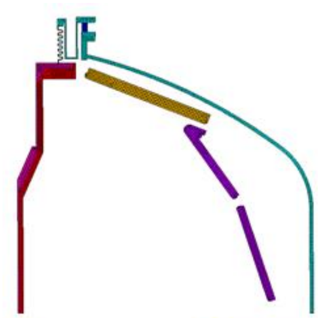
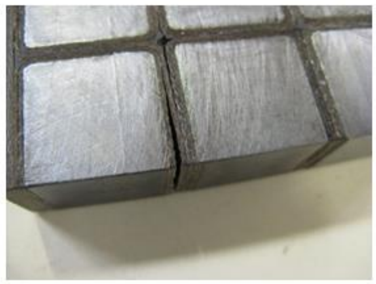
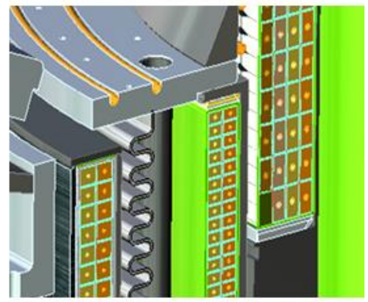
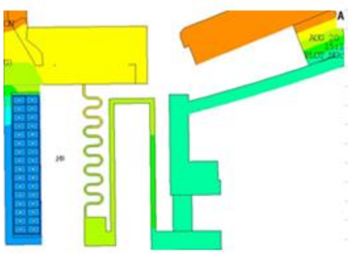
NSTX Upgrade
Bake-Out Evaluations
NSTXU-CALC-10-4-0

DRAFT

September 2015

Prepared by P. Titus	Reviewed by
Section 10.0,11.0 Prepared by Han Zhang	Reviewed by
Section 8.0 Prepared by A. Brooks	Reviewed by
Section 10.1,10.2 Stephan Jurczynski	Reviewed by

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, particularly near the PF1b mandrel/case. We are doing structural and electrical tests on the winding packs at 225 and 250C and these are included in this calculation. 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. . The extra radial motion of the hotter PF1b coil is less than a mm, and is e4valuated for the bake-out condition. The peak PF1b coil temp 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 we allow the coils to go to 150C for bakeout, 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 bakeout 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 displacements and should allow the extra <1 mm displacement. The calculations of record 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 8.0-1, 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.)

PF1b should be initially run at 70C during the bake-out. The new thermal control system will be capable of going up to 110C during the bake-out if the tile temperatures are not high enough . At 70C inlet to PF1b, the G-10 shim between the ground wrap and the winding turn-to-turn insulation goes to ____ at 110 C the shim goes to ___ and the tile surface goes to____

Cognizant Engineer's printed name, signature, and date

____

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

Checker's printed name, signature, and date

____

2.0 Table of Contents

3.0 Revision Status Table

Rev 0	Initial Issue

4.0 Executive Summary

This calculation is a collection of analyses relating to the bakeout 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, bakeout analyses performed throughout calculations qualifying NSTX Upgrade are collected and referenced or models are exercised with bakeout temperature distributions. The goal of this calculation is to support the content of the bakeout procedure, D-NSTX-OP-G-156.[16]

4.1 Cross Reference to Other Bake-Out Structural Requirements:

Input to the bake-out procedure [16] 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 outerleg 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 between the upper and lower coils	Loosen the Phenolic block clamps on the flex 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

In rev 4 there isn't a reference to the PF 4/5 columns. They should have been loosened in the original NSTX bake-out procedure. At the original PF4/5 support locations, the new columns need to be disconnected. 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. Six new columns have been added between PF4/5 U&L that don't connect to the vessel. These should also be loosened, but there is a possibility that the coils could flex to accommodate the vessel growth. Analysis can be performed 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 one near the Thompson scattering system, and s 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.

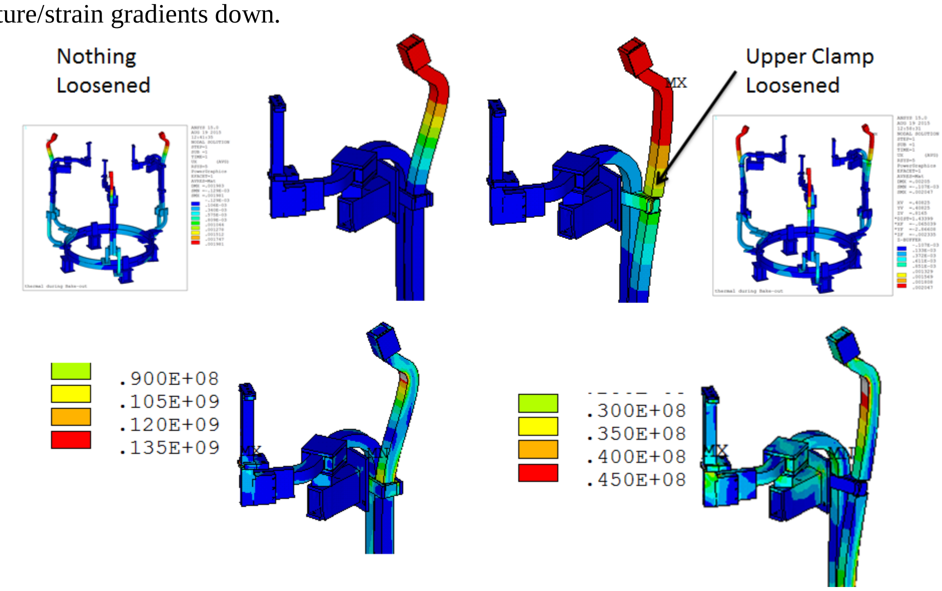


Figure 4.1-1 Stress and Displacement Results With and Without Loosening the Upper Clamp

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 I did, assumed all the end points were fixed. I re-did the model with ~2mm radial growth of the vessel imposed on the CHI vessel Lug. The stresses are qualifiable, I think, 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. I think this will be enough to adequately off-load the vessel lugs.

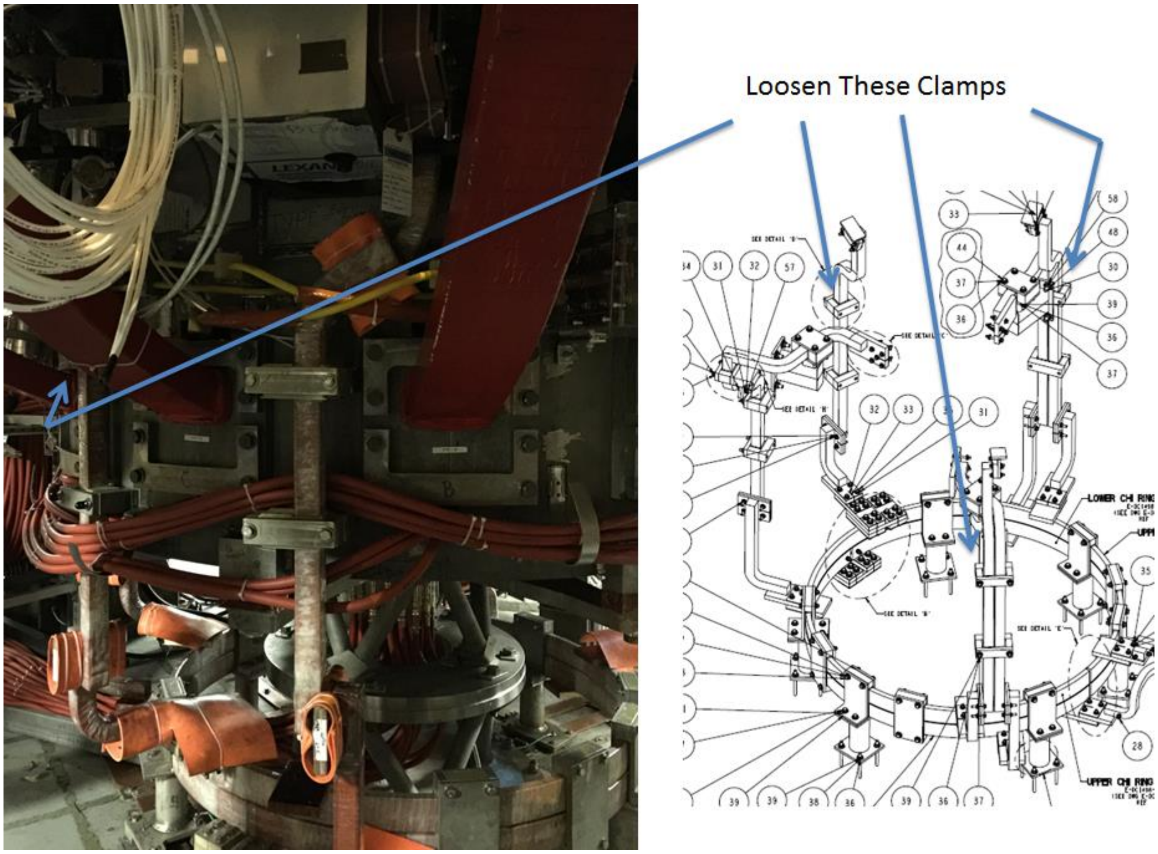


Figure 4.1-4

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. I have a question in to Neway as to the load path of these supports. If they are tied to the vessel, they will need to be loosened.

4.2 Monitoring During the Bake-Out

There are a few places that we would like to verify are sliding properly - like the PF2,3,4,and 5 support pads umbrella feet, and 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 will be inspected to make sure the slides have returned to their pre-bake-out positions.

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. . A. Brooks 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 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. Figure 4.0-1 is intended to emphasize the advantages of getting the tiles to 300 to 350 degrees C. The higher temperatures substantially reduce the require time for the bake-out to feasible time scales.

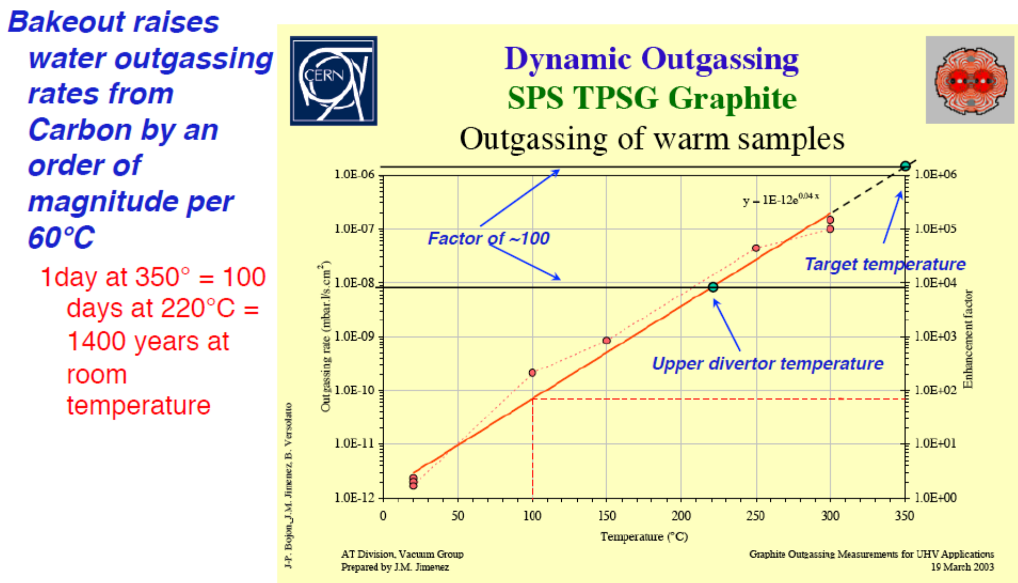


Figure 4.0-1 Slide from Dennis Mueller's Operators Class Showing the Temperature Sensitivity of the Bakeout OutGassing.

Unfortunately there are a few temperature sensitive components that limit the ability to get the divertor area up to temperature. 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.

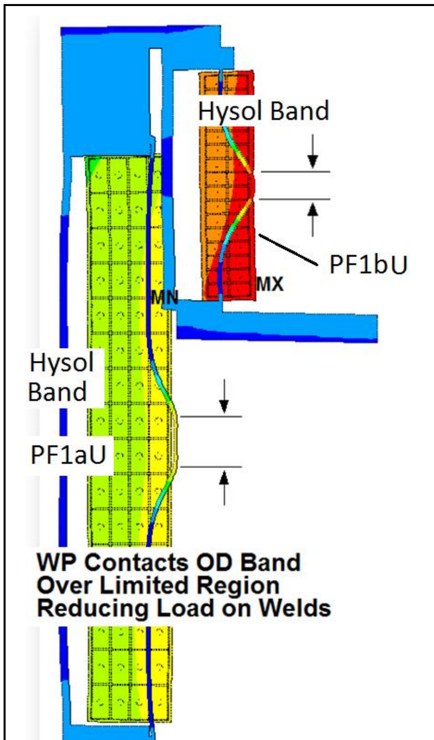


Figure 4.0-1 Excerpt from NSTXU-CALC-133-01-01[9]. Showing HYSOL band

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
PF1b to Casing weld Shear Stress
Excessive temperatures in the PF1b Hysol centering band
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.
Maintain acceptable temperatures in the O ring seal

There are a number of "knobs to turn" to achieve the highest divertor tile temperature while meeting the temperature limits of the various components near the divertors.

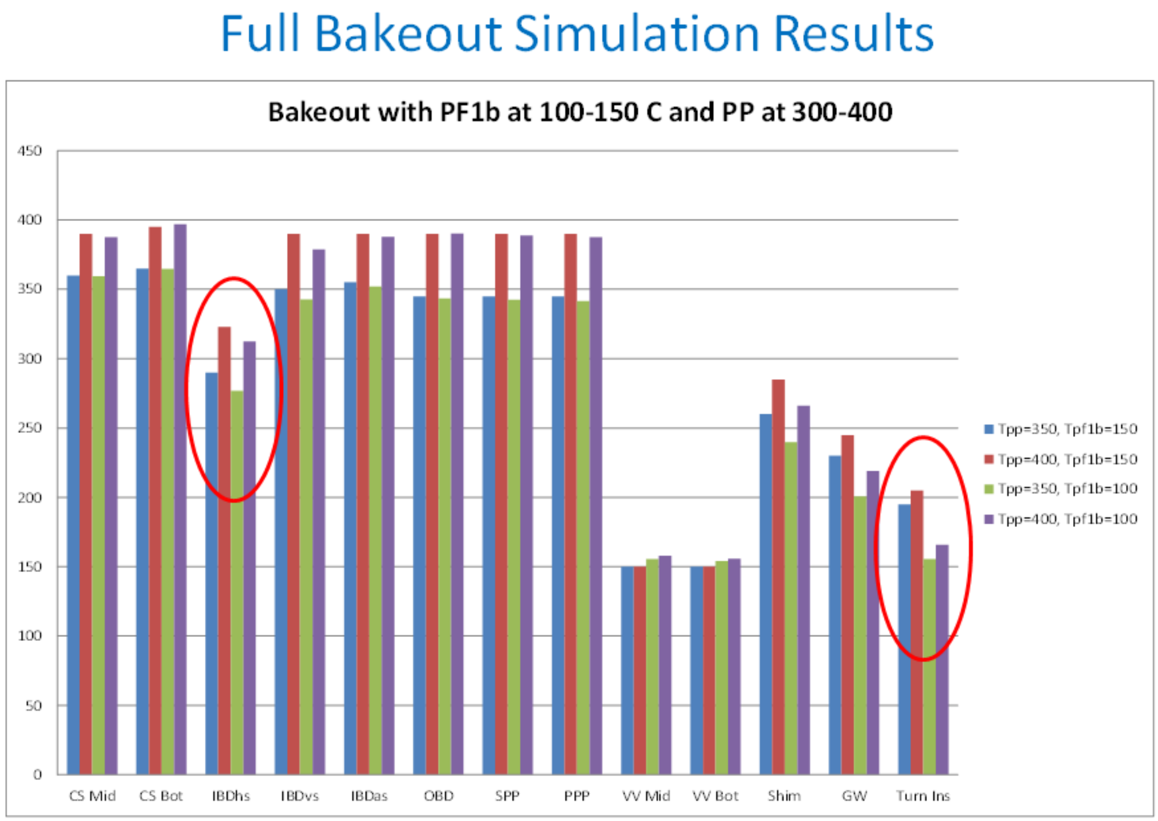
"Knobs to Turn"

Raise the temperature of the cooling water inPF1b
Emissivity – Remove uncertainty
Actively heat the horizontal divertor flange of the casing with hot He 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 air circulation in the area below the inner PF coils

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.

. Through realistic thermal modeling and on-going material temperature testing, a bakeout heating scheme will be chosen if any before the bakeout. Risk-benefit assessment for PF-1B will be performed in deciding the heating system if any before the bakeout. The cause of the CHI leads discoloration will be determined prior to CD-4.

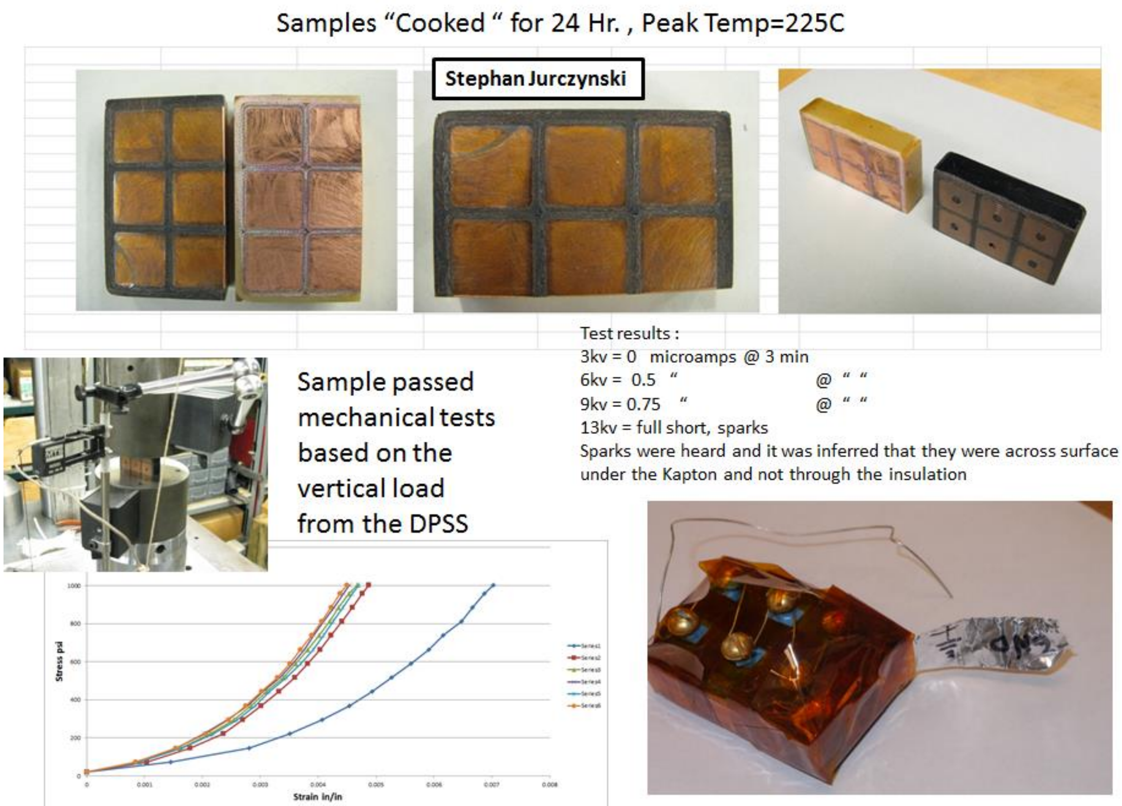
Actively heating the horizontal divertor flange had to be abandoned because the tubes are copper, are limited to low pressure at the desired operating temperature and were found to leak anyway. Additionally the copper tubes were laid in a groove with an end loop with no allowance for thermal growth – even to accommodate the thermal expansion differential between the 625 and copper materials. Higher temperature compatible feed tubes tubes were installed. This modification enables the divertor tiles to be heated to desired temperature of 350°C. However, a leak was discovered in the upper horizontal divertor cooling tube which preclude the use of helium-based heating. " The present plan is not to actively heat the upper divertor horizontal tile sections. The copper tubes used in the Centerstack casing divertor flanges and shells may have to be operated at a pressure lower than 200 psi if they are supplied with 350C gas. and the temperature differential between the flange and tube will have to be limited" This is discussed in more detail in section 12.0.
The modeling calculations indicate that the PF1b coil being cooled at 12 °C will cause unacceptable level of stress on welds attaching the PF 1b coil to the horizontal divertor plate. This will also cause the divertor tiles temperature to be well below the required 300 °C. The suggested remedy is to use 150°C water for the PF 1b 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 PF 1b hoses is pursued presently at high priority.



	Actively Cooled/Heated?						
PF1b Temp	No, Yes to 100C or 150C						
Horizontal IB Divertor Flange	HYSOL Limit is:						
Vertical IB Divertor Casing Shell							

4.5 PF1b Epoxy Temperature Limits

There are a number of areas around the machine that require adherence to temperature limits. Globally the machine is to have the vessel internals limited to 350C and the vessel limited to 150C. Interpretations of these temperature are 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 protected by running normal cooling water through them during the bake-out



We are doing structural and electrical tests on the winding packs at 225 and 250C and these should be documented in a calculation.

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	

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.

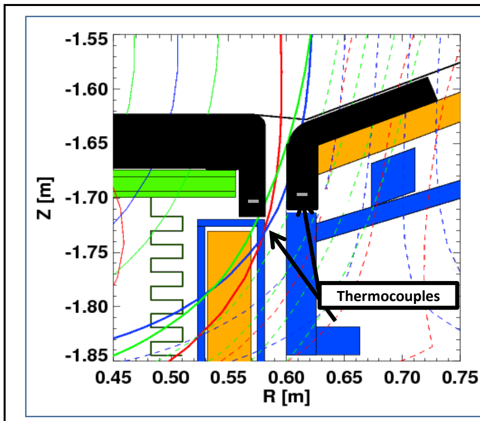
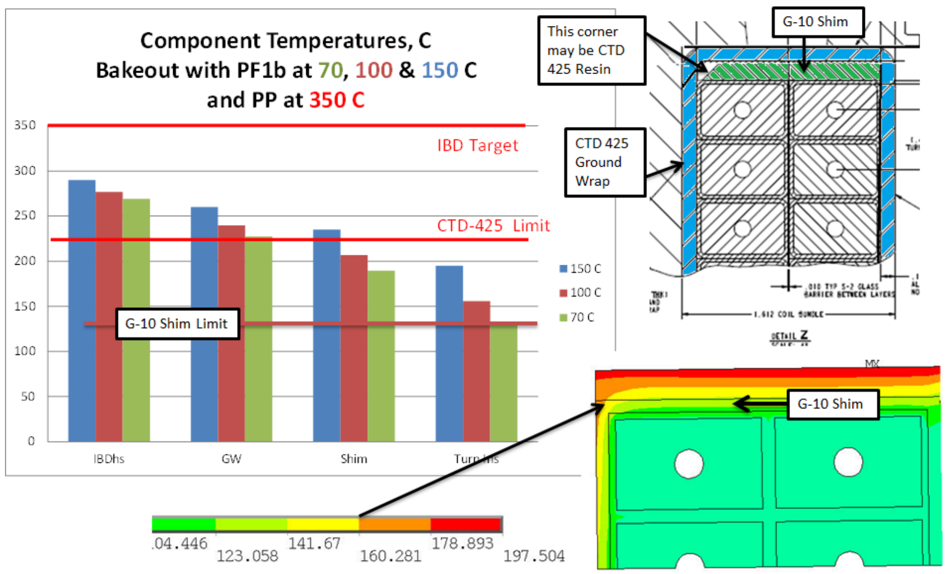
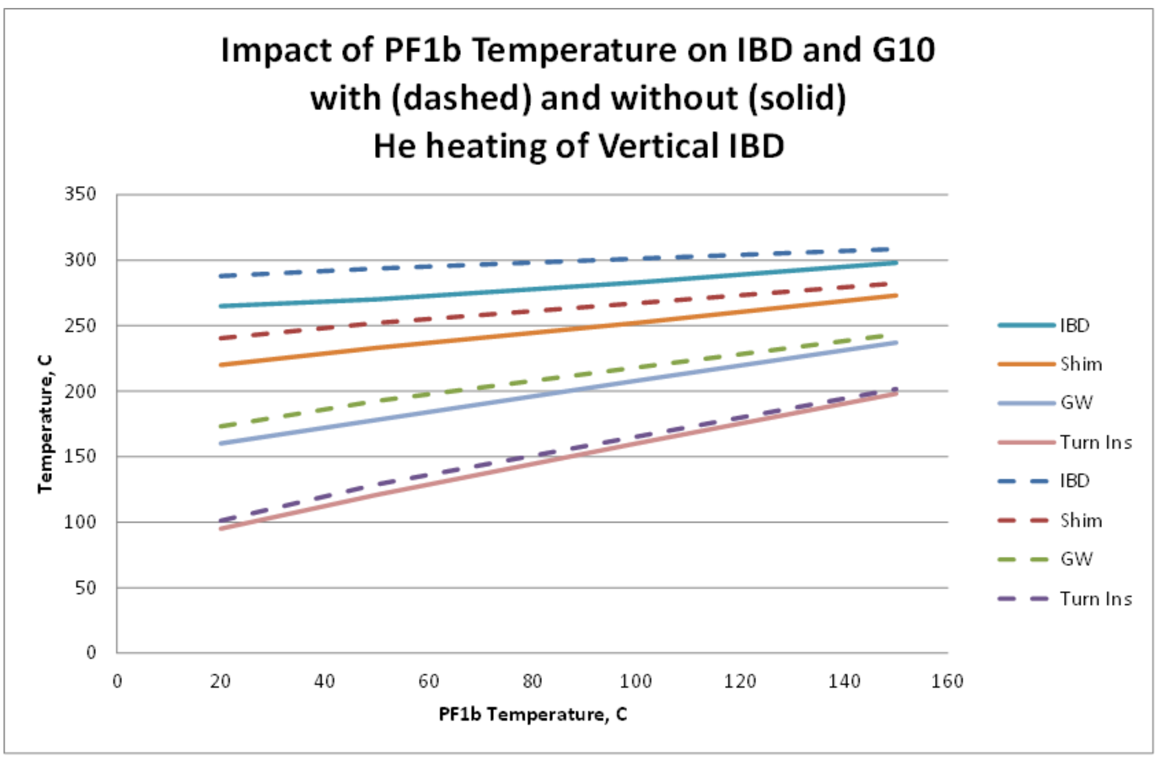


Figure 4.0-3 Figure from Stefan Gerhardts presentation on the potential for flux lines intercepting the corner of the pF1c case outer shell

Art's heat balance calculations need to be documented. The extra radial motion of the hotter PF1b coil is less than a mm, but needs checking. The peak PF1b coil temp 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 we allow the coils to go to 150C for bakeout, 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 bakeout 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 displacements and should allow the extra <1 mm displacement. The calculations of record are from Art, Ali, Andrei, and Len Myatt and we would at least have to cross reference these. Probably a separate bake-out calculation is in order.



	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



The Bake-Out Task have/will include current efforts to find the right combination of cooling and heating of various components in the divertor area.

This has included:

Baking, and Mechanical tests of the PF1b winding pack (Steve Jurzynsky)

Electrical Tests after Baking and Mechanical loads (Mike Anderson and ?)

One set of test is complete at 225C (passed) - Tests are being repeated at 250C

Contacts with CTD to verify Chemistry of CTD-425 can survive high temp - Answer was in the affirmative up to 300C

Analysis of the heat transfer during bake-out (Art is doing this and has run many cases)

Benchmark with mini-bake earlier this year, Art and Stefan are working on this

Analysis of PF1b mandrel to casing weld for various PF1b/casing temperature differentials (Art is doing this) We are basing the weld strength on previous tests.

Analysis of the loss of a layer of microtherm and assessment of time available to connect service water to the OH if the water supply fails during bake-out.

Consequences of having the OH outer winding layer warmer than the rest of the coil if cooling all 4 layers is retained. Tensile strain assessment is planned. (P Titus is doing this)

Reassessment of the water supply fault time to mitigate if we run the OH at a higher temp during bake-out (Art

Mechanical tests of the HYSOL after exposure to 150C if we choose to run PF1b at 150C. PF1b employs a HYSOL "belly band" as a part of its centering feature.

Hose replacement to allow PF1b to run at 150C

Water System reconfiguration to allow PF1b to run at 100C and 150C

Hose replacement to allow the horizontal divertor flange to be heated with Helium Gas

Stress due to expansion differentials of the cooling loop tightly fit in the groove.

Abandonment of this option because of vacuum leak

Investigation of low pressure helium heating or the horizontal divertor plate

Investigation of low pressure (copper refrig tubing can't take high pressure at temperatures around 300C

System reconfiguration to support heated Helium or air if these options are chosen

Re-evaluation of PF1b terminal buss bar connections for PF1b operation >100C

As of today, the most attractive option is to run 100 to 150C water through PF1b, This will

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 IB horizontal and vertical divertor cooling pipes.

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 yet to be designed and purchased. When the preferred option solidifies we can have a design review.

4.6 PF4/5 Column Bake-Out Behavior.

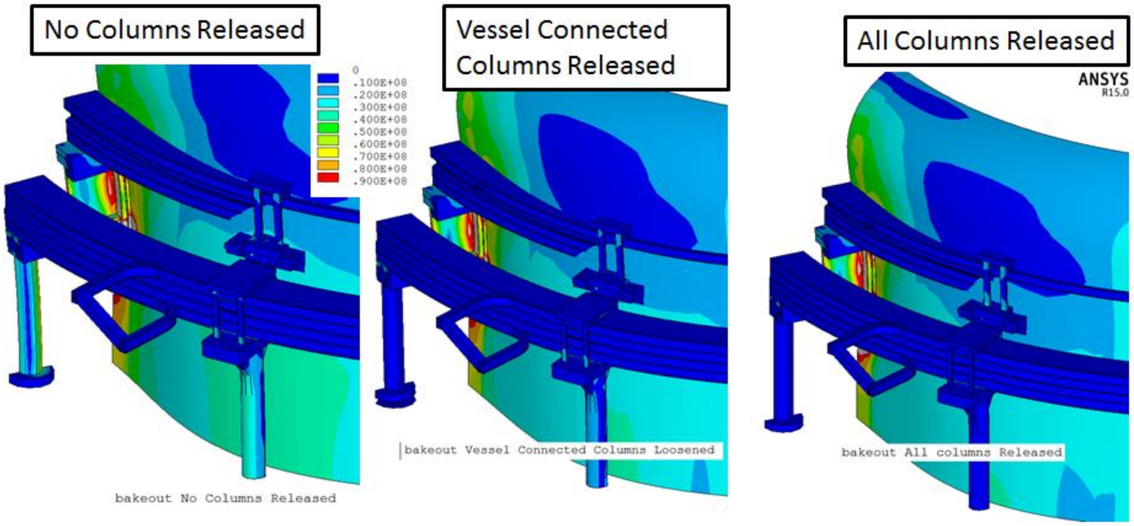


Figure 4.0-4 Comparison of stresses for various column connections

Stress analysis doesn't show a significant difference between the column restrain cases. Part of the vessel stress shown in the figure is the result of the cold clevis on the hot vessel shell. Stresses from the column tensile load were superimposed on the thermal stresses the vessel would be locally above yield and plastically deform

In the bake-out procedure[16], the instruction to disconnect the " coil turnbuckles". is included in section 5.8. This should probably say " TF coil support truss links or turnbuckles". The clevis pins at the TF clamp were removed and temporarily replaced with ½ inch bolts to hold the pieces loosely in place.

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.

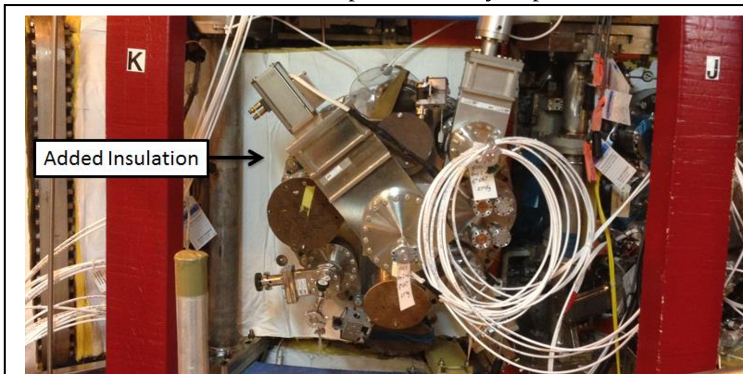


Figure 4.0-5 Photo taken Sept 4th 2015

5.0 Digital Coil Protection System.

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

6.0 Design Input

6.1 Criteria

Posted in the control room is the safety certificate that describes in a succinct way, the operational limits imposed on NSTX, including bake-out. This is a simplification of the more detailed requirements in the GRD, SAD and this calculation. An important pointer in the safety certificate is the requirement that the bake-out be performed in accordance with the approved bake-out procedure Figure 6.1-1 includes photos of the safety certificate as it hang on the control room wall.

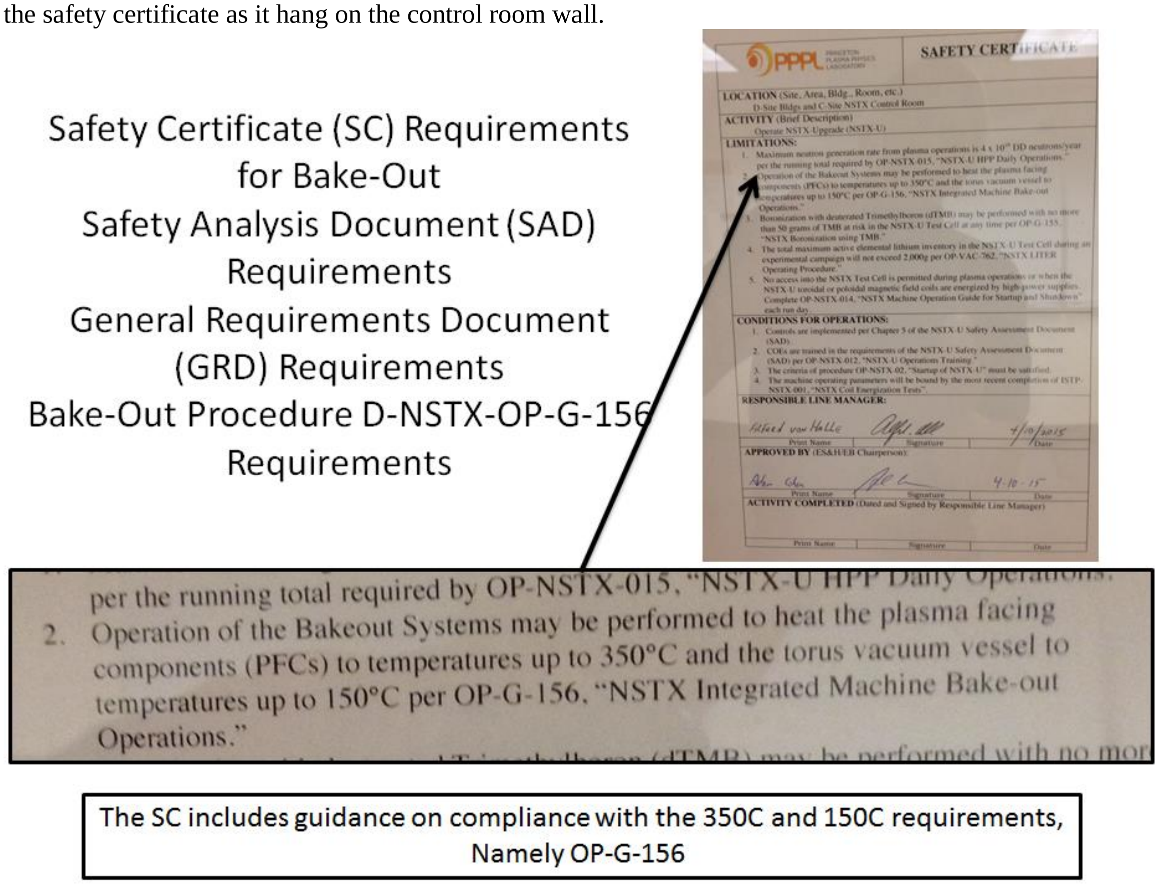


Figure 6.1-1 Safety Certificate hung in the Control Room.

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 350 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 isvrated 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. I think a +/- tolerance on the 350C is implied and the 370C would be acceptable, especially on the centerstack casing.

From the bake-out procedure [16]

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). One key element in the guidance is the word “average” Appendix D has a calculation of the average centerstack temperature which meets the requirements of the procedure, even though there are temperatures in excess of 350 degrees. 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 Criteria Document. Disruption and thermal specifications are outlined in the GRD -Ref [7] and are discussed in more detail in section 6.5. Cyclic requirements for the PF1c mandrel shell shall be 20,000 full power operating pulses. These are assumed to develop the full 100 C temperature which imposes a full radial deflection on the coil centering components. Actually looking at figure 6.3-1, the number of planned equilibria that use the full PF1c current is limited. For design and analysis it will be assumed that each normal operating pulse heat the coil to 100C.

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] "DISRUPTION ANALYSIS OF PASSIVE PLATES, VACUUM VESSEL AND COMPONENTS", NSTXU-CALC-12-01-01,February , 2012, P. Titus, and Yuhu Zhai

[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

[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] NSTX Integrated Machine Bakeout Operations, D-NSTX-OP-G-156. M. Cropper, Rev 4 August 28 2015

6.3 Photos and Drawing Excerpts

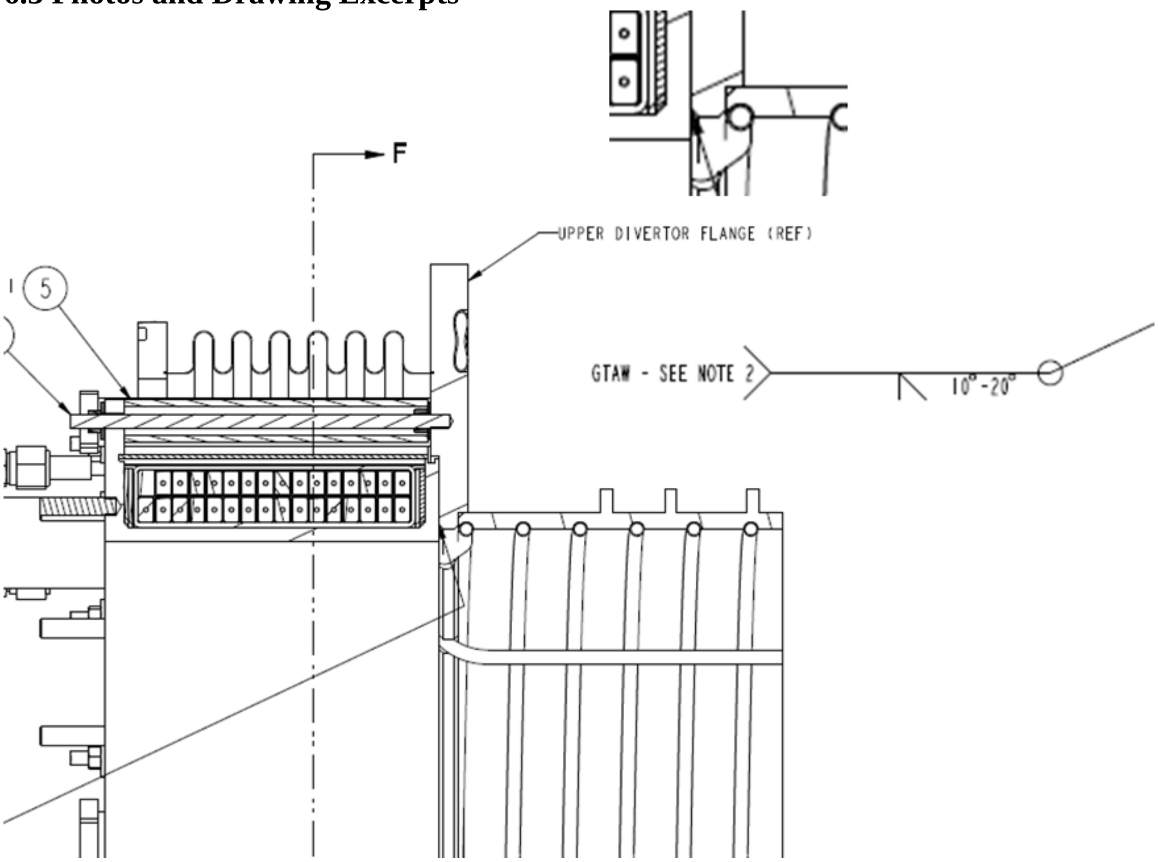


Figure 6.3-1 Divertor Flange Details

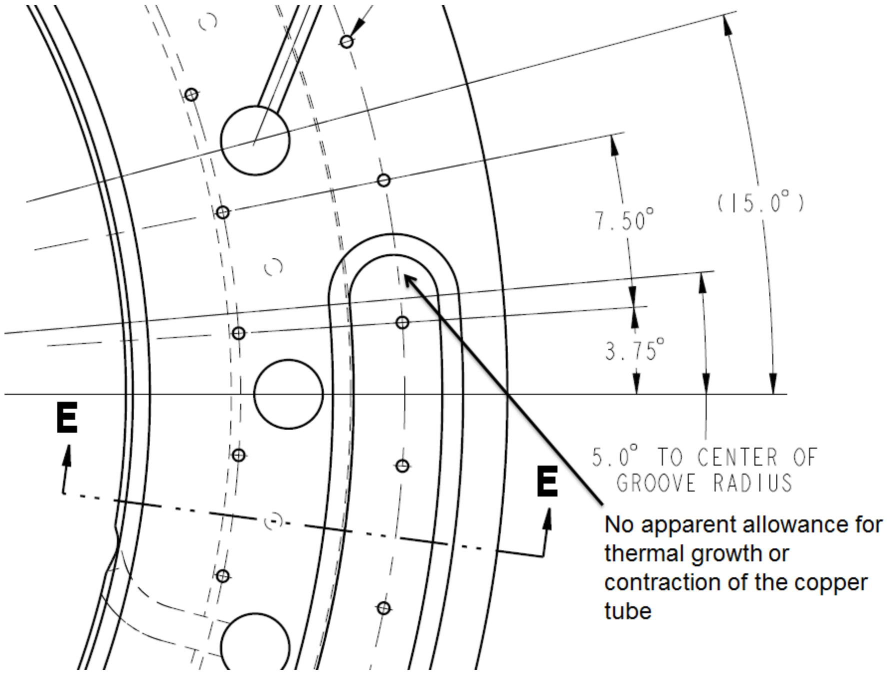


Figure 6.3-2 Divertor Flange Cooling Tube Details

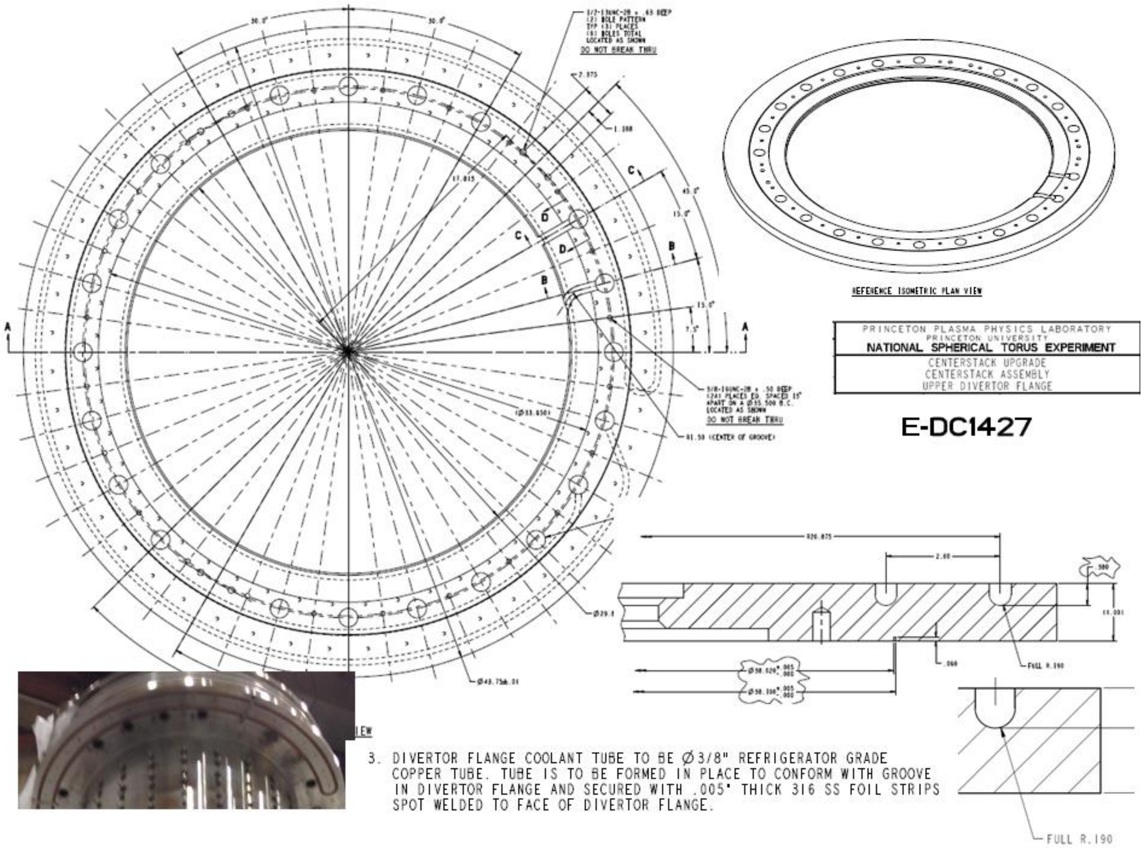


Figure 6.3-3 Divertor Flange Cooling Tube Details

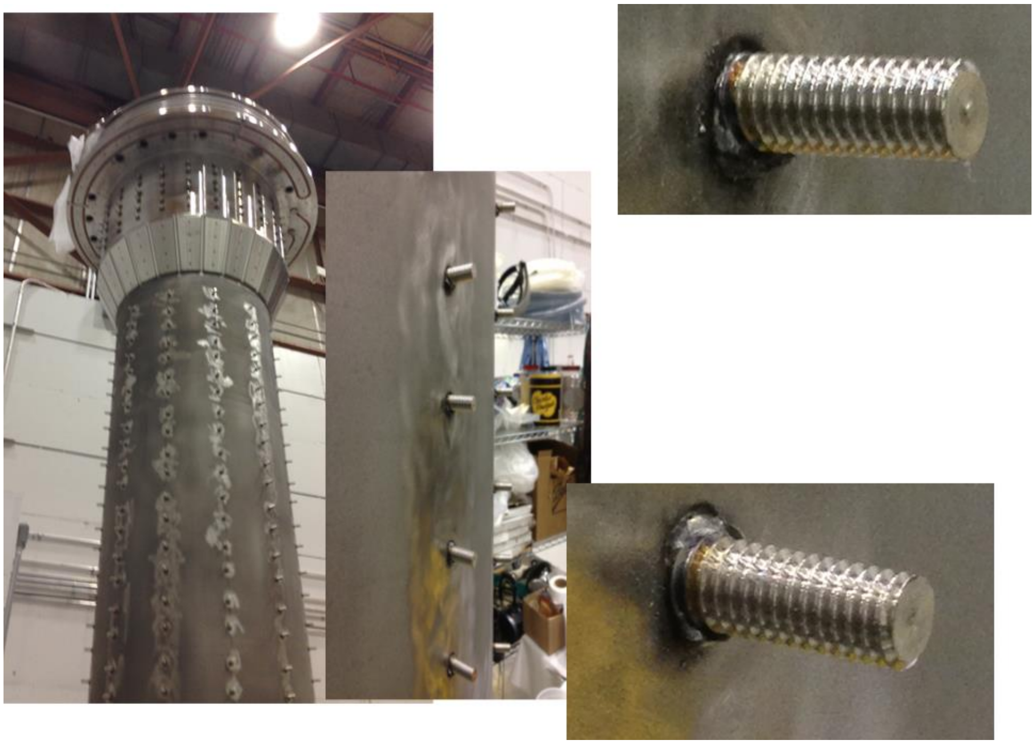


Figure 6.3-4 Centerstack Case Showing upper Inner Divertor Cooling Loop (That Leaks)

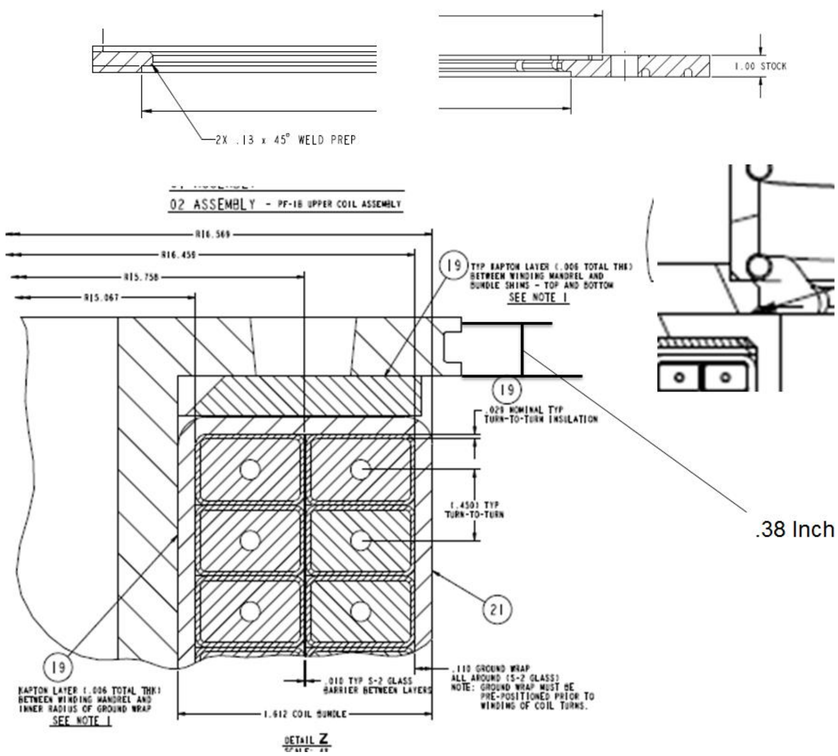


Figure 6.3-5 PF1b Case Details

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 a 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

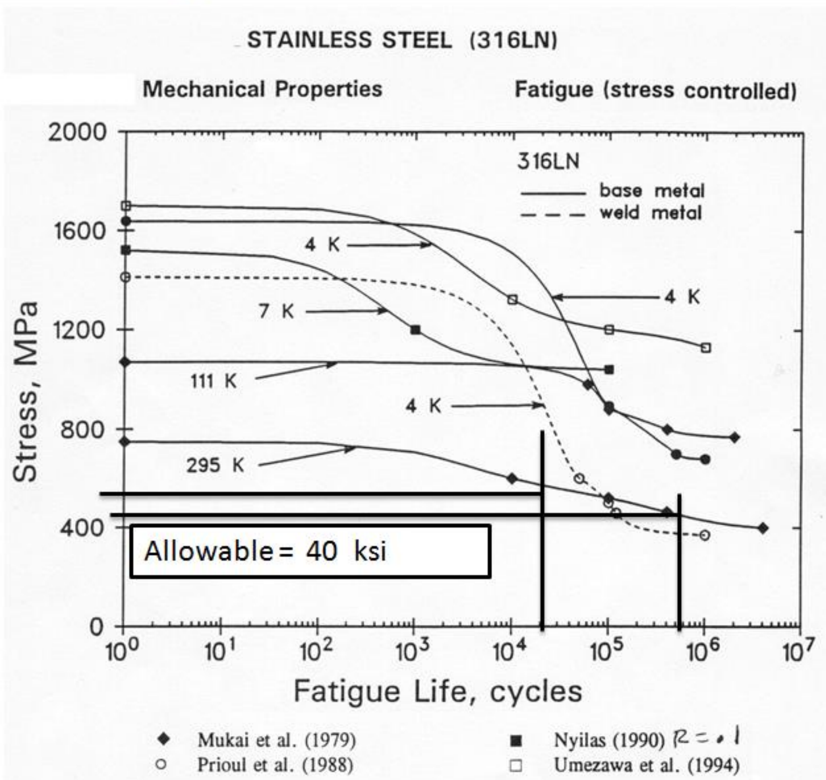
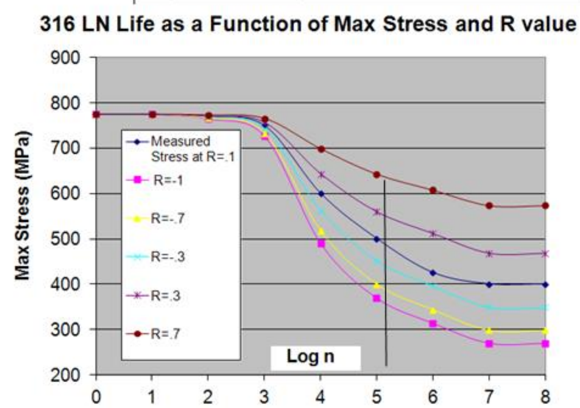


Figure 6.4.1-2 (NIST)

3	E-DC1417-3	PF-IC COIL SUPPORT MANDREL SECONDARY FLANGE	316 S/S	1
2	E-DC1417-2	PF-IC COIL SUPPORT MANDREL TUBE	316 S/S	1
1	E-DC1417-1	PF-IC COIL SUPPORT MANDREL MAIN FLANGE	316 S/S	1
ITEM NO.	DRAWING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	QTY REQD

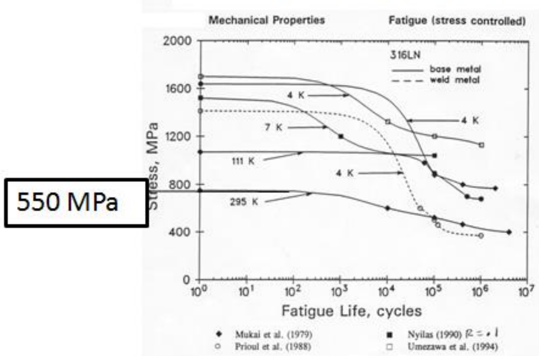
T=292 K

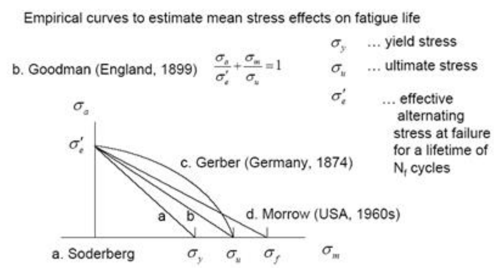


The allowable R=.1 Max stress for n=3e4 cycles would be 550/2=275 Mpa or 275 Mpa or 40 ksi Stress Range.

As designed the weld is stressed to 400 ksi

Upgrade to a 1/8 inch weld is stressed to 100 ksi





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.

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

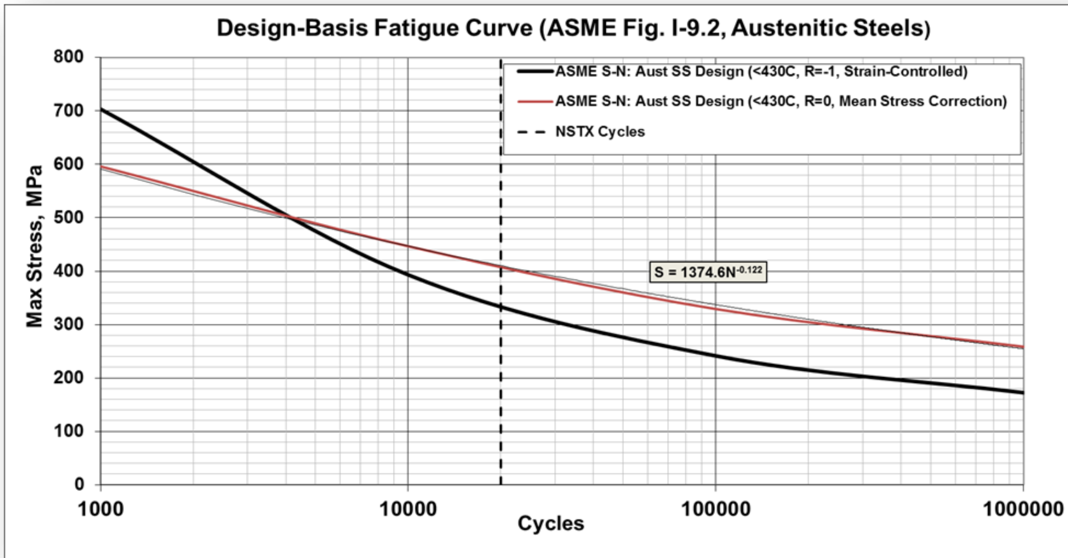


Figure 6.4.1-3 ASME Design SN curve with R=0 Correction by L. Myatt [81]

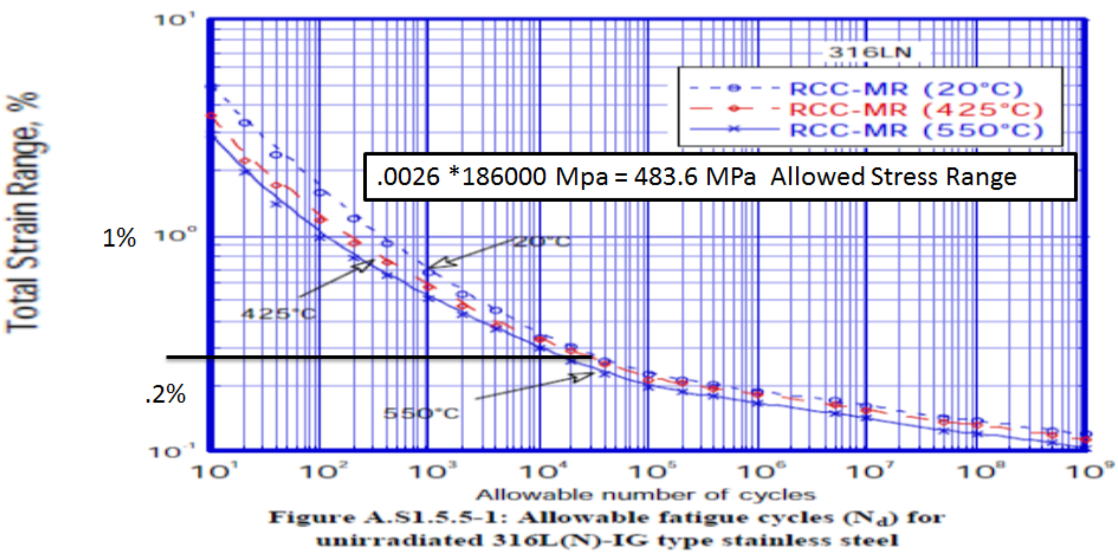
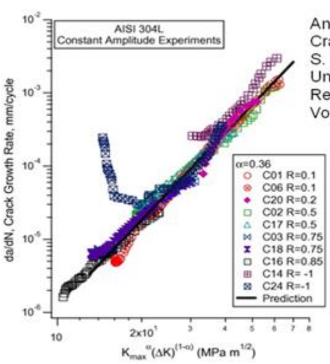


Figure 6.4.1-4 RCC-MR Design Design Fatigue curve Total Strain Range



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 6.4.1-5 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 I have 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. -Peter

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]	—	—	—

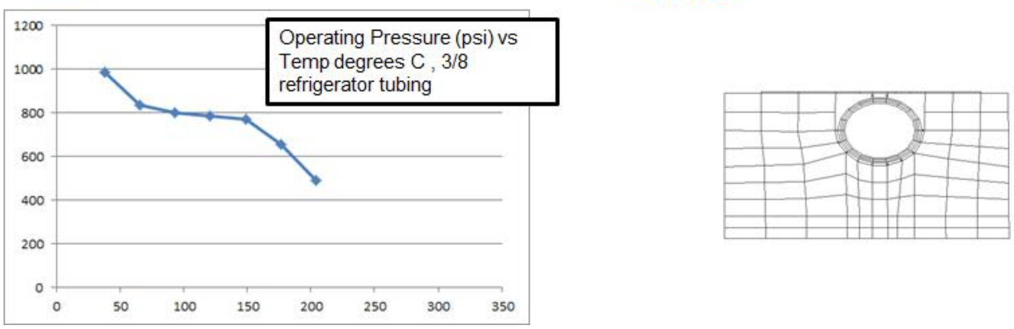
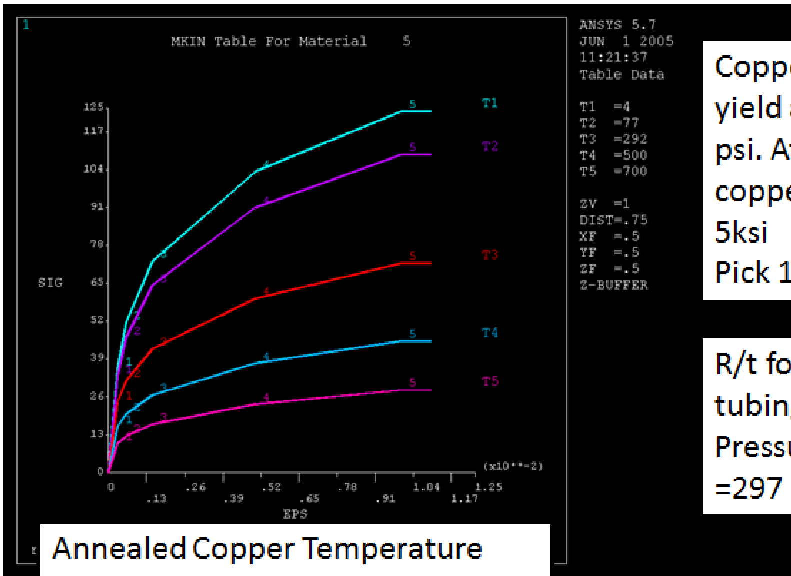


Figure 6.4.2-1 Copper Refirgerator Tubing Pressure Rating vs. Temperature



Annealed Copper Temperature Dependent Stress Strain

Copper at 350C or 622K has a yield around 13 Mpa or 1885 psi. At room temperature copper yield is 35 Mpa or 5ksi
Pick 1000 psi as an allowable

R/t for 3/8" refrigerator tubing = 5.3595
Pressure = 1000/5.3595 =297 psi

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

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.

Figure 6.5.3-1 .

6.6 Design Currents and Lorentz Forces

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

6.8 Thermal Expansion Cycles

Thermal stresses in the outer shell of the case result from the PF coil heating and radially expanding. In addition, the case can be heated by the plasma through the CHI gap. Thermal loading of the case due to radiation from the plasma occurs each shot. Thermal loading on the PF1c coils and the outer shell of the case due to direct plasma impingement and from the largest of the coil Joule heating is relatively in-frequent. In figure 6.6-1, the PF1c currents are plotted and the number of equilibria that use PF1c significantly are a small percentage of the total. CHI operations are a small percentage of the total and operations which place the X point near the CHI gap are supposed to be avoided. So the number of thermal cycles applied to the case wall should be a fraction of the 20,000 planned full power shots.

7.0 Models
7.1 Structural Model

The structural models are swept from a 2D mesh. The last one (p1cz.dat) analyzed, Shown in figure 7.1-1 includes a new annular plate that places the close-out weld away from the O ring detail and allows a much larger weld cross section.

Figure 7.1-1 Inner Horizontal Divertor Flange Cooling Tube Model

This model went through many evolutions of corner/close-out weld details and inclusions and deletions of thermal shields. The thermal shield is still included in the model in figure 7.1.

7.2 Divertor Flange Cooling Tube Model

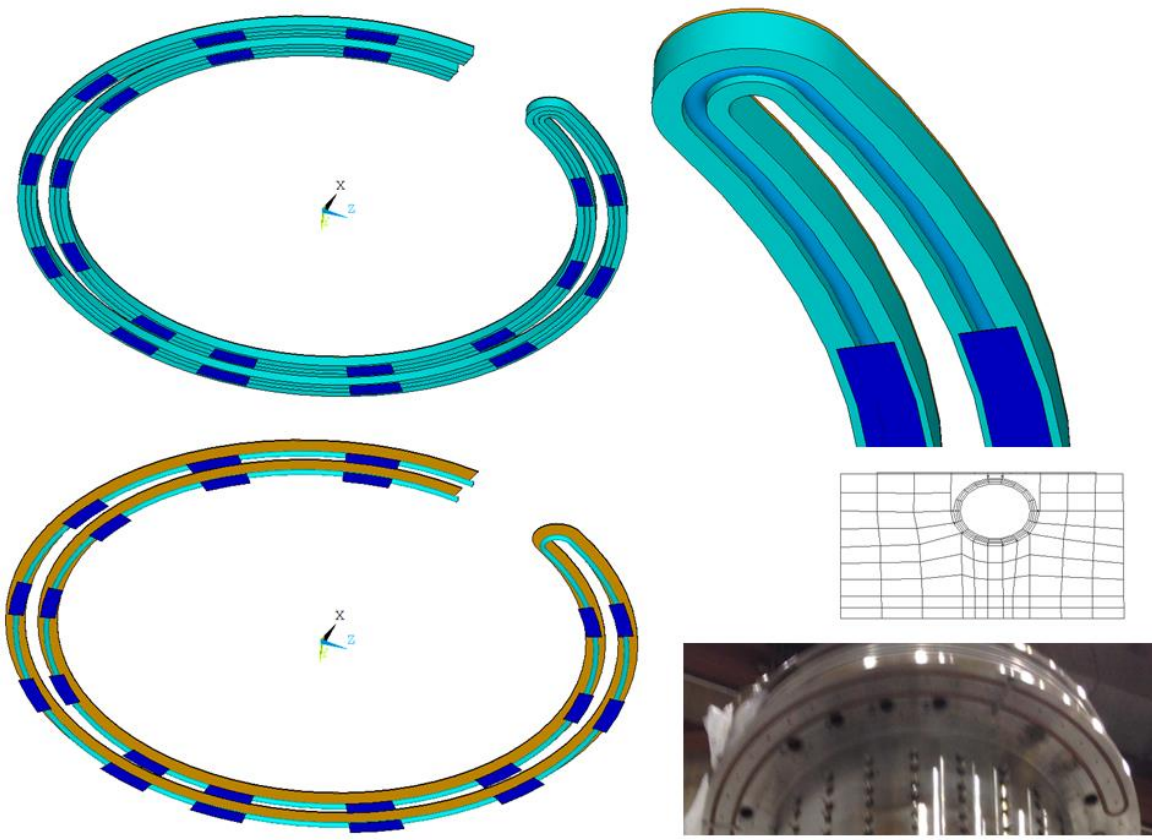


Figure 7.2-1 Horizontal Divertor Plate Cooling Tube Model

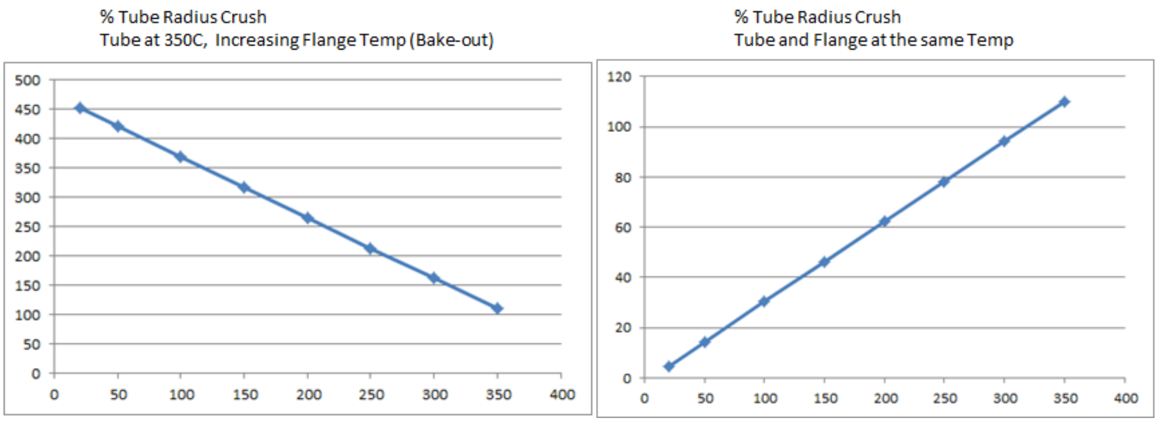
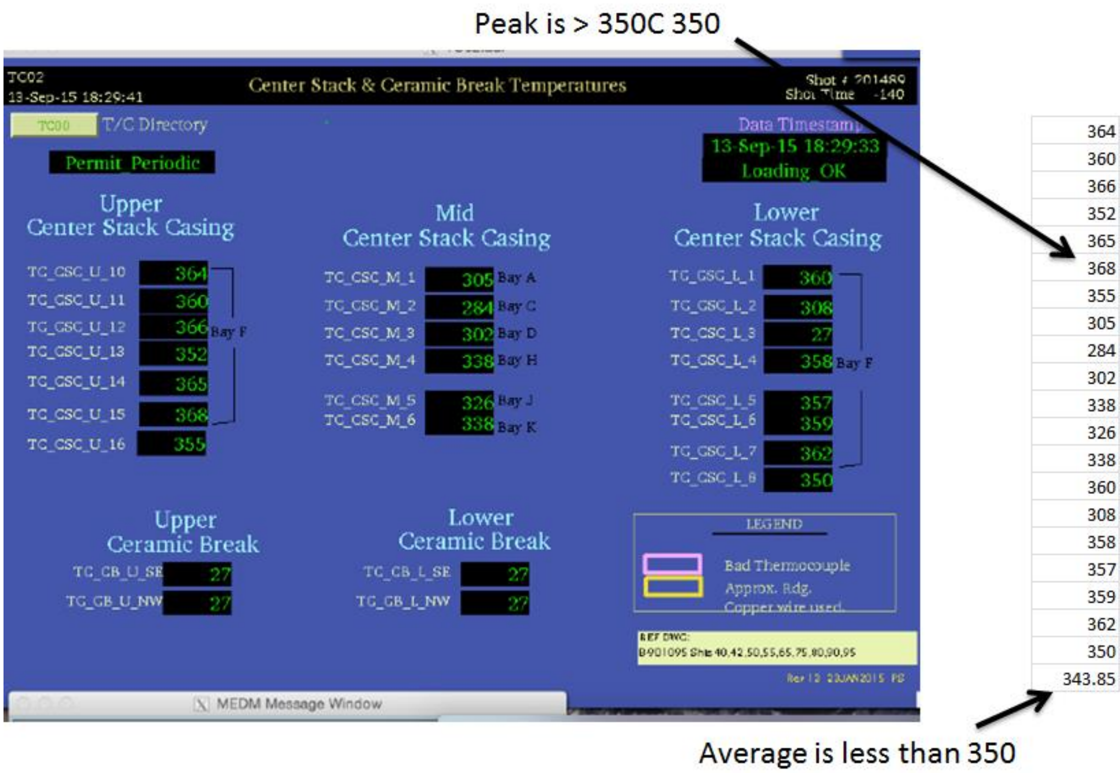


Figure 7.2-2 Horizontal Divertor Plate Cooling Tube End Crush

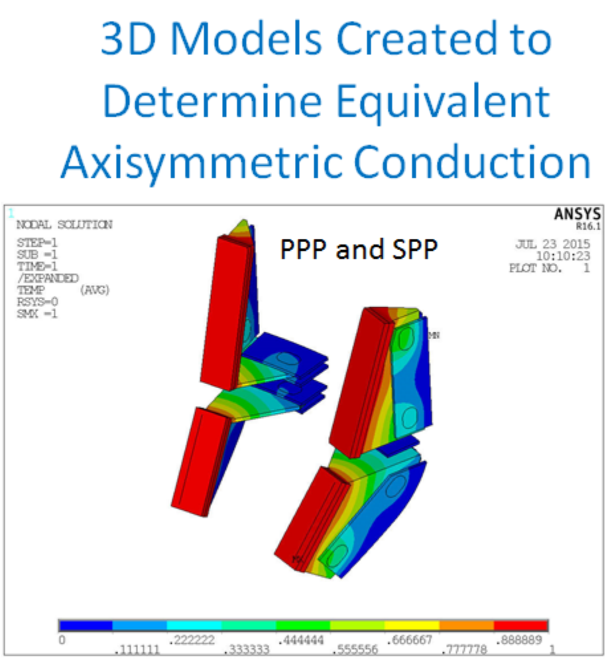
Figure 7.2-3 ANSYS Model

8.0 September 2015 Bake-Out Experience



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 StackHeat Balance",NSTXU-CALC-11-01-00. This simulation employs a 2D axisymmetric ANSYS model of NSTX.

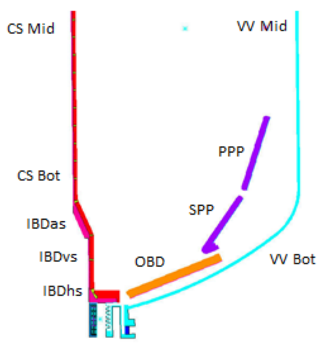


Comparison of Conduction and Radiation between PP and VV			
Conduction (ANSYS Model of Supports)			
	Full	15-Apr	
Q/dT per support	1.1239	1.1239	w/C
Number of Support	48	48	
Q/dT, total	53.9472		
Tpp	350	150	C
Tvv	150	25	C
dT	200	125	C
Qcond	10,789	6,743	w
Radiation			
Area	15	15	m2
sigma	5.67E-08	5.67E-08	
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 Bakeout 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 bakeout
  - 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

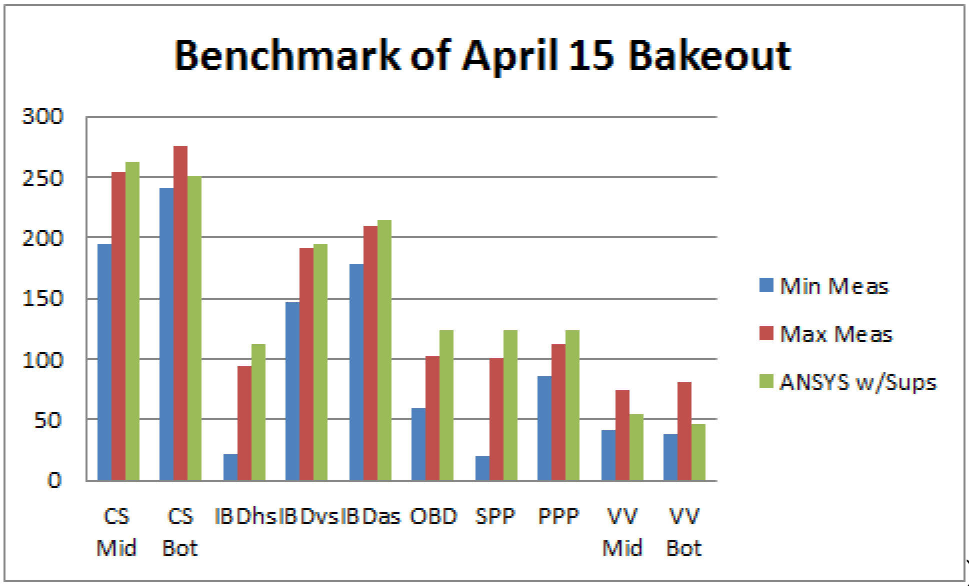


	Measured		ANSYS				
	Min	Max	e=0	e=1	e=.7	e=.7/.27	e=.27
CS Mid	195	254	658	220	255	274	350
CS Bot	241	276	591	207	238	262	325
IBDhs	22	94	207	91	100	127	125
IBDvs	147	192	419	158	180	205	240
IBDas	179	209	546	172	202	227	285
OBD	60	102	25	86	96	150	125
SPP	21	101	25	93	104	158	138
PPP	86	112	25	93	105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

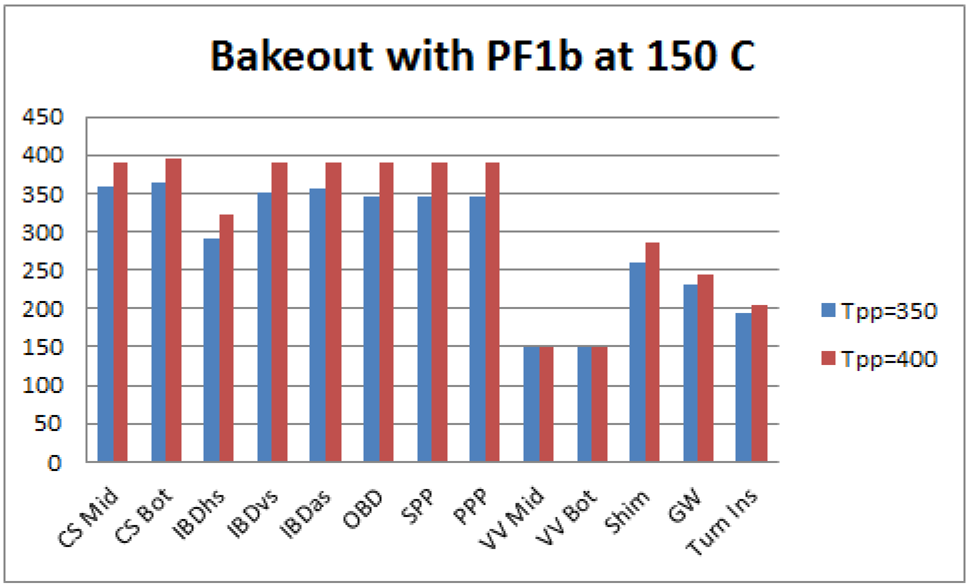
After adding conducting supports from the PP & OBD to the VV the agreement is fairly good even without change the surface emissivities:



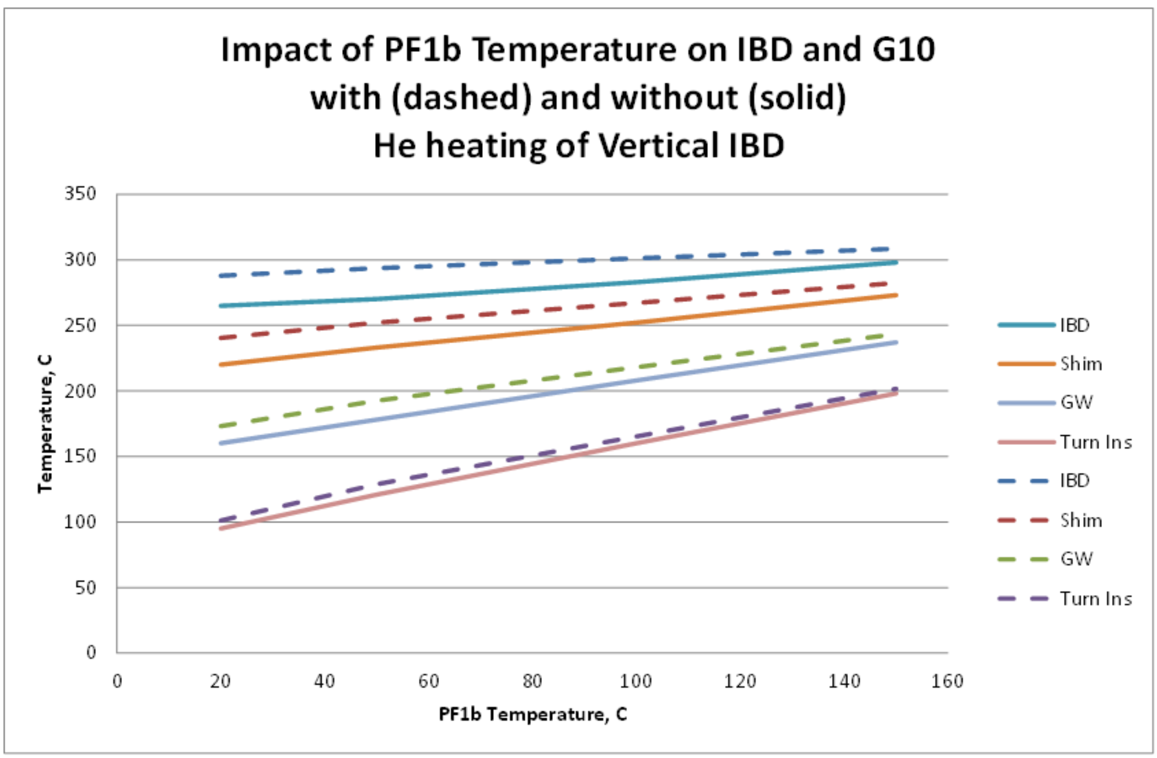
)

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 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.8.2 Bake-Out Simulation

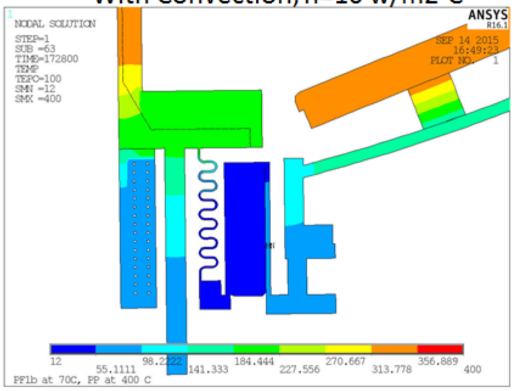


	Case	Description	IBDhs Tile Temp	G-10 PF1b Coil Shim Temp	PF1b Ground Wrap Temp	PF1b Conductor Insulation
Near Term	1	No Heating or cooling of IBD, OBD, PP or VV	205	180	135	80
	2	PP & OBD He Heating Turned On	290	240	180	110
	3	VV Heating/Cooling at 150 C turned on	260	225	162	95
	4	IBD Heating at 350 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

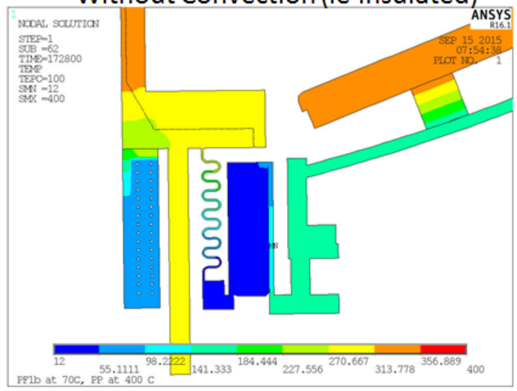


9.3 Impact of Convection from Tubes and Bolts at IBD Flange

With Convection, h=10 w/m2-C



Without Convection (ie Insulated)

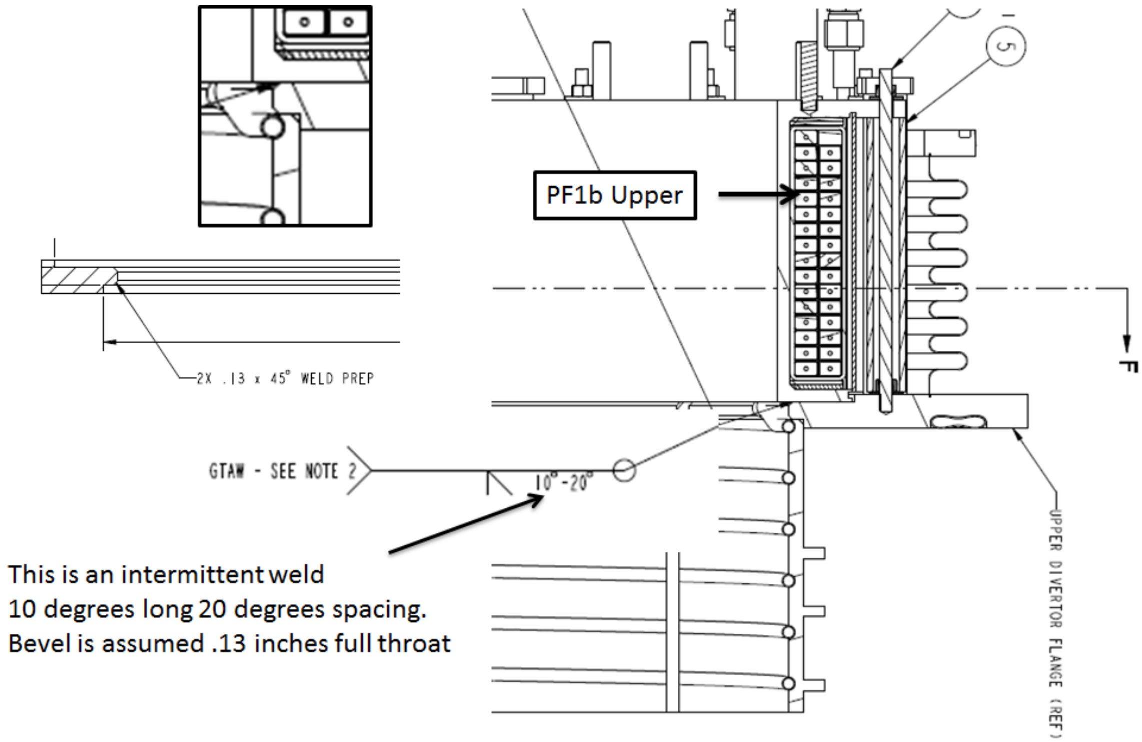


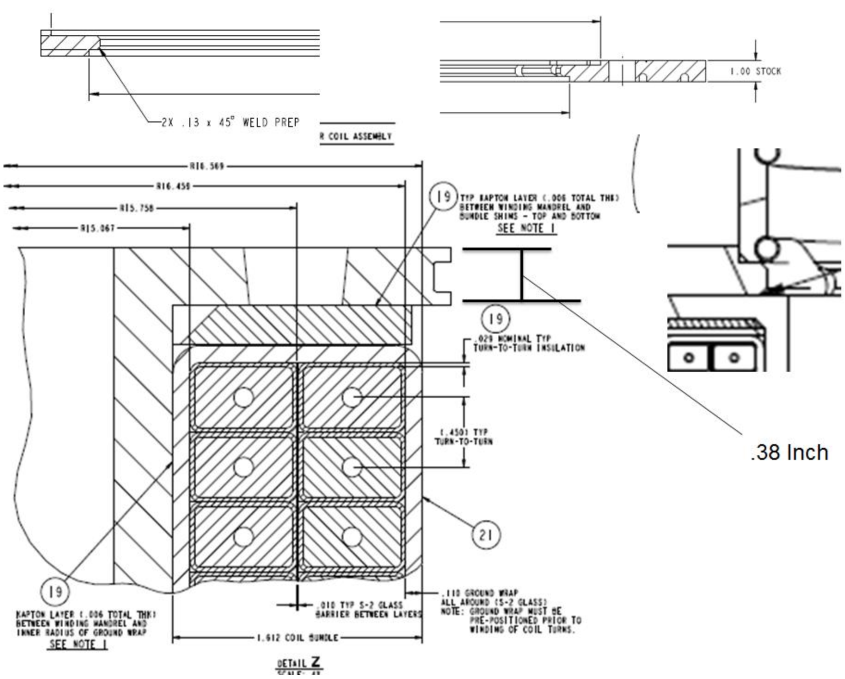
4.7 kW Convection Loss Total, top and bottom
Additional to
1.2 kW thru pf1c
3.1 kW thru pf1b
8.5 kW thru OH

IBDhs reaches less than 220 C instead of 280 C, drop of more than 60 C

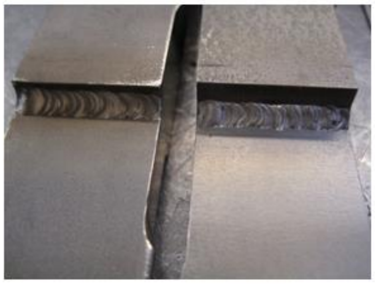
Bakeout simulation assumes Helium enters at 400 C and exits at 350 C

10.0 PF1b to Casing Weld

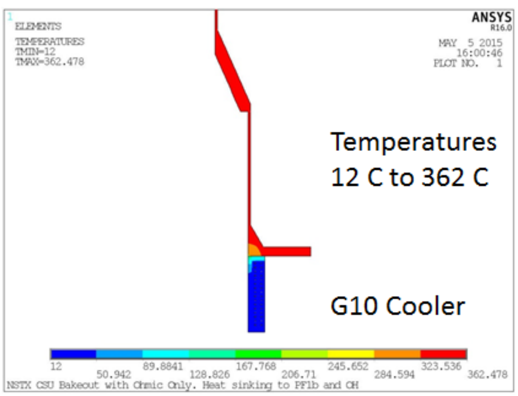


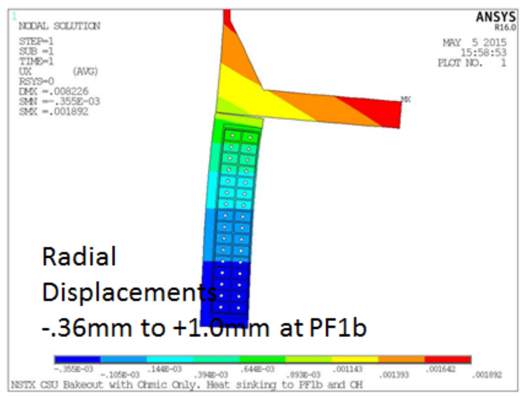


1/8 inch Fillets on ¼ inch and greater stock are not accepted by AISC an AWS – But were used on NSTX for PF 2 and 3 Supports. These were qualified by test.



Shear At Weld from Thermal Growth

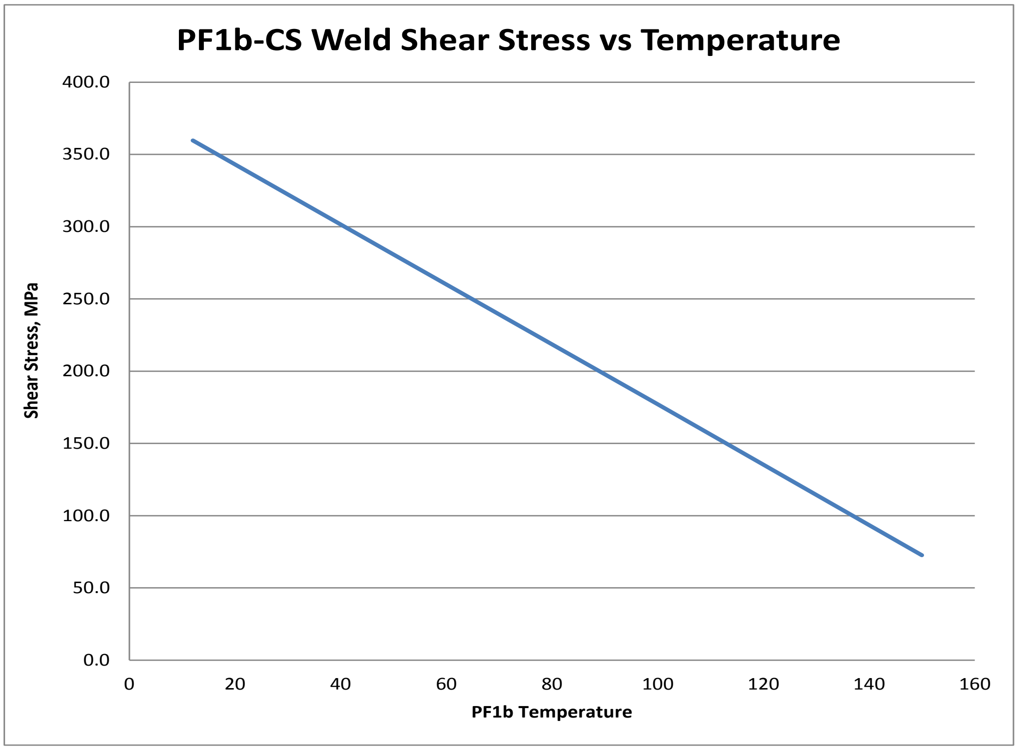




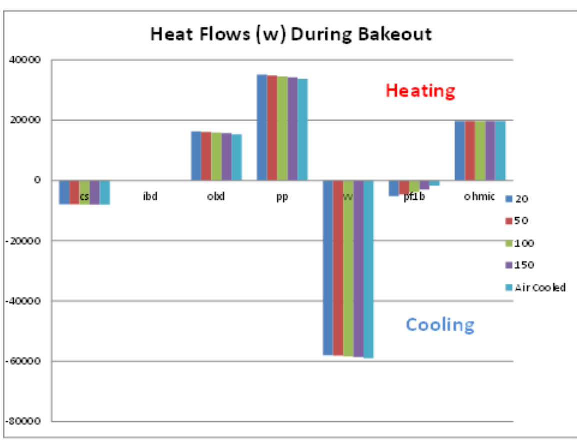
723.63MPa is 104949 psi

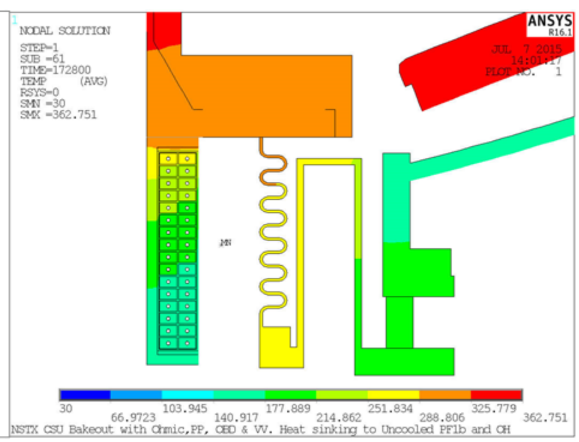
Weld Shear from Thermal Growth		
Radius	0.381	m
Weld Depth	0.003175	m
Weld Fraction	0.5	
Weld Area	0.0038	m2
Radial Force, 360deg	2.75	MN
Shear	**723.63**	**MPa**

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



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

11.0 PF1b Winding Pack Thermal/Elecrtical/Mechanical Evaluation

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 Bake

The 225C test piece "passed" the mechanical and electrical test. It went to 9kV and then sparked externally, and we believe it is 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 and let it float to no more than 250C.

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

To simulate Bake-out thermal effects on PF1b, bake a sample mock-up of the PF1b winding to 250 C for 24 hrs. 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

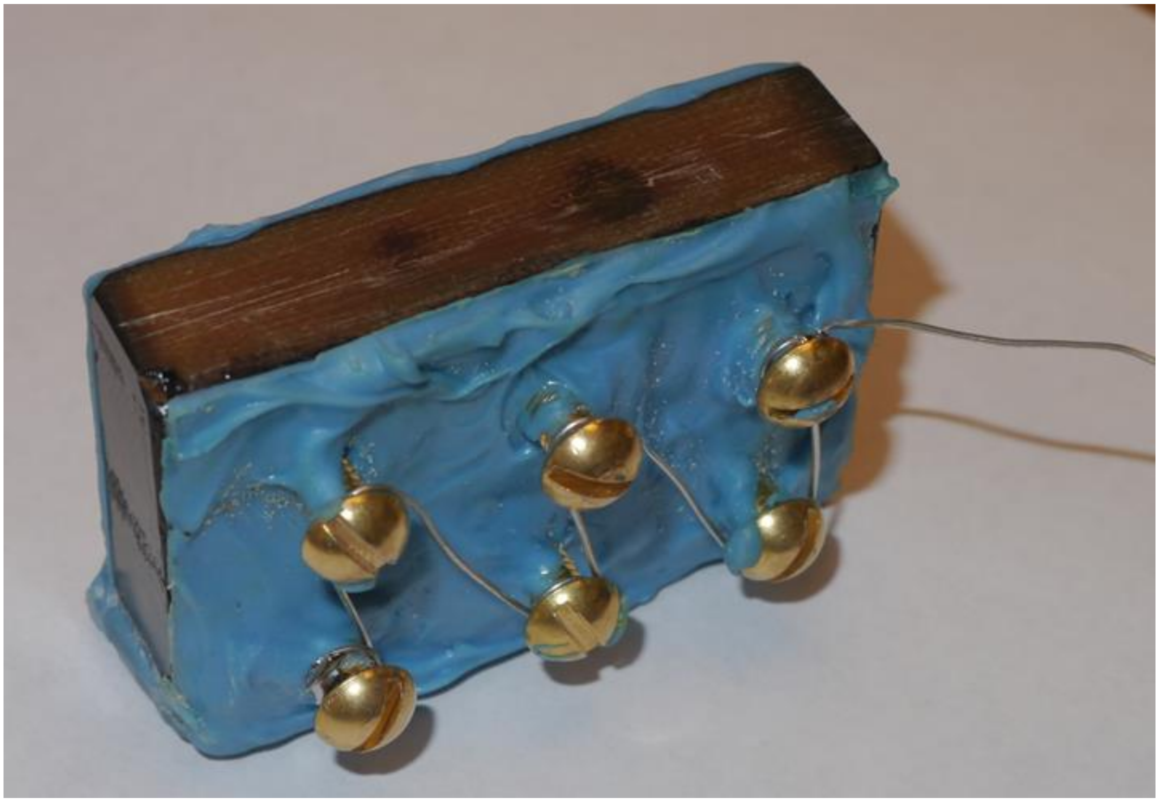
6kv = 0.5 " @ " "

9kv = 0.75 " @ " "

13kv = full short, sparks

____
Larry

Lawrence E. Dudek
ldudek@pppl.gov



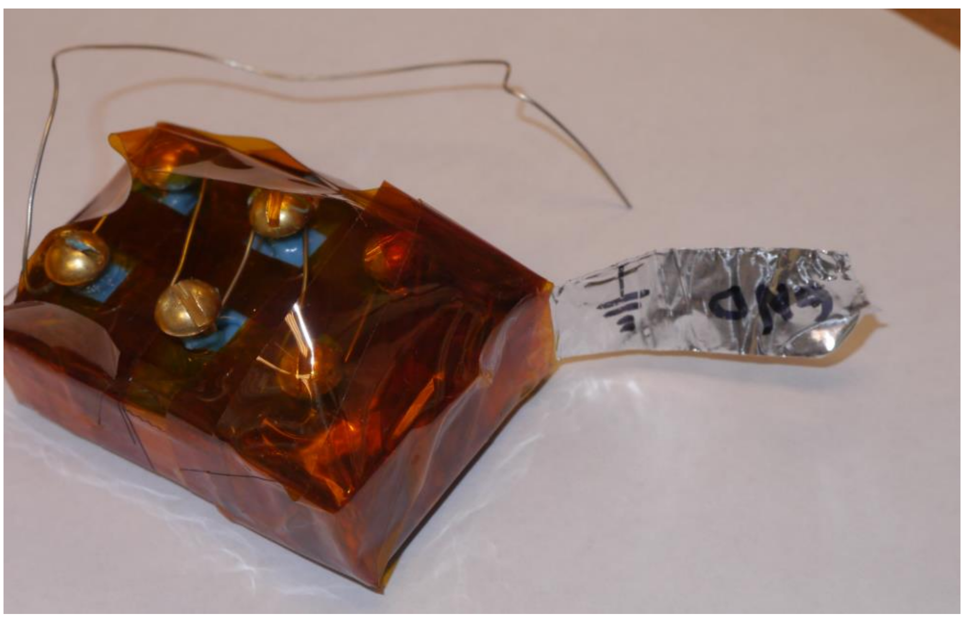
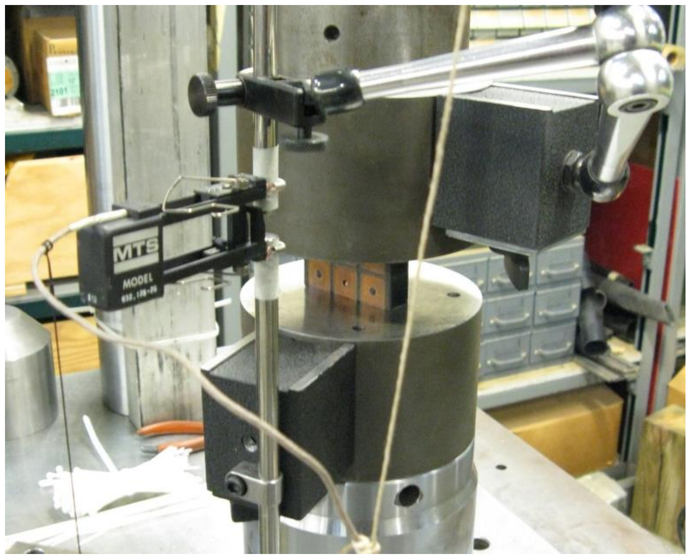


Figure 10.1-Samples “Cooked “ for 24 Hr. , Peak Temp=225C



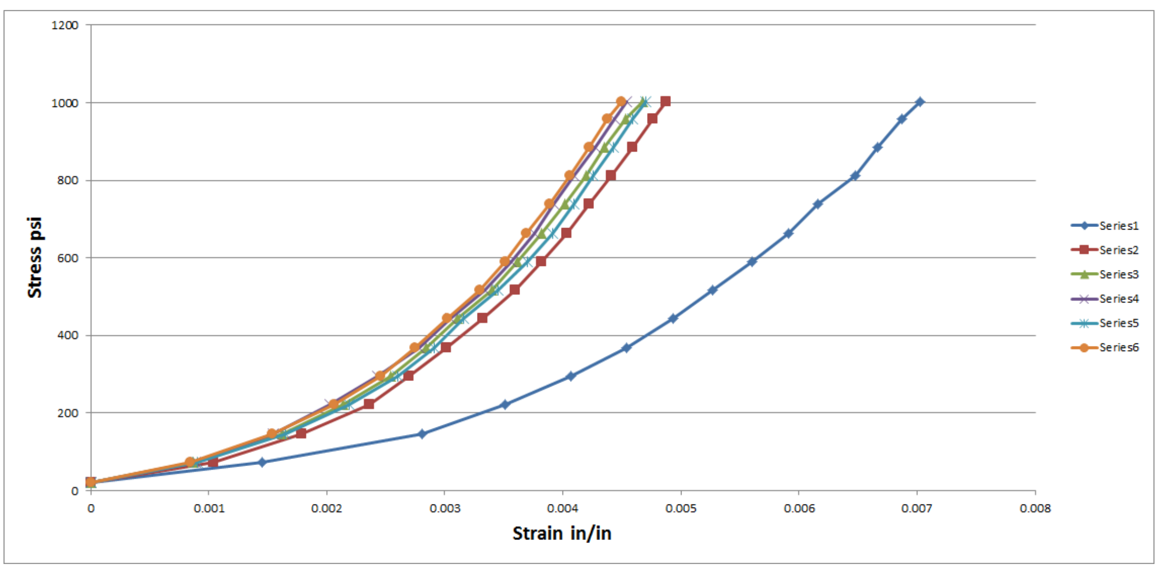


Figure 10.1-2 Load deflection of the 225 degree C sample

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

Figure 10.1.2-1 Photos of the 250C sample

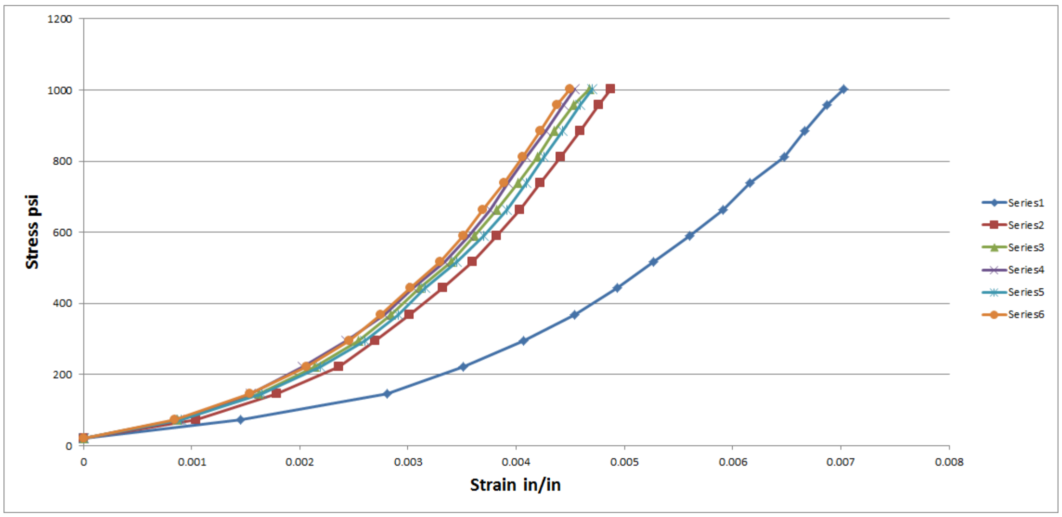


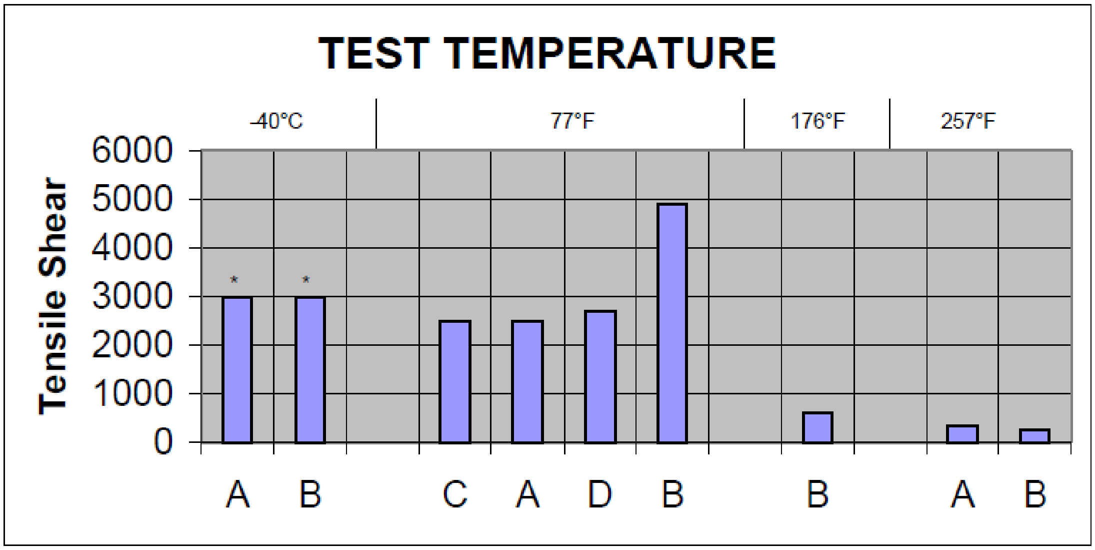
Figure 10.1.2-2 Load deflection of the 225 degree C sample

11.1.3 PF1b Long Term Bake

Work Request: 20142467
for the Job: "Long Term Bake Out Survival PF1b Insulation System" has been submitted for techshop 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 week. This is intended to support the Sept bake-out, so we need baking results 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
In a August 19th phone call, Steve Jurczyensky called to let me know the two tests can't be done concurrently. We 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.

11.2 Hysol Centering Band Bake Tests

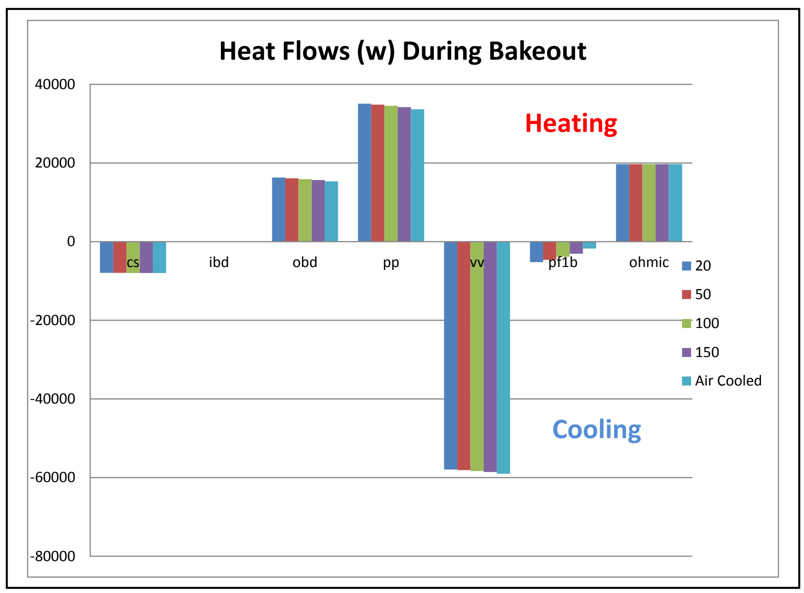
In order to get the divertor tiles near 300C, active control of the PF1b water supply is being investigated to maintain the PF1b coil at an elevated temperature. The winding pack epoxy system is being tested separately. The PF1b centering system used a HYSOL/glass band wet layup . If PF1b is heated to 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. 1/4 inch thickness is sufficient. Sample pieces then should 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.



11.3 PF1b Cooling Water Flow Tests

From: John Desandro <desandro@pppl.gov>
Date: July 15, 2015 at 7:55:37 PM EDT
Subject: PF1B-U flow test
To: Neway Atnafu <natnafu@pppl.gov>

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



12.0 Inner Horizontal Divertor Flange Tubing

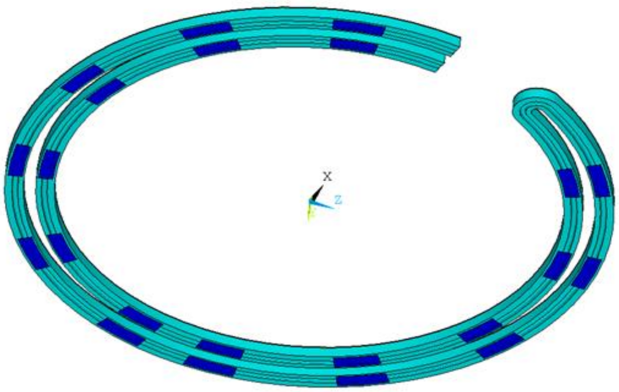
The hose feeding coolant to the Hose replacement to allow the horizontal divertor flange to be heated with Helium Gas

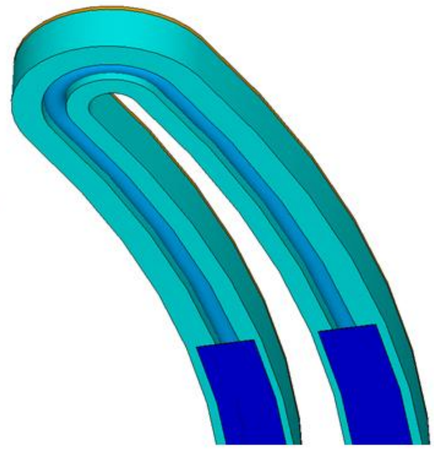
Stress due to expansion differentials of the cooling loop tightly fit in the groove.

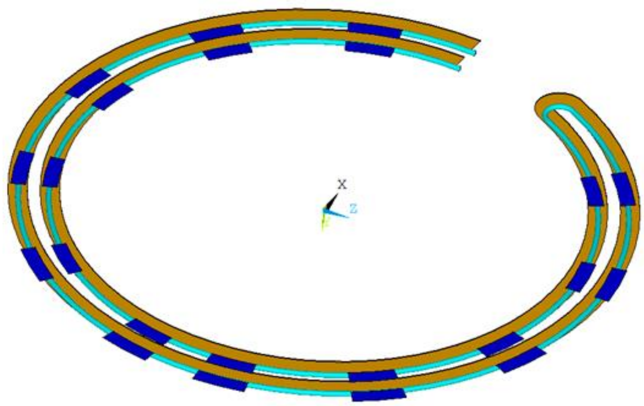
Abandonment of this option because of vacuum leak

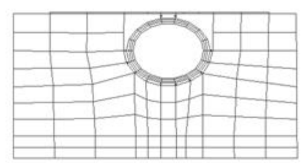
Investigation of low pressure helium heating or the horizontal divertor plate

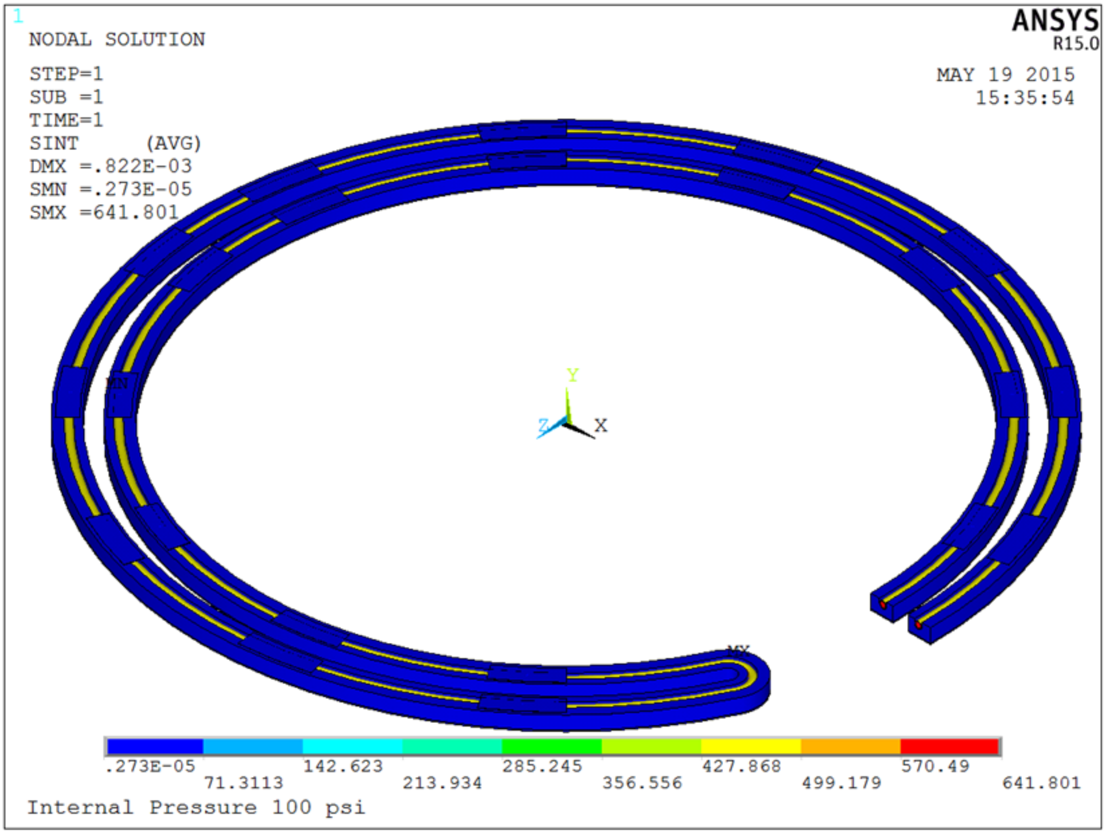
Investigation of low pressure (copper refrig tubing can't take high pressure at temperatures around 300C

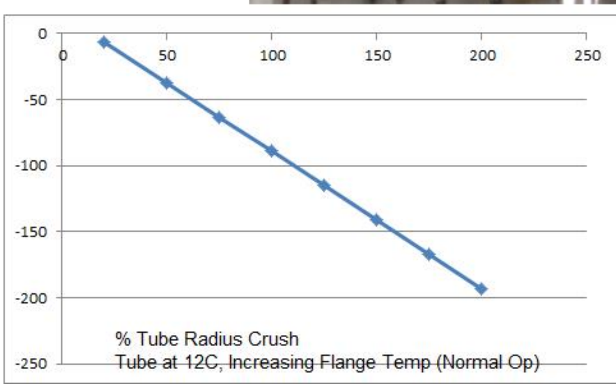


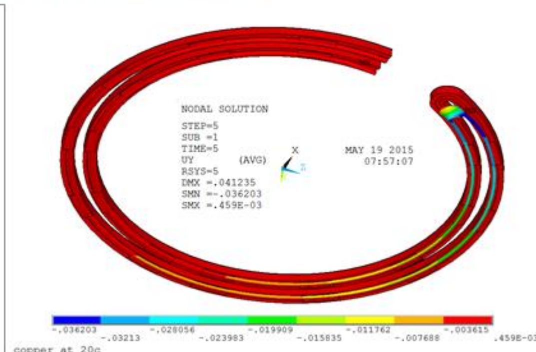


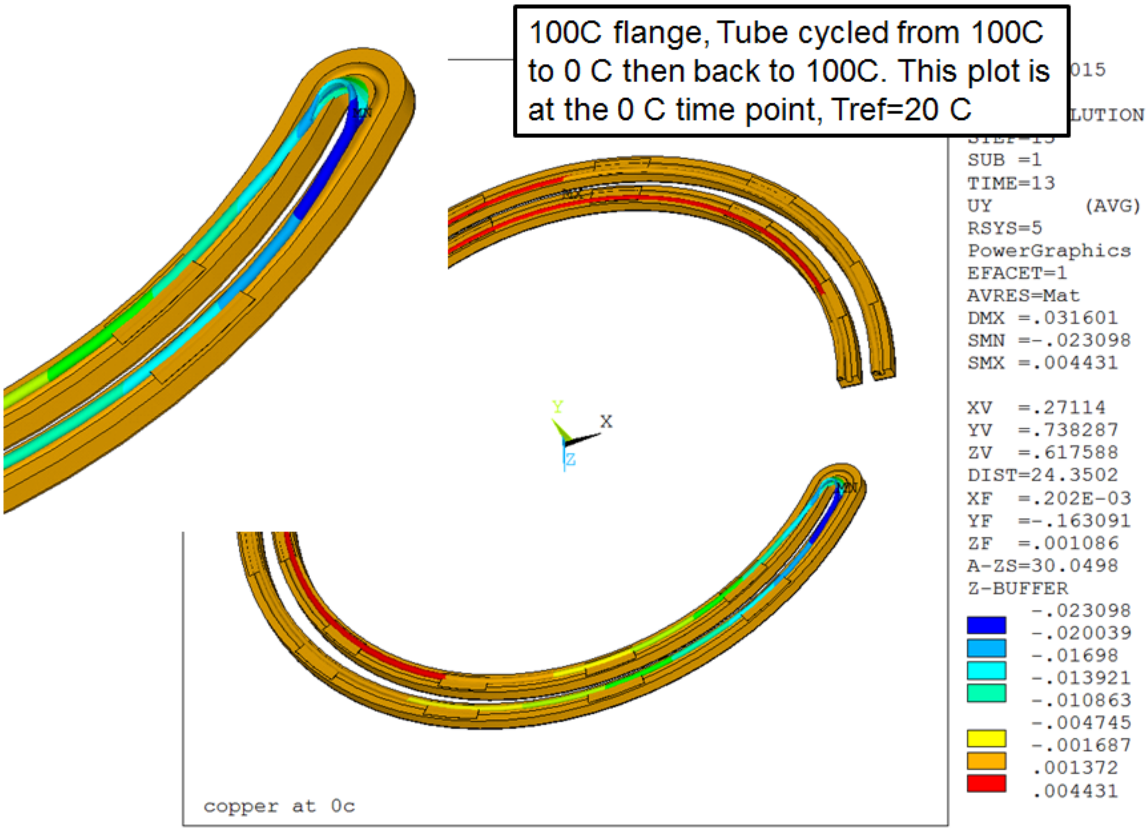


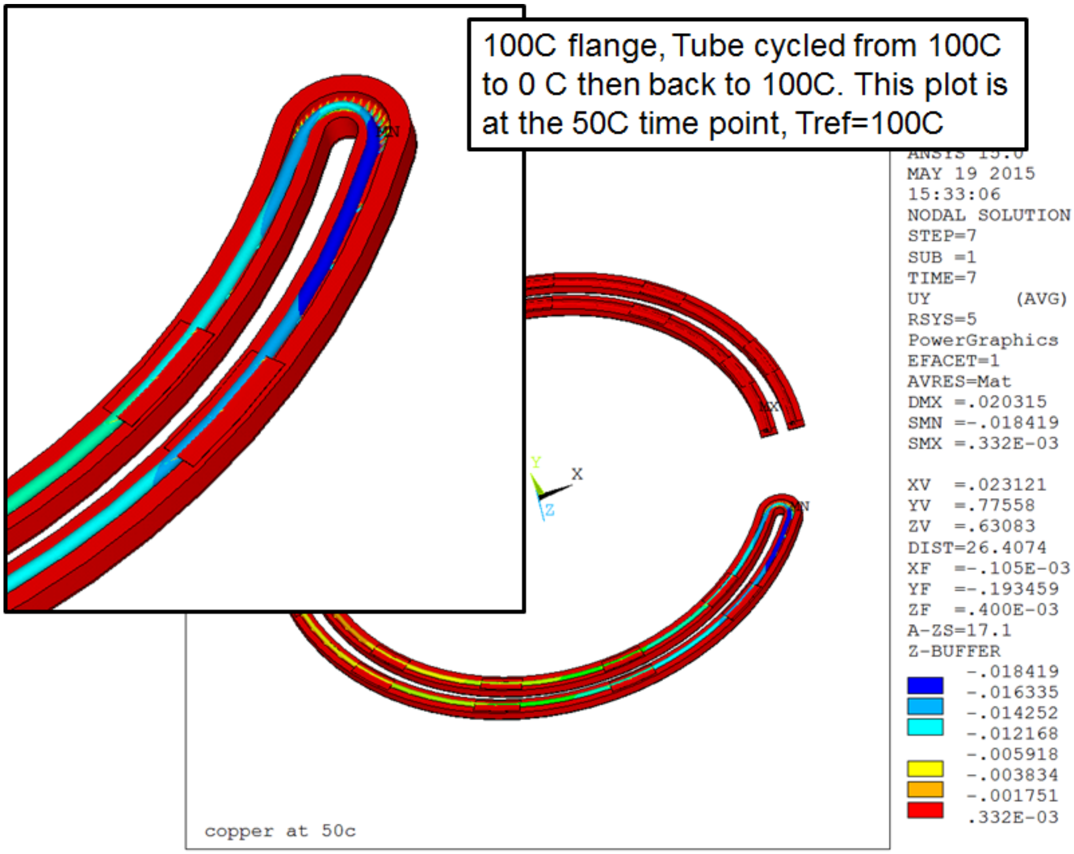



NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SINT (AVG)
DMX =.822E-03
SMN =.273E-05
SMX =641.801
ANSYS
R15.0
MAY 19 2015
15:35:54
.273E-05
71.3113
142.623
213.934
285.245
356.556
427.868
499.179
570.49
641.801
Internal Pressure 100 psi


0
-50
-100
-150
-200
-250
0
50
100
150
200
250
% Tube Radius Crush
Tube at 12C, Increasing Flange Temp (Normal Op)


NODAL SOLUTION
MAY 19 2015
copper at 20c


100C flange, Tube cycled from 100C to 0 C then back to 100C. This plot is at the 0 C time point, Tref=20 C
015
LUTION
SUB =1
TIME=13
UY (AVG)
RSYS=5
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.031601
SMN =-.023098
SMX =.004431
XV =.27114
YV =.738287
ZV =.617588
DIST=24.3502
XF =.202E-03
YF =-.163091
ZF =.001086
A-ZS=30.0498
Z-BUFFER
-.023098
-.020039
-.01698
-.013921
-.010863
-.004745
-.001687
.001372
.004431
copper at 0c



13.0 Helium Heating/Cooling System

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 not to be feasible for a couple of reasons. Raising the temperature of the copper refrigerator tubes beyond around 200 C. The pressure rating of the tubing is plotted vs 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 ____ 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 takeout 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.

14.0 Microtherm Layer Removal

13.1 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

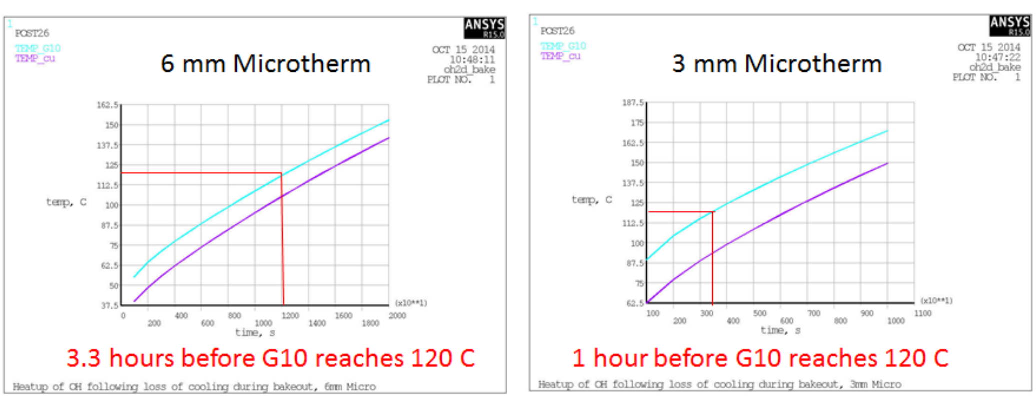
Heat Balance to Account for Water Heating		
dia	0.0057	m
v	2.1336	m/s
dens	1000	kg/m3
Cp	4186	J/kg-C
area	2.55176E-05	m2
flow	5.44443E-05	m3/s
	0.862954922	gpm
mdotcp	227.9039327	kg/s-C
dT_water	17.0	31.1
Tin	12	12
Tout (ie T_oh)	29.0	43.1
	w/6 mm	w/3 mm

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

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

A bigger concern is the fault scenario during bakeout when we must assume that cooling to the OH is lost. If nothing is done, the OH would eventually be driven close to the bakeout temperature of 350 C. However we have time to react. With the 6 mm Microtherm we had over 3 hours to reestablish cooling flow. With 3 mm, and the end regions modeled the same as the central region of the OH, there would be just under 1 hour.

Heatup of OH following Loss of Cooling during Bakeout
Response time needed to avoid Damage to G10
drops from 3.3 hours to 1 hour



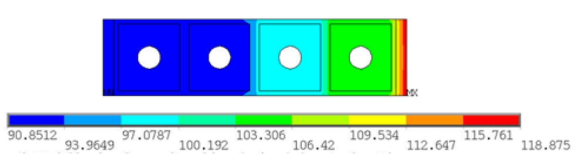
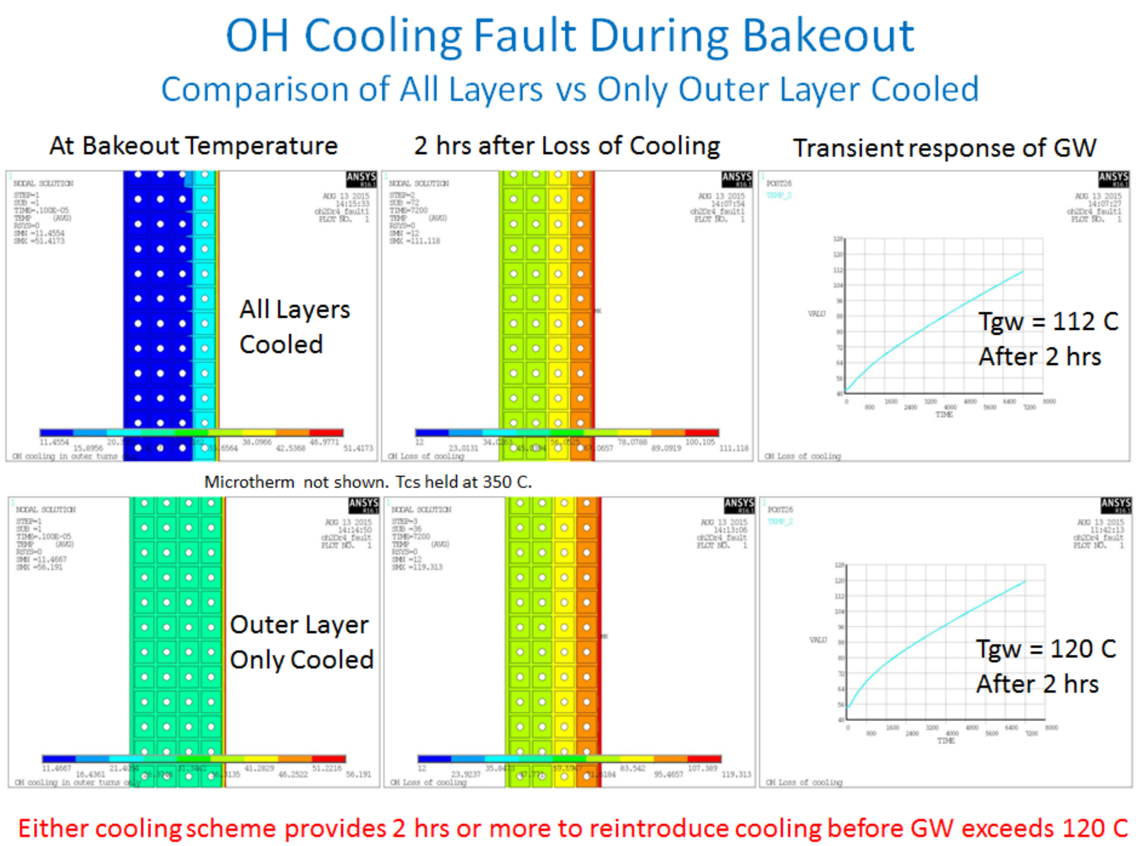


Figure 13.2-1 Time to Reach 120C at the OH Coil Surface During a Loss of Cooling Fault During a Bake-out

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 [16]. Around September 10, 2015, the cooling in the inner layers was restored at a reduced rate because the outer layer was approaching 90C.



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 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 PF1aU&L . With this taken into consideration,2 hrs is allowed to avoid a peak OH surface temperature of 120C.

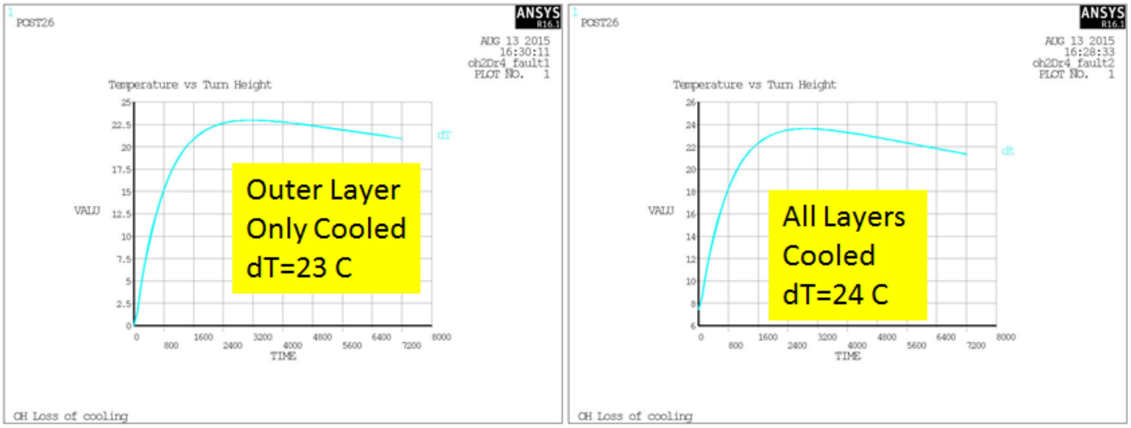
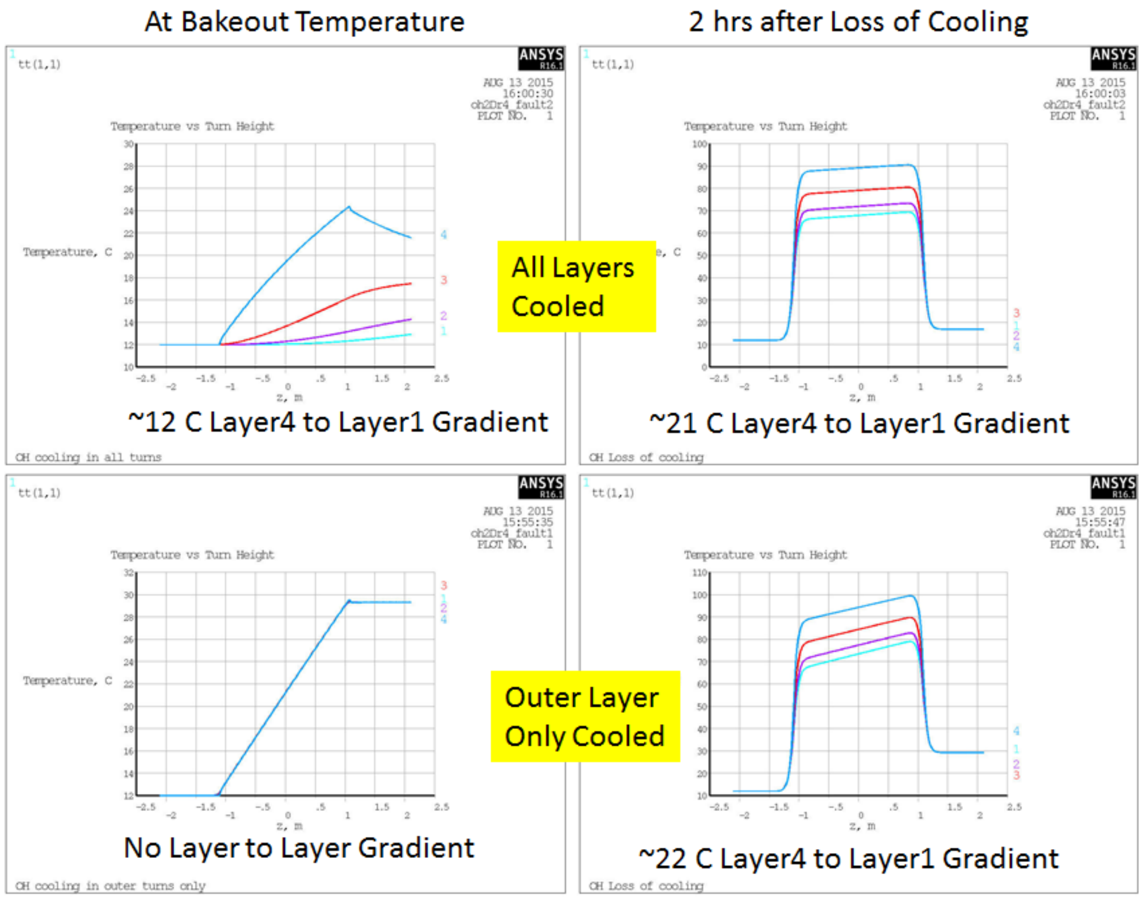


Figure 13.2-2 Peak Temperature Difference between Inner and Outer Layers occur ~ 1 hr after loss of cooling

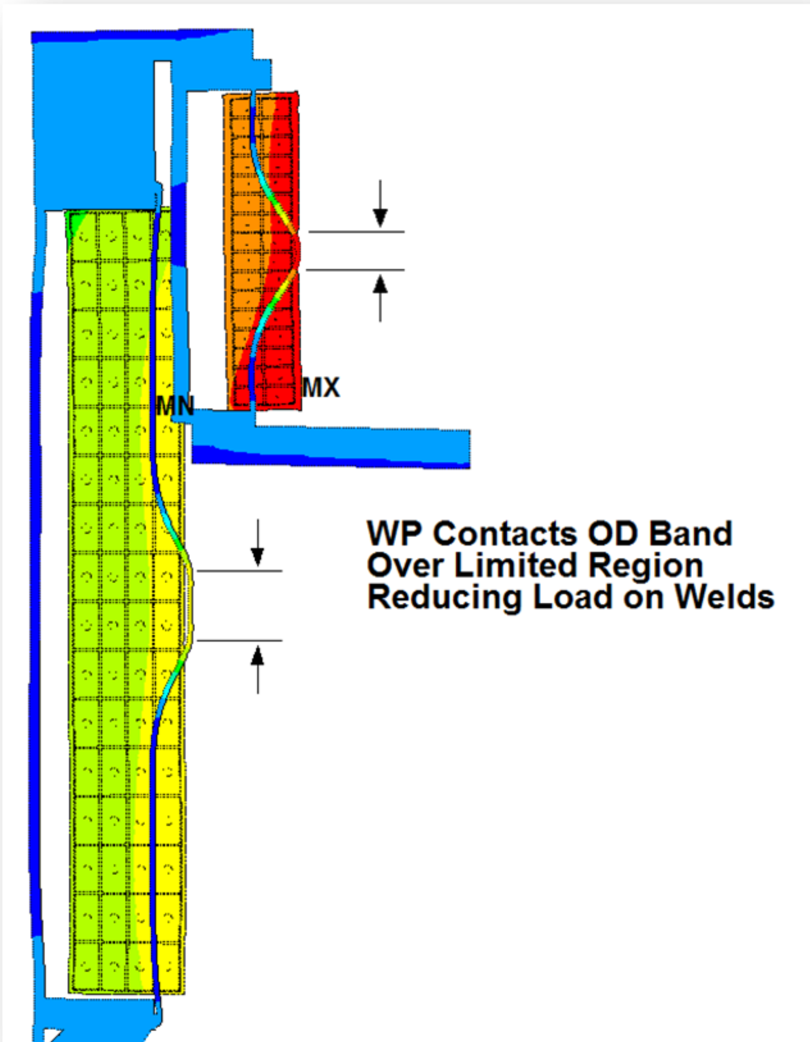
After only 1 hour, the peak temperature difference between the outer layer and inner layers reaches a peak of 23 degrees. This would introduce axial tensile strains in the inner turns, and it would be good to avoid as much of this as possible.



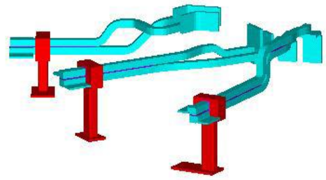
Both cooling scheme provides 2 hrs or more to re-introduce cooling before GW exceeds 120 C Cooling outer turns only eliminates the 12 C layer to layer gradient while increasing peak conductor temperature from 24.5 C to 29.5. During a fault both schemes develop an inner to outer layer gradient of ~24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

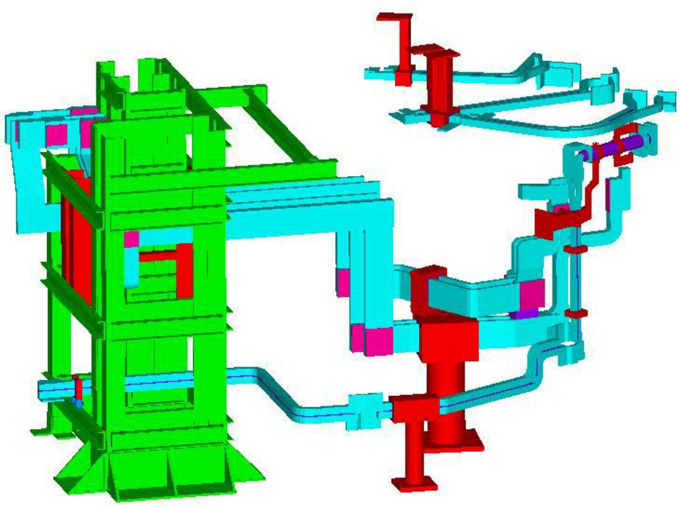
15.0 Nominal PF1B Behavior

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:



16.0 PF1b to PF2 Support Clamp Bake-out Bus Motion





17.0 PF1b Low Flow Heat Removal Capability

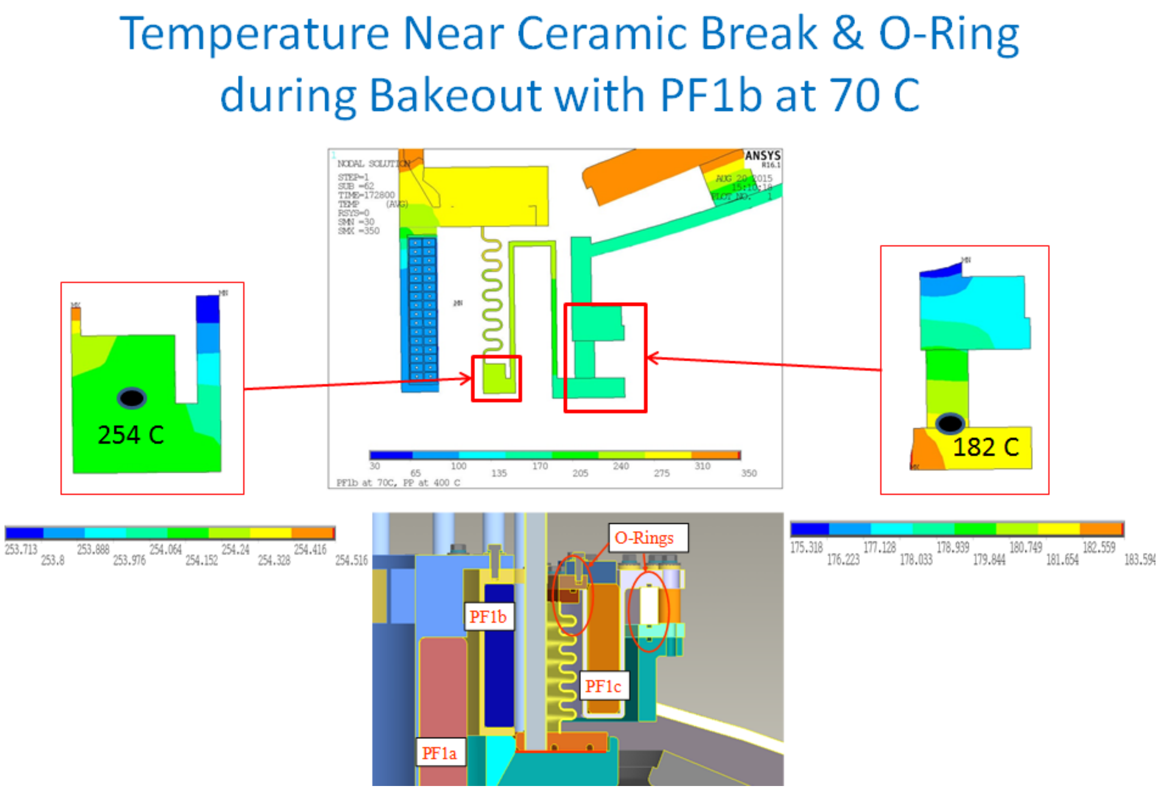
John Desandro measured the following flows in PF1b for low pressure water heating/cooling:

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

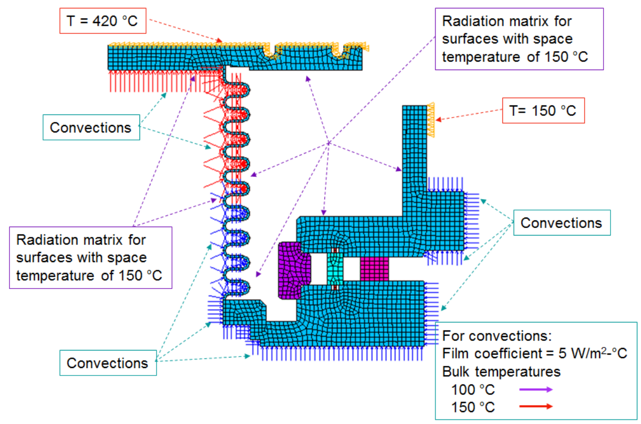
18.0 Ceramic Break O Ring Temperature

The operating temperature limit of the Viton seal is 200C



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

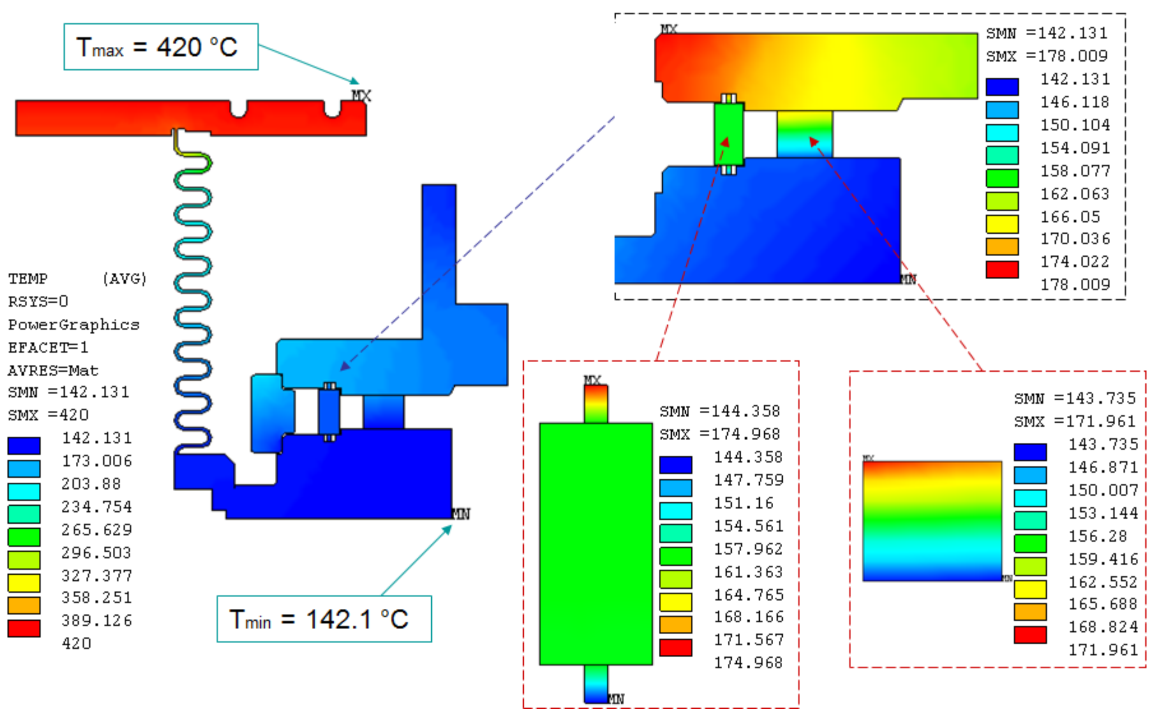
Thermal Loads at Lower Ceramic Break



The working temperature range ifor 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.

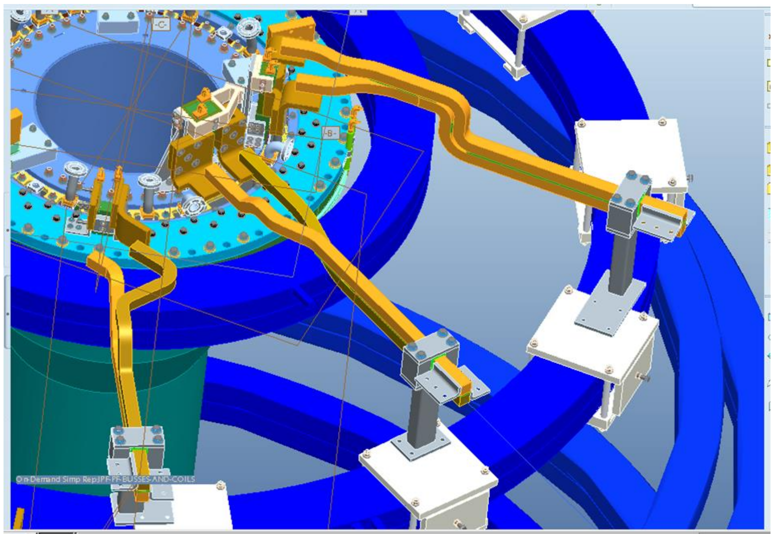
Thermal Distribution of the Lower Ceramic Break

- Maximum Viton seal temperature is 174.97 °C



19.0 Inner PF Bus – Disconnect? – or Not?

In the bus bar calculation, NSTX-CALC-55-01, the connections of PF1 a,b,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 PF1 a,b,c bus bars during bake-out.



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]

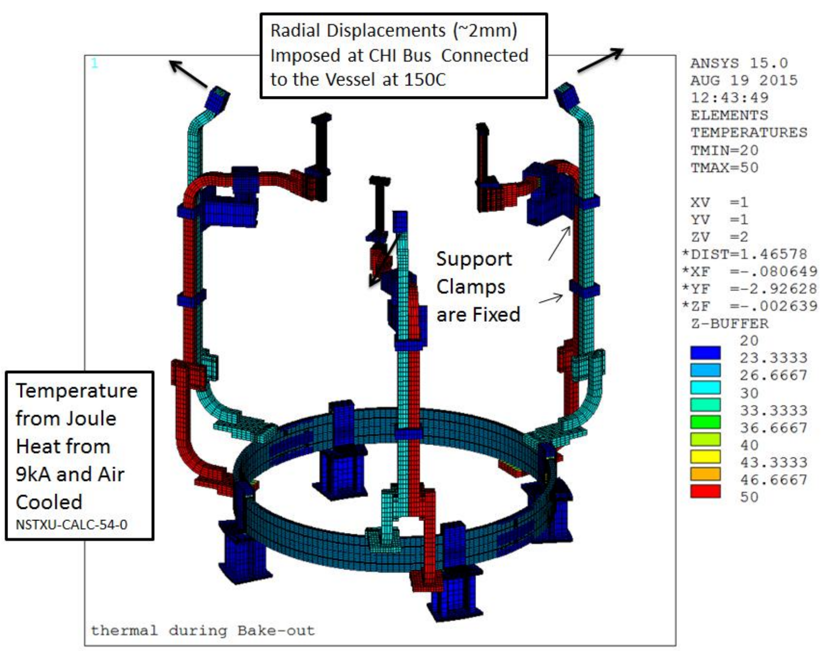


Figure 20.1-1

The CHI bus connection to the CS through the CHI bars was analyzed in calculation for the bake-out condition and is OK. The CHI Bus connection to the outer vessel will grow with the vessel. The analysis I did, assumed all the end points were fixed. I re-did the model with ~2mm radial growth of the vessel imposed on the CHI vessel Lug. The stresses are qualifiable, I think, 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.

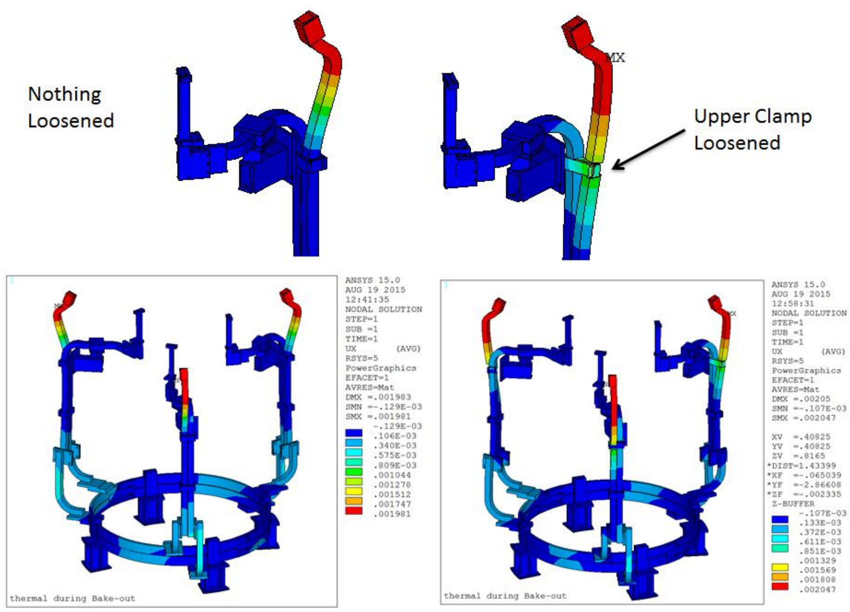


Figure 20.1-2

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

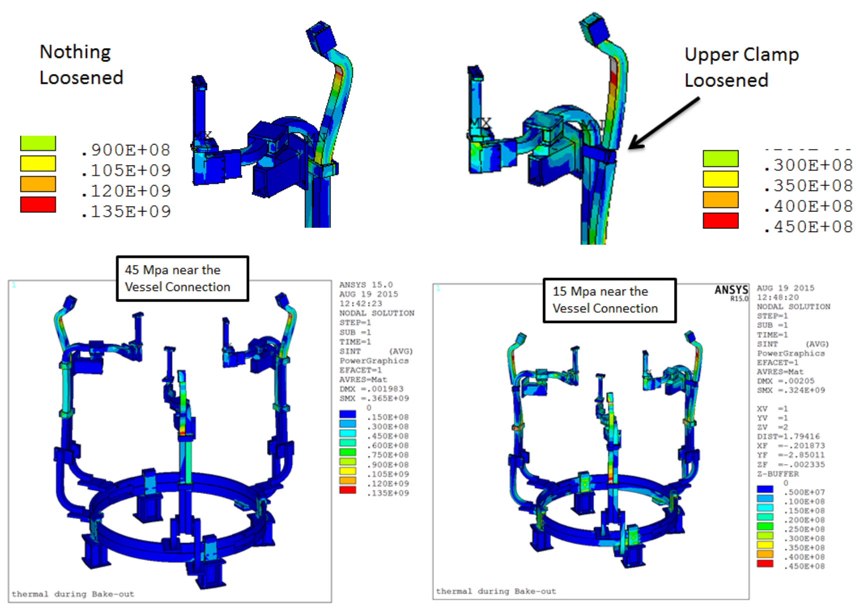


Figure 20.1-3

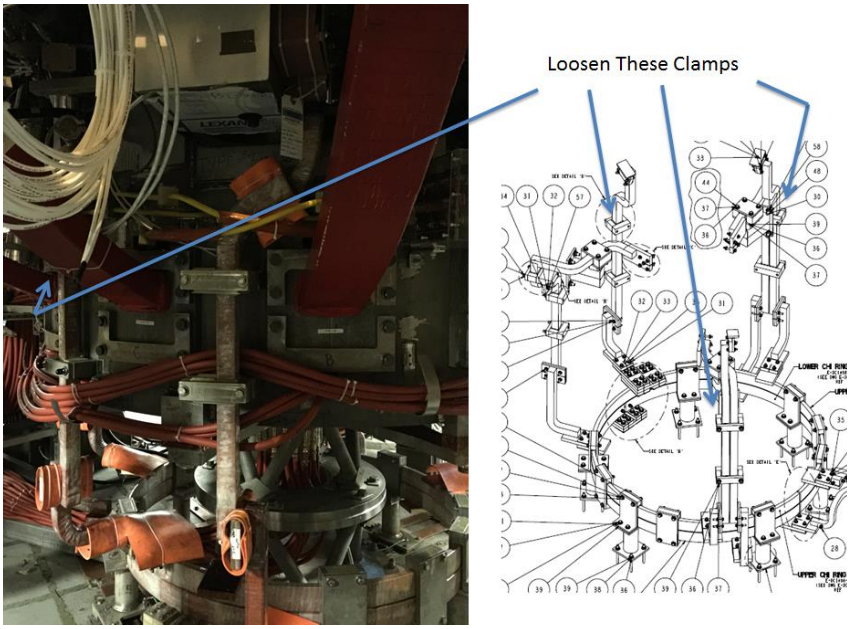
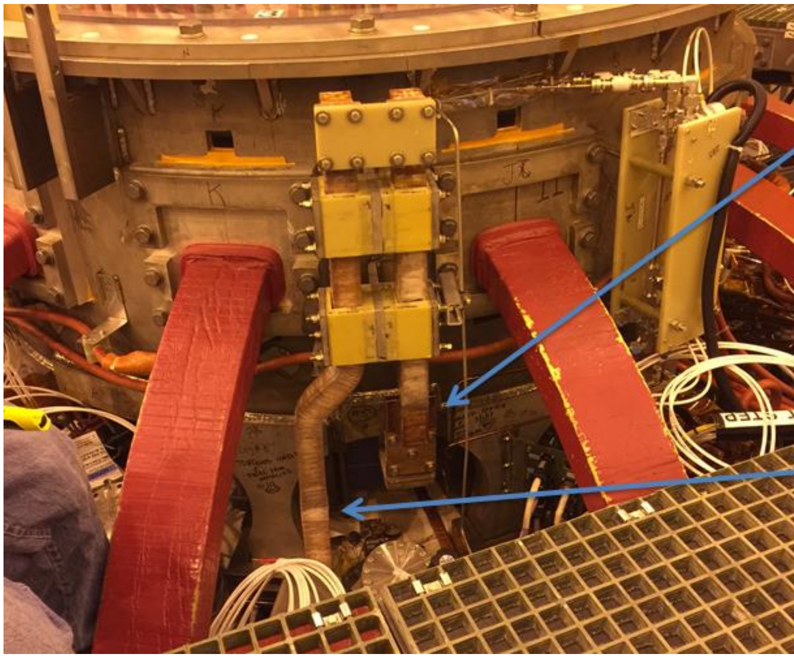


Figure 20.1-4

20.2 Upper CHI Busbar Power Connections



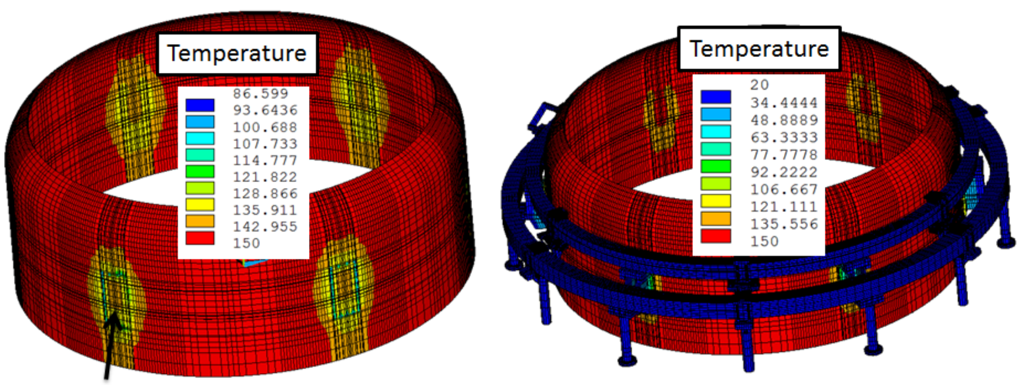
There is a flex on the bus connection to the inner vessel

on the bus connection to the outer vessel, the clamp shims are relatively loose and should allow 1 to 2 mm motion and in addition the bus run from vessel to first clamp is similar to the lower bus run after one lower bus clamp is loosened

Figure 20.0-1

21.0 PF 4 and 5 Support Columns

E* Alpha* delta T = 200e9*17e-6*(100C) = 340 Mpa = 50 ksi



"Cool" spots resulting from the PF support brackets convecting to the test cell atmosphere and conducting heat away from the vessel shell. (This distribution was approximated from measured temperatures by J. Winston during a NSTX bake-out)

Thermal mechanical loads from cold connected columns add moments to the shell that superimpose on the E*Alpha*deltT stress and could yield the attachment points

Disconnect the columns attached to the vessel

Figure 21.0-1

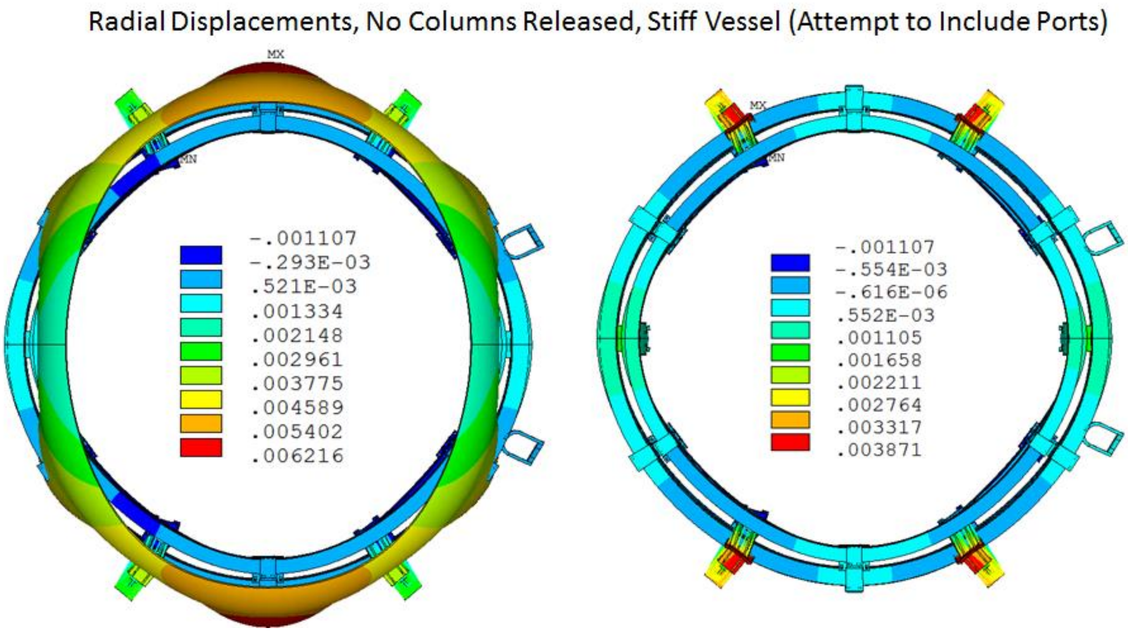


Figure 21.0-2

The slides are important to keep the coils from being stressed by the vessel motions.
Thus the addition of aluminum tapes

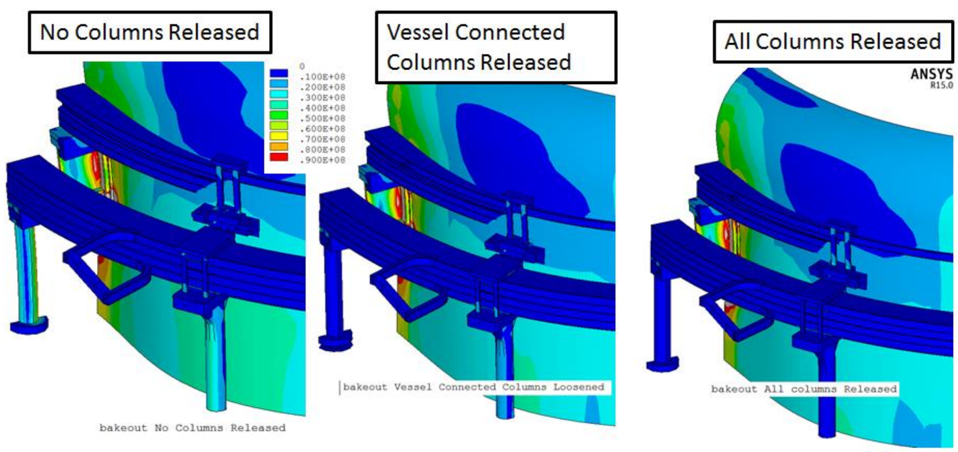


Figure 21.0-3

Stress analysis doesn't show a significant difference between the column restrain cases. Part of the vessel stress shown in the figure is the result of the cold clevis on the hot vessel shell. Stresses from the column tensile load were superimposed on the thermal stresses the vessel would be locally above yield and plastically deform

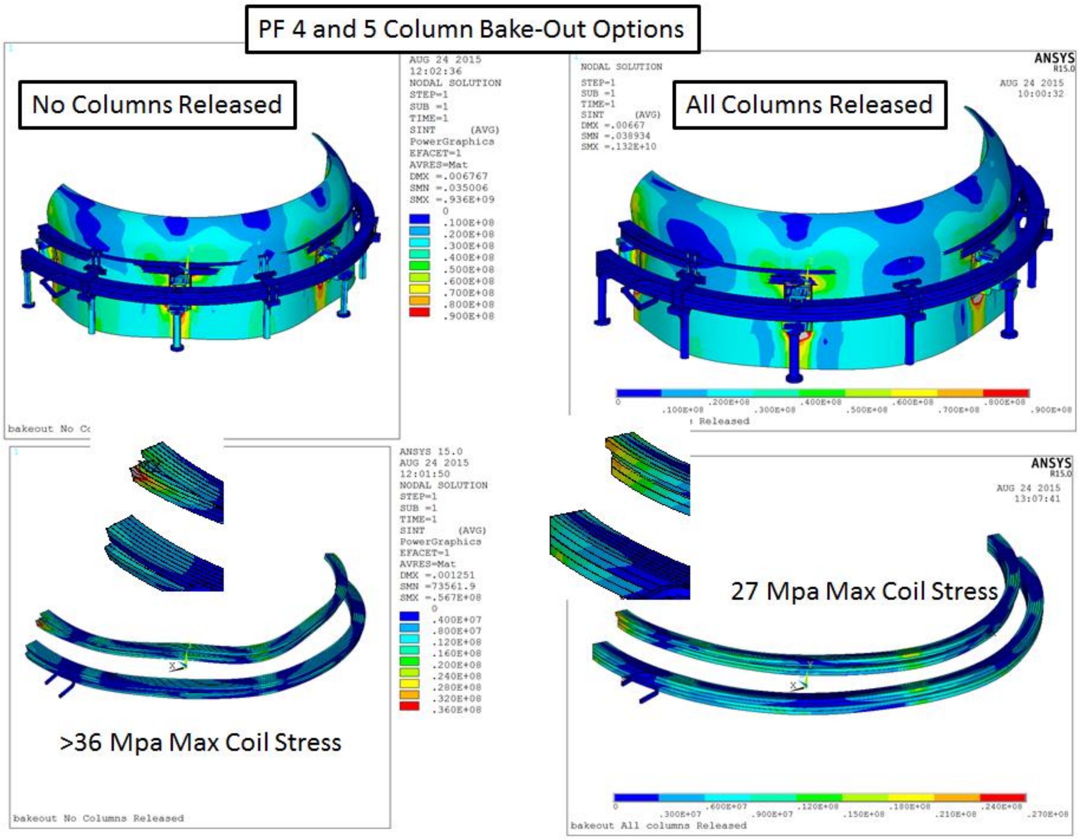


Figure 21.0-4

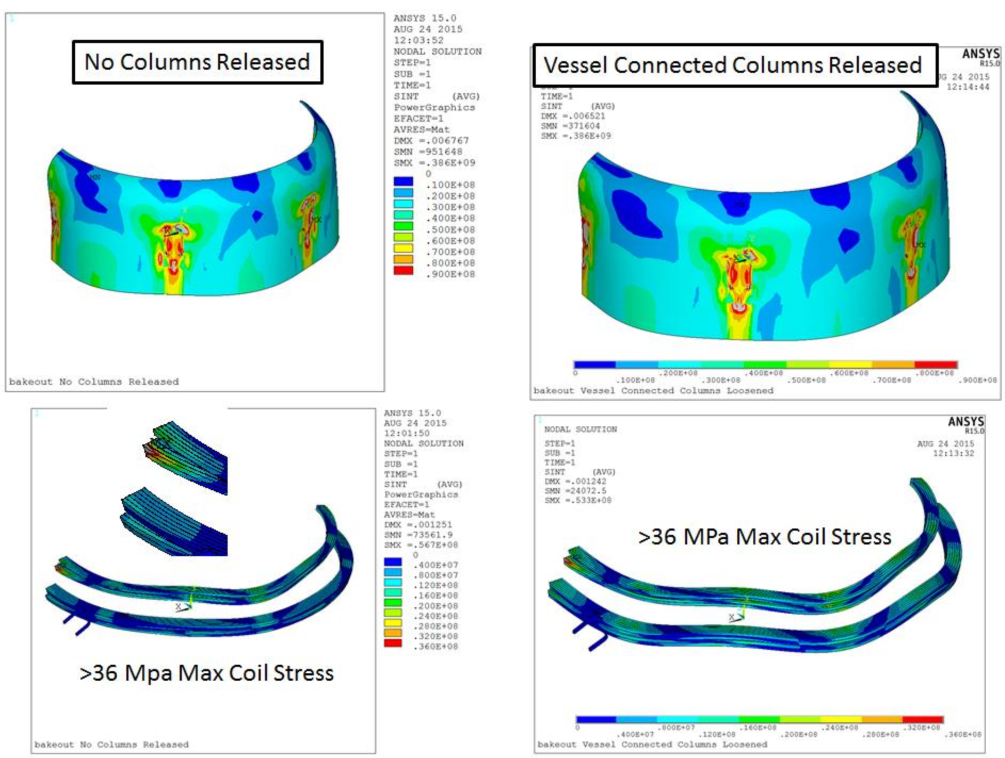


Figure 21.0-5

22.0 TF Truss Behavior – Loosen or Not

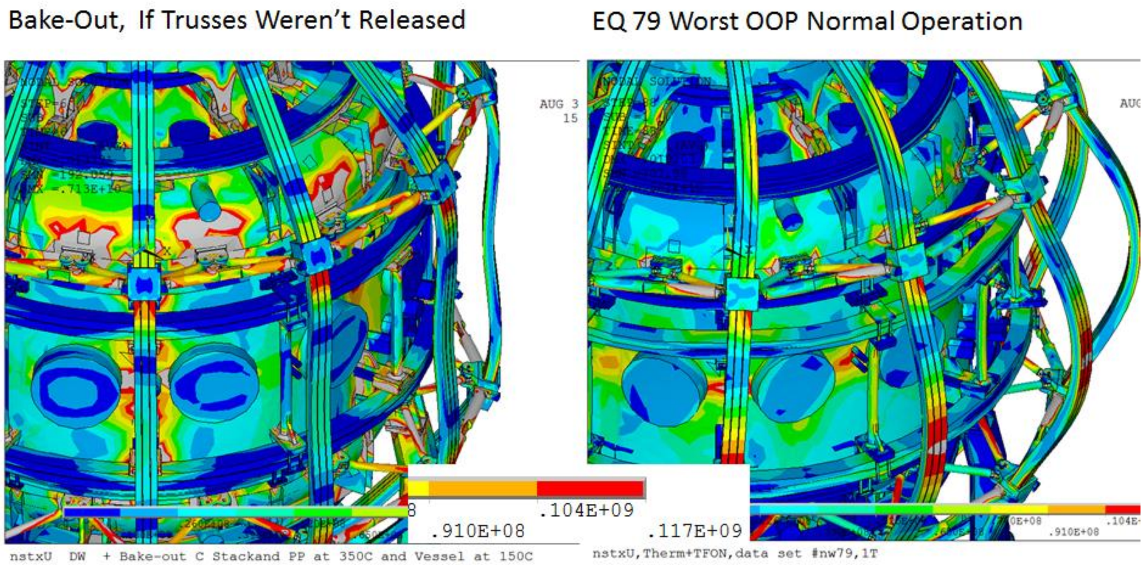


Figure 22.0-1 TF Truss, Peak Contour=117 MPaBake-out Compared with Normal Operating Max OOP loading

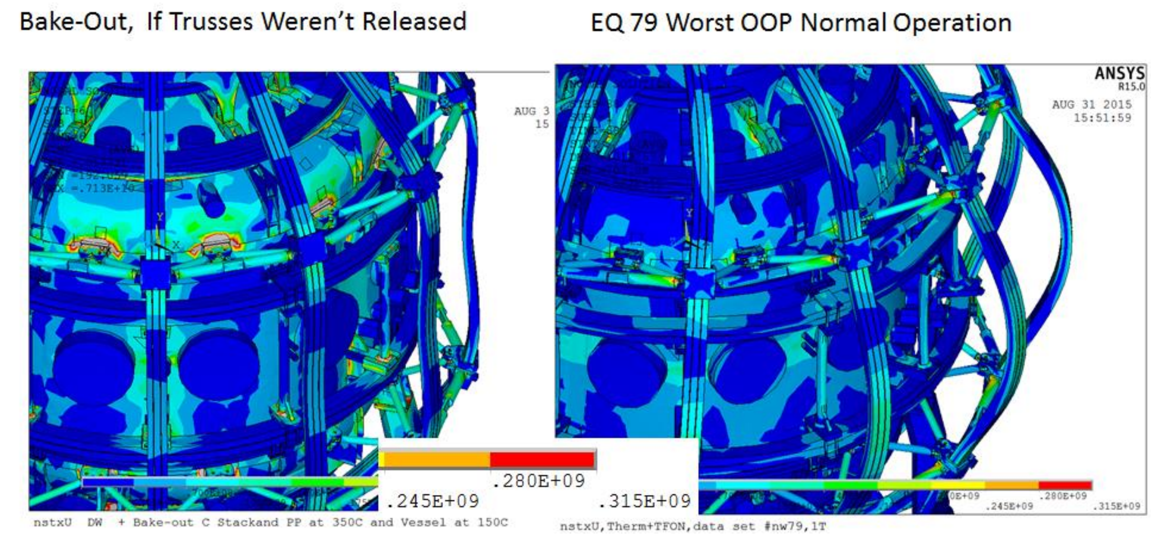


Figure 22.0-2 TF Truss, Peak Contour -= 315 MPa Bake-out Compared with Normal Operating Max OOP loading

At many locations, individual stresses are comparable. 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

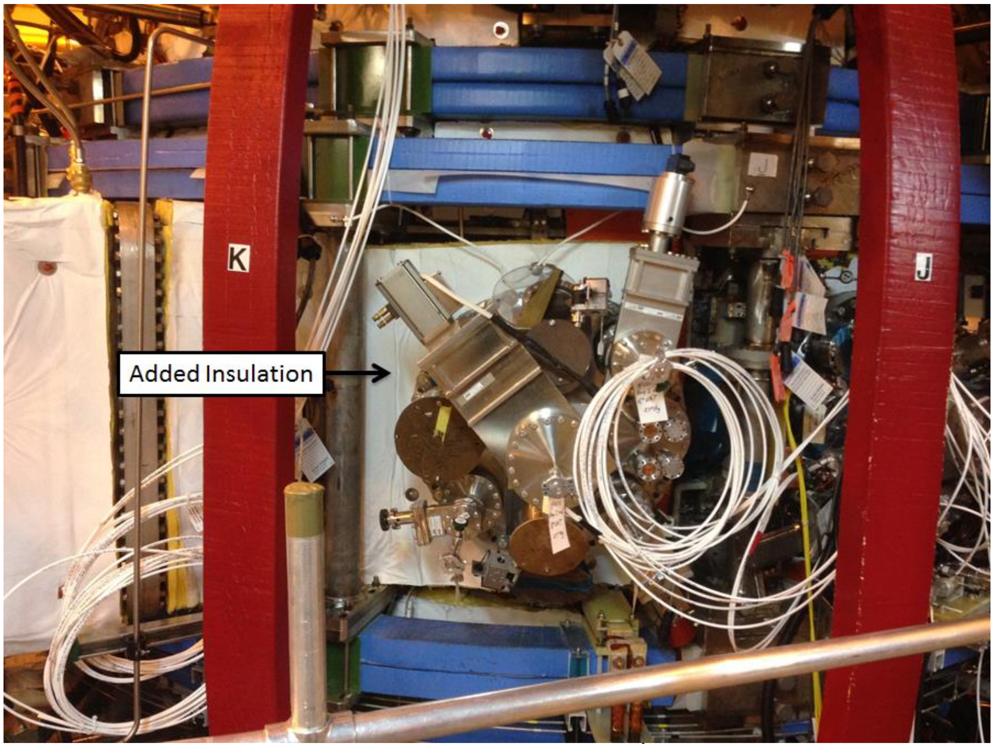


Figure 23.0-1 Photo taken Sept 4th 2015

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.

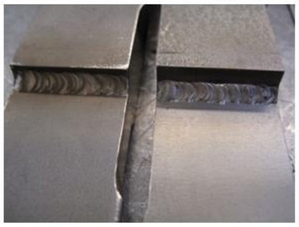
Attached is a product brochure and MSDS for the Microtherm Blanket. We used the "Microtherm SG Hydrophobic Quilted Panel".

Thanks,

Steve

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

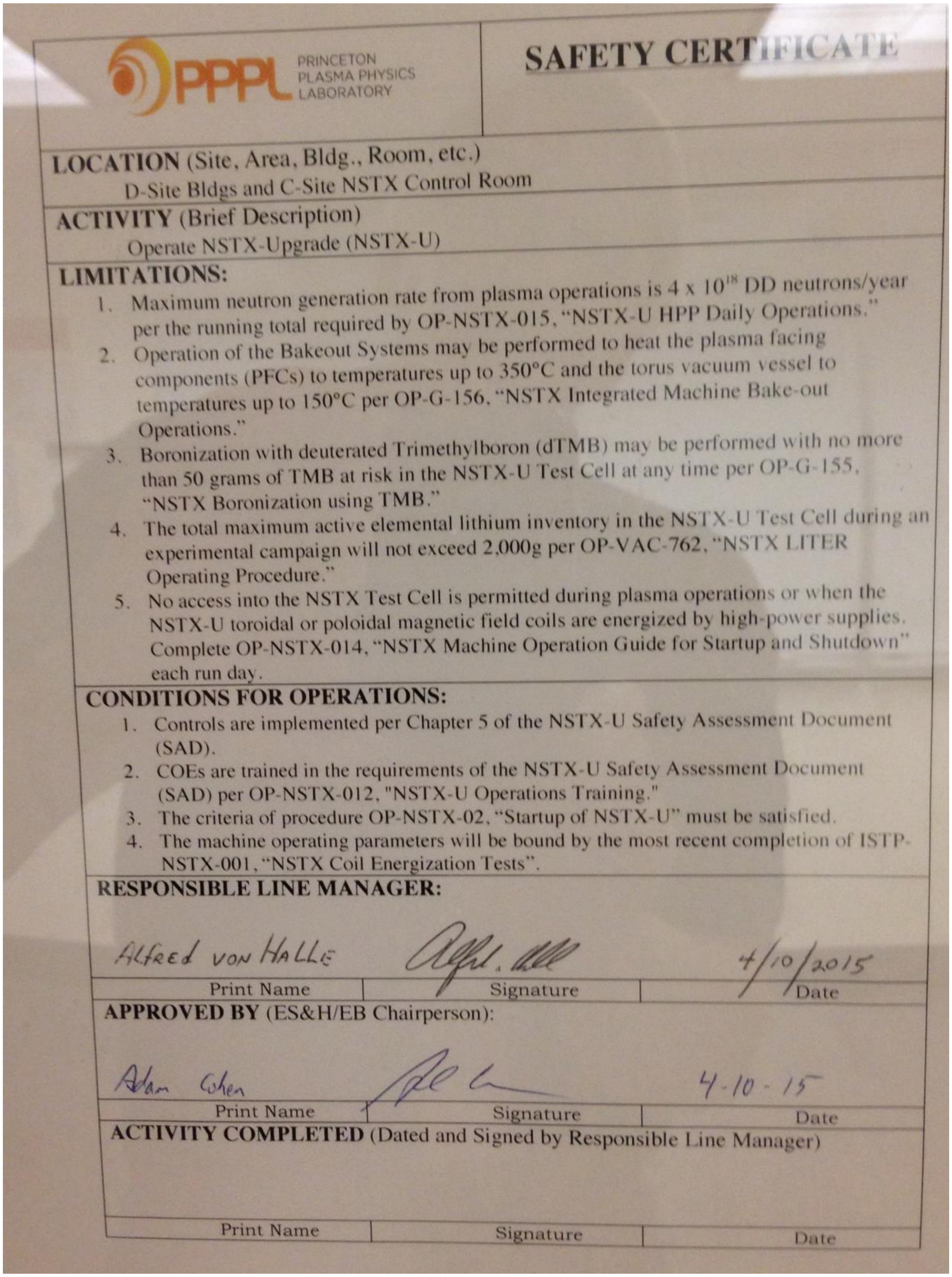
Stresses the Samples Survived:

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 x 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
First September 2015 Bake Data