohen	[signature]	4-10-15

ACTIVITY COMPLETED (Dated and Signed by Responsible Line Manager)

Print Name	Signature	Date

Appendix D
Emails from Steve Jurczynski Transmitting Test Results

Stephan Jurczynski <sjurczyn@pppl.gov> 9/23/15

to me,
Steve,
Erik,
Lawrence

Peter,
Sample testing attached. This should complete WR# 20142467.
I've also completed the mechanical tests of the wrapped Hysol samples, that write-up and photos coming next. Thanks.

Steve

Attachment: Copy of PF1b Sample 1 -2 compressive test 2015-09-22.xls

Stephan Jurczynski <sjurczyn@pppl.gov> 9/25/15

to me,
Steve,
Erik,
Lawrence

Peter,
Hysol/Glass compressive tests attached. WR# 20142399.

Steve

Attachment: 2015-09-25 HysolGlass test samples.xls

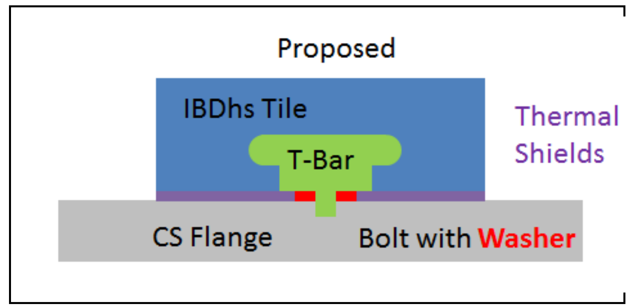
Appendix E

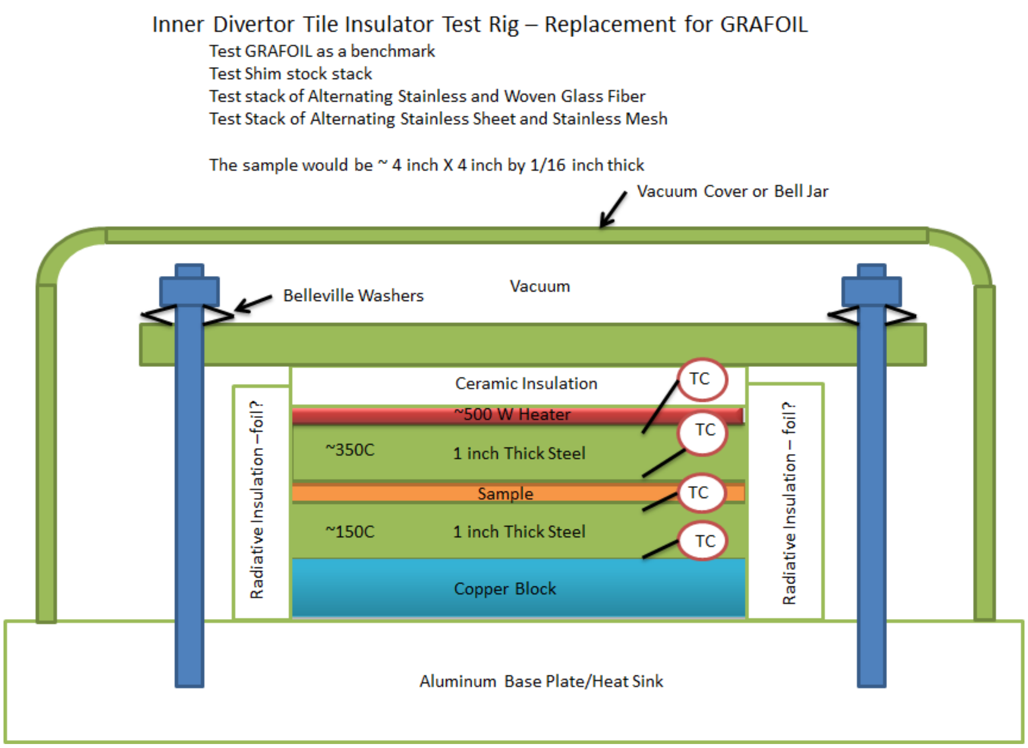
Test of Inner Divertor Tile Insulation

Steve Jurczynksi, Steve Raftopoulos, A. Brooks, P. Titus

1150****X150, Work Request 20150280

During bake-out, the temperature of PF1b had to be kept below the temperature that would damage the winding pack insulation. This was done with active cooling in the coil, but with a slightly elevated cooling water temperature. The mandrel of Pf1b is connected to the inner divertor mounting flange and consequently the tiles, which are thermally connected to the flange and thus PF1B, did not reach the desired 350C bake-out temperature. Even with the elevated cooling water temperature, tile temperatures were too low. A desirable fix would be to replace the Grafoil under the tile which is thermally conducting, with an insulation layer. To design and choose an appropriate insulating material, tests of the thermal conductivity of the material needs to be made. Tests are to be performed on the currently employed Grafoil as a benchmark, and a few (~4) candidate materials. The figure below is a conceptual sketch of the test rig which is intended to be a starting point for a test fixture made up from available parts





Insulation performance is to be measure in vacuum. Testing should be done in phases:

1. Detailed design of the test rig. Review available equipment and propose the test rig specific design. We should have a review or meeting in the lab to discuss before assembly of the test fixture.
2. Grafoil benchmark and testing of the fixture itself. The ability of the heater to reach the desired temperatures and the functioning of the thermocouples should be confirmed. Bolt preload and Belleville stack deflections will be quantified and sized (A.Brooks).
3. Selection of the test samples. At this point three are proposed. A stack of shim stock, a stack of alternating shim stock and glass fiber, and a stack of alternating shim stock and wire mesh. Other samples can be proposed. It is desired that we qualify insulation material that is 1/16 inch thick if possible.
4. Evaluate the results and determine if the projected tile temperature is acceptable
5. A second round of tests may be needed if thicker insulation is needed or other insulation concepts are to be investigated.