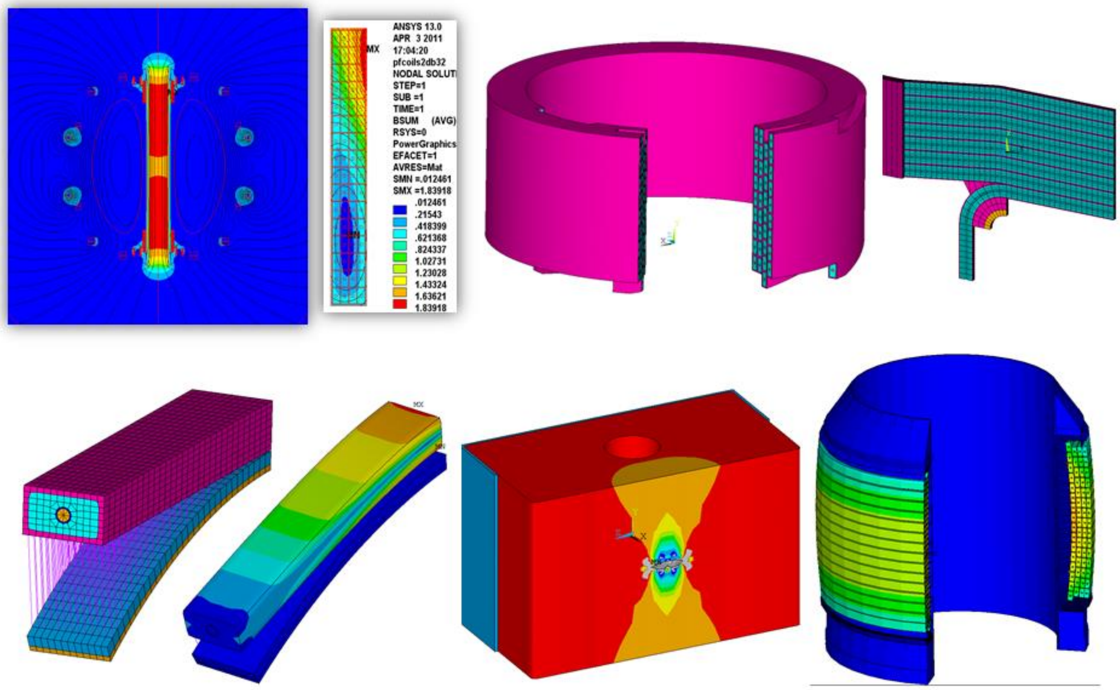
PF 1a Upper and Lower Replacement Stress Analysis

NSTXU-CALC-133-18-00

January 23, 2017



(PF1a Field Plot (left) PF1a Layer Joggle Model (Middle) and PF1a Terminal "un-wrapped" model (right)
Winding Simulation (Left bottom) Fracture Analysis (bottom middle) and Free standing Test stress (right bottom)

Preparer	Sections	Signature	Reviewer	Signature
P. Titus	8.0-20.0 Appendix D		Irving Zatz	
A Brooks	11.0, 17.0			
	Appendix A		Han Zhang	
G Loesser	19.2 Mandrel winding Stress		P. Titus	

PPPL Calculation Form

Calculation # **NSTXU-CALC-12-3-** Revision # **01** ____ WP #, **1903**
(ENG-032)

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

The first purpose of this calculation is to qualify the design of the new (Fall 2016) PF1a coil design This will include assessments of the normal pulse loading, cooldown behavior and the qualification tests. Additionally this calculation includes evaluations of possible causes of the failure of PF1a upper. The coil postmortem [30] should provide a definitive conclusion as to the cause.

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 6.2

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

One significant assumption is that we can proceed with the design and analysis of the new PF1aU coil without definitive conclusions from the post mortem of the failed PF1aU coil. As of October 2016 the precise cause of failure is not known.

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.)

The new coil will not have braze joints, and because of manufacturing limits, production of the required length of conductor, makes achieving hardened copper properties difficult. The high yield of the original conductor presented winding difficulties that may have been the cause of insulation damage. The new coil will have a lower yield conductor. Cooldown strains were found to be more limiting than stresses due to Lorentz forces. This has required an elastic-plastic analysis to show acceptable shake-down and to quantify the stress range for fatigue qualification. The new coil design without the layer joggles and more gradual transitions produces end turn windings that present a more complicated geometry facing the flanges. Turn compression in the ends of the coil can be concentrated on one layer and over a relatively short azimuthal extent. This was analyzed with a series of 2D slices and found to produce local compressions similar to the compression due to flange flexure in the original coil. Both end turn layouts have acceptable compression. The primary conductor manufacturer has produced conductor with the required yield of 9ksi, targeting an as-wound yield of 12 ksi. The vendor can produce conductor with a guarantee of no flaw exceeding 1mm. Fracture mechanics calculations have confirmed that this will provide an acceptable life.

There were no design details that analytically were demonstrated to cause a fault. This includes assessments of braze joints, layer joggles

Cognizant Engineer's printed name, signature, and date

George Loesser ____

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

Checker's printed name, signature, and date

Reviewed By:

Preparer	Sections	Signature	Reviewer	Signature
P. Titus	**8.0-20.0 Appendix D**		**Irving Zatz**	
P Titus	**16.1**		**A Khodak**	
A Brooks	**11.0, 17.0 Appendix A**		**Han Zhang**	
A Khodak	**16.2**			
G Loesser			**P. Titus**	
			Bill Beck	

2.0 Table of Contents

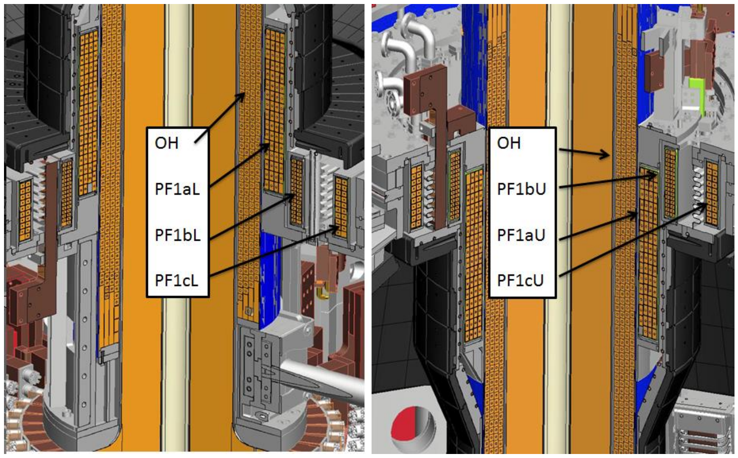
Appendix D Free Standing Coil NTFTM and ANSYS Files
Appendix E
Appendix F Paris Integral True Basic Program
Appendix G Emails

3.0 Revision Status Table

Rev	Date	Description
0	9-2016	Original Issue

4.0 Executive Summary

A failure of PF1a has initiated the process of its replacement. Some of the events relating to the failure are discussed, along with design details that may have been possible sources of trouble, but the purpose of this calculation is not to determine the cause of the failure. The report prepared by Irv Zatz and Joe Petrella has provided a proper post-mortem of the failure[30].There is still not a firm determination of the cause of the coil failure as of November 18 2016.



Inner PF Coils at the Top and Bottom of the Centerstack

The original PF1a qualification calculation is : "Stress Analysis of the Inner PF Coils (1a,1b &1c), Center Stack Upgrade" NSTXU CALC 133-01-2 [9]. Additional bus bar related calculations that include treatment of PF1a are: NSTX Upgrade PF 1 Flex Bus Analysis NSTXU-CALC-55-03-00, NSTXU. Structural Analysis of PF1, TF and OH Bus Bars NSTXU-CALC--55-01-02 [12]. In [9], Len Myatt plots the winding pack stress for PF1a for all the 96 Equilibria. The max stress is less than 20 MPa. The model is a 2D model without the winding joggles and terminal break-out stresses but the basic winding pack stress is low and even with stress concentrations at the winding transitions, the stress is well below the allowable established for NSTX-U copper conductor s of 125 MPa.

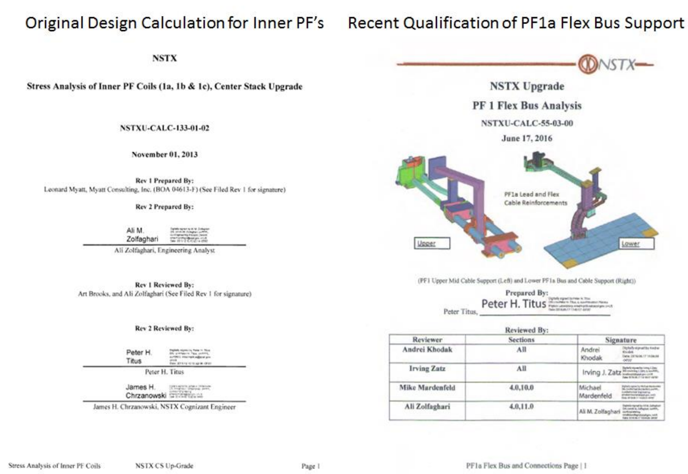


Figure 4.0-1 Existing Qualification Calculations

Another calculation addresses the local interactions between PF1a and the OH to augment the DCPS calculations of the OH hoop stress, NSTXU CALC 133-14-00 [25]. Another calculation addresses the magnetic stability between PF1a and the OH NSTXU-CALC-133-11-00[26]. Important characteristics of the PF1a coil were addressed in the Upgrade project. The main conclusion regarding PF1a from the analytic effort during the Upgrade project was that the Lorentz stresses in the coil were low and justified avoiding the analysis of winding details.

In reviewing the original qualification calculations and subsequent estimates of joggle and terminal stress concentrations, there is no indication that there is a design flaw or failure to satisfy design allowables with exception of the cooldown thermal strains – but these never reached a level that should have caused a failure . For the replacement coil there is an effort to eliminate design details such as use of un-necessarily hard copper, braze joints and layer joggles that made the manufacture more challenging.

For the new PF1a coil, a few design changes are being implemented:

- Lower Copper Conductor Yield is Specified to Ease the Winding Process (9ksi on the spool and 12 ksi after winding)
- An Insulation System Like the OH Will be Used to Allow PF1a Qualification to Rely on the OH Insulation Tests and Qualification
- 1mm Maximum Flaw is Allowed Based on 100% NDE
- Stress Concentrations due to new Ramps and Fillers Are Being Qualified
- Ramps and Fillers will be High Temperature (G-11) High Pressure Laminate
- 12C Water Cooling will be OK.-It Will Not Damage Insulation, No Special Preheater is Specified, (see section 21.0) but may be necessary as a Back-Up.
- Thinned Mandrel Shells to Allow More Radial Build to Accommodate More Insulation
- Check for Cuprous Oxide, NDE tails – like Luvata did (Included in the New Purchase Specification)

Based on the present design, 12C water entering the outer layer produces a E*alpha*delta T stress of 196 MPa - or 28 ksi - This is above the fatigue allowable of 125 MPa (based on a .7mm flaw). So if the conductor was a high yield and remained elastic it would fail fatigue for cooldown cycles. With the current 9ksi on the spool and 12 ksi as wound, 80 MPa tension stress range after the initial yielding has been calculated. Some uncertainty in this needs to be accommodated because of the complexity of the stress strain simulations. It is recommended that as delivered conductor have cyclic stress strain curves measured. The 80 MPa tensions passes the fatigue assessment with a 1mm flaw. The tensile strains that develop as the outer layer moves, are within the strains qualified by test for the OH. If there is some concern with how much strains are developing in the insulation, we would have to consider mixing/recirculating exit water with inlet water. but this takes longer to cool. The qualification tests include full performance cooldown with 12C (actually ~17C in the FCPC) water, so the tests will help qualify the cooldown thermal “shock”

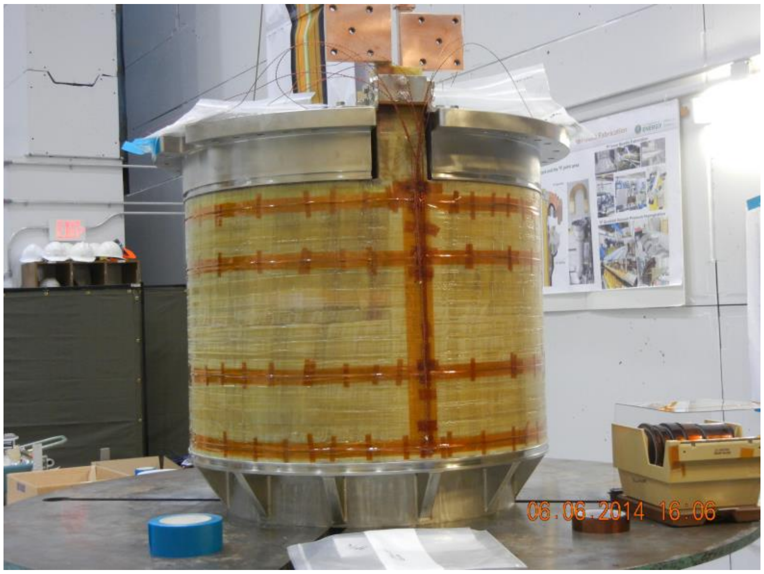


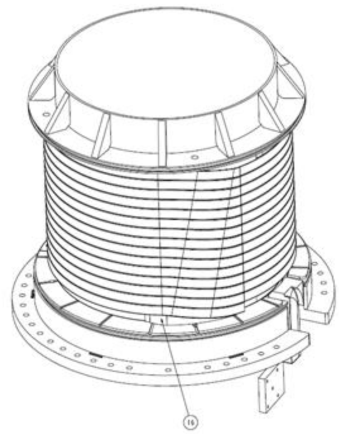
Figure 4.0-2 PF1a Coil as it appeared during construction prior to assembly in the machine (The outer flex panels have not yet been installed)

Figure 4.0-3Photo of the Failed PF1a upper Coil after Removal and Before being sent for Radiography

The coil looked pretty good as it came out of the machine, even though it had shorted and been leaking water in the last part of the 2016 run. The analyses done for the Upgrade and a review of these analyses did not reveal any stress issue that would have indicated a failure. There were however some design details that would make the coil un-necessarily difficult to wind.

Layer Joggle Stress Concentration

There are layer joggles intended to pack as much conductor into the coil as possible. With this array of nested joggles, every time you approach an azimuthal joggle array you have to anticipate precisely the position of the joggle, bend it with a fixture or a 3 point bender twice, either leave the glass on and risk damage to the glass/Kapton or take it off, and risk making a mess by re-applying. The joggle bends keystone, and work harden at the tighter bend, and won't conform to the coil radius when you wind it down. So even if you file the keystone, you will get local "flats" and high and low spots. It is not certain what was done with the winding tension during these operations. From an Everson Tesla Phone Conversation, the “Take-it-off and reapply” method is what they did. The techs in our coil shop probably developed ways of doing all this. This has been a suspect area in the post mortem [30] but not a clear cause of failure.



Layer Joggles Disrupt Normal Winding An Example of Layer Winding with No Joggle

Figure 4.0-5 Layer Joggles Effects on the Winding Process

The joggle stresses are not an unacceptable source of stress concentration – 1.17 times the nominal winding pack stress for a well bonded coil, and3 times the nominal stress if de-bonding occurs (See section 13.0). Even the factor of 3 applied to the 20 MPa winding pack stress would not indicate a failure. The joggles mainly they present a difficulty in manufacture. The process of forming them – removing and replacing insulation after use of a forming tool tends to handle the insulation roughly . Mistakes during this process have contributed to the failure. I discussed this with Lew, and I don't think there is any experience with these types of joggles in a layer would coil. Lew copied the joggles from a S-1 pancake wound coil.

At this writing, the rest of the inner PF coils, including PF1aL may be retained and these have the joggles. So consideration of the joggles needs to be included in the qualification of the PF1a.

A couple of approaches have been used to quantify the Stresses on the PF1a coil. The first is to quote the Upgrade calculation of record [9] ,

Winding Details of the Coil Ends

The new coil design without the layer joggles and more gradual transitions produces end turn windings that present a more complicated geometry facing the flanges. Compression in the ends of the coil can be concentrated on one layer and over a relatively short azimuthal extent. This was analyzed with a series of 2D slices and found to produce local compressions similar to the compression due to flange flexure in the original coil. Both end turn layouts have acceptable compression. This is discussed in more detail in section 16.0.

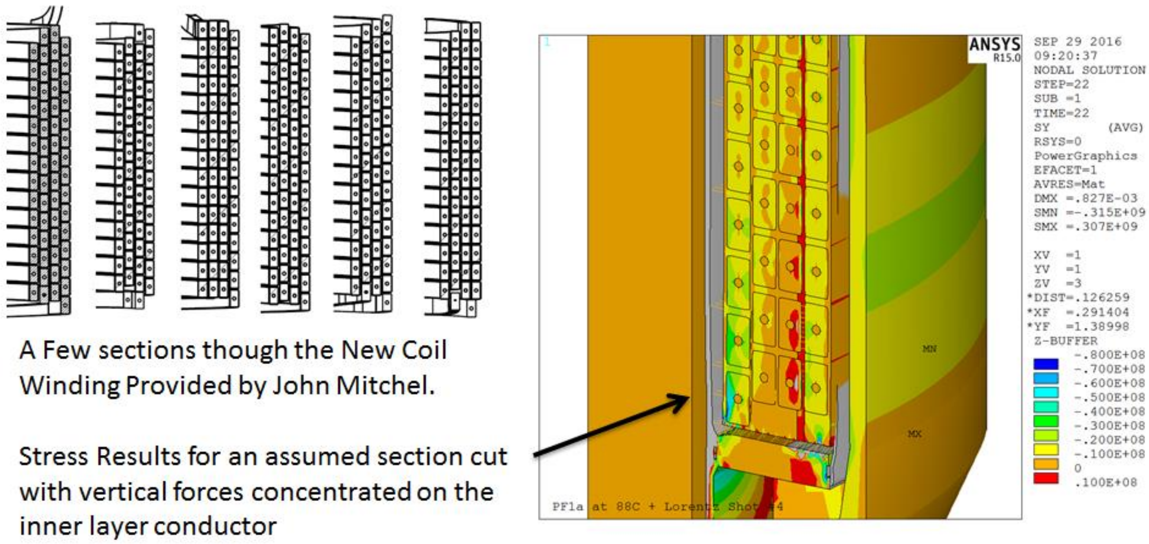


Figure 4.0-12 Coil End Stress Due to the New Coil Winding Pattern

Three Dimensional Model of the Winding Pattern at the Ends of the New Coil

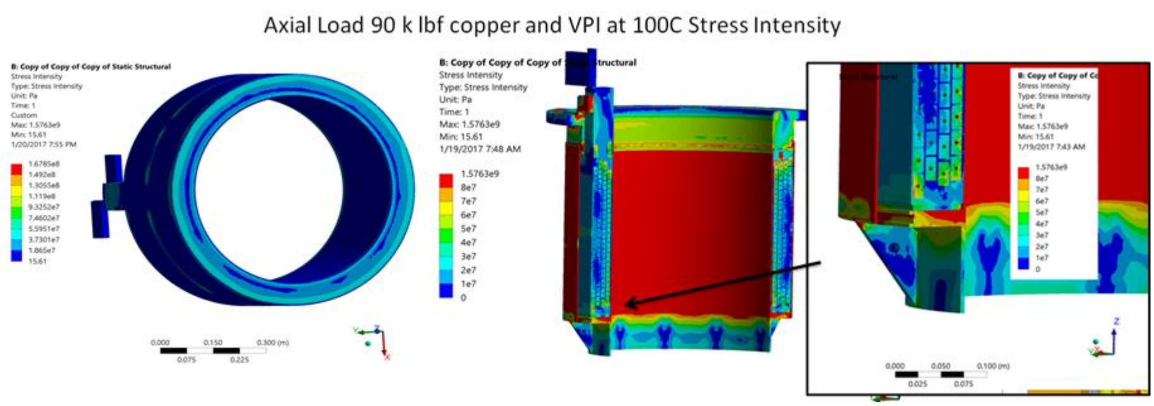


Figure 4.0-13 Tresca Stress at the end of the coil (Left) and Section (Right)

In section 16.2, a three D model was developed from the coil solid model, including all the radial and vertical transitions and G-10 volumes that represent the ramps and fillers. The main purpose of this was to investigate the accuracy of analyzing the 2D slice used in section 16.1, and provide a cross check of the two analyses. The results confirm both modeling approaches. The end view of the coil at the left shows no severe hard point that concentrates too much load inventory on the lower extremities of the winding/transition pattern.

Coil Elastic-Plastic Response with Lorentz and Cooldown

The new coil will not have braze joints, and because of manufacturing limits, production of the required length of conductor, makes achieving hardened copper properties difficult. The high yield of the original conductor presented winding difficulties that may have been the cause of insulation damage. The new coil will have a lower yield conductor. Cooldown strains were found to be more limiting than stresses due to Lorentz forces. This has required an elastic-plastic analysis to show acceptable shake-down and to quantify the stress range for fatigue qualification. The primary conductor manufacturer has produced conductor with the required yield of 9ksi, targeting an as-wound yield of 12 ksi. The vendor can produce conductor with a guarantee of no flaw exceeding 1mm. Fracture mechanics calculations have confirmed that this will provide an acceptable life.

New conductor with a minimum yield of 9ksi has been purchased intending to achieve 12 ksi as wound. Cooldown is expected to yield the conductor and we have to demonstrate that the purchased conductor will cycle acceptably and not strain the insulation any more than we have qualified for the OH glass and Kapton CTD 425 system. This effort has required a re-calculation of the cooldown behavior and sophisticated elastic –plastic analysis in order to demonstrate that the cyclic behavior "shakes down" and the behavior of the conductor is repetitive and does not grow. The cyclic stresses will need to be qualified for fatigue and that is done in section 18.0 .

Elastic Plastic analyses have utilized multi kinematic hardening models – for the winding simulation, and Chaboche models for the cyclic simulation. Three Copper Chaboche models have been considered. The first two sets of data are derived from research done for the CIT project at MIT-PSFC in 1989 [28]. The third is from published data for a copper lined rocket nozzle [27]

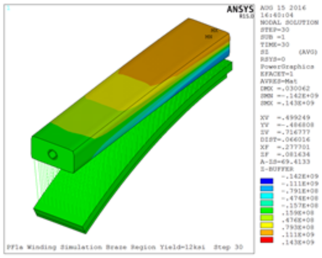
Art's interpretation of the Chaboche parameters from the CIT J Chen MIT-PSFC data is included in Appendix A. His results from a simple segmented cylinder are presented below. This is for the higher yield version of the copper stress strain curve for which Art developed Chaboche parameters. The higher yield version has a yield of 100 Mpa, or 14.5 ksi – larger than the target in the purchase spec of 12 ksi.

For Next Coil

- Increase Mandrel geometry to at least allow second half-lap of glass and Kapton (Planned by Mike Kalish)
- Eliminate layer joggles – mainly because they are difficult to wind
- Eliminate braze joint – stress requirement can be relaxed if cooldown stresses can be improved.
- Check water chemistry for crevice corrosion and pitting - check O2 level?

Winding Manufacturing Simulations

The use of braze joints in the coil was looked at as a probable risk in the winding of the coil. It has been a special area of interest in the post mortem of the coil. PPPL qualifies its braze operators by having them perform a braze and then the joint is tension tested to failure. The criteria is that the joint must fail outside the braze joint. All joints are post tensioned to a 5% reduction in area to recover some of the cold work. This same procedure was imposed on Everson Tesla. However Everson Tesla failed to get an acceptable braze joint, with the break occurring at the braze plane. This however occurred at 23 ksi, well above the applied Lorentz Stress, and higher than stresses that would occur during cooldown which for PF1a are more limiting. The "failed" braze joint test was accepted. It should be pointed out that as a part of the acceptance of these braze tests, a recommendation was made to increase the braze temperature a bit, and in a phone conversation with Everson Tesla, Greg Nomovich indicated this had been done. This would probably be OK if in the process of bending the conductor – including the braze joint- the braze plane was not stressed above the tested tensile capacity of the braze joint. In the following calculations, a simulation of the winding process is done with varying values of what might be expected of the brazed and partially annealed section of the conductor. These calculations are not only useful for assessments of the stress applied to the braze joints, but also as an indication of the degree of cold work expected from the winding process.



	Von Mises After Winding	Sz After Winding	Required before NCR	Capacity Allowed by NCR
8 ksi Braze Region Yield	82 Mpa 11.8 ksi	122 Mpa 17.7 ksi	255 MPa 37 ksi	151.7MPa 22 ksi
12 ksi Braze Region Yield	100 Mpa 14.5 ksi	143 Mpa 20.7 ksi	255 MPa 37 ksi	151.7MPa 22 ksi
14 ksi Braze region Yield	112 Mpa 16.2 ksi	160 Mpa 23.2 ksi	255 MPa 37 ksi	151.7MPa 22 ksi

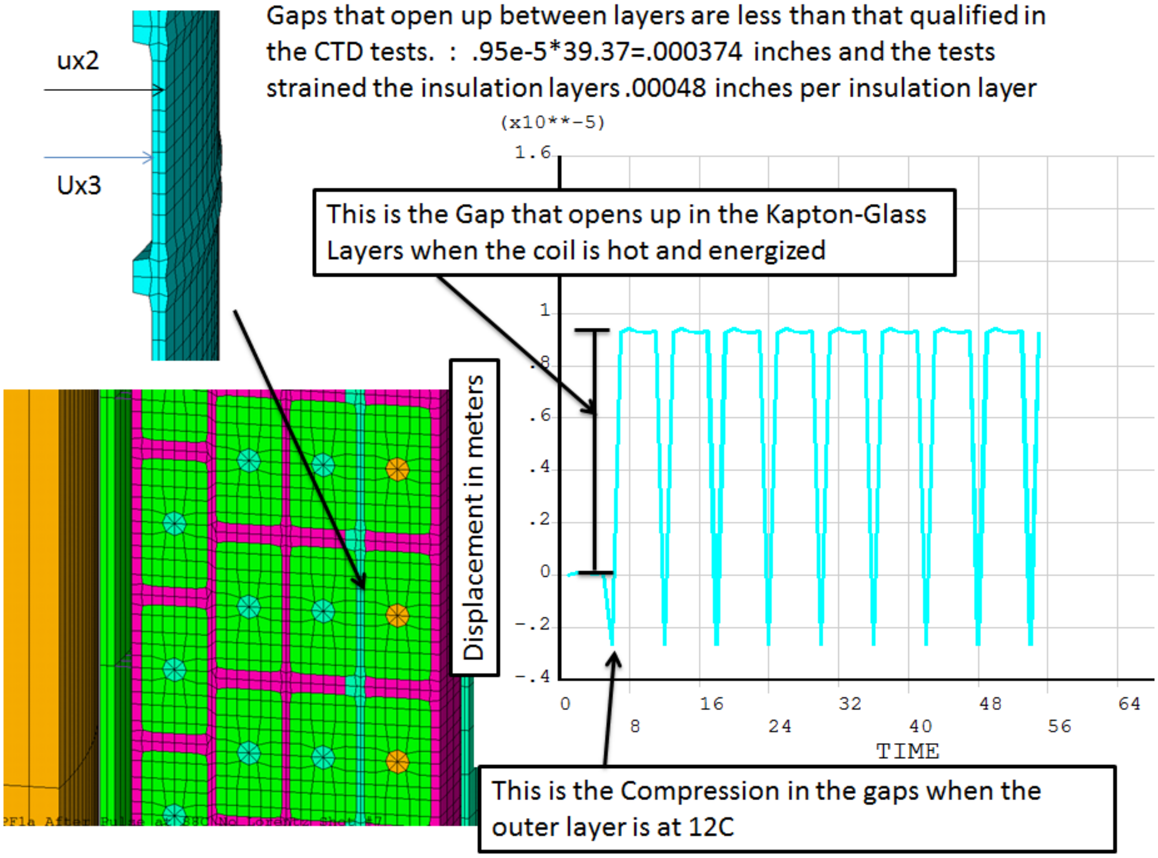
Supplier Document Type & Number: NCR SC14023

SAMPLE ID	(ksi) TENSILE STRENGTH	(lbf) TENSILE LOAD	FRACTURE LOCATION	FRACTURE TYPE	(in^2) AREA	KEY C/NC/R
002	22.1	12,503	Braze Joint	Ductile	0.5649	R
003	25.5	14,318	Braze Joint	Ductile	0.5621	R
004	24.0	13,585	Braze Joint	Ductile	0.5658	R

Figure 4.0-14 Stress Results for the winding simulations

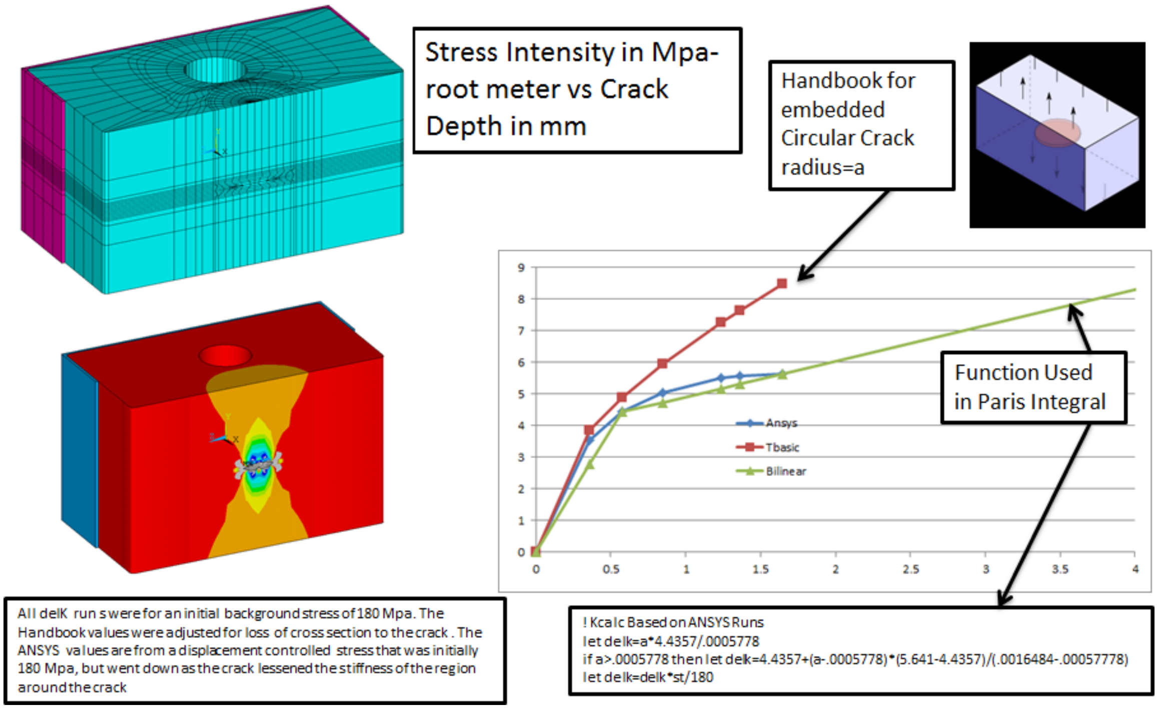
Assessment of Insulation Strains

There will be a growth of the outer layer of the coil away from the rest of the coil build . In actuality the behavior will not be limited to layer 4 but will occur to lesser degrees in the inner layers. The intention of the interleaved Kapton-glass system is to provide some tolerance to local strains in the coil. Multiple Kapton wraps are usually used around the terminals to provide insulation integrity if the terminal move under Lorentz loads or thermal motions. Kapton has a very large % elongation before it will break and can stretch and bridge epoxy cracks. But excessive motion of the insulation system during cooldown can damage the Kapton tape or propagate cracks. This issue came up with the OH coil and the approach was to test the insulation system in strain controlled tests that enveloped the cooldown wave behavior and in parallel design a warming system for the OH cooling water that would produce a more gradual distribution of thermal strains in the coil. CTD was contracted to do the tests. The fixture and test specimen are shown in Figure 17.2-2 The CTD Test specification and test report are references [23] and [24]



The simulation produces .9e-5m gap or .000374 inches , less than .00048 gap in the test a test gap The planned qualification tests include 20 cycles of full performance cooldown without recirculation. Strains will be monitored and electrical properties will be recorded. Initially the old/original PF1a Lower coil will be tested and if there is any indication of electrical degradation, then coolant water pre-heating and recirculation can be considered.

Fracture Mechanics – Evaluation of a 1mm Flaw



For the tensile range of 80 MPa ,taking credit for compressive crack closure, the life is 2.7 million cycles. This must be divided by 4 to satisfy the Structural Design Criteria or 675,000 allowed cycles. If the tensile stress range shifts to 120 MPa, because the elastic-plastic analysis is not accurate or not conservative, then the allowed cycles is 643210/4=160802 cycles – well above the required 20 to 30,000 full power cycles.

Mandrel Qualification

The nominal original mandrel thickness is .25 inches and the vertical steel outer bands are 1/8"– see Figure 6.3-7. With proposed added insulation wraps and a bit more clearance at the ID for assembly, the intention is to thin the inner mandrel to about .150". The outer bands may be thinned as well. As of this writing, the thickness is uncertain. Consequently this analysis assumes a minimum thickness of .125 for the inside and 1/16" for the bands. In the original qualification calculation, the bands were not intended to take the primary vertical loading from the coil. They were added to aid centering of the coil. The bending of the lower flange ledge was taken by stresses in the inner shell. To allow the thinning of the shells, the vertical steel bands will be included as necessary structural elements.

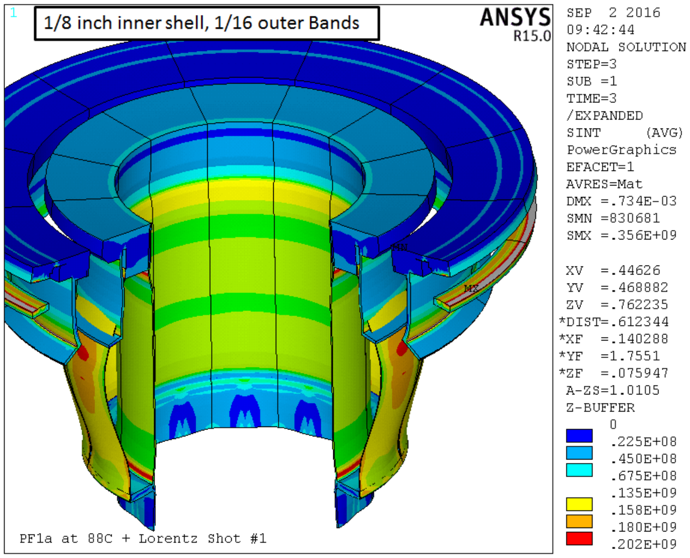


Figure 4.0- Stress with 88C Coil Temperature and Full Lorentz (Vertical and Radial) Loads

Acceptance Test, Analysis of the Free Standing Coil Test

The current plan is to perform a "full performance" test on the new coil, to qualify it's use in the machine. Full current of 19 kA is planned and 20 full j^2*t heat-up pulses with cooldown will be included. PF1a lower will be available for test first. Testing this coil to full performance can qualify it for re-installation into NSTXU and/or build confidence in the quality of the PF1b and c coils, and help determine if PF1b, and c U&L should be re-manufactured. Cooldown from the full j^2t heat-up will provide a qualification of the thermal strains and plasticity expected even in the harder conductor of the existing coil. The planned test will be conducted in the FCPC on a fixture mounted to the floor. Using the existing bus bars that have been taken out of the machine, will eliminate one fabricated component and add some confidence that the leads and bus bar connections used in the machine are acceptable. The connection to flex cables will also be as is used in the machine. . The bus support brackets that connect to the umbrella structure could also be used. As of this writing the plan is to use an existing bus bar connection. Loading of the bus bar connections to the free standing coil will be less than they experience in the machine due to the lack of toroidal field and background field from the rest of the poloidal field coils. The free standing 19 kA case produced 24 MPa peak around a coolant hole. The details of this analysis are included in section 20.0

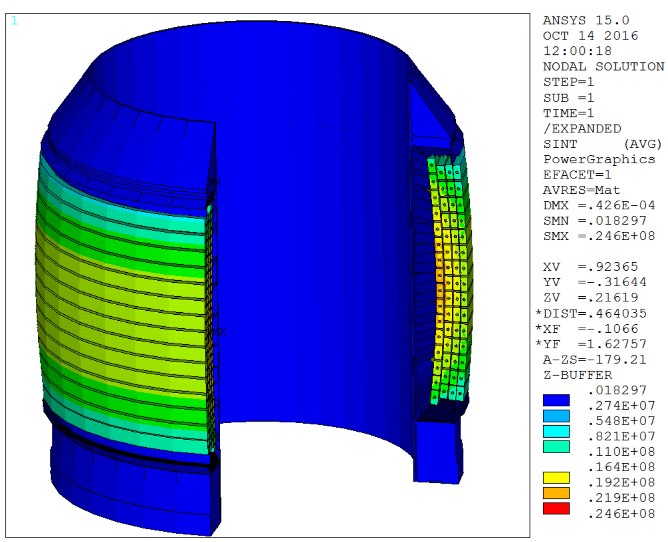
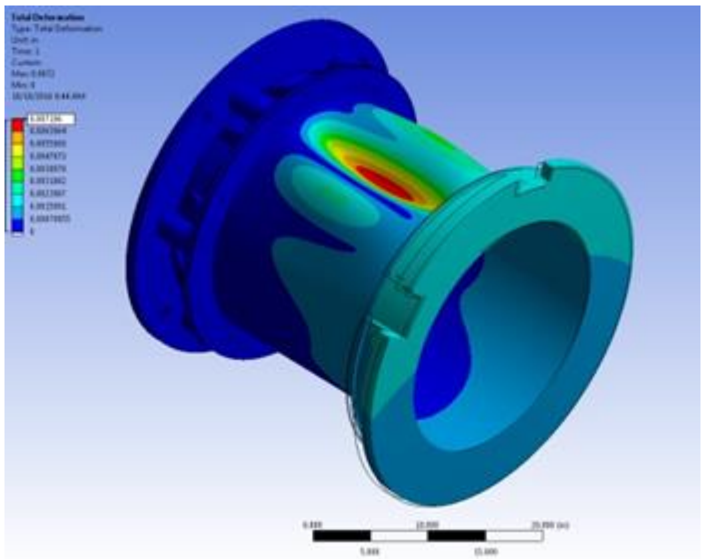


Figure 4.0-10 Free-standing Test Coil Conductor Stress

The proposed test will not include the 95770 lbs vertical load on the coil from the interaction with the rest of the PF coils. This is a significant driver in the local insulation stress as it concentrates on the corners due to the flange flexure. . However the restraint of thermal expansion is an even larger source of corner compressive stress and this will be included in the tests. Normal operating corner stress is about twice that in the test at 80 MPa Tresca and 10 to 20 MPa Shear. The insulation system is strong in compression , > 400 MPa for G-11 used for the ramps and fillers. The CTD 425 system compressive strength isn't known but I will be well above the 80 MPa experienced in the corner. Compression augments the shear capacity. G-11 strengths are included in Table 6.4.1.2 -2 and [15]. Corner insulation integrity will rely on the integrity and plasticity of the Kapton Tapes around the conductors and in the ground wrap.

Winding Process Loads



Stresses on the thinner inner wall of the mandrel were evaluated. This is discussed in section 19.2. Loads applied in the winding process were estimated in section 15.0 The conclusion is that no internal stiffener is essential, however internal supports were built for the machining and these are planned for use during winding.

5.0 Digital Coil Protection System.

The protection of all inner PF coils is included in the DCPS. Vertical loads and hoop stresses due to Lorentz loads are included. Cooldown stresses are not. Stress concentrations due to local details of the winding patterns are not large and the existing DCPS multipliers are deemed adequate. I the future, if cycle counting is implemented outside the DCPS, then the severity and number of cooldown cycles should be considered.

6.0 Design Input

6.1 Criteria

The main guidance on the design requirements for the inner PF coils is found in the Upgrade project General Requirements Document[1], the John Menard 96 equilibria spreadsheet (in the design point spreadsheet [2]) and the design point spreadsheet. Stress Criteria are found in the NSTX Structural Criteria Document[11]. The stress criteria has been simplified into one tensile stress limit for copper conductors based on an assessment of the fatigue life capabilities of the OH conductor [10]. Maintaining the tensile stress below 125 MPa will satisfy the fatigue limit of all the copper except copper that has been annealed by the brazing operation. It should be pointed out that brazed conductor was included in the assessments in reference [10] for components that may be fully annealed, low cycle fatigue and elastic-plastic shake-down are considered.

6.2 References

[1] NSTX Upgrade General Requirements Document, NSTX_CSU-RQMTS-GRD Revision 5, C. Neumeyer, June 14 2012

[2] NSTX-U Design Point Spreadsheet, **NSTXU-CALC-10-03-00** C. Neumeyer, http://w3.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html

[3] NSTX-U Manufacturing Specification, Fabrication of Inner Poloidal (PF) Coils D-NSTX-SPEC-134-137 Rev 0

[4] Drawing E-DC1500 PF-2 and PF-3 Coils Lead Reinforcement Bracket Details

[5] NSTX Upgrade CHI Bus Bar Analysis NSTXU-CALC-54-01-1 Rev 0 November 21, 2013 by P. Titus, Reviewed by A. Khodak

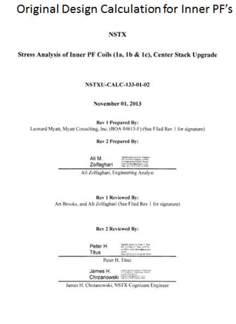
[6] Power Supply Cables PF and TF flag adapter plate details, Drawing E-DC1201

[7] 1EDC1742.pdf CENTERSTACK UPGRADE PF COIL SYSTEMS PF-1A UPPER COIL LEAD SUPPORT BRACKET ASSEMBLY

[8] October 10 2016 email from Mike Kalish with production dimensional values and yields for the copper conductor for the new PF1a coil – Included in Appendix B

[9] "Stress Analysis of the Inner PF Coils (1a,1b &1c), Center Stack Upgrade" NSTXU CALC 133-01-2 L. Myatt and A Zolfaghari

Original Design Calculation for Inner PF's


NSTX

Stress Analysis of Inner PF Coils (1a, 1b & 1c), Center Stack Upgrade

NSTXU-CALC-133-01-02

November 01, 2013

Rev 1 Prepared By:
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Rev 2 Reviewed By:

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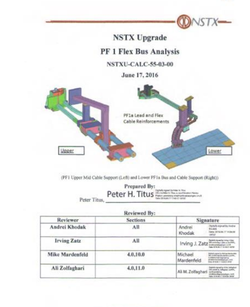
Stress Analysis of Inner PF Coils NSTX CS Up-Grade Page 1

Recent Qualification of PF1a Flex Bus Support


NSTX Upgrade

PF 1 Flex Bus Analysis

NSTXU-CALC-55-03-00

June 17, 2016

(PF1 Upper Mid Cable Support (Left) and Lower PF1a Bus and Cable Support (Right))

Prepared By:
Peter Titus, Peter H. Titus

Reviewed By:

Reviewer	Sections	Signature
Andrei Khodak	All	Andrei Khodak
Irving Zatz	All	Irving J. Zatz
Mike Mardenfeld	4.0,10.0	Michael Mardenfeld
Ali Zolfaghari	4.0,11.0	Ali M. Zolfaghari

PF1a Flex Bus and Connections Page | 1

[10] P. TITUS OH Conductor Fatigue Analysis NSTXU-CALC-133-09-00 Rev 0 Jan 7 2011, PPPL

[11] NSTX Structural Design Criteria Document, NSTX_DesCrit_IZ_080103.doc I. Zatz Plasma Physics, APS 2011 Conference November 14-18 2011 Salt Lake City

[12] NSTX Structural Analysis of PF1, TF and OH Bus Bars NSTX-CALC--55-01-02 February 15, 2011 , Rev 2 June 2015, Andrei Khodak

[13] " Thermal Conductivity of Polymide Film between 4.2 and 300K With and Without Alumina Particles as Filler" Rule, Smith, and Sparks, NISTIR #3948. August 1990.

[14] NSTX Upgrade OH & Inner PF Coil CONDUCTOR SPECIFICATION D-NSTX-SPEC-13-129 Rev.00 WP#1672 Date: August 23, 2011

[15] "Mechanical, Electrical and Thermal Characterization of G10CR and G11CR Glass Cloth/Epoxy Laminates Between Room Temperature and 4 deg. K", M.B. Kasen et al , National Bureau of Standards, Boulder Colorado.

[16] Flex Cable Catalog, Northern Connectivity Systems Inc Commodore Machine Company 1749 Northwood Drive, Troy Michigan

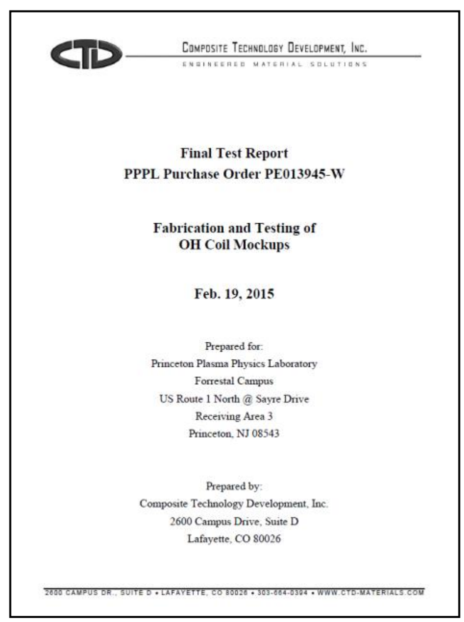
[17] NSTX Upgrade PF 2/3 Terminal and Flex Bus Analysis NSTXU-CALC-55-02-01

[18] Centerstack Upgrade PF Coil System Upper PF1a Bus Assembly, Drawing #E-DC1804

[19] PF-1aU Bus Bending FDR Slides S.P. Gerhart, Last Updated 5/26/2016

[20] drawing #DC11003 Centerstack Upgrade PF Coil System PF1a Upper Bus Support

[21] OH Cooldown System and Preheater, NSTXU CALC-133-17-0 March 4 2015, P. Titus


Composite Technology Development, Inc.
Engineered Material Solutions

Final Test Report
PPPL Purchase Order PE013945-W

Fabrication and Testing of
OH Coil Mockups

Feb. 19, 2015

Prepared for:
Princeton Plasma Physics Laboratory
Forrestal Campus
US Route 1 North @ Sayre Drive
Receiving Area 3
Princeton, NJ 08543

Prepared by:
Composite Technology Development, Inc.
2600 Campus Drive, Suite D
Lafayette, CO 80026

2600 Campus Dr., Suite D • Lafayette, CO 80026 • 303-664-0394 • www.ctd-materials.com

[22] email from Jim Chrzanowski forwarding the physicals Luvata could supply for the OH coil, Included in Appendix B
[23] STATEMENT OF WORK FOR NSTX-U OH Coil Insulation Strain-Controlled Tests and Elevated Temperature Creep Tests D-NSTXU-SOW-13-197 REVISION 0 DATED *October 22, 2014*
[24] Final Test Report, "PPPL Purchase Order PEO13945-W" "Fabrication and Testing of OH Coil Mockups", Feb 19 2015, Composite Technology Development Inc.
[25] local interactions between PF1a and the OH to augment the DCPS calculations of the OH hoop stress, NSTXU CALC 133-14-00.
[26] "Magnetic stability between PF1a and the OH" NSTXU-CALC-133-11-00
[27] Cyclic Stress Analysis of a Rocket Engine Thrust Chamber Using Chaboche, Voce and Creep Constitutive Models, A.K.ASRaff, The Indian Institute of Metals Copyright 2016
[28] The Cyclic Stress Strain Response of Copper, GRD-39 (CIT Project) July 15 1988, J. Chen MIT-PSFC
[29] July 13 2016 email from Arthur Brooks <abrooks@pppl.gov> with ACOOL results – See Appendix B
[30] Forensic Analysis of the NSTX-U PF1A-Upper Coil Failure Rev. 0 November 18, 2016, Irving Zatz, Joe Petrella
[31] Email from Paul Fabian to C. Neumeyer, December 14 2016 CTD indicated that the G-10 should survive theCTD 425 VPI process process acceptably. Included in Appendix G
[32] CALCULATION OF OH COIL STRESSES IN THE NSTX CSU NSTXU-CALC-133-08-01 October 17, 2013 A. Zolfaghari

6.3 Photos and Drawing Excerpts

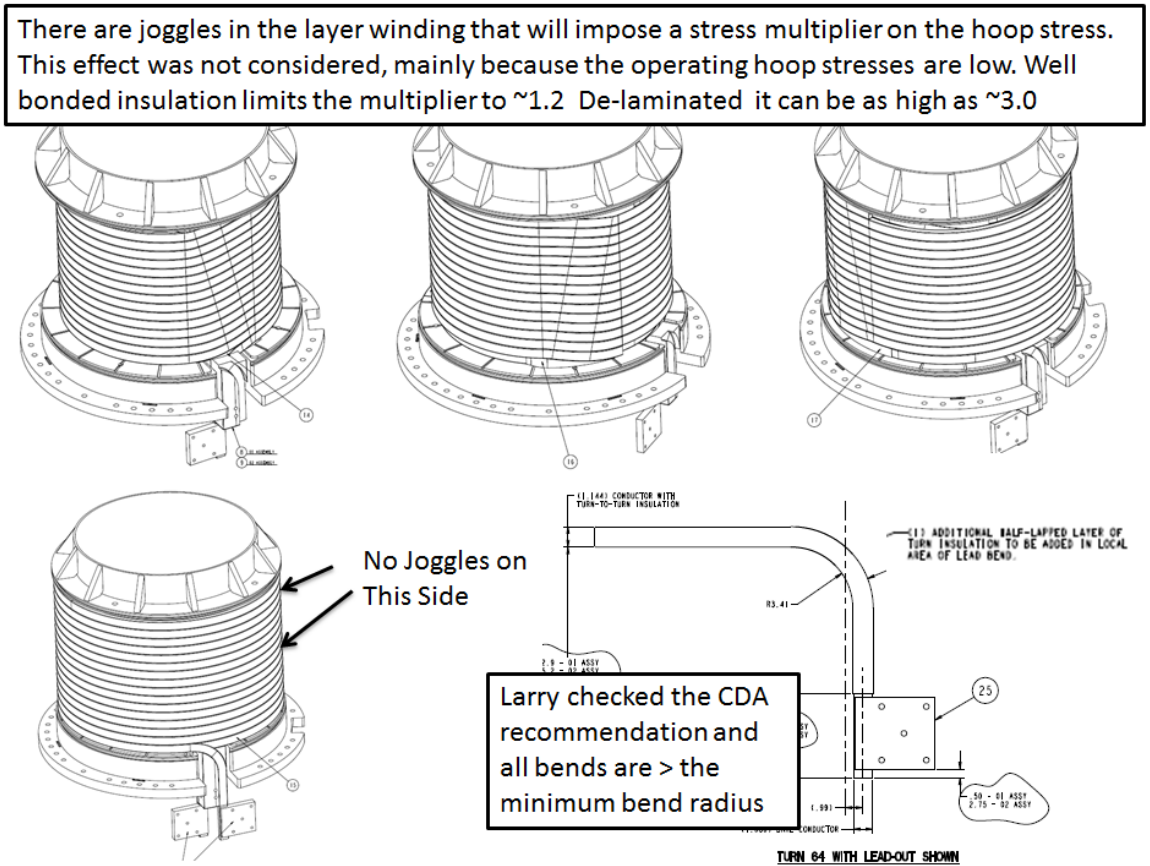


Figure 6.3-1 PF1a Winding Layout from the Drawing [20]

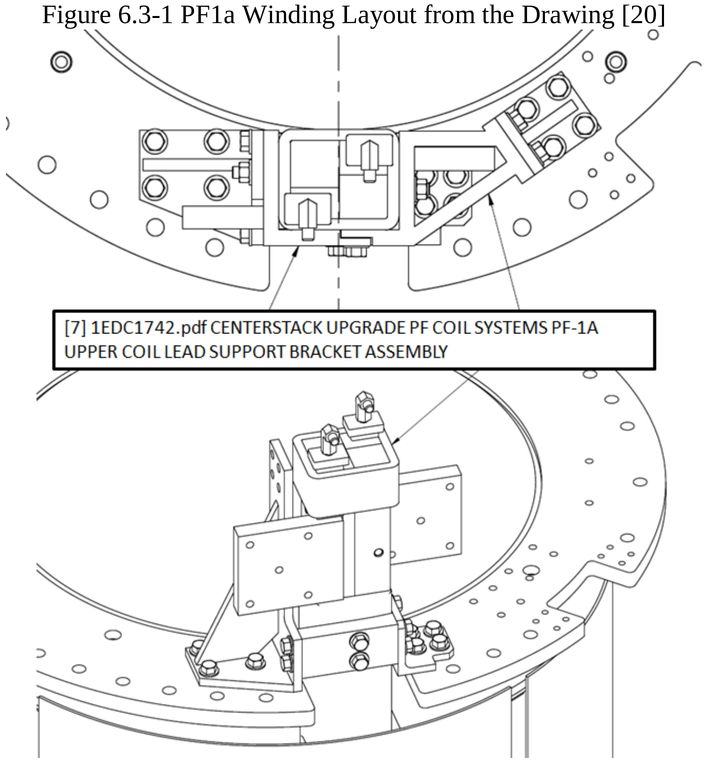


Figure 6.3-2 PF1a Upper and Lower Terminal Tower Assembly and Partial Assembly

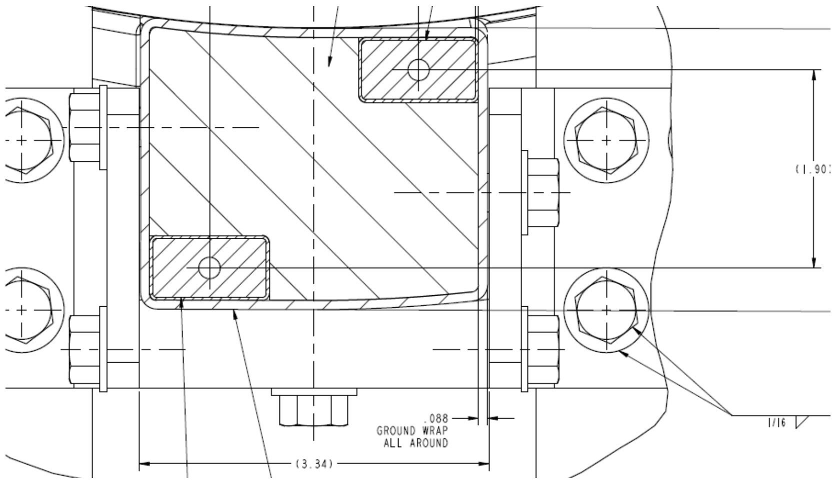
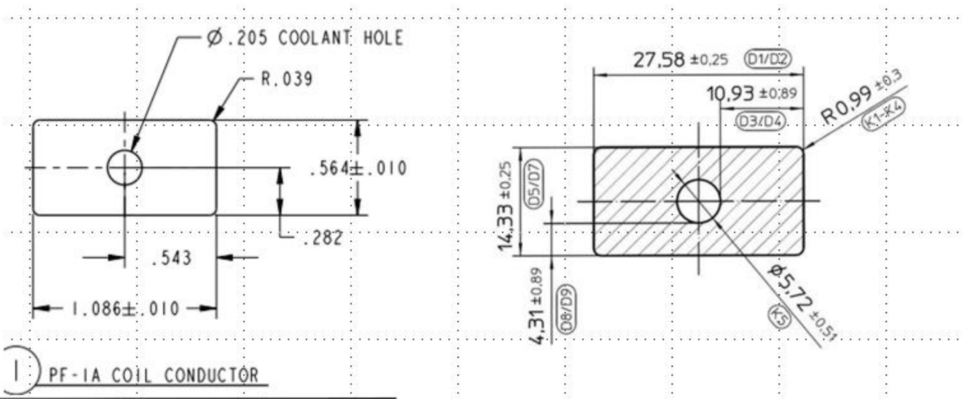


Figure 6.3-3 Cross Section of PF1a, and Terminal "Tower"



PF1A comparison	Existing	Modified
height (in)	1.086	1.086
width (in)	0.564	0.564
hole dia (in)	0.205	0.2252
CS area (in2)	0.5795	0.5727
Coil volume per model (in3)	2939.4	2775
conductor length (in)	5072.3	4846.4
conductor length (ft)	422.6937	403.9
mean circumference Length (ft)	6.72	6.70
# mean turns	62.9	60.3
Turn delta (#)		2.6
Turn ratio (%)		95.8%
Volume delta (%)		94.4%

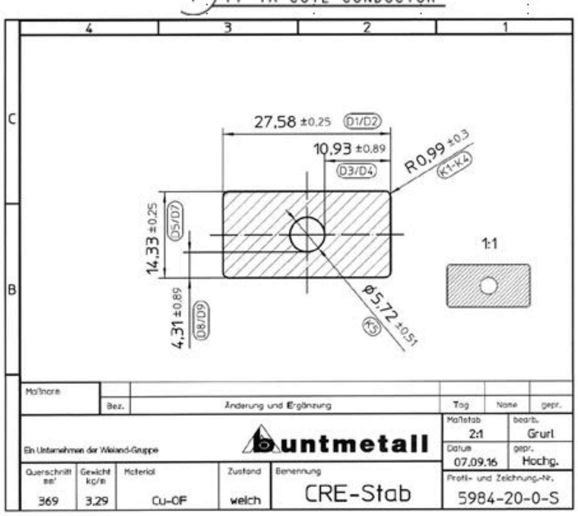


Figure 6.3-4 PF1a Replacement Coil Conductor Cross Section

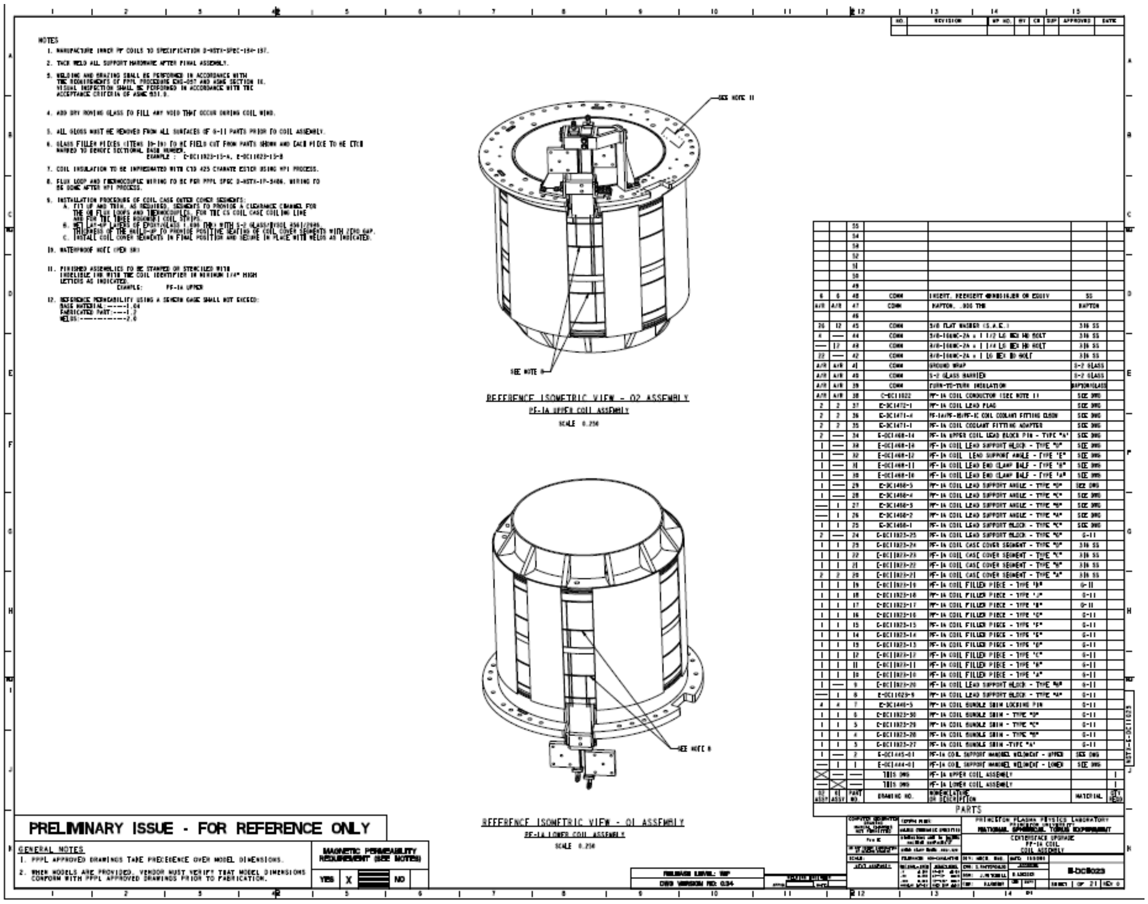


Figure 6.3-4 Preliminary Drawing of the New PF1a Coil

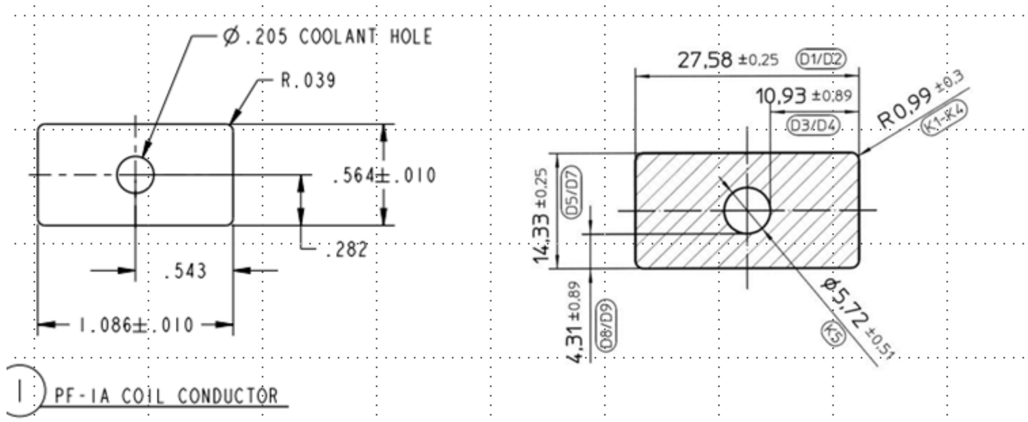
From Reference 8, Appendix B:
Pete,
fyi... I'm resending the email I sent last week with the Wieland conductor test results. This will be useful for your 1mm crack calculation.
Note that in the attachment the wall thickness on the drawing is 4.31mm +/- .89mm or
3.42mm minimum wall thickness required
The wall thickness in the inspection report attached is 4.31mm - .293mm =

4.02mm minimum wall thickness as built
The yield strength test results are also included in the attachments.
Thanks,
Mike

From a 2011 email from Jim Chrzanowski, Reference [22] in Appendix B:

Tensile Strength min. PPPL requested: 36-38 ksi / Luvata Proposal: 33 000 psi (min. 227 N/mm2)
Yield 0,5 % Strength: PPPL Requested: 28-30 ksi / Luvata Proposal: 29 000 - 36 000 psi (200-250 N/mm2)
Elognation A 5 min 25 %
Hardness max.: PPPL Requested: 60-70 HRF / Luvata Proposal ; 81 HRF (max. 90 HV)

The OH calculation [32] included a qualification of the primary stress limit for the OH coil based on a minimum yield of 28 ksi or 193 MPa



PF1A comparison	Existing	Modified
height (in)	1.086	1.086
width (in)	0.564	0.564
hole dia (in)	0.205	0.2252
CS area (in2)	0.5795	0.5227
Coil volume per model (in3)	2939.4	2775
conductor length (in)	5072.3	4846.4
conductor length (ft)	422.6937	403.9
mean circumference Length (ft)	6.72	6.70
# mean turns	62.9	60.3
Turn delta (#)		2.6
Turn ratio (%)		95.8%
Volume delta (%)		94.4%

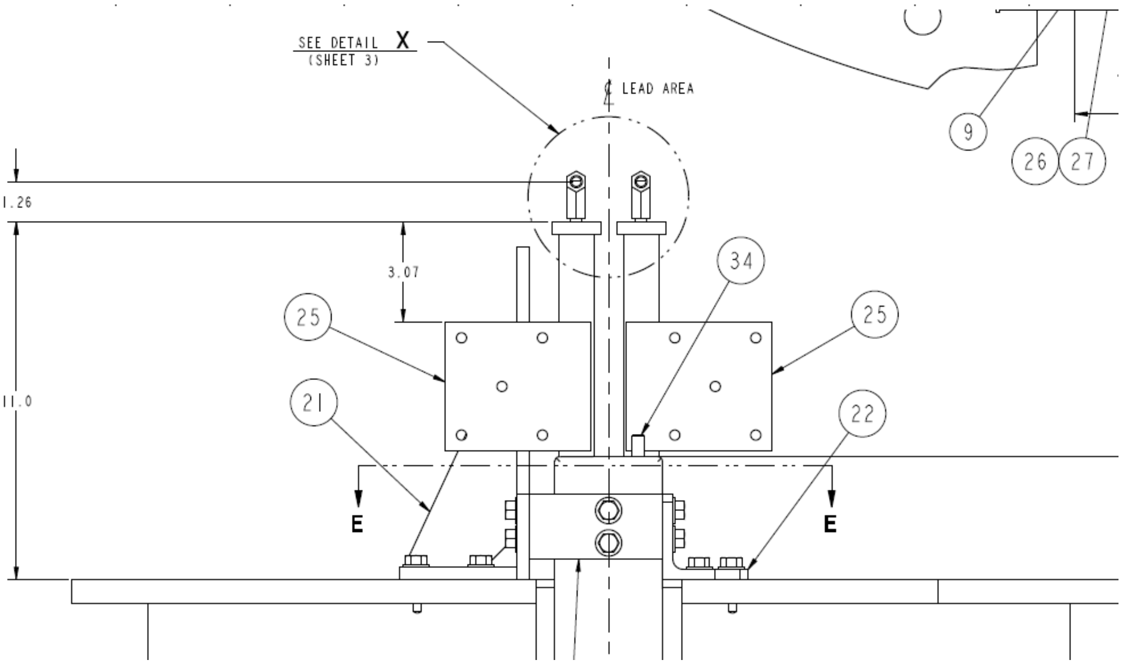


Figure 6.3-5PF1a Terminal Layout - Elevation

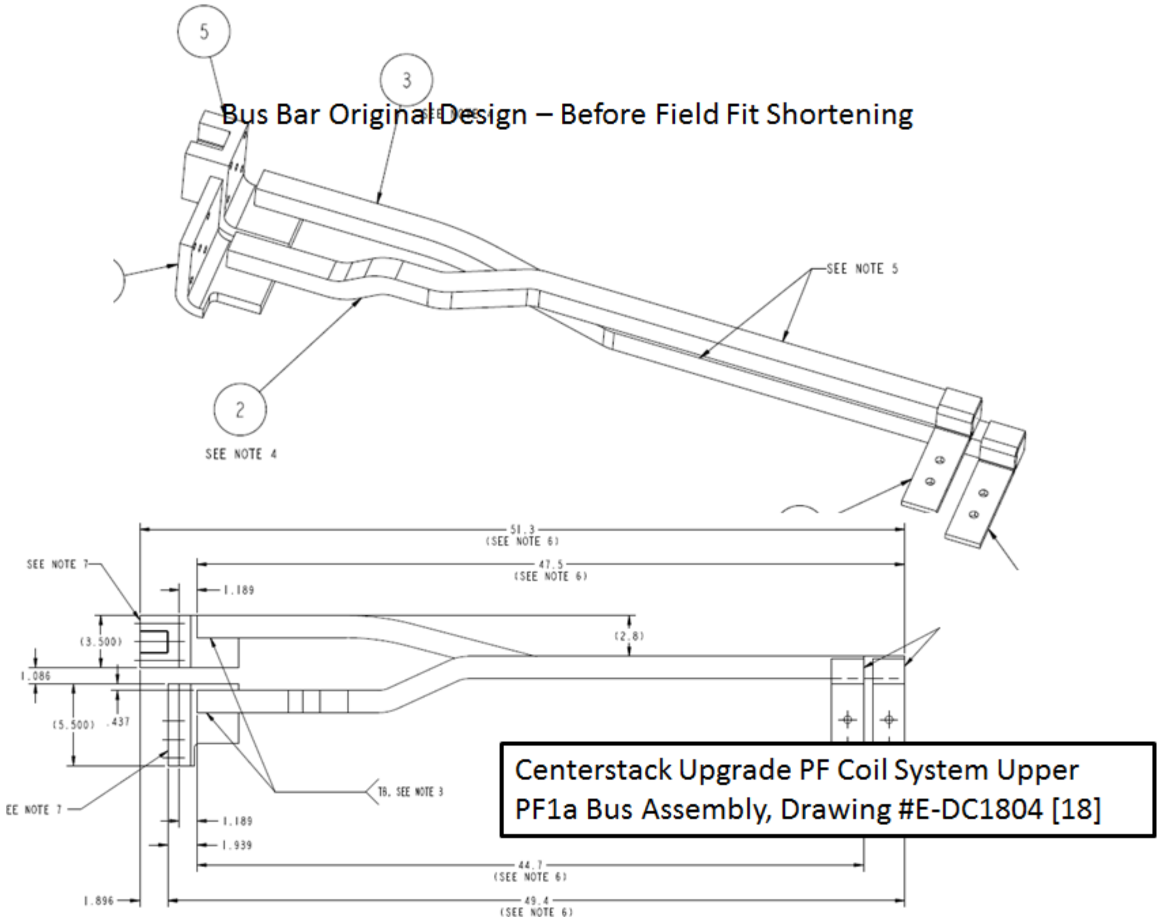


Figure 6.3-6 Original PF1a Upper Bus Design – Before Field Fit-Up

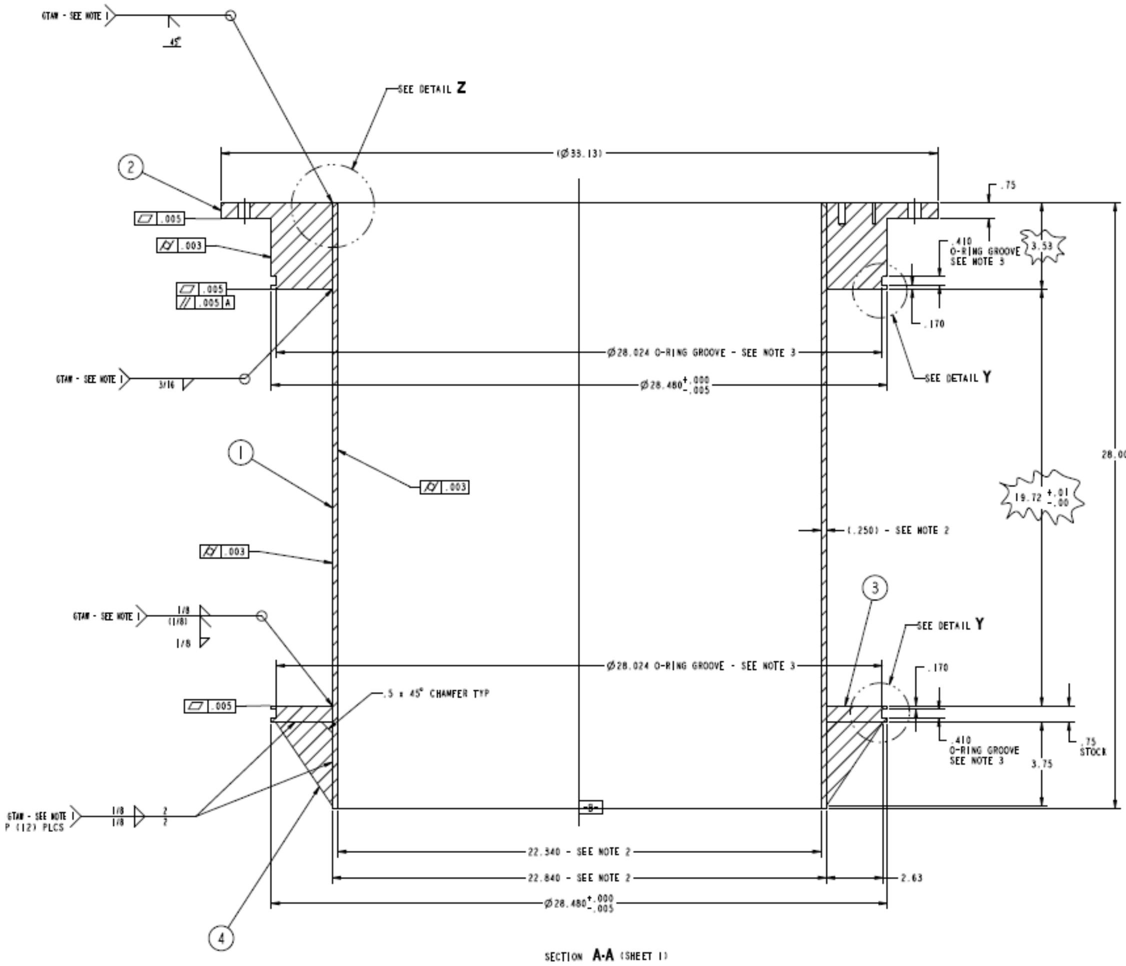
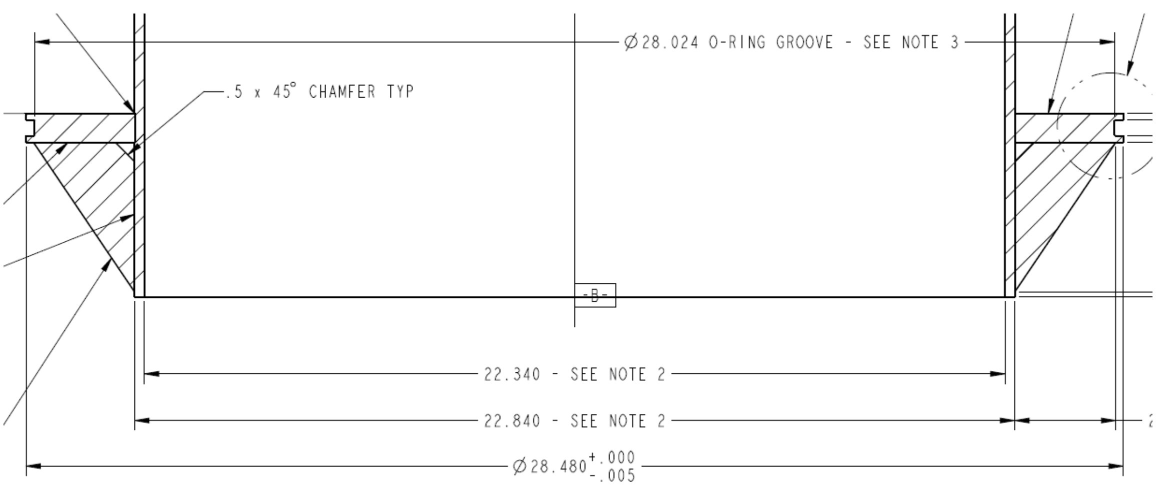


Figure 6.3-7 Original PF1a Mandrel Cross Section



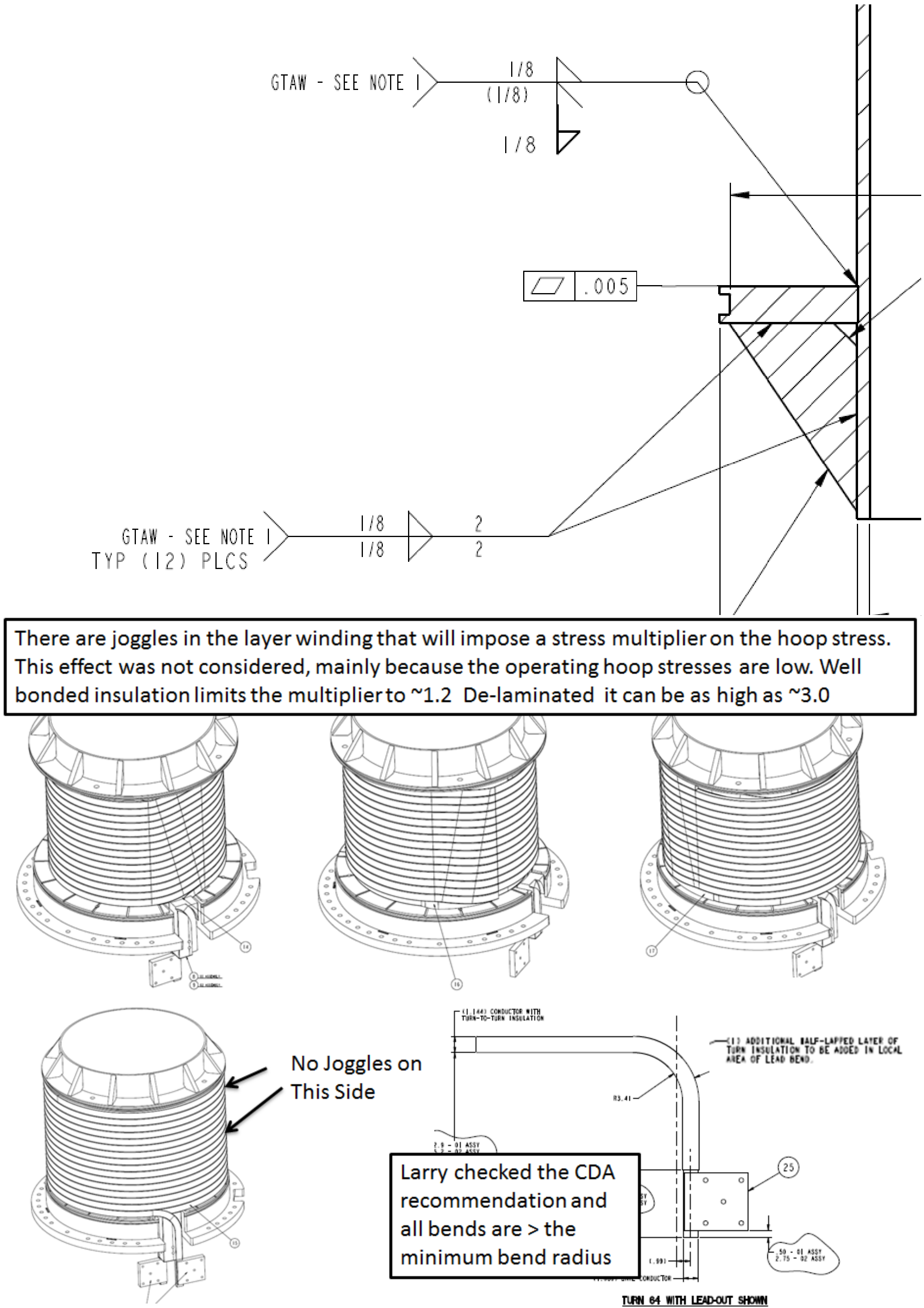


Figure 6.3-7 PF1a Layer Winding Layout

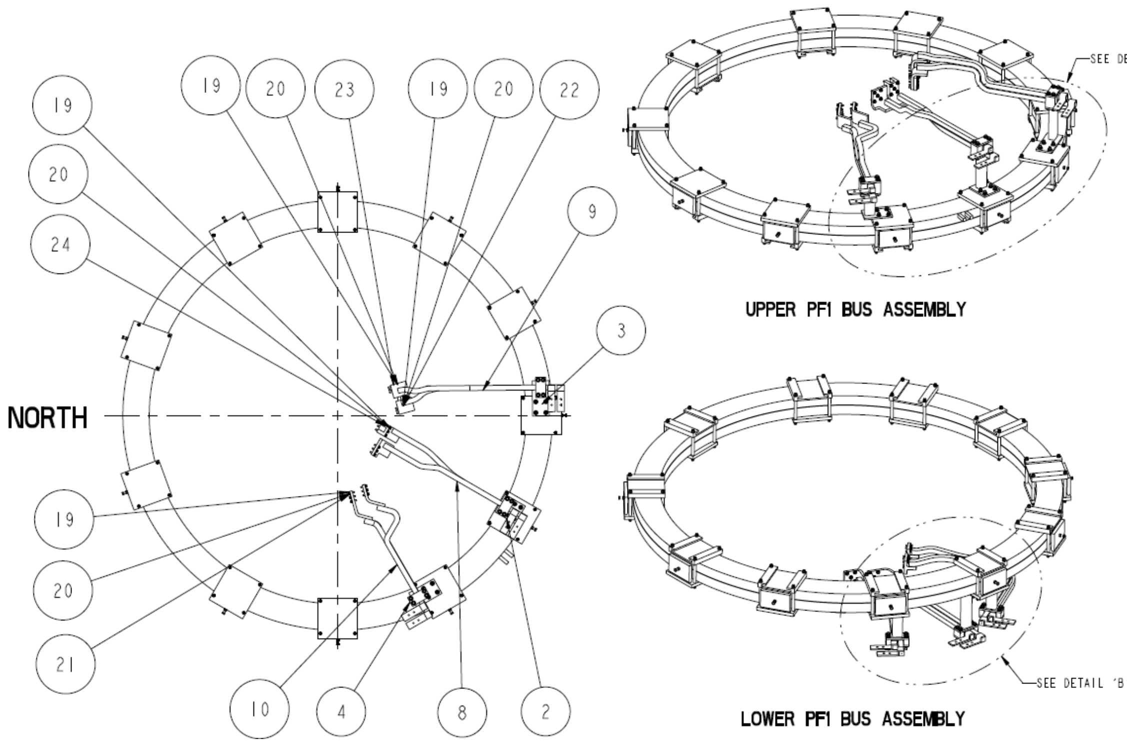


Figure 6.3-8 Original Configuration/Drawing of the PF1 solid bus bars. As-Installed Conditions are Different.

6.4 Materials and Allowables
6.4.1 Properties for Analysis
6.4.1.1 Copper

From the original copper purchase specification [14] :

The material required is UNS C10700 oxygen-free copper with silver content of 25 troy oz/ton (.085% Ag). The material shall be of such quality and purity that the finished product shall have the properties and characteristics prescribed in this specification and shall be cold drawn to produce the required temper, edge and surface finish. The conductors shall be furnished in the cold drawn condition.

1.1.1 E-DC1536 and Inner PF Coil Conductor drawing C-DC1486.

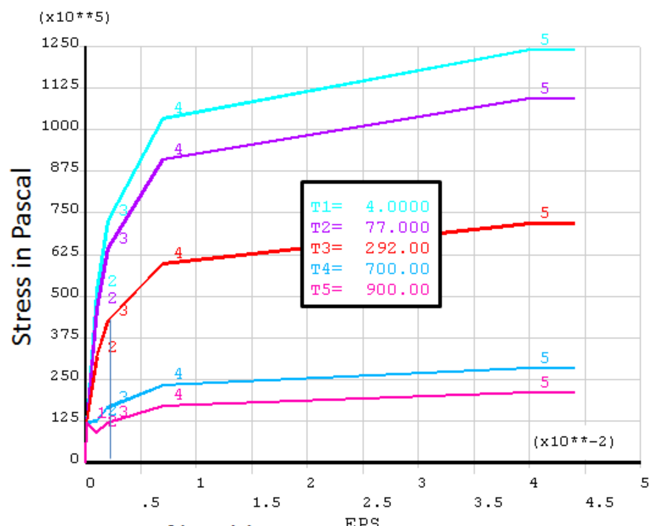
1.2 Strength

1.2.1 Yield Strength shall range between 28,000 psi min. to 30,000 psi (0.5% elongation) at room temperature. (Temper: Quarter to Half Hard)

1.2.2 Ultimate Tensile Strength shall range between 36, 000 to 38,000 psi minimum @ 35% elongation at room temperature. (Temper: Quarter to Half Hard)

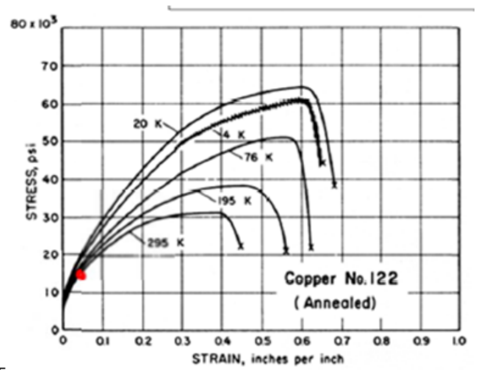
The Replacement copper will meet the same chemical requirements,but the yield is specified at 9 ksi before spooling and winding with a target yield of 12 ksi as wound on the coil

Annealed Copper Stress-Strain Used in This Calculation

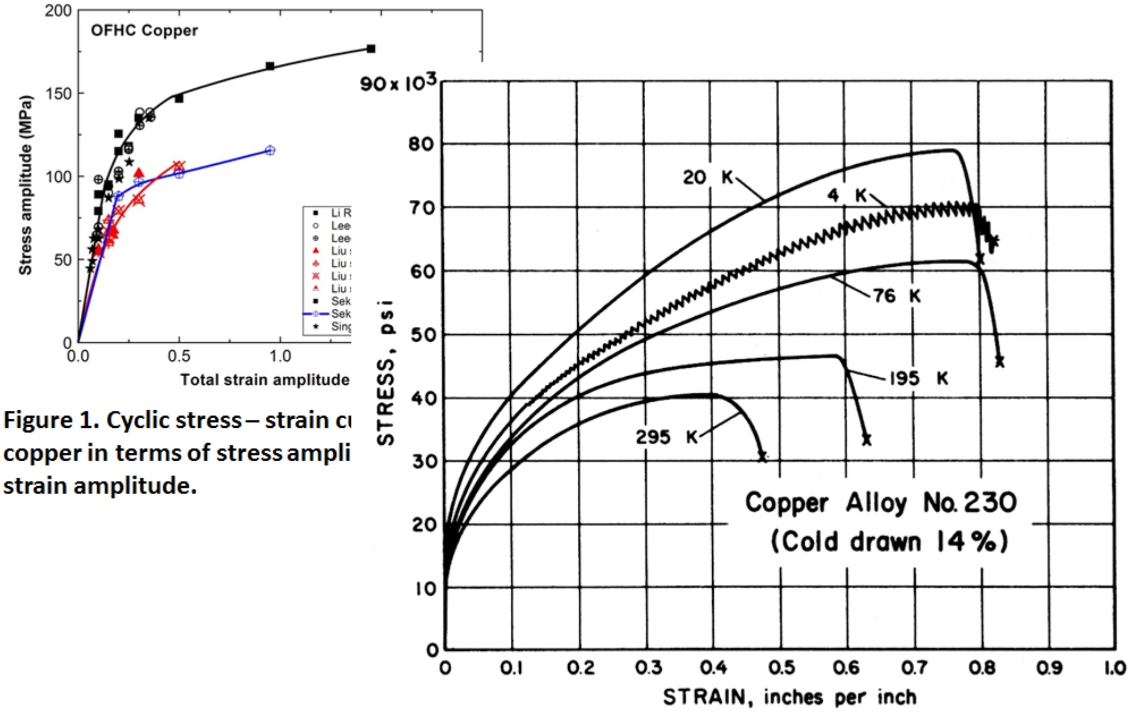


.2 % Yield ~40 Mpa = 5800psi

Annealed Copper Stress-Strain Used by M. Mardenfeld – See Appendix D



.2 % Yield ~8000psi



From: Jörg Tauchner [mailto:joerg.tauchner@buntmetall.at]
Sent: Friday, September 16, 2016 4:26 AM
To: aamaya@pppl.gov; Arlene White
Cc: dloesser@pppl.gov; fmalinowski@pppl.gov; kurt.emsermann@wieland.com; ldudek@pppl.gov; mkalish@pppl.gov; Steve Raftopoulos; Thomas Egebo; Johannes Skarek; Vilja Kolmer
Subject: Antwort: Re: Wieland Metals Purchase Order PE-015264-W

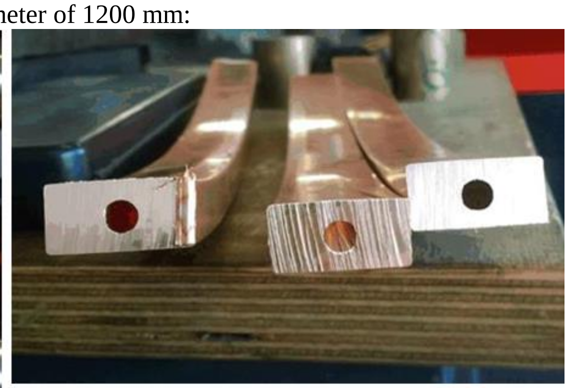
Dear Aldofo, dear Arlene,

as agreed in our last phone meeting we finished our first internal trials with following technical results we have to clarify again.
Is it possible for you to approve our mechanical results for production start or can we make an additional technical clarification via phone meeting next week?

Thank you in advance for your technical support in this project.

- Requirements acc. Offer from 07.09.2016: Rt0,5: 60 - 137 MPa ; Rm: min. 220MPa
- Results in our first trials with spooling inner diameter of 1200 mm:





Rp0,2 is .2%offset Yield, Rp0,5 is .5% offset Yield, Rm is Ultimate and A5 is percent elongation

Results after respooling

Coil No.	Rp0,2 [MPa]	Rp0,5 [MPa]	Rm [MPa]	A5 [%]	Remarks	Meters	kg
Coil 1	75	82	213	56	Coil 1 A start after winding on diameter 600 mm	143,5 + 3,5 m	484 kg
Coil 1	78	84	212	55	Coil 1 E end after winding on diameter 1200 mm		
Coil 2	81	87	211	52	Coil 2 A start after winding on diameter 600 mm	143,5 +2 m	479 kg
Coil 2	81	90	211	52	Coil 2 A start after winding on diameter 1200 mm		
Coil 2	77	83	212	54	Coil2/E end after winding on diameter 1200 mm		
Coil 3	76	83	210	54	Coil3/A start after winding on diameter 1200 mm	143,5 m + 0,5 m	474 kg
Coil 3	75	81	212	54	Coil3/E end after winding on diameter 1200 mm		
Coil 4	79	86	212	54	Coil4/A start after winding on diameter 1200 mm	143,5 + 5 m	489 kg
Coil 4	79	86	212	54	Coil4/E end after winding on diameter 1200 mm		

```
chaboche_1D_strain.txt - estimated from stress stain curve for annealed copper
  Ex=119e9  ! Elastic Modulus
  Et1=110.e9  ! Tangent Modulus1 - small strain
  Et2=7.e9  ! Large strain tangent modulus
  Sy=70.e6  ! Yield Stress
  Slim=175e6 ! Limiting Stress = C1/G1 (from C1 = dS/de = d(Slim*(1-exp(-G1*e)))/de = Slim*G1)
  C1=Ex*Et1/(Ex-Et1)  ! Plastic Tangent modules1 (?)
  G1=C1/Slim
  C2=Ex*Et2/(Ex-Et2)
  G2=0
-----------------------------------------------------------------------
chaboche_1d_strain2.txt - fit to CIT data
  Ex=122.5e9  ! Elastic Modulus
  !Et1=110.e9  ! Tangent Modulus1 - small strain
  Et2=7.e9  ! Large strain tangent modulus
  Sy=105.e6  ! Yield Stress
  Slim=77e6 ! Limiting Stress = C1/G1 (from C1 = dS/de = d(Slim*(1-exp(-G1*e)))/de = Slim*G1)
  !C1=Ex*Et1/(Ex-Et1)  ! Plastic Tangent modules1 (?)
  !G1=C1/Slim
  G1=667
  C1=Slim*G1
  C2=Ex*Et2/(Ex-Et2)
  G2=0
!Mat 17, Copper
pex=ex
YIELDSTR = Sy   !Yield Strength of Material
 POISS = .3          !Poisson's Ratio for the material
 alpx,17,17e-6
 MP,EX,17,pex ! ELASTIC CONSTANTS
 MP,NUXY,17,POISS

 TB,CHAB,17,1,3 ! CHABOCHE TABLE
 TBDATA,1,YIELDSTR,C1,G1
 tbdata,4,C2,G2
```

6.4.1.2 Insulation

Table 6.4.1.2 -1. Modulus of Elasticity for G-10 at several temperatures.

Temp Deg. K	G-10 Warp/Fill Gpa	G-10 Normal Gpa	Epoxy Only Gpa
295	27.8	14.0	3.81

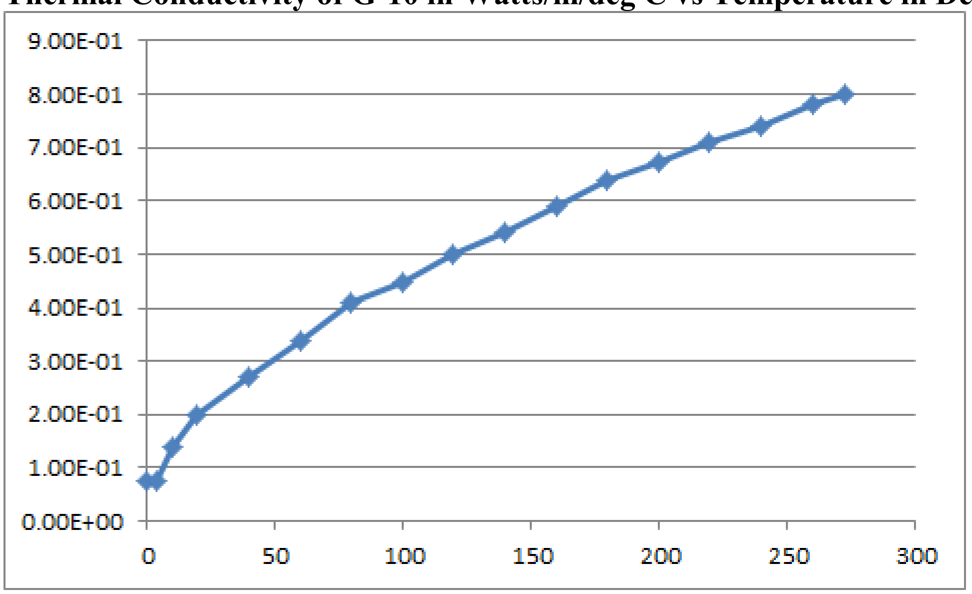
250	29.5	16.5	5.25
200	31.3	18.8	6.69
150	32.5	20.5	7.84
100	33.0	21.5	8.54
76	33.5	21.8	8.68

Table 6.4.1.2 -2 Insulating Material Strengths

	@4	@77	@292 degK
Comp.Strength Normal to Fiber			
G-10CR	749	693	420 Mpa Ref[15]
G-11CR	776	799	461 MPa Ref[15]
Tensile Strength (Warp)			
G-10CR	862	825	415 MPa Ref[15]
G-11CR	872	827	469 MPa Ref[15]
Tensile Strength (Fill)			
G-10CR	496	459	257 MPa Ref[27]
G-11CR	553	580	329 MPa Ref[27]

The insulation layer is modeled three, .001" thicknesses of Kapton tape. The thermal conductivity of the tape is about .14 W/(m-K) at 100 k and was taken from " Thermal Conductivity of Polymide Film between 4.2 and 300K With and Without Alumina Particles as Filler" Rule, Smith, and Sparks, NISTIR #3948. August 1990. [13]

Thermal Conductivity of G-10 in Watts/m/deg C vs Temperature in Degrees K



6.5 Static Allowables
6.5.1 Copper
6.5.1.1 Static Allowables for Copper Stresses

. The yield is 12ksi (262 MPa). Sm is 2/3 yield or 25.3ksi or 173 MPa – for adequate ductility, which is the case with this copper which has a minimum of 24% elongation. Note that the ½ ultimate is not invoked for the conductor (it is for other structural materials) . These stresses should be further reduced to consider the effects of operation at 100C. This effect is estimated to be 10%, so the Sm value is 156 MPa. and the bending allowable is 82.7 MPa

- From: 2.4.1.1 Design Tresca Stress Values (Sm), NSTX_DesCrit_IZ_080103.doc [11]

- • (a) For conventional (i.e., non-superconducting) conductor materials, the design Tresca stress values (Sm) shall be 2/3 of the specified minimum yield strength at temperature, for materials where sufficient ductility is demonstrated (see Section 2.4.1.2). [3]

PF1a normal operating stress of 20 MPa is well below these limits.

6.5.1.2 Fatigue Limits for Copper

The normal operating, fatigue based conductor allowable is taken to be 125 MPa based on the assessment of OH conductor fatigue based allowable in ref [10]. In This has been re-calculated for the PF1a conductor cross section and for a 1mm maximum flaw

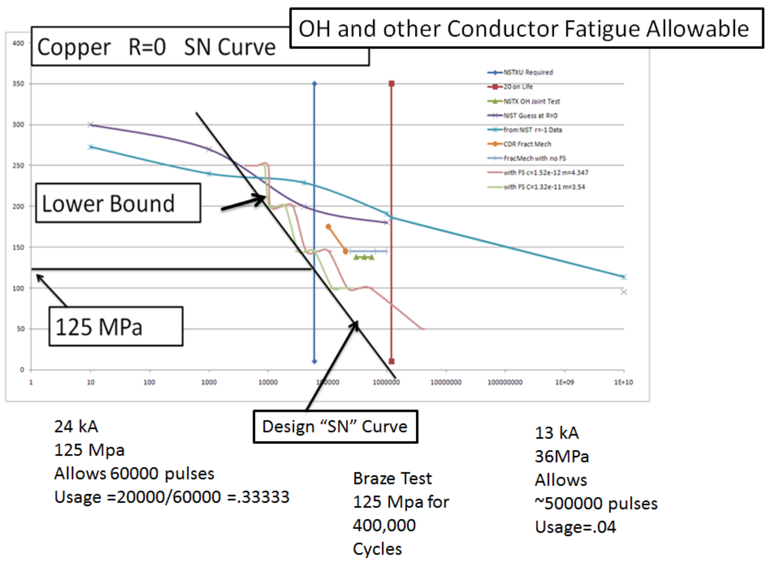


Figure 6.5.1.2 -1 Copper Fatigue Allowable Adopted for NSTX-U Conductors [10]

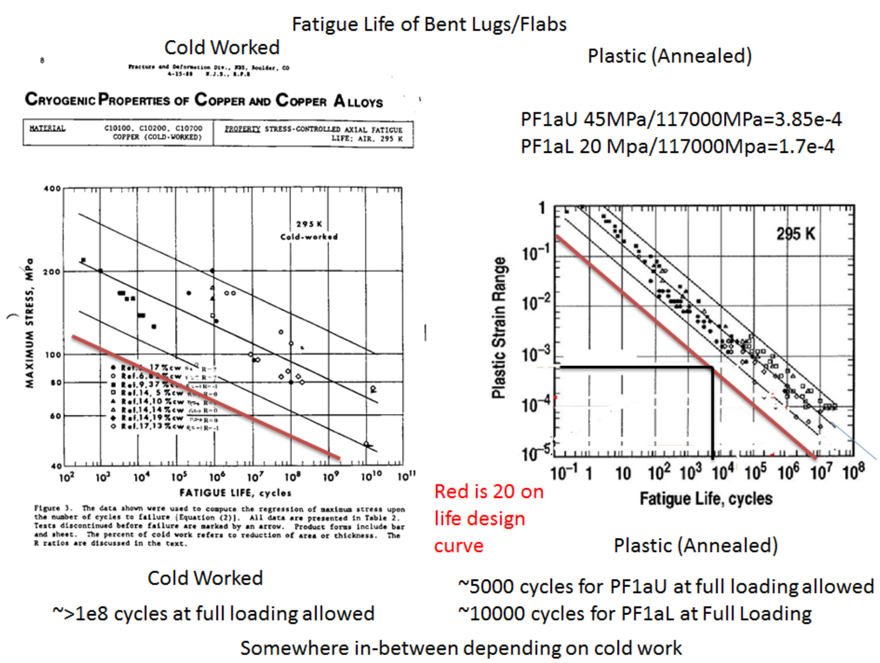


Figure 6.4.3 -2 Copper Fatigue Allowable for Elastic High Cycle vs. Plastic Low Cycle Fatigue

Disruption loading has minimal effect on the PF1 bus bars. Severe disruption loads and bake-out loads are assumed to occur only a few cycles and do not require a fatigue assessment. Stresses for these cases should meet static allowables.

6.4.1 Stainless Steel Fatigue Allowable

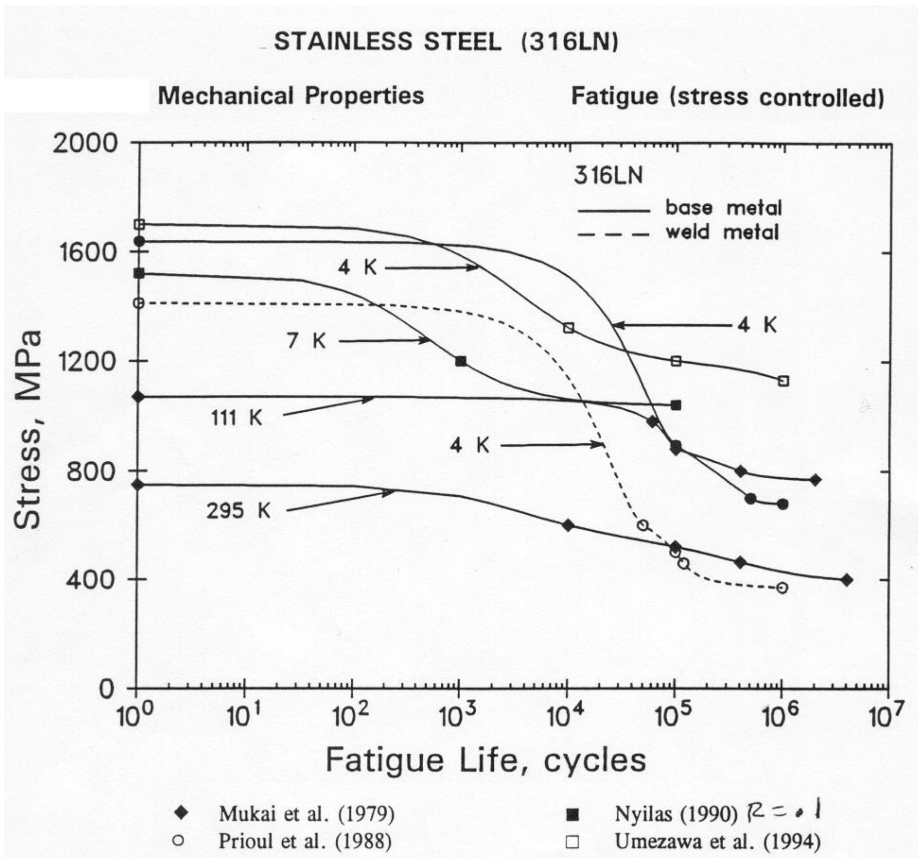


Figure 6.4.1-2 (NIST)

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

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

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

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

6.6 Coil Parameters and Max Currents for pf 1a Upper and Lower

Coil	R (center)	dR	Z (center)	dZ	nR	nZ	Turns	Fill	Turn CSA
	(in)	(in)	(in)	(in)					in^2
H (half-plar	9.531	2.73	41.934	83.868	4	111	444	0.7012	0.3616
PF1a	12.778	2.46	62.622	18.246	4	16	64	0.8244	0.5782
PF1b	15.758	1.332	71.031	7.142	2	16	32	0.7883	0.2343
PF1c	21.669	1.478	71.402	6.552	2	10	20	0.8495	0.4113

		PF1A	PF1B	PF1C
Conductor width	m	0.0143	0.0161	0.0179
Conductor height	m	0.0276	0.01	0.0153
Cooling hole diame	m	0.0052	0.0032	0.0032
Corner radius	m	0.001	0.001	0.001
Turn insulation	m	0.0007	0.0007	0.0007
nr		4	2	2
dr (over Cu)	m	0.0625	0.0338	0.0375
r_center	m	0.3246	0.4003	0.5504
nz		16	16	10
dz (over Cu)	m	0.4634	0.1814	0.1664
z_center	m	1.5906	1.8042	1.8136
n		64	32	20
Packing fraction		0.8244	0.7883	0.8495
Current	kA-turn	1216	416	320
Current per turn	amp	19000	13000	16000
ESW at Max Currer	sec	5.5	2.1	4.3
Action	A^2-sec	1.99E+09	3.56E+08	1.10E+09
T_max	deg_C	92	100	100
Max Power Supply	volt	2026	2026	2026
Voltage per turn	volt	31.7	63.3	101.3
Layer-layer voltage	volt	1013	2026	2026
Turn insulation max	kv/mm	0.6	1.2	1.2
Ground insulation	m	0.0022	0.0028	0.0018
Ground & turn insul	m	0.0029	0.0035	0.0026
Turn-ground stress	kv/mm	2.1	1.7	2.4
Hipot voltage	Volt	13103	13103	13103
Turn-ground stress	kv/mm	4.5	3.7	5.1

		PF1A	PF1B	PF1C
Conductor width	in	0.564	0.633	0.705
Conductor height	in	1.086	0.392	0.603
Cooling hole diame	in	0.205	0.126	0.126
Corner radius	in	0.0394	0.0394	0.0394
Turn insulation	in	0.029	0.029	0.029
nr		4	2	2
dr (over Cu)	in	2.46	1.332	1.478
r_center	in	12.778	15.758	21.669
nz		16	16	10
dz (over Cu)	in	18.246	7.142	6.552
z_center	in	62.622	71.0315	71.4016
n		64	32	20
Packing fraction		0.8244	0.7883	0.8495
Current	kA-turn	1216	416	320
Current per turn	amp	19000	13000	16000
ESW at Max Currer	sec	5.5	2.1	4.3
Action	A^2-sec	1.99E+09	3.56E+08	1.10E+09
T_max	deg_C	92	100	100
Max Power Supply	volt	2026	2026	2026
Voltage per turn	volt	31.7	63.3	101.3
Layer-layer voltage	volt	1013	2026	2026
Turn insulation max	Volt/mil	14.9	30.7	29.8
Ground insulation	in	0.086	0.11	0.072
Ground & turn insul	in	0.115	0.139	0.101
Turn-ground stress	Volt/mil	52.6	43.5	59.9
Hipot voltage	Volt	13103	13103	13103
Turn-ground stress	Volt/mil	113.9	94.3	129.7

For many of the NSTX calculations, EQ 79 is used as the most limiting. This results from global torque assessments for which EQ 79 is the largest. It is not clear if that is the worst for the PF 1a upper and lower. The worst – or maximum current from the design point spreadsheet [2] is 19 kA. This was used in developing the Lorentz forces to apply on the structural model. In Figure 9.1.1, the 96 equilibria currents are plotted. Some equilibria have negative currents. These are only 7.161 kA vs. the 19 kA that was used in developing the loading on the finite element models. Stefan Gerhardt has presented that showed no reversal of the PF1a Currents in early operation.

Fr(lbf)	PF1aU	PF1bU	PF1cU	PF1cL	PF1bL	PF1aL
Min w/o Plasma	-35364	-39917	-71314	-71290	-5460	-35367
Min w/Plasma	-86091	-3452	-51380	-51356	-3452	-86092
Min Post-Disrupt	-56775	-1387	-49577	-49552	-1387	-56777
Min	-86091	-39917	-71314	-71290	-5460	-86092
Worst Case Min	-308932	-259553	-280590	-280542	-259506	-308941
Max w/o Plasma	244828	141199	98727	46515	141221	124108
Max w/Plasma	390442	176824	17578	17561	176800	221474
Max Post-Disrupt	271221	159652	18316	18297	159632	139721
Max	390442	176824	98727	46515	176800	221474
Worst Case Max	1202680	427957	291802	291843	427989	1E+06
Fz(lbf)	PF1aU	PF1bU	PF1cU	PF1cL	PF1bL	PF1aL
Min w/o Plasma	-80237	-34659	-18534	-58912	-84182	-42574
Min w/Plasma	-71687	-49080	-32610	-50407	-78646	-31269
Min Post-Disrupt	-95770	-33155	-22126	-59782	-83221	-35298
Min	-95770	-49080	-32610	-59782	-84182	-42574
Worst Case Min	-169764	-204276	-126322	-114523	-139881	-300586
Max w/o Plasma	53473	84182	58912	20585	34659	80236
Max w/Plasma	37012	78647	50408	32609	49080	71686
Max Post-Disrupt	46450	83220	59782	22125	33155	95770
Max	53473	84182	59782	32609	49080	95770
Worst Case Max	300589	139882	114523	126322	204275	118263

Maximum PF 1a U,L Currents

These are as specified in the design point spreadsheet :

Coil	Min Curr*	Max Curr*
	(kA)	(kA)
OH (half-plane)	-24	24
PF1a	-8	19
PF1b	-6	13
PF1c	-5	16
PF2a	-11	15
PF2b	-11	15
PF3a	-16	12
PF3b	-16	12
PF4b	-16	6
PF4c	-16	6
PF5a	-34	0

These are maximum currents possible for the individual coils. Below the max currents expected for the 96 Equilibrium are plotted.

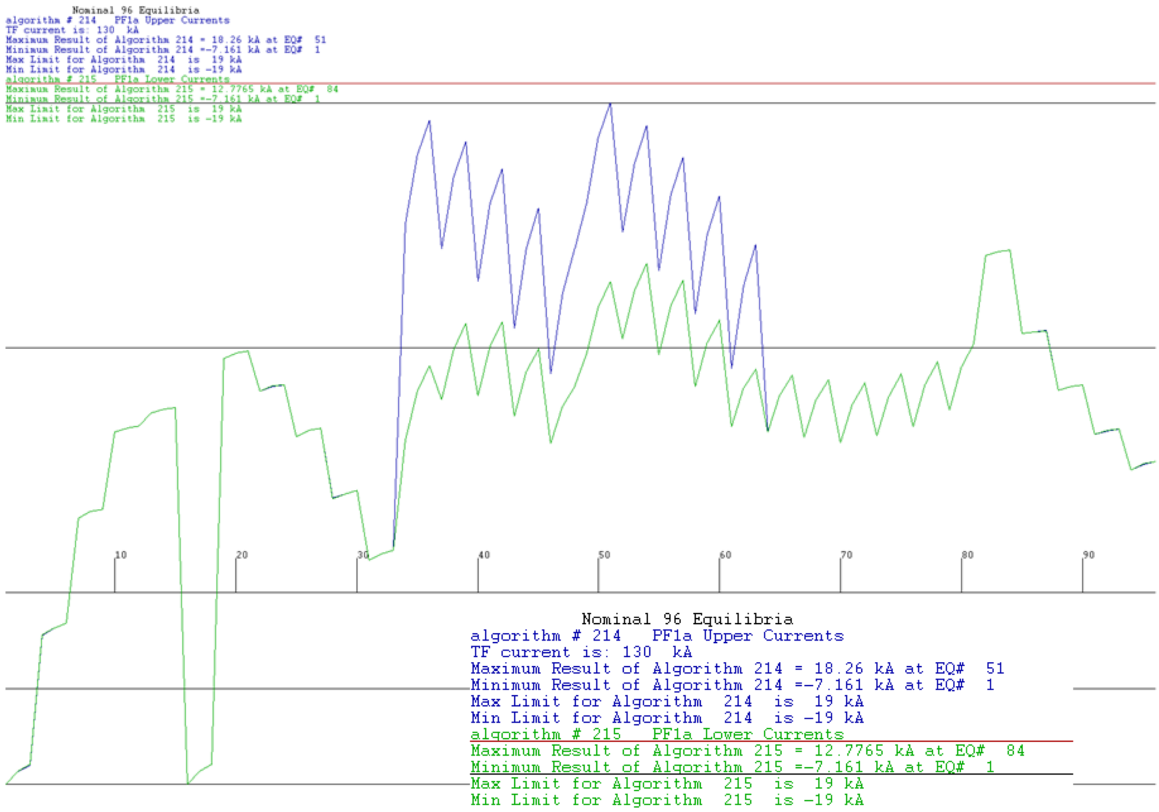


Figure 6.2-2 PF 1a Radial Field for all 96 EQ.

7.0 Models

7.1 PF1a Axisymmetric Model

An axisymmetric model is one of the models used for the analysis of the free-standing coil qualification test (See section 20.0)

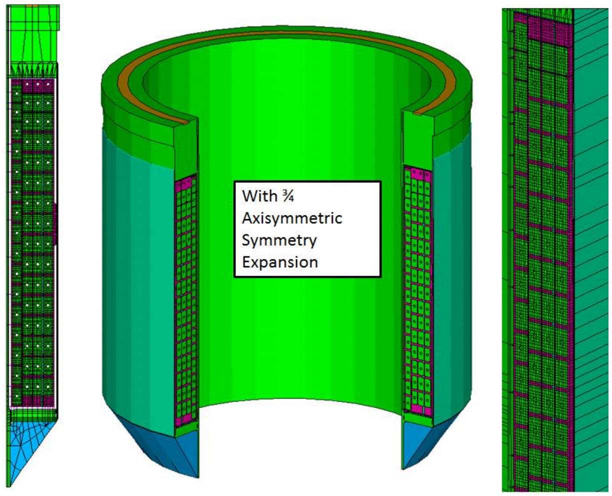


Figure 7.1-0 Axisymmetric Model Used for the Qualification Test

7.2 PF1a Upper Model – 30 Degree Cyclic Symmetry Model

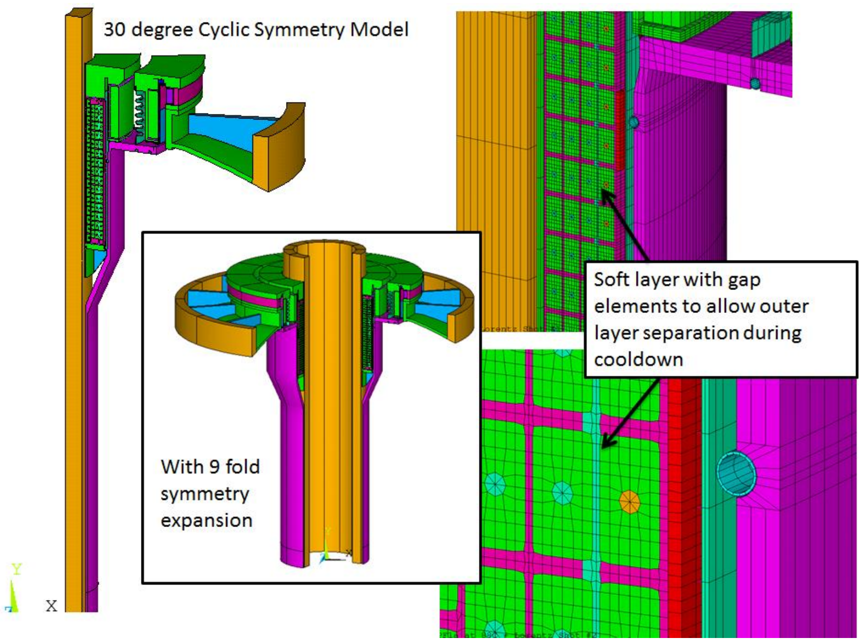


Figure 7.2-1 1/12 Cyclic Symmetry Model Used in Elastic-Plastic Simulations

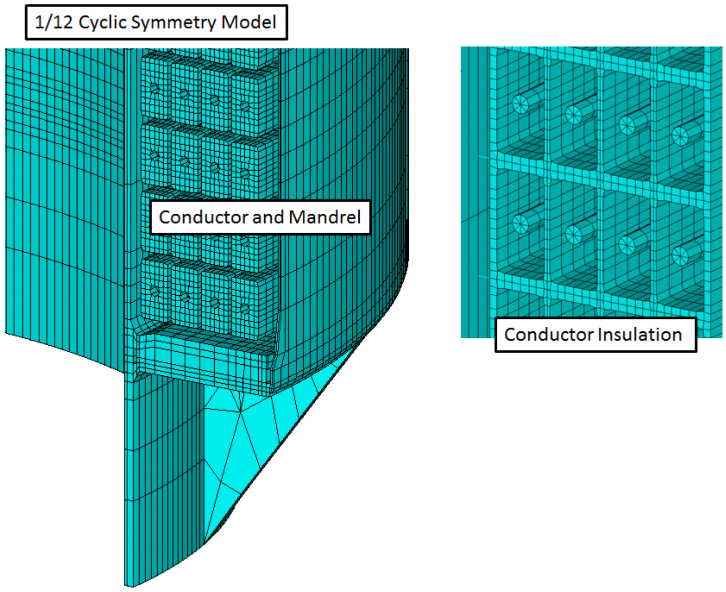


Figure 7.2-2 Model of NSTX PF1a Upper

7.3 PF1a Layer Joggle Model

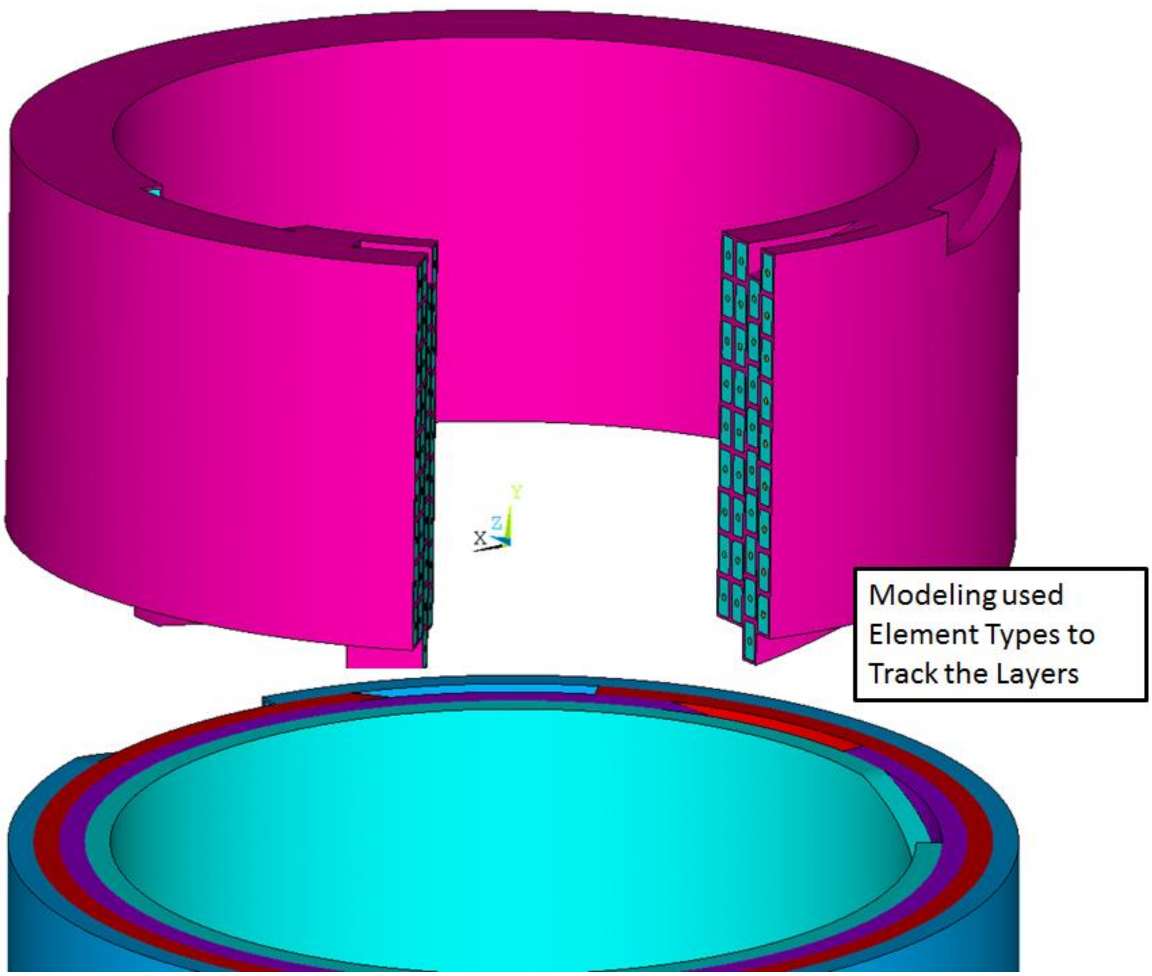
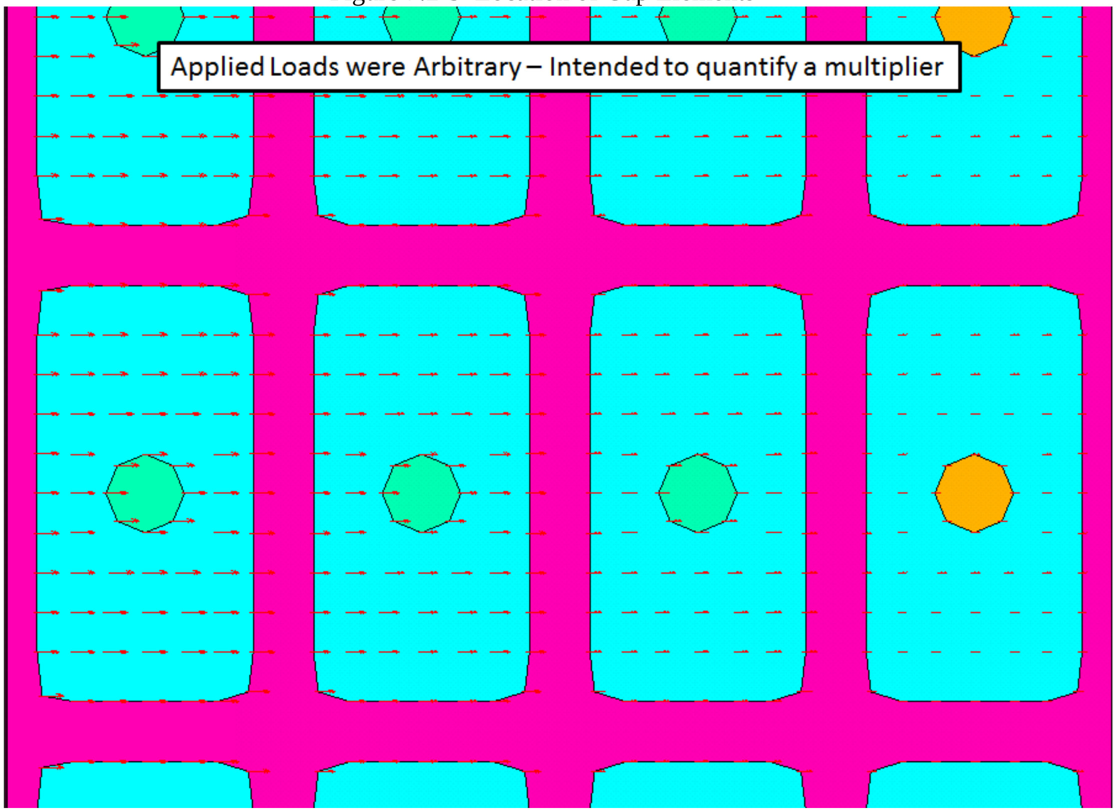


Figure 7.2-3 Location of Gap Elements



The model is multiply non-linear – It has sliding gap elements, elastic-plastic copper properties and a large displacement solution

7.4 PF1a Terminal Model

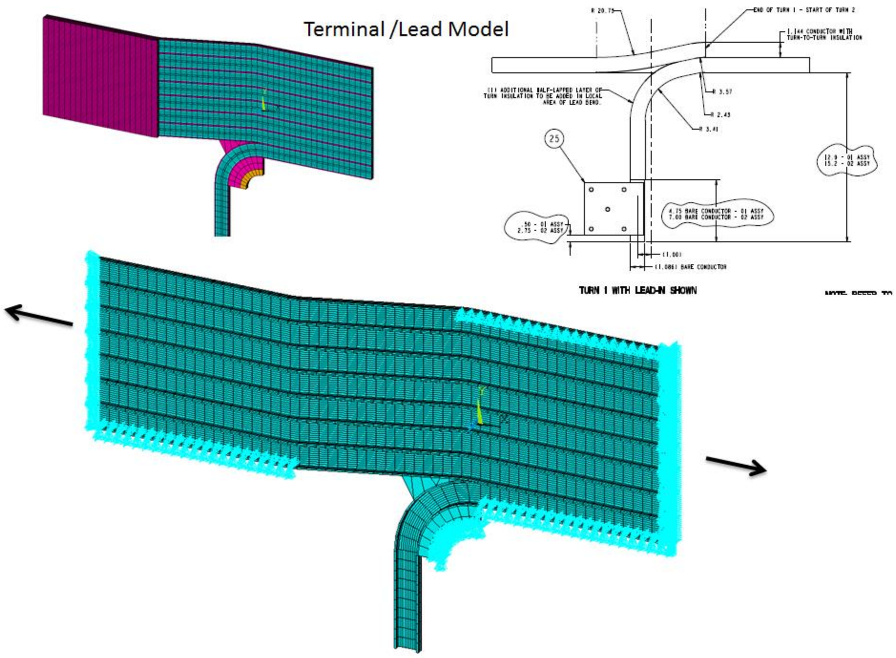


Figure 7.4-1 Model of NSTX PF1a Terminal Area

8.0 Original Qualification Calculations

The original PF1a qualification calculation is : "Stress Analysis of the Inner PF Coils (1a,1b &1c), Center Stack Upgrade" NSTXU CALC 133-01-2 [9]. Additional bus bar related calculations that include treatment of PF1a are: NSTX Upgrade PF 1 Flex Bus Analysis NSTXU-CALC-55-03-00, NSTXU. Structural Analysis of PF1, TF and OH Bus Bars NSTXU-CALC--55-01-02 [12]

.

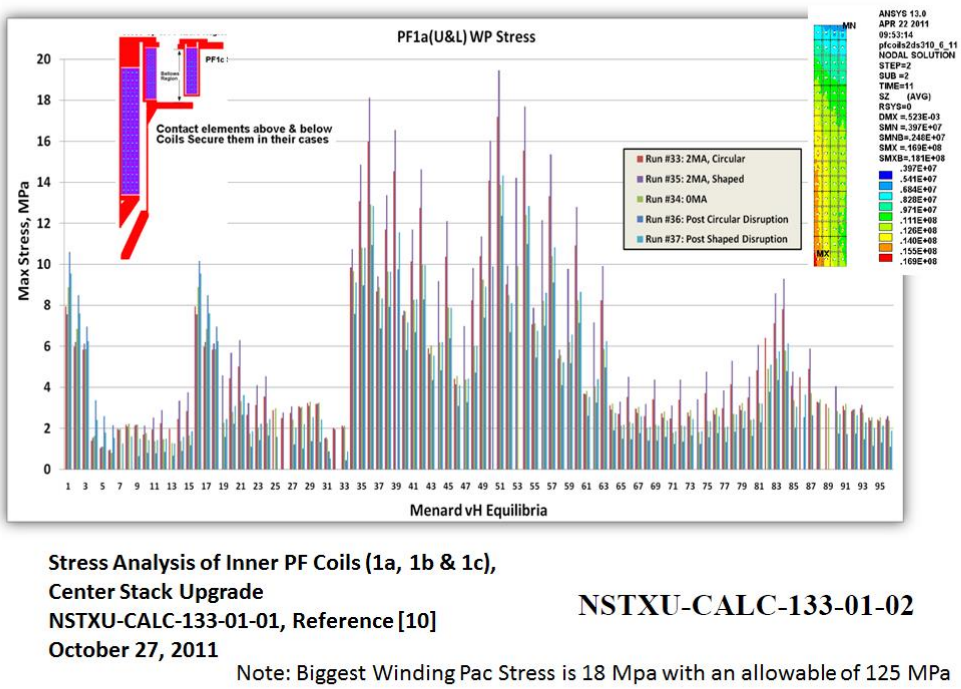


Figure 8.0-1 Plot of PF1a Winding Pack Stress from [9]

In [9], Len Myatt plots the winding pack stress for PF1a for all the 96 Equilibria. The max stress is less than 20 MPa. The model is a 2D model without the winding joggles and terminal break-out stresses but the basic winding pack stress is low and even with stress concentrations at the winding transitions, the stress is well below the allowable established for NSTX-U copper conductor s of 125 MPa.

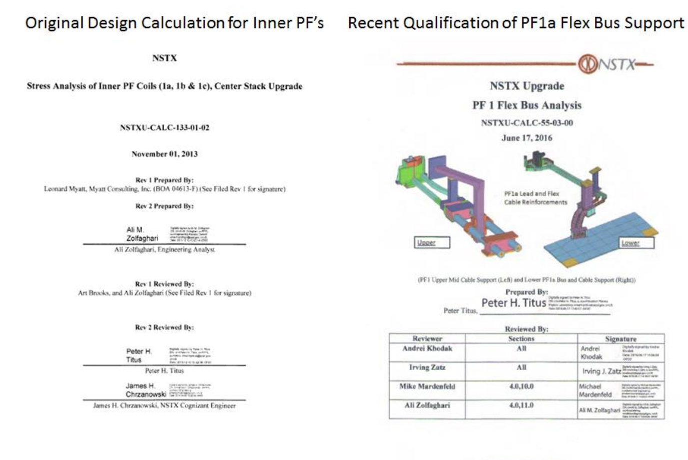


Figure 8.0-2 Existing Qualification Calculations

Another calculation addresses the local interactions between PF1a and the OH to augment the DCPS calculations of the OH hoop stress, NSTXU CALC 133-14-00 [25]. Another calculation addresses the magnetic stability between PF1a and the OH NSTXU-CALC-133-11-00[26]. Important characteristics of the PF1a coil were addressed in the Upgrade project. The main conclusion regarding PF1a from the analytic effort during the Upgrade project was that the Lorentz stresses in the coil were low and justified avoiding the analysis of winding details

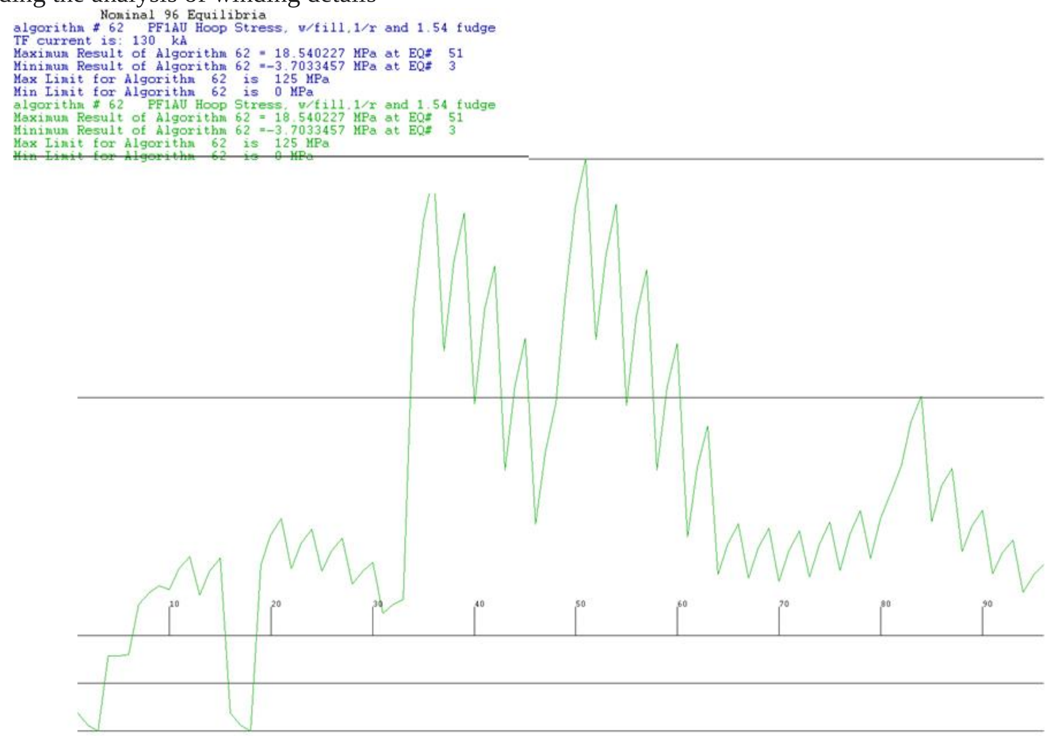


Figure 8.0-3 PF1a Hoop Stress from the (Titus) DCPS Simulation/checking Code for Comparison to [9]

.

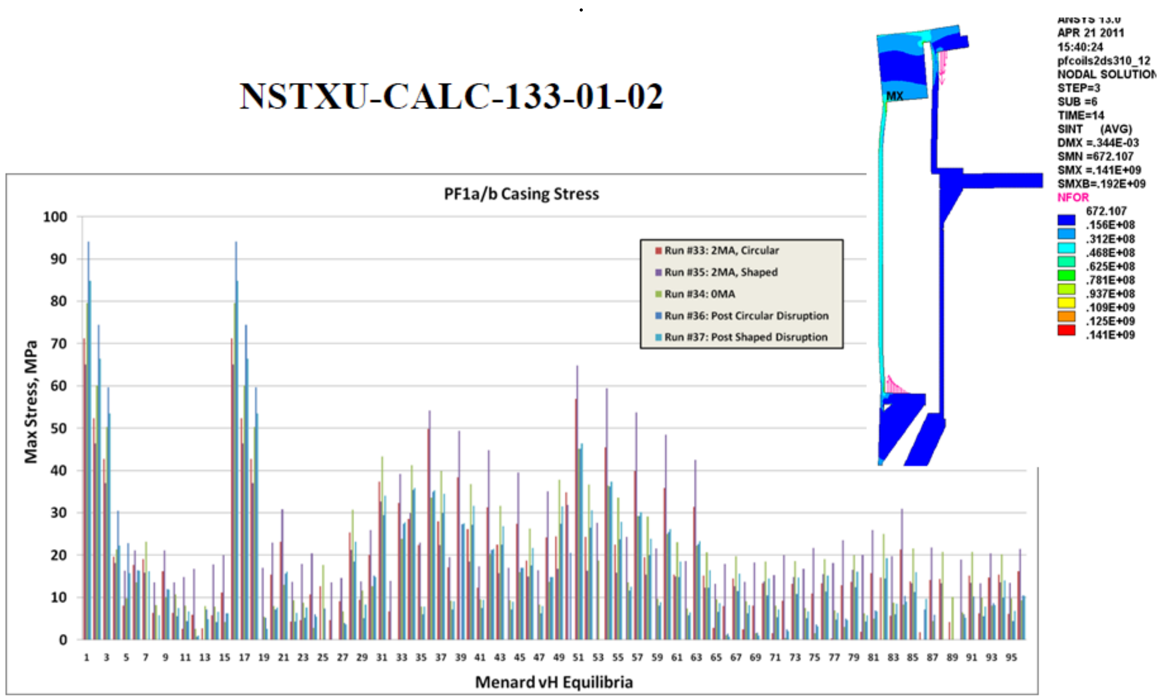


Figure 8.0-4 PF1a Mandrel Stress from [9].

Enveloping Static and Fatigue Evaluation:

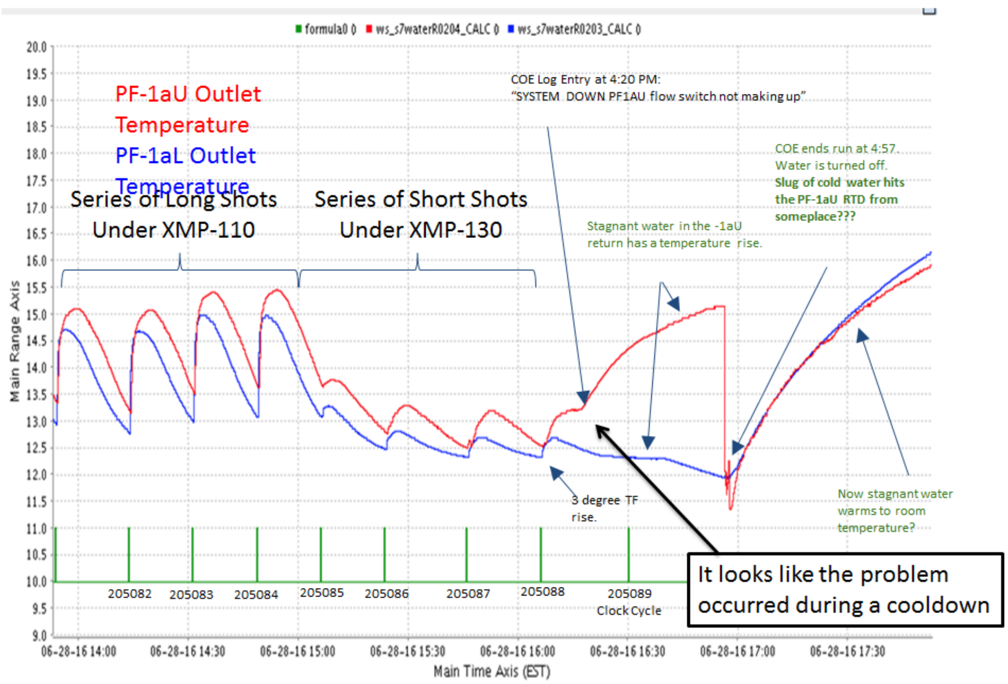
- Local M+B<140 MPa <276 MPa
- Total Stress=140 MPa <350 MPa
- Static & Fatigue: Qualified

9.0 PF1a Post Mortem Possible Suspects and Evaluation

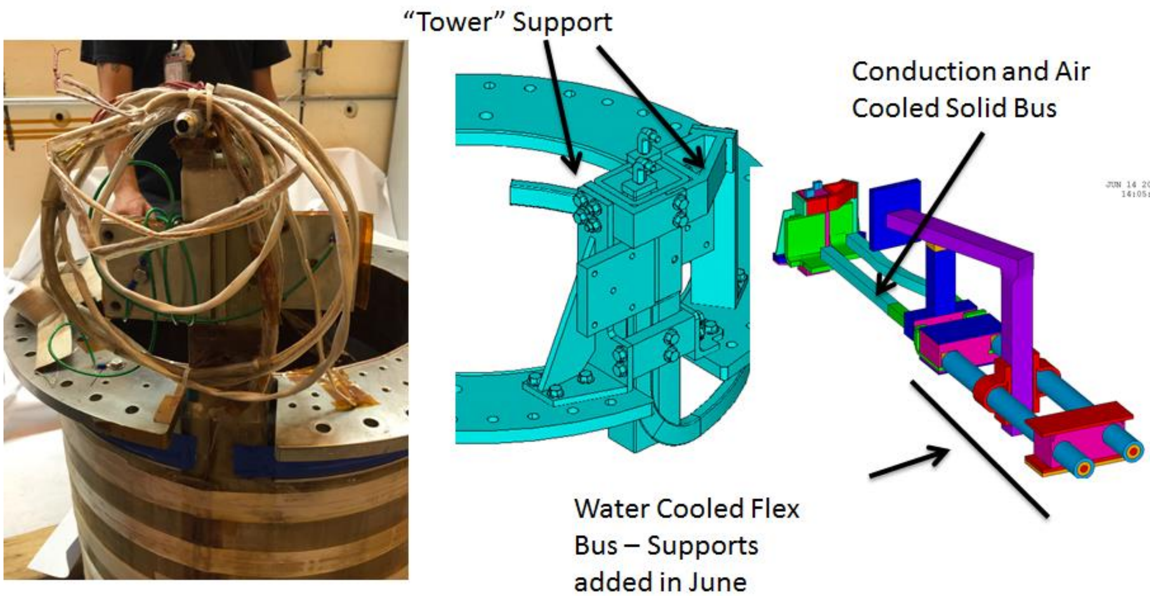
This discussion is not intended to replace the post-mortem investigation report [30], only to provide a discussion of some of the calculations performed to understand some of the issues relating to the failure.

August 30 phone call with Gregg Naumovich: They did increase the temperature of the braze process per the NCR but did not re-qualify.

Flow Problem Only Developed on Final Shot of 6/28



Initial operation had poorly supported flex buses, but it was concluded that the "tower" support and length of solid bus would minimize bending strains on the terminal. Considered not a likely cause of the leak

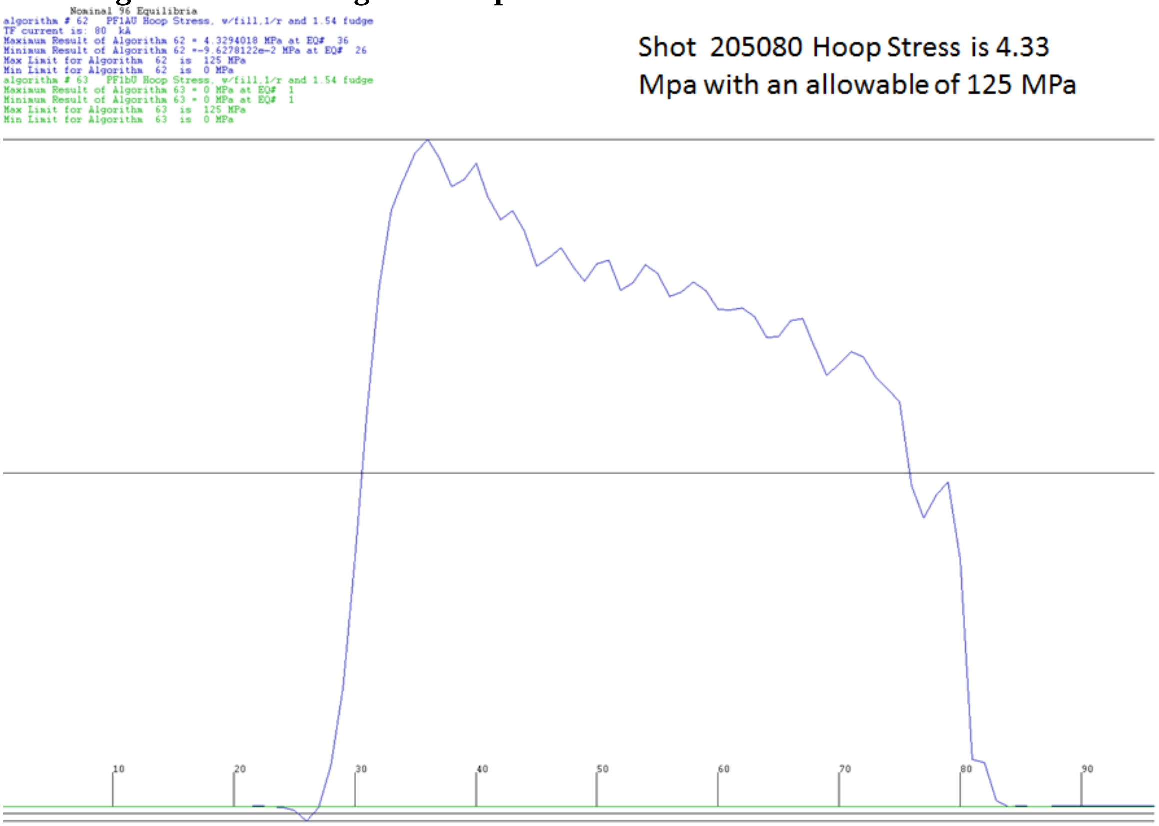


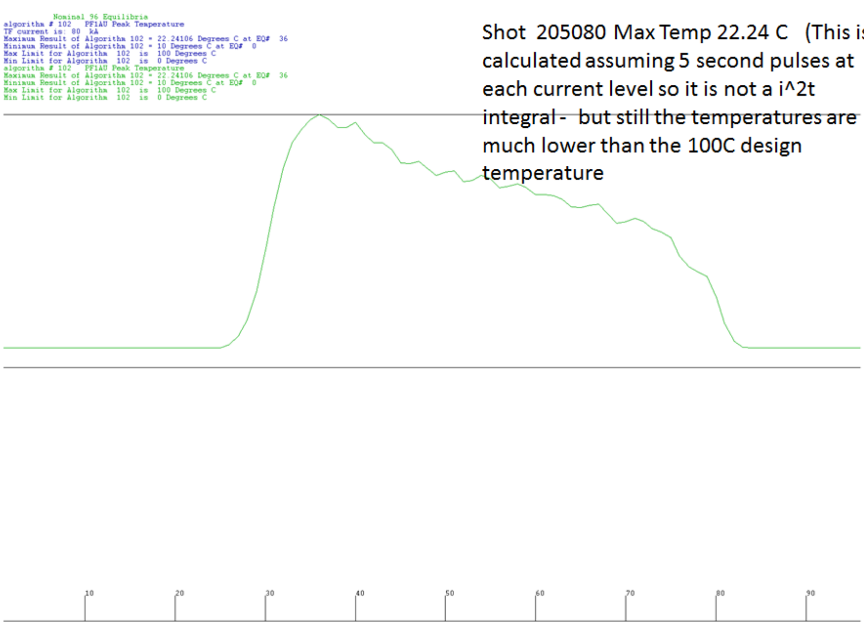
G-10 was specified on the drawings for the tower supports pieces and the fillers and shims in the winding. This had to survive the 170 degree C cure temperature in the CTD 425 VPI process. The terminal supports looked pristine when PF1a was removed from the centerstack. There was no indication of thermal damage to what is believed to be G-10 (or FR4). In December 2016 Charlie Neumeyer contacted CTD and they indicated that the G-10 should survive the process acceptably.

In normal service, G-10 will not survive 170C. In the VPI process, the G-10 would be exposed to the high temperature with epoxy surrounding it, probably reducing the effects of oxidation.

10.0 Operating Lorentz Stresses

10.1 Original Coil Loading and Hoop Stress





11.0 Cooldown Simulations (A. Brooks)
11.1 Cooldown Simulations with Design Basis Parameters

Unlike the TF and OH coils, which have had extensive analysis of cooldown strains, the inner PF coils have only had the design point spreadsheet assessment of the cooldown behavior. The OH in particular received significant attention outlined in ref [21] The "wave" cooldown strains were a potential source of insulation failure. Running ACOOL without consideration of the conduction and thermal inertia of the insulation, the results is a cooling wave propagation much like that seen in the OH

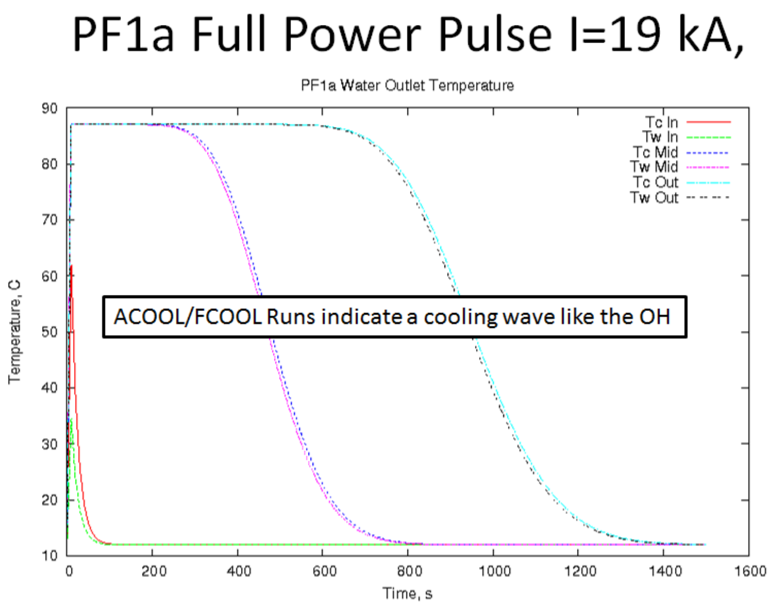


Figure 11.1-1 ACOOL simulation of the Nominal Cooldown of PF1a [29]

Note also the cooldown wave is quite different when the insulation is modeled. There is significant heat transfer thru the insulation with k=0.3 w/m-C. This is all with the initial hole size of 0.205"

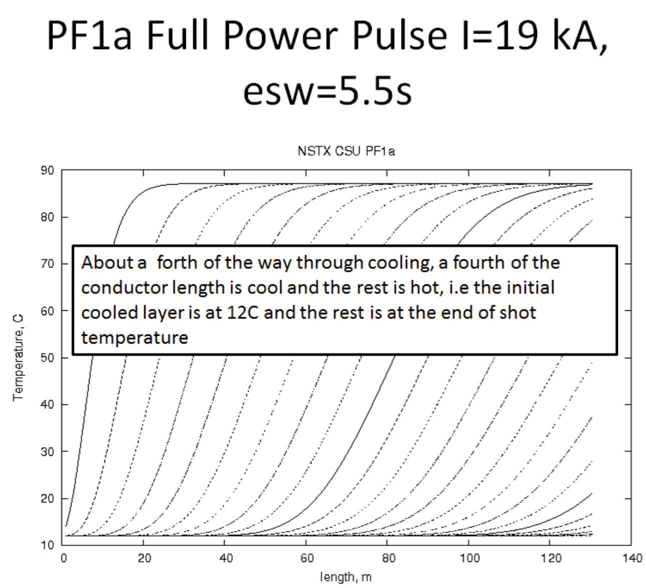


Figure 11.1-2 ACOOL simulation of the Nominal Cooldown of PF1a

This figure was used as justification for modeling the coil with the outer layer cooled while the inner three layers were warm. This produced simulations in which the outer layer went beyond the elastic range.

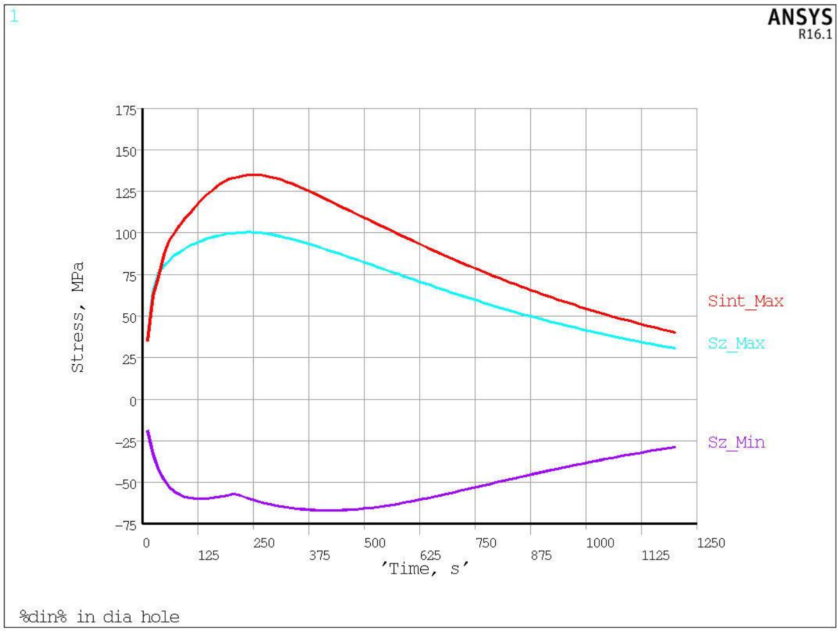


Figure 11.1-3 Baseline - No Recirculation 19 kA

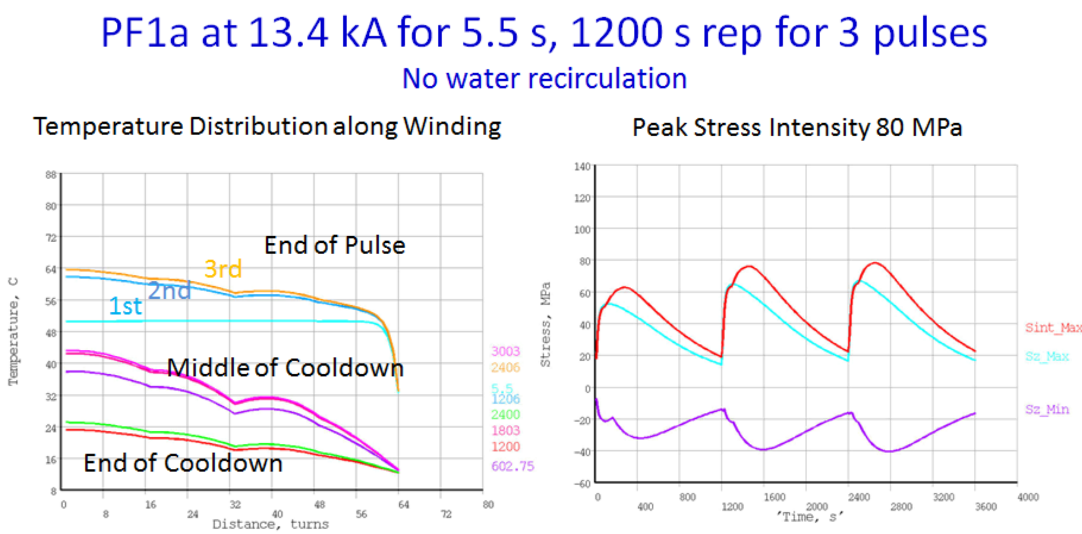


Figure 11.1-4 Multiple Cycles at a Lower Current Than the Max 19 kA

I've run the pf1a coil with half the I2t (13.4 kA = 19 kA/1.414). The temperature ratchets from 50 C to 64 C after three pulses and looks to be settling down. The corresponding peak stress is 80 MPa based on the axisymmetric model.

I've assumed as I did before a flow velocity of 2.13 m/s which is comparable to the OH and seemed to fit the data earlier but still needs to be verified.

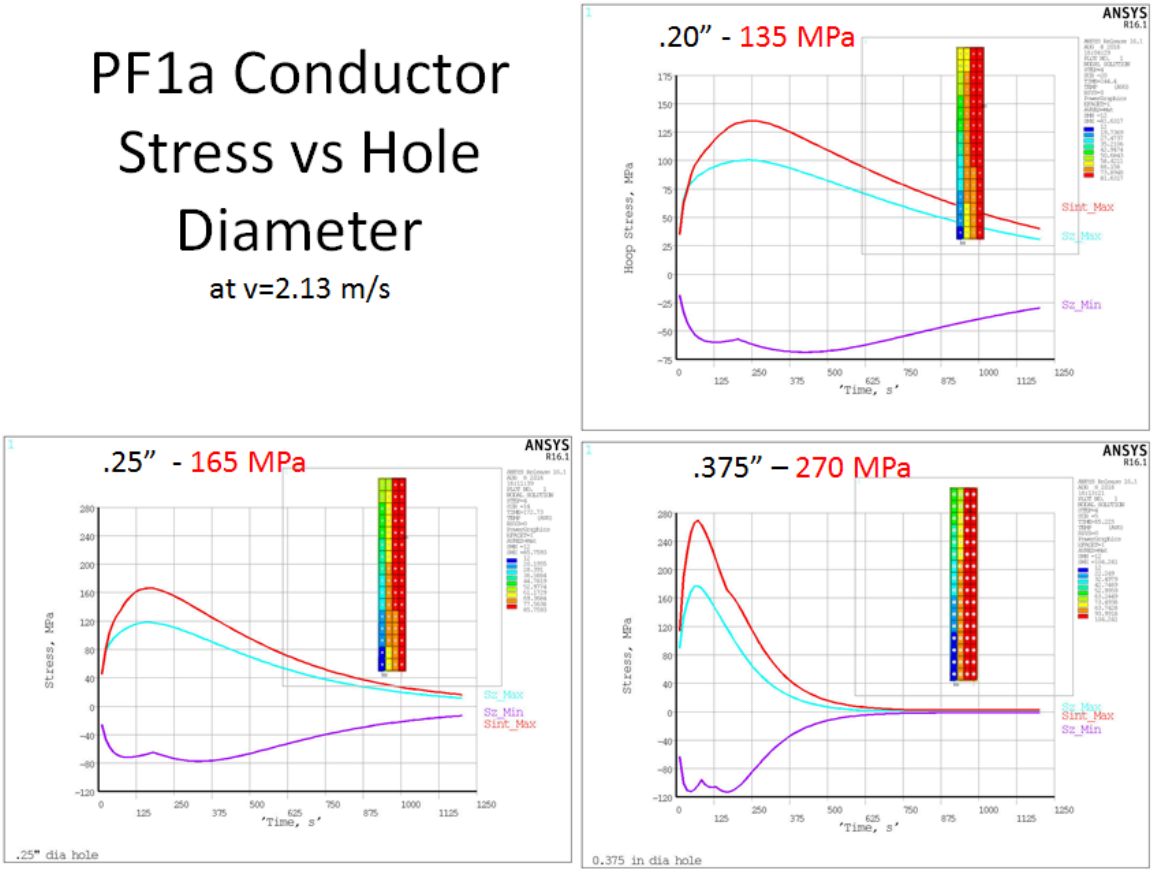


Figure11.1-5 Effect of Hole Size Variation

This was counter-intuitive – The increased hole size worsened stress.

11.2 Cooldown Simulations with Recirculation

Mixing heated outlet water with the inlet water can provide a more gradual cooldown and less thermal shock from the instantaneous input of 12C water.

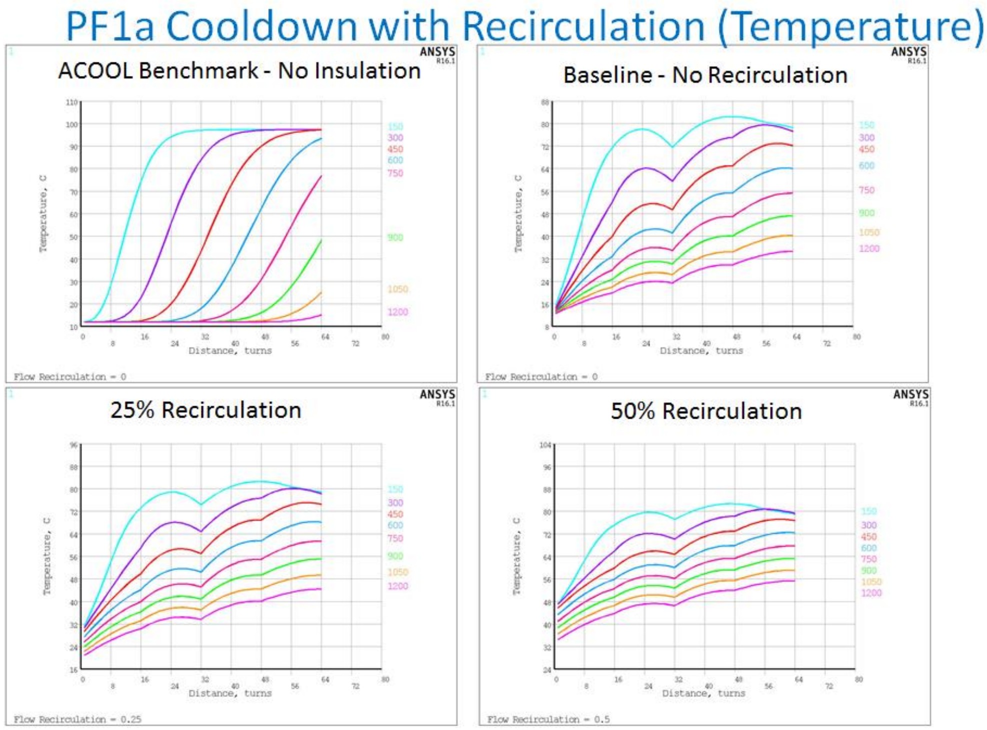


Figure 11.2-1 Effects of Various Recirculation Percentages on Coil Temperature

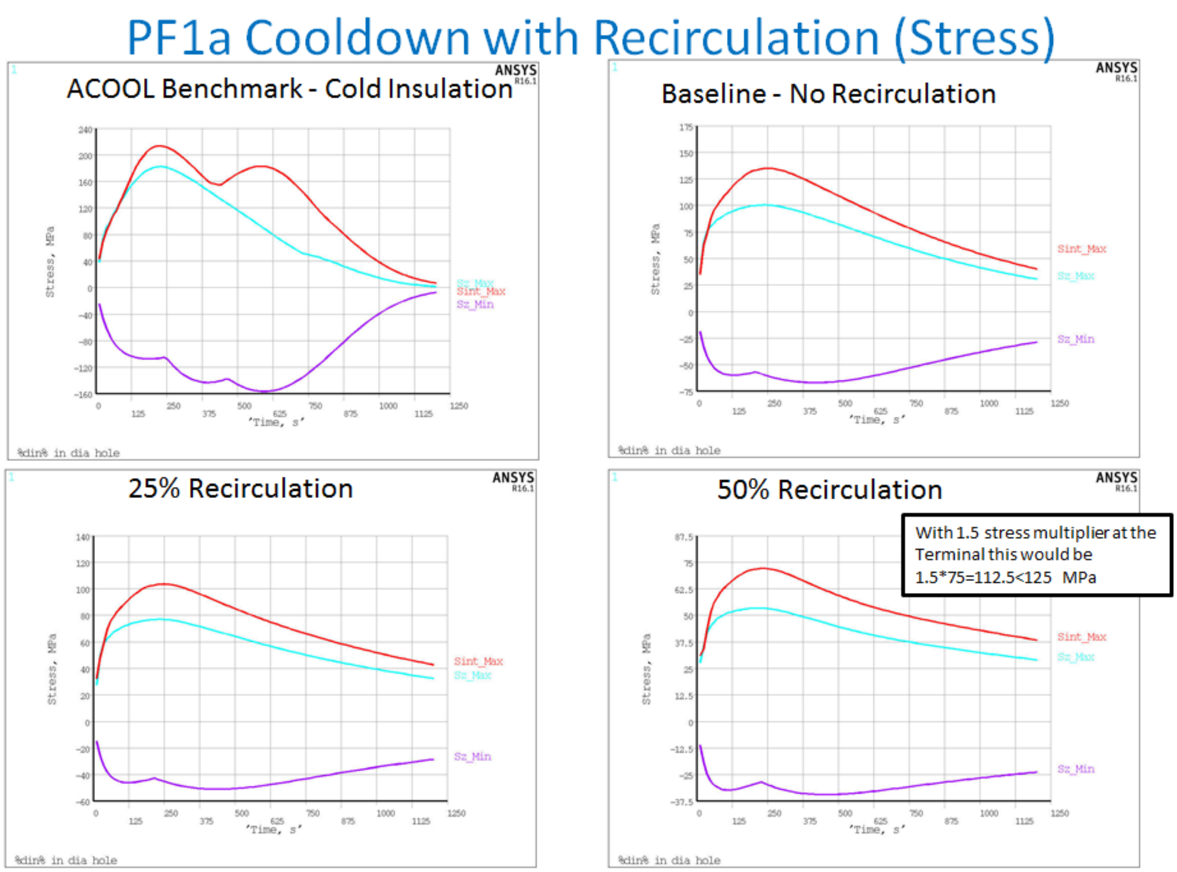


Figure 11.2-2 Effects of Various Recirculation Percentages on Coil Stress

50% recirculation was effective in mitigating the stress in the coil, but after 1200 seconds or 20 minutes, the coil still had not reached equilibrium. It took 40 minutes to reach a point where the coil ratcheting would be acceptable. This is much larger than the 20 minute cooldown allowed for the rest of the coils and is unacceptable from an experimental operations standpoint.

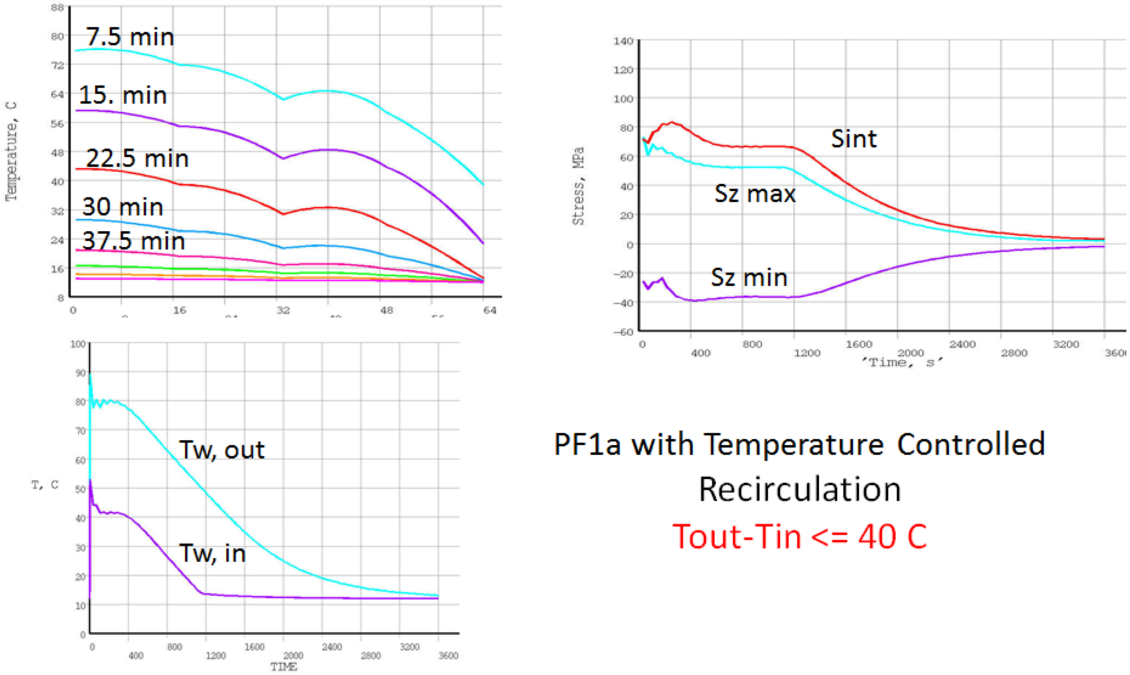


Figure 11.2-3 Recirculation With Temperature Control

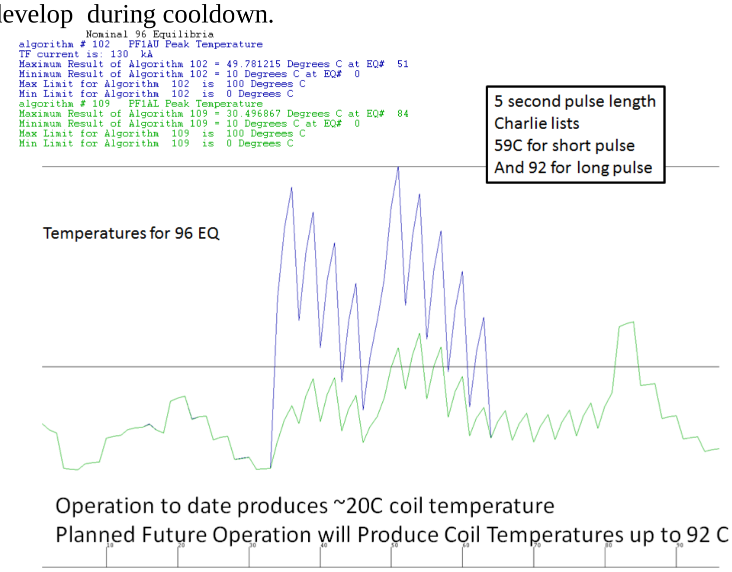
The cool down was programmed to limit the temperature difference in the coil to 40 C to keep the stresses less than 80 MPa. Figure 11.2-3 shows the outcome. The cool down is initially linear since it is controlled by the mdot*Cp*dT of the water which is held constant. The cooling slows, decaying exponentially, once the Tout-Tin falls less than 40 C. After 40 minutes the coil is down to ~18 C.

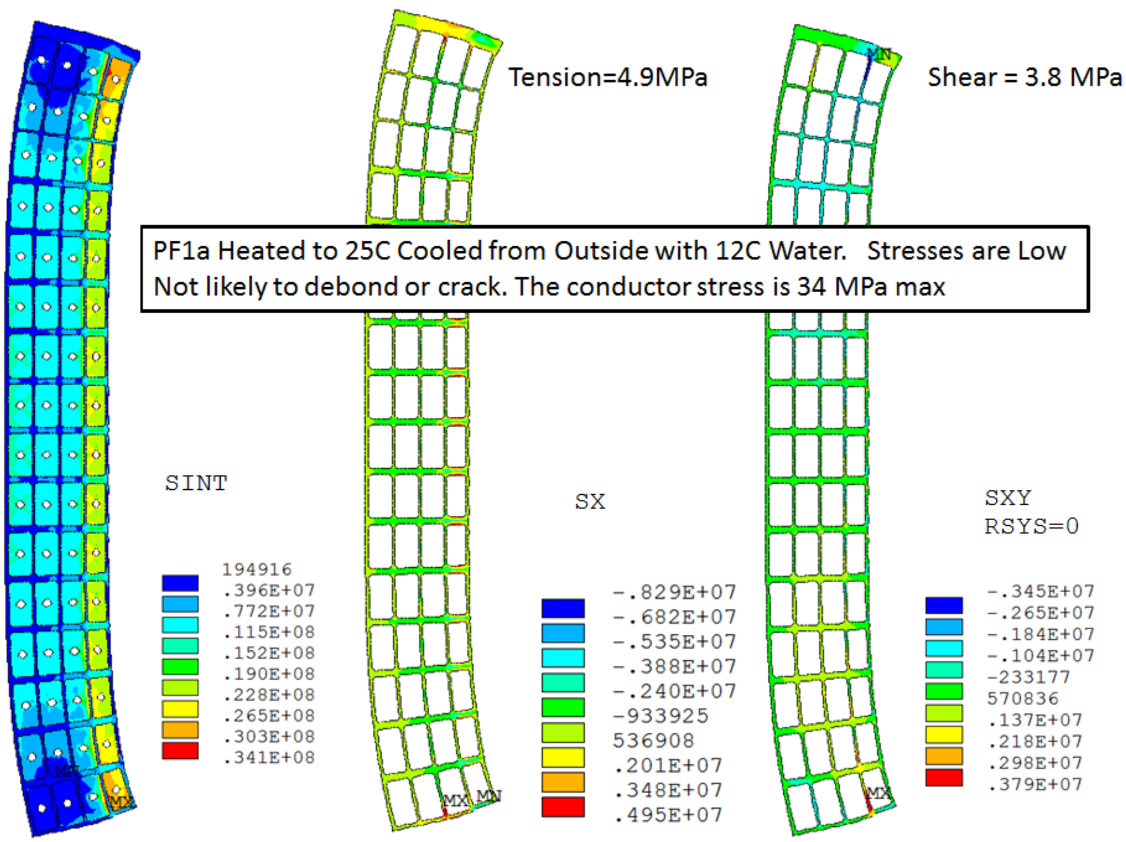
To achieve this requires a variable control value controlled by the outlet water temperature readings.

12.0 PF1a Cooldown Stress Analysis Elastic Outer Layer Assumed at 12C

12.1.1 Early Operation leading up to the Failure

Early operation did not utilize the PF1a coil to its full extent. Prior to the failure, the coil experienced peak temperatures of 25C or less. From current and temperature traces during operation prior to the fault, a water leak appeared to develop during cooldown.





Note that operating stress the coil was experiencing is ~4 Mpa, but the cooldown stress is 34 Mpa max. The Joggles will multiply hoop stresses. Still a failure is not indicated – the allowable is 125 MPa

12.1.2 Full Performance Cooldown Thermal Stress

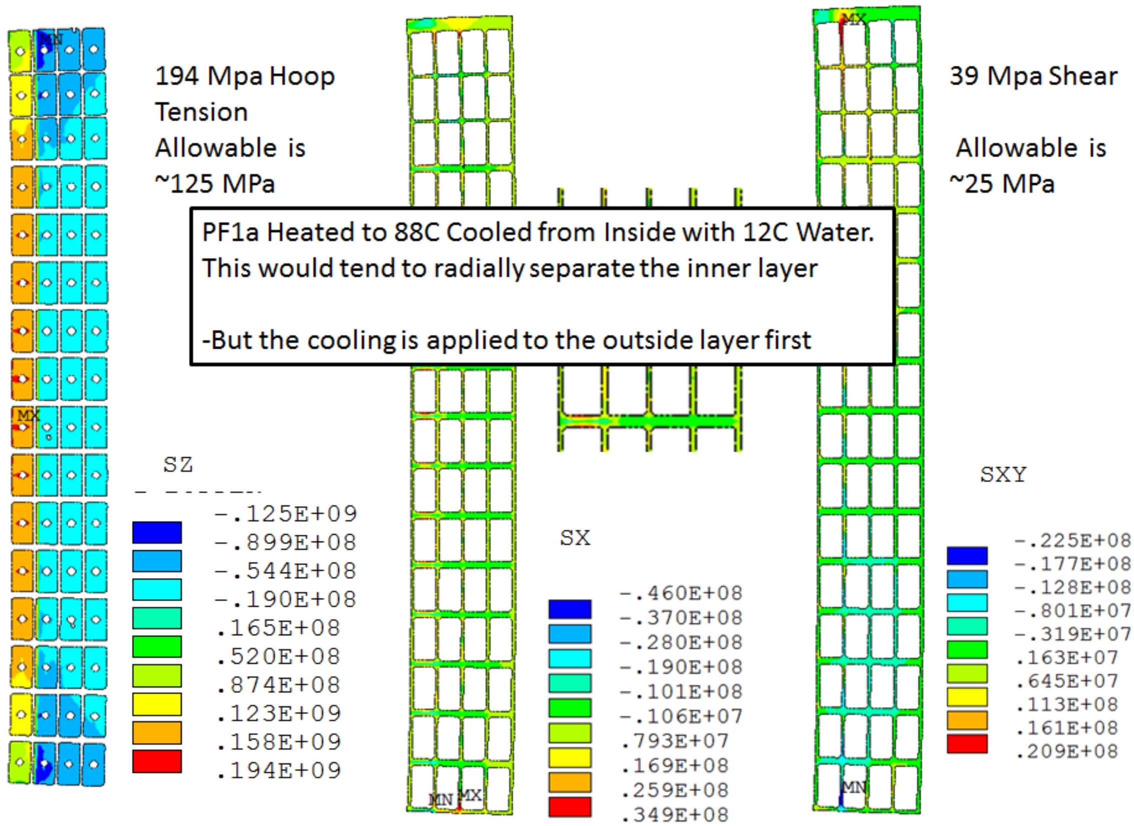


Figure 12.1-2 Inner Layer Stress with Coolant Fed From the Inside

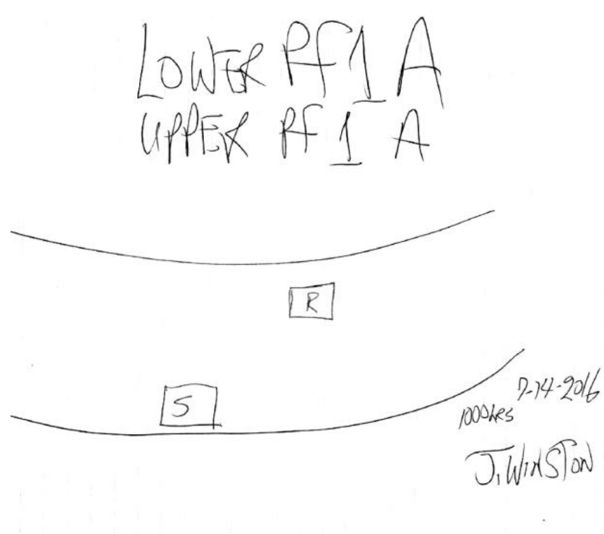


Figure 12.1-2 Joe Winston Inspection Results Showing Coolant Feed From the Outside

Feeding from the outside “S” or Supply on the outside, is preferred because it puts the insulation in compression during cooldown

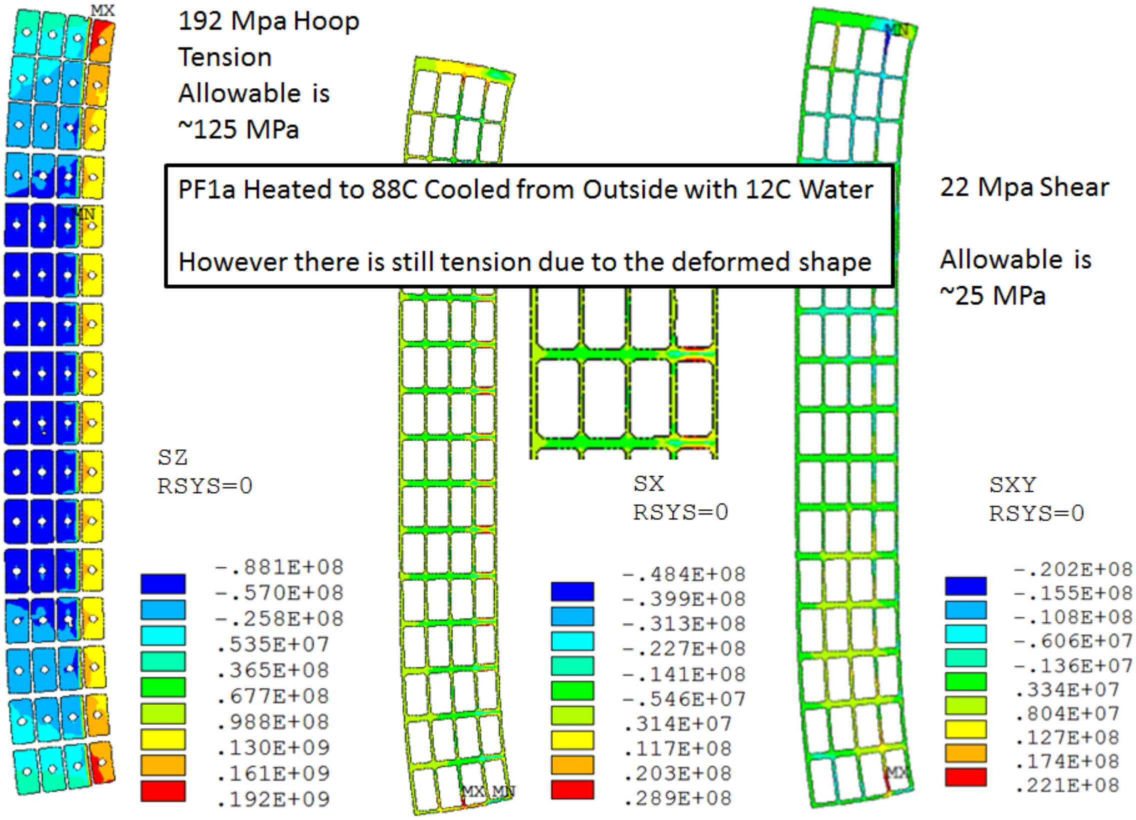


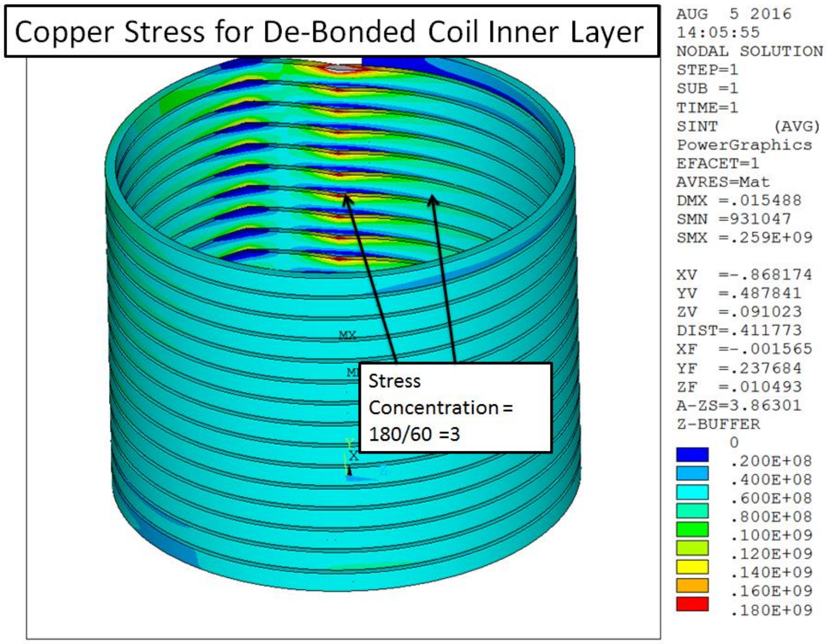
Figure 12.1-2 Outer Layer Conductor Stress for Full Operational Joule Heat

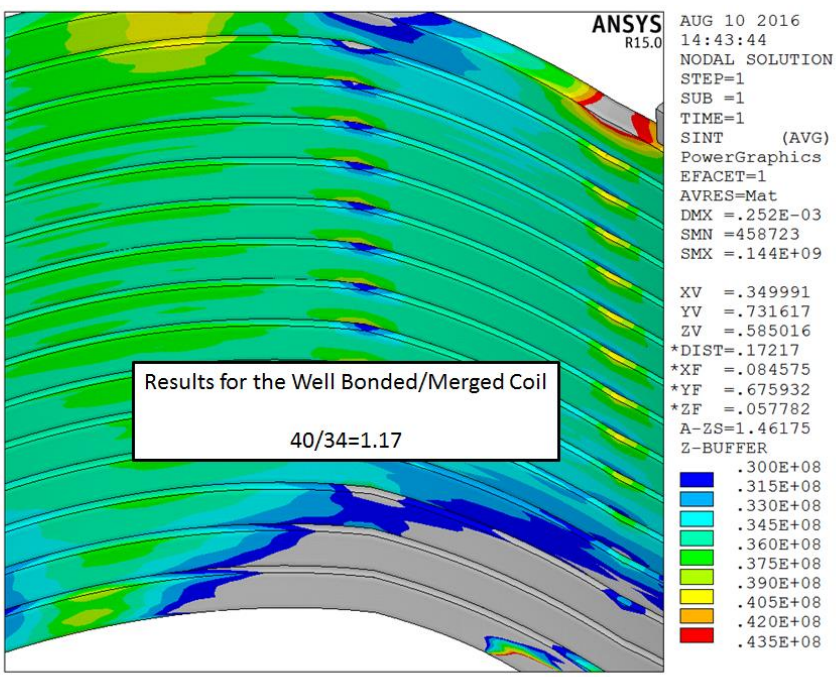
The peak stress is 130 to 192 MPa or 19 to 28 ksi. This is above the yield of the conductor. Either the differential temperatures need to be reduced or an elastic-plastic analysis is required to qualify the coil stress.

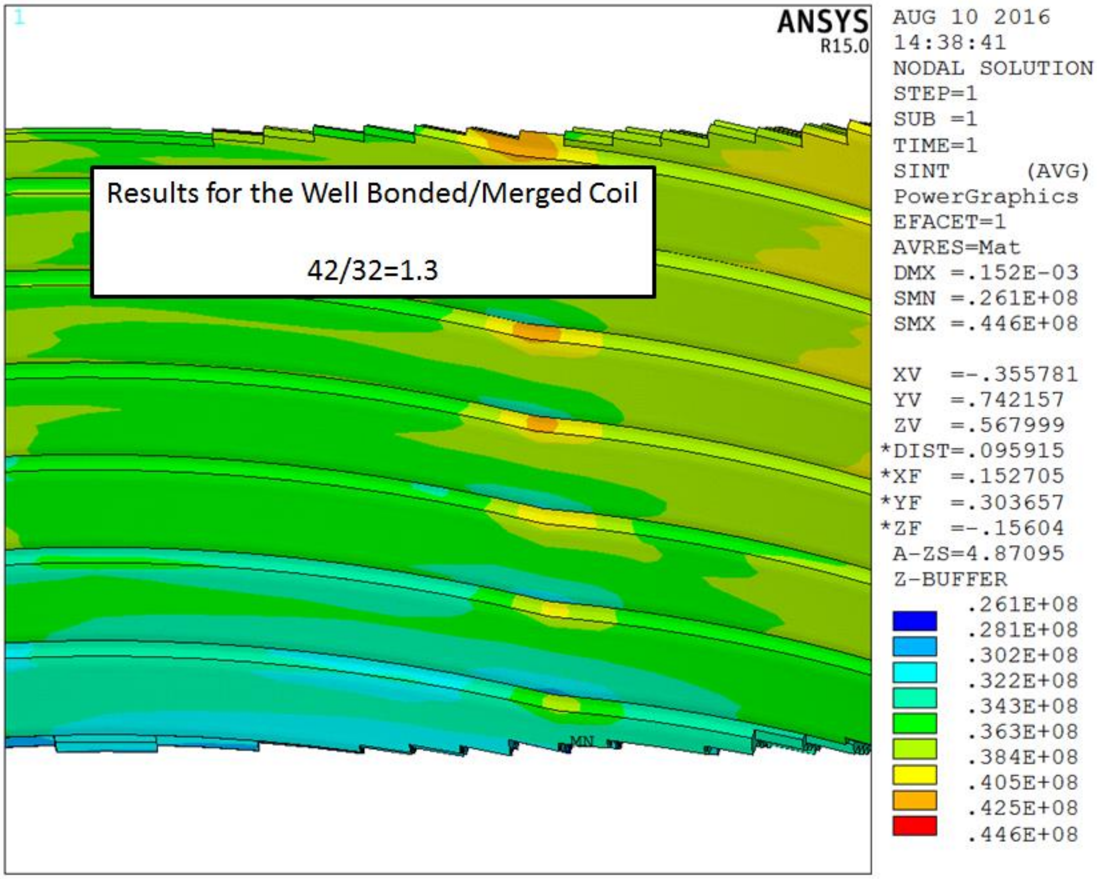
13.0 Layer Joggle Stress Concentration

Layer joggle stresses in the original coil are considered in this section. The joggle stresses are not an unacceptable source of stress concentration - but mainly they present a difficulty in manufacture. The process of forming them – removing and replacing insulation after use of a forming tool tends to handle the insulation roughly . Mistakes during this process have contributed to the failure. I discussed this with Lew, and I don't think there is any experience with these types of joggles in a layer would coil. Lew copied the joggles from a S-1 pancake wound coil.

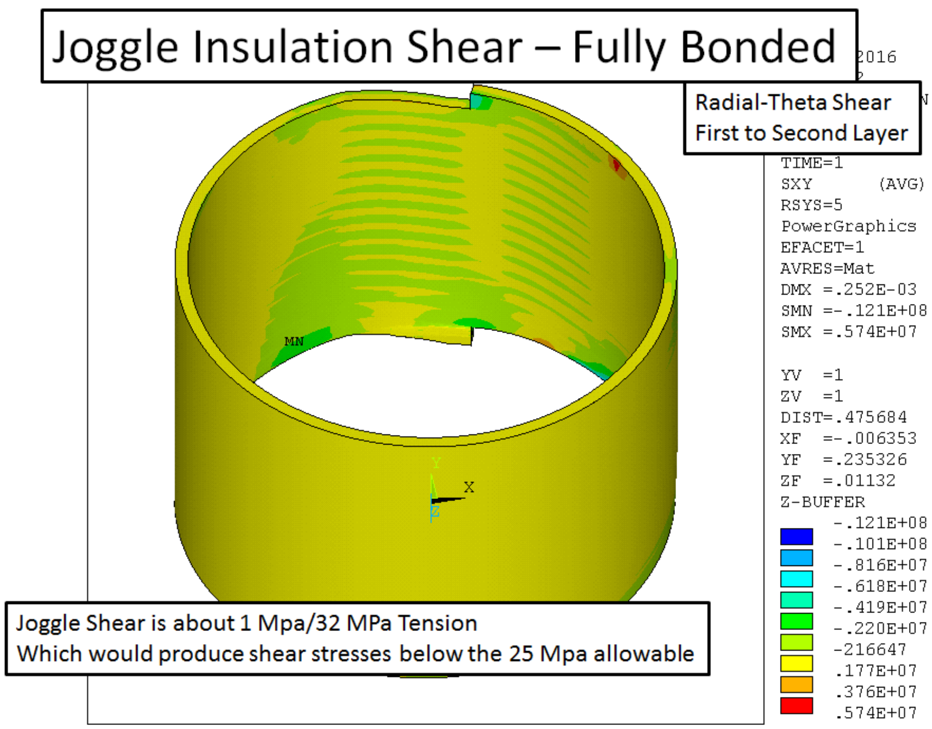
At this writing, the rest of the inner PF coils, including PF1aL may be retained and these have the joggles. So consideration of the joggles needs to be included in the qualification of the PF1a.



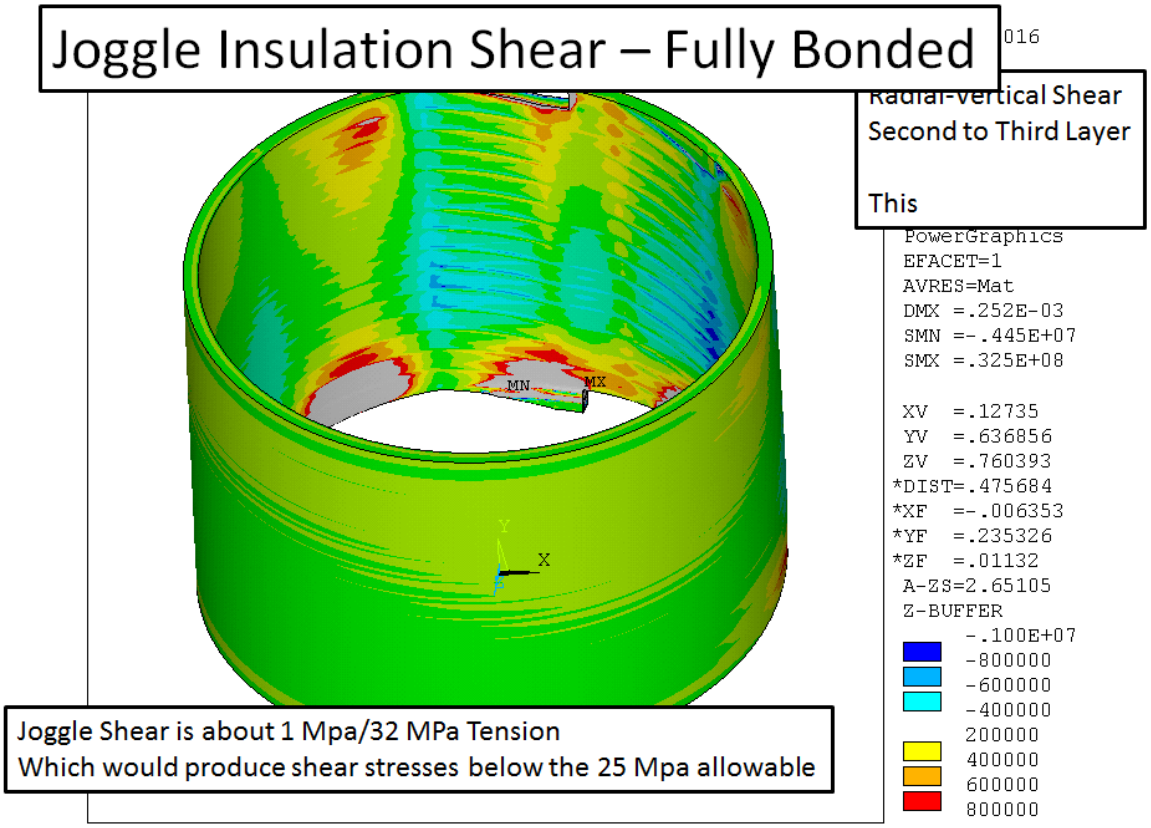




ANSYS
R15.0
AUG 10 2016
14:38:41
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SINT (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.152E-03
SMN =.261E+08
SMX =.446E+08
XV =-.355781
YV =.742157
ZV =.567999
*DIST=.095915
*XF =.152705
*YF =.303657
*ZF =-.15604
A-ZS=4.87095
Z-BUFFER
.261E+08
.281E+08
.302E+08
.322E+08
.343E+08
.363E+08
.384E+08
.405E+08
.425E+08
.446E+08
Results for the Well Bonded/Merged Coil
42/32=1.3
MN



Joggle Insulation Shear – Fully Bonded
Radial-Theta Shear
First to Second Layer
TIME=1
SXY (AVG)
RSYS=5
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.252E-03
SMN =-.121E+08
SMX =.574E+07
YV =1
ZV =1
DIST=.475684
XF =-.006353
YF =.235326
ZF =.01132
Z-BUFFER
-.121E+08
-.101E+08
-.816E+07
-.618E+07
-.419E+07
-.220E+07
-216647
.177E+07
.376E+07
.574E+07
MN
X
Joggle Shear is about 1 Mpa/32 MPa Tension
Which would produce shear stresses below the 25 Mpa allowable


Joggle Insulation Shear – Fully Bonded
016
Radial-vertical Shear
Second to Third Layer
This
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.252E-03
SMN =-.445E+07
SMX =.325E+08
MN
MX
XV =.12735
YV =.636856
ZV =.760393
*DIST=.475684
*XF =-.006353
*YF =.235326
*ZF =.01132
A-ZS=2.65105
Z-BUFFER
-.100E+07
-800000
-600000
-400000
200000
400000
600000
800000
Y
X
Joggle Shear is about 1 Mpa/32 MPa Tension
Which would produce shear stresses below the 25 Mpa allowable

14.0 Terminal Break-Out Stress Concentration

The terminal model is an “unwrapped model intended to provide an appropriate stress concentration. Other models of the terminals are found in the bus bar calculations. The flags and terminal stems are supported by the mandrel and lead support structures. And example of this is found in

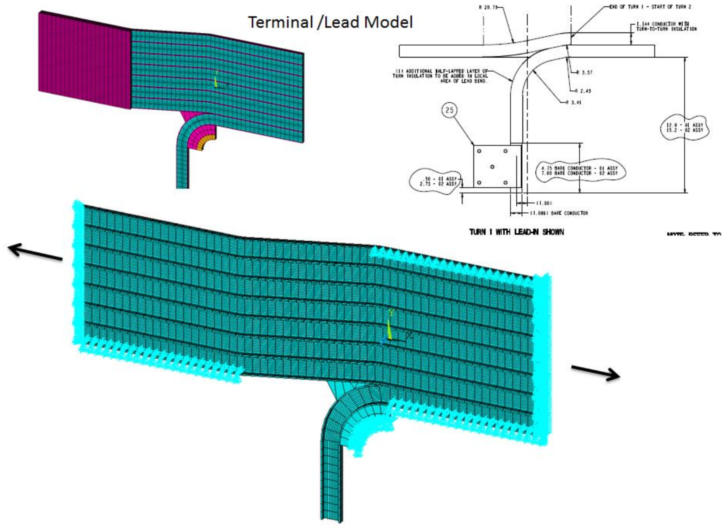


Figure 14.0-1 Terminal Break-Out Model

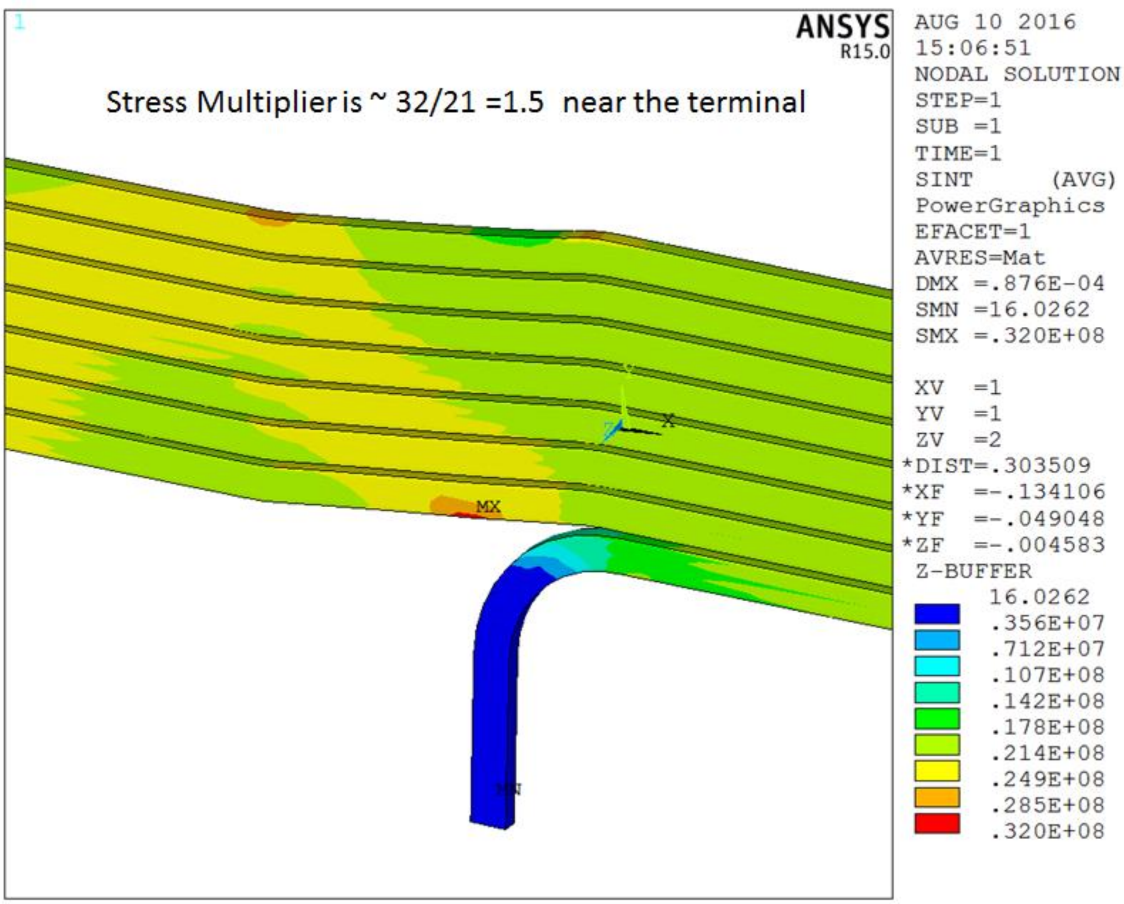


Figure 14.0-2 Terminal Break-out Stress Concentration

15.0 Winding Strains vs. Braze Strength

The use of braze joints in the coil was looked at as a probable risk in the winding of the coil. It has been a special area of interest in the post mortem of the coil[30]. PPPL qualifies its braze operators by having them perform a braze and then the joint is tension tested to failure. The criteria is that the joint must fail outside the braze joint. All joints are post tensioned 5% reduction in area to recover some of the cold work. This same procedure was imposed on Everson Tesla.

NSTX-U

MANUFACTURING SPECIFICATION

Fabrication of Inner Poloidal Field (PF) Coils

D-NSTX-SPEC-134-137 Rev.00

5.2.2.2 Tensile Test: Apply a tensile load across the brazed joint during the helium leak test. [Approximately 12 to 14 ksi (82.7 to 96.5 Mpa) is required]

5.2.2.4 Post Tensile Visual Inspection: A visual inspection of the finished joint shall be made following the tensile test to ascertain whether any cracks developed in the Braze joint area. ***Acceptance criteria*** *The joint shall be free from all cracks*
Failed joints shall be rejected, and dispositioned with a NCR. The braze joint shall be cut out and a new joint made.

Figure 15.0-1 Excerpt from the NSTX-U Coil Fabrication Specification

However Everson Tesla failed to get an acceptable braze joint, with the break occurring at the braze plane. This however occurred at 23 ksi (158 ksi), well above the applied Lorentz Stress, and higher than stresses that would occur during cooldown which for PF1a are more limiting. The "failed" braze joint test was accepted. It should be pointed out that as a part of the acceptance of these braze tests, a recommendation was made to increase the braze temperature a bit, and in a phone conversation with Everson Tesla, Greg Nomovich indicated this had been done. This would probably be OK if in the process of bending the conductor – including the braze joint- the braze plane was not stressed above the tested tensile capacity of the braze joint. In the following calculations, a simulation of the winding process is done with varying values of what might be expected of the brazed and partially annealed section of the conductor.

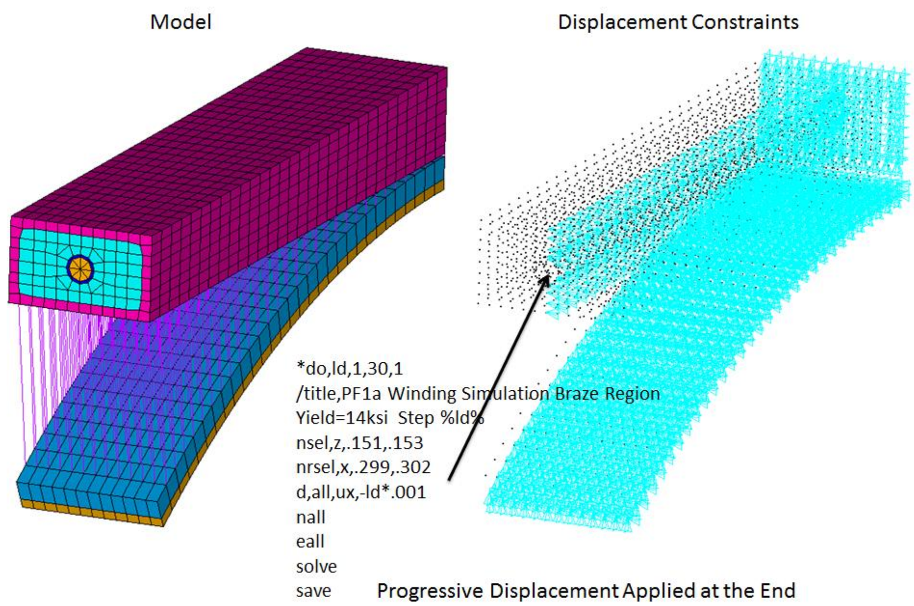


Figure 15.0-2 Winding Simulation Model

These calculations are not only useful for assessments of the stress applied to the braze joints, but also as an indication of the degree of cold work expected from the winding process. In this model, gap elements with gaps calculated in a APDL script are used to simulate the winding down of the conductor onto the mandrel or inner conductor layer.

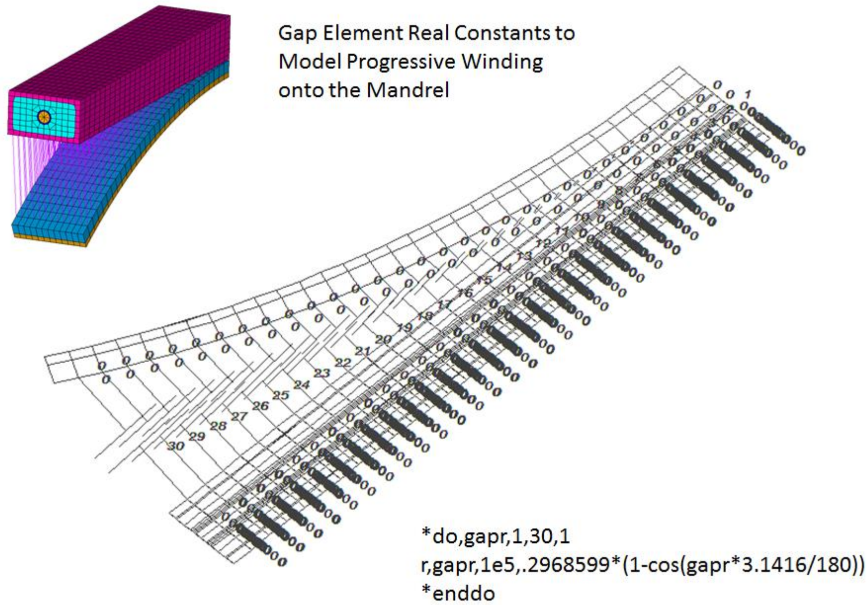


Figure 15.0-3 Curvature input using gap real constants

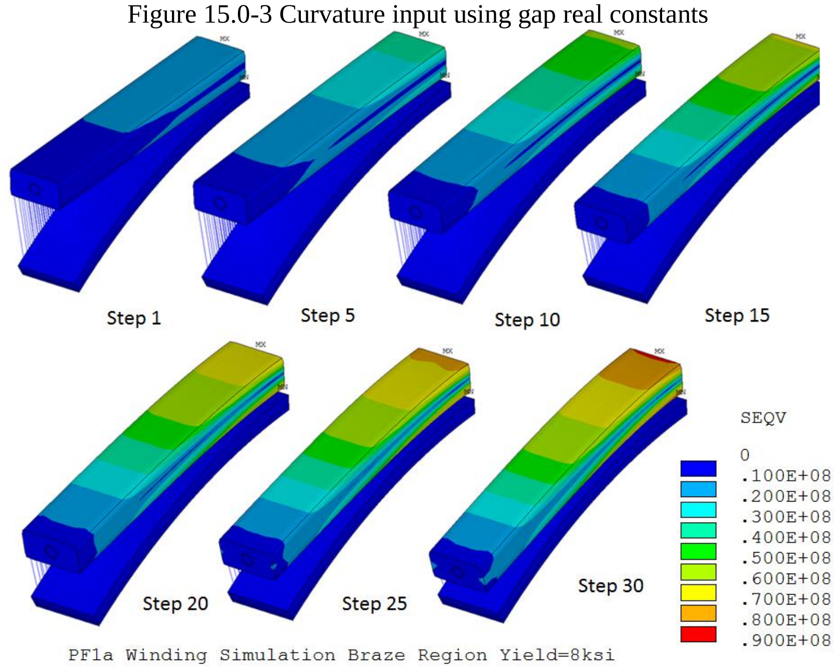
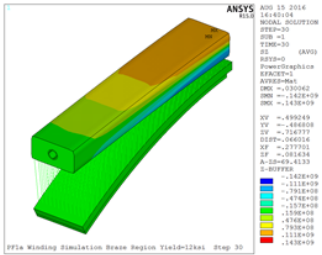


Figure 15.0 -4 Von Mises Stress in the conductor as it is Wound Down



	Von Mises After Winding	Sz After Winding	Required before NCR	Capacity Allowed by NCR
8 ksi Braze Region Yield	82 Mpa 11.8 ksi	122 Mpa 17.7 ksi	255 MPa 37 ksi	151.7MPa 22 ksi
12 ksi Braze Region Yield	100 Mpa 14.5 ksi	143 Mpa 20.7 ksi	255 MPa 37 ksi	151.7MPa 22 ksi
14 ksi Braze region Yield	112 Mpa 16.2 ksi	160 Mpa 23.2 ksi	255 MPa 37 ksi	151.7MPa 22 ksi

Supplier Document Type & Number: NCR SC14023

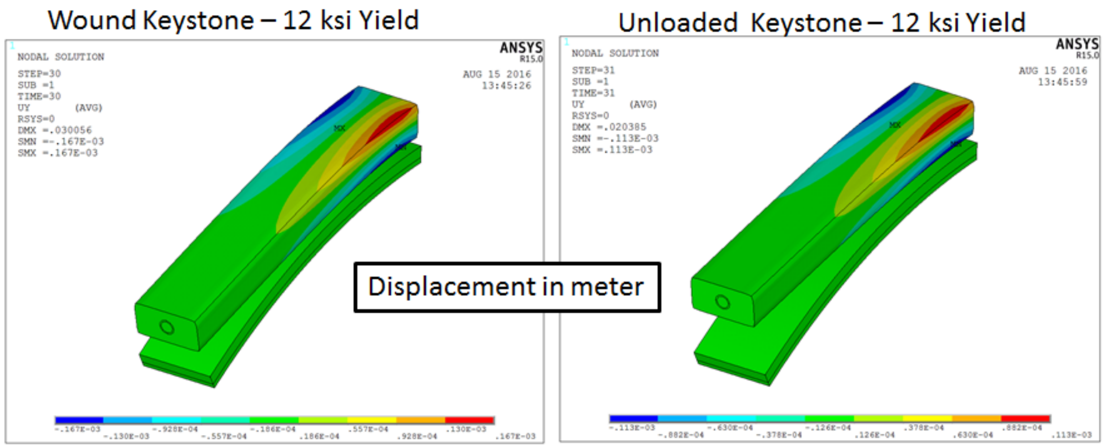
SAMPLE ID	(ksi) TENSILE STRENGTH	(lbf) TENSILE LOAD	FRACTURE LOCATION	FRACTURE TYPE	(in²) AREA	KEY C/NC/R
002	22.1	12,503	Braze Joint	Ductile	0.5649	R
003	25.5	14,318	Braze Joint	Ductile	0.5621	R
004	24.0	13,585	Braze Joint	Ductile	0.5658	R

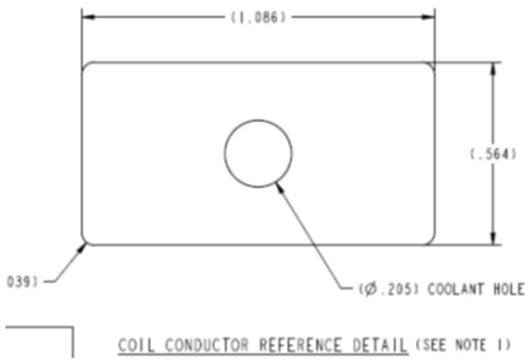
Figure 15.0-5 Summary of Winding Plastic Strains and Work Hardening

The results of these analyses show the work hardening of the conductor as it is wound down, and computes the peak stress in the braze joint as a result. The virtue of having a small yield after the braze in this circumstance is evident. The higher yields would impose higher stresses on the braze joint and for a 14 ksi yield, the stress would come dangerously close to the braze ultimate. As a consequence, the braze joints were considered a risk, and were removed in the replacement coil. The X rays of the coil as of October 17, 2016, showed no indication of a failure near the braze joints, but it reamins an area of concern. To avoid braze joinnts, one continuous conductor length is needed. To get this, lower yields must be allowed – At lease according to the conductor suppliers Luvata and Weiland.

Conductor Keystoning

The winding process deforms the conductor to the required coil radius, and in the process, poisson expansions and contractions occur. A simple rule of thumb to estimate the transverse strains is H/(2*r) where H is the conductor height in the radial direction as wound, and r is the radius of the winding.



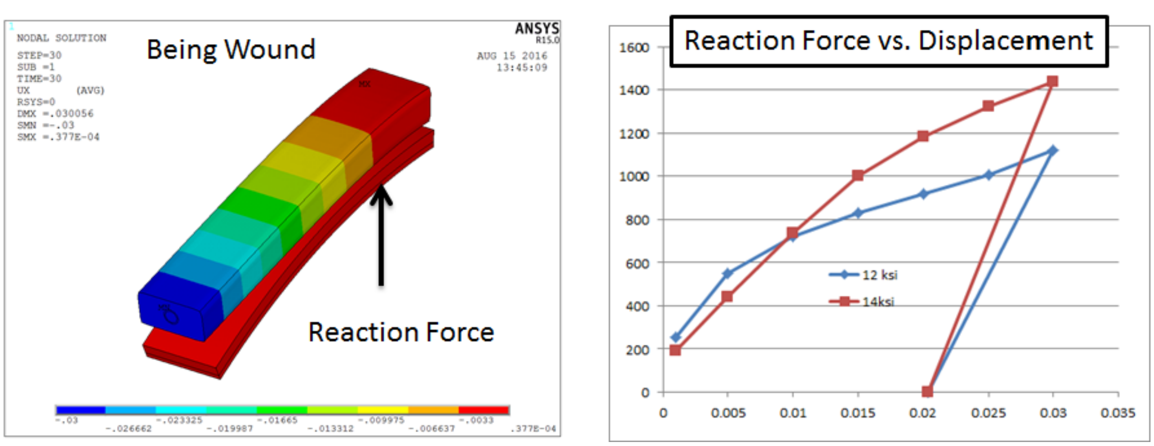


H/(2*r)=.564/2/11.687 = 2.413% (based on elastic strain)
So the contraction of the long dimension= .02413*1.086= .026204 inches. Or .35e-3 m per edge.
For fully plastic bending the keystoning is half this, or .175e-3 compared with .167e-3m in the ANSYS simulation

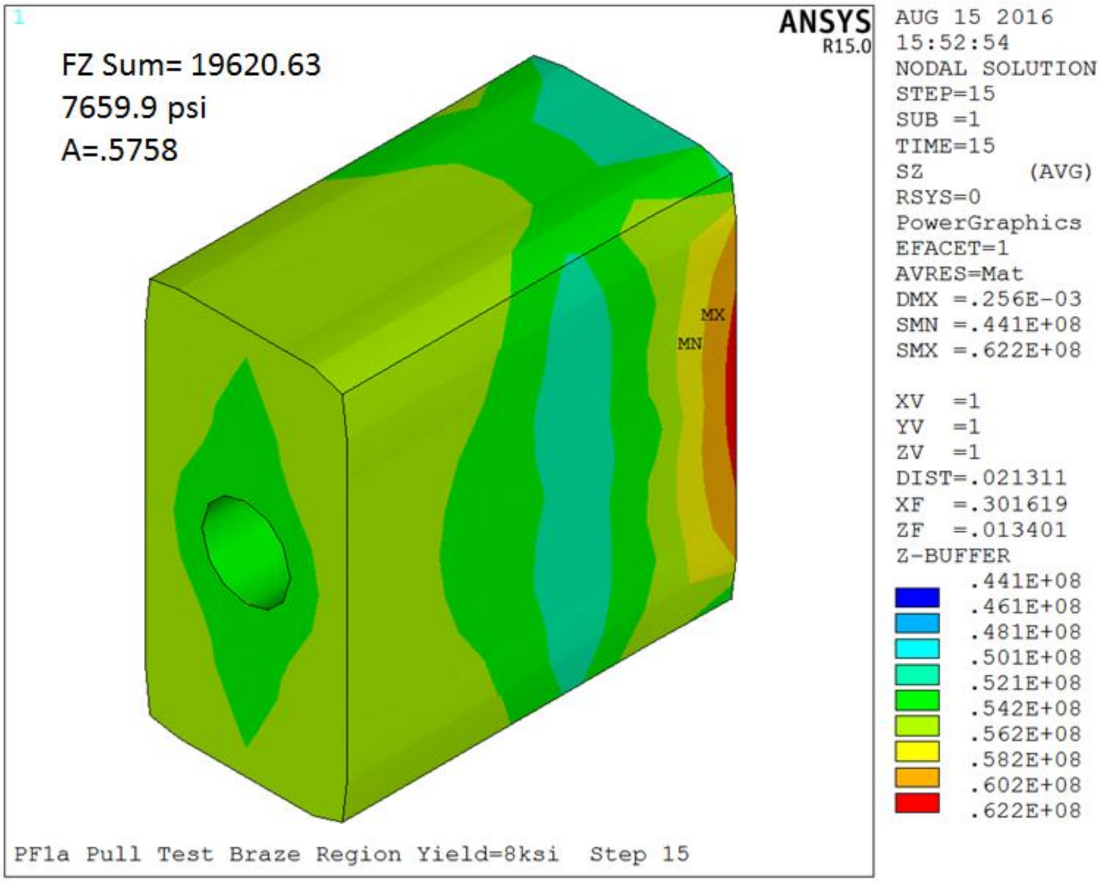
For PF1a, .3*H/(2*r)=.3*.564/2/11.687 = .00724 or .7% (based on elastic strain), where .3 is the elastic poisson ratio for copper.

For fully plastic bending the keystoning is .5*.564/2/11.687=.01206 or 1.2% strain

So the contraction of the long dimension= .01206*1.086= .013097 inches. Or .00654 in per edge, or .166mm per edge. Compared with.167e-3m in the ANSYS simulation



Winding Reaction Force on the Mandrel for 12 ksi Yield and 14 ksi Yield Conductor



Everson Tesla does a tensile pull on the brazed region to test the joint and raise the yield. If the distribution of the stress is strongly affected by the geometry of the conductor, including the hole, then the strain and work hardening might vary across the cross section. This appears not to be the case – he variation on the right of the model. Is due to the constraints. The stress variation on the left is small.

16.0 Axial Stress – Lorentz and Thermal (2D Analysis)
16.1 2D Modeling of the Axial Stress

We have eliminated the tight layer joggles that were difficult to wind, but with the more gradual transitions, the ends of the coil no longer have mostly flat faces of conductor facing the mandrel flange. The concentrated loads on the conductors needs to be qualified. The maximum vertical load from the design point spreadsheet is 95770 lbs. The average Axial stress due to the max of the 96 EQ is: 95770/(12.778*2*pi*2.73) = 436 psi = 3 MPa. Which is small. This goes up some due to the flexure of the flange.

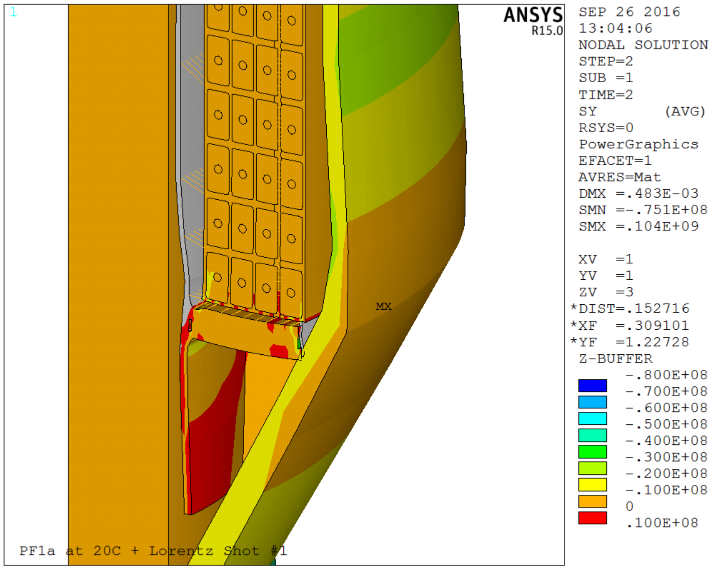


Figure 16.0-1 Coil Stress from Lorentz Loads Only

The finite element model produces a peak compressive stress of about 10 MPa in one of the corners of the winding that is in contact with the flange. More compression results from the restraint of expansion

The new coil will have conductor high spots and low spots that will be in hard contact with the flange, and will have regions – in fact most of the end volume – that are supported by fillers. The fillers have a lower modulus than copper and will shed load to the copper conductors. The difference between the two coil designs would be expected to be dramatic except that the flexure of the flange causes one edge of of conductor to pick up most of the load anyway.

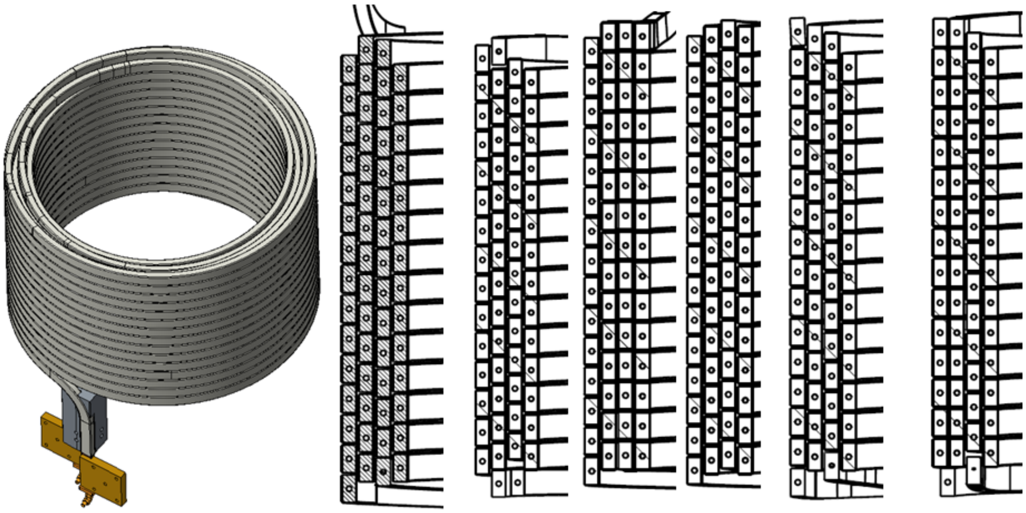


Figure 16.0-2 Winding Sections in the Proposed New Coil Showing Single Conductor Contact Points

From Figure 16.0-2, it is evident that for most of the circumferential extent of the winding, there is only one layer resting on the end flanges. The void spaces or ramps and fillers will have to be filled with High density G-11 to help distribute the load, but if only the end turn of one layer of the coil is taking the Lorentz Load, then the axial stress will be 4 times larger than the average or 4*436=1747.8 psi or 12 MPa. This doesn't include the thermal expansion interaction between the coil and mandrel. With this added, even the model based on the rectilinear array of conductors produces an inner corner compressive stress of 80 MPa or 11.6 ksi. Or locally near the specified yield of 12 ksi.

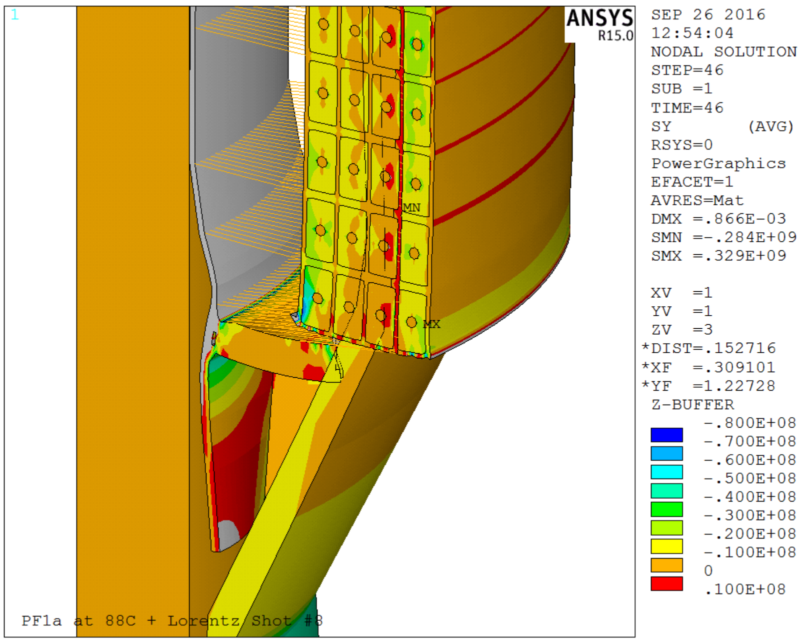


Figure 16.0-3 Original PF1a with Rectilinear Conductor Array, Lorentz + Thermal

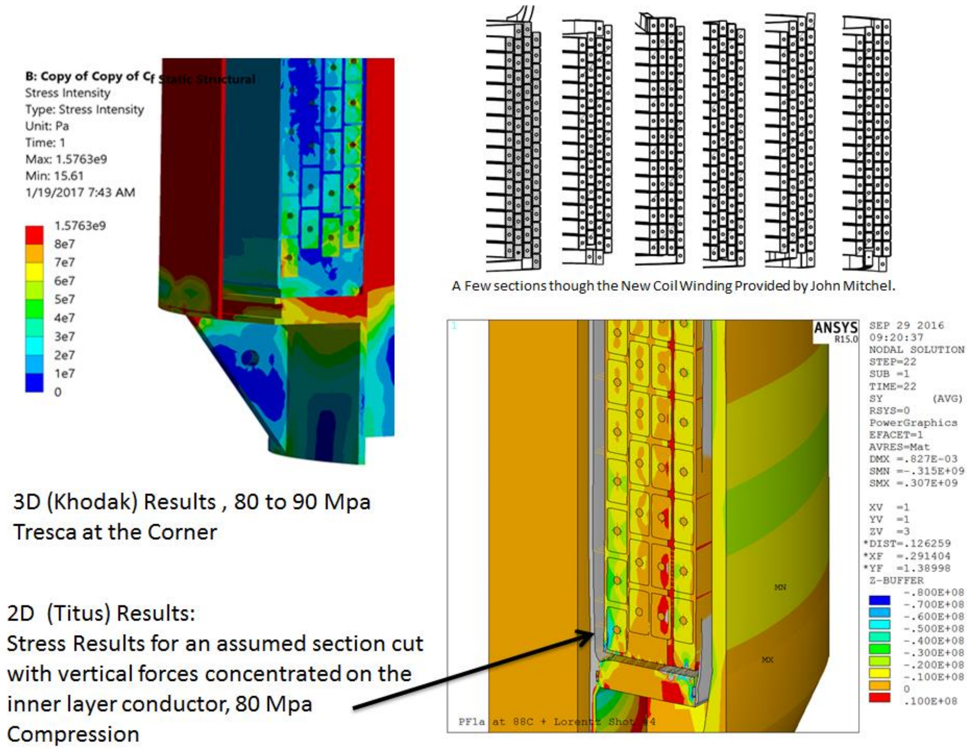


Figure 16.0-4 New PF1a Design with Misaligned Conductors

The local conductor compression is similar to the original design. With the fillers utilizing dense high pressure laminate, the compressive loads can distributed as evenly as the flange flexure and shell thicknesses will allow.

16.2 3D Modeling of the Axial Stress (Andrei Khodak)

A three Dimensional model was developed from the coil solid model, including all the radial and vertical transitions and G-10 volumes that represent the ramps and fillers.

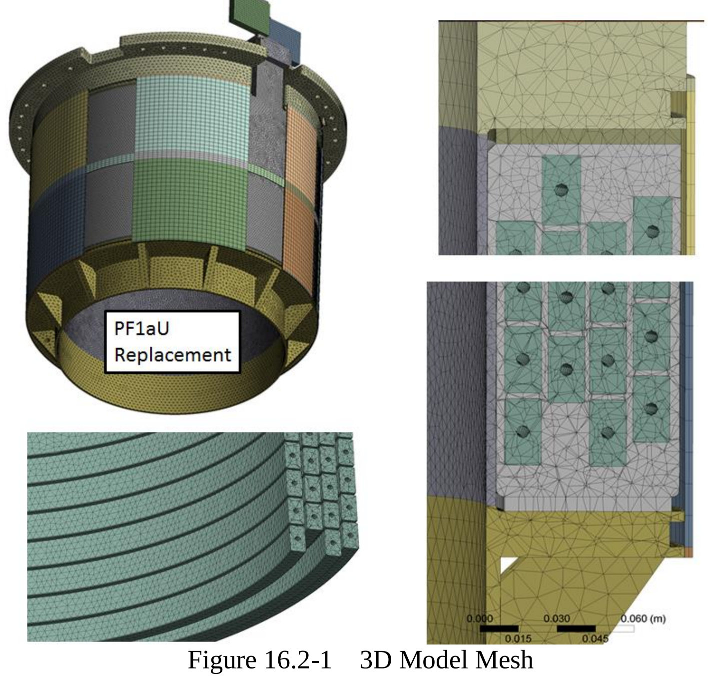


Figure 16.2-1 3D Model Mesh

The main purpose of this was to investigate the accuracy of analyzing the 2D slice used in section 16.1, and provide a cross check of the two analyses. The results confirm both modeling approaches.

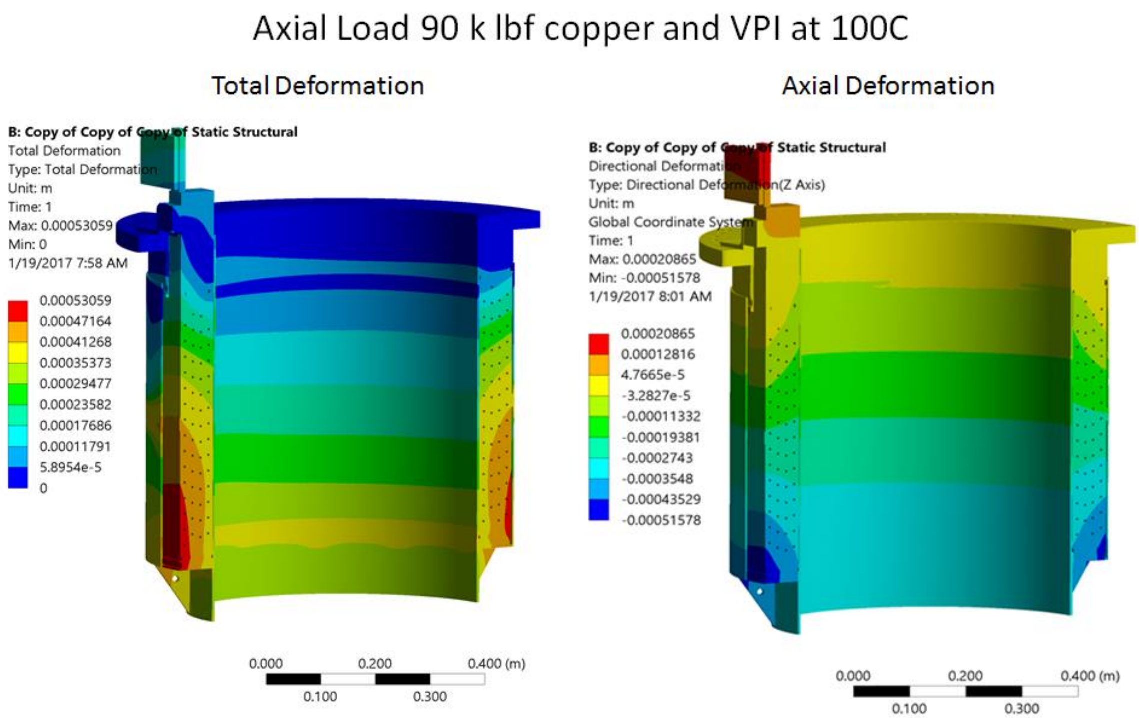
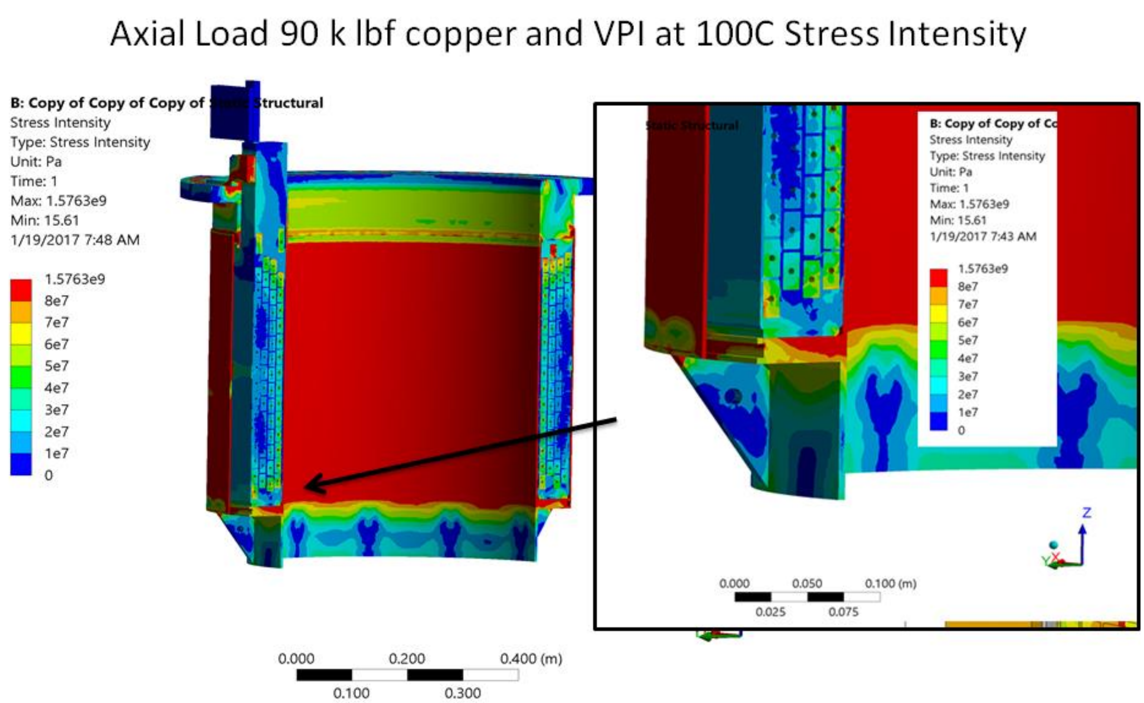


Figure 16.2-2   3D Model Displacements



3D Model Tresca Stress

Figure 16.2-3 3D model of PF1a Section Showing Local Conductor Compression

90klbf 100C copper and VPI

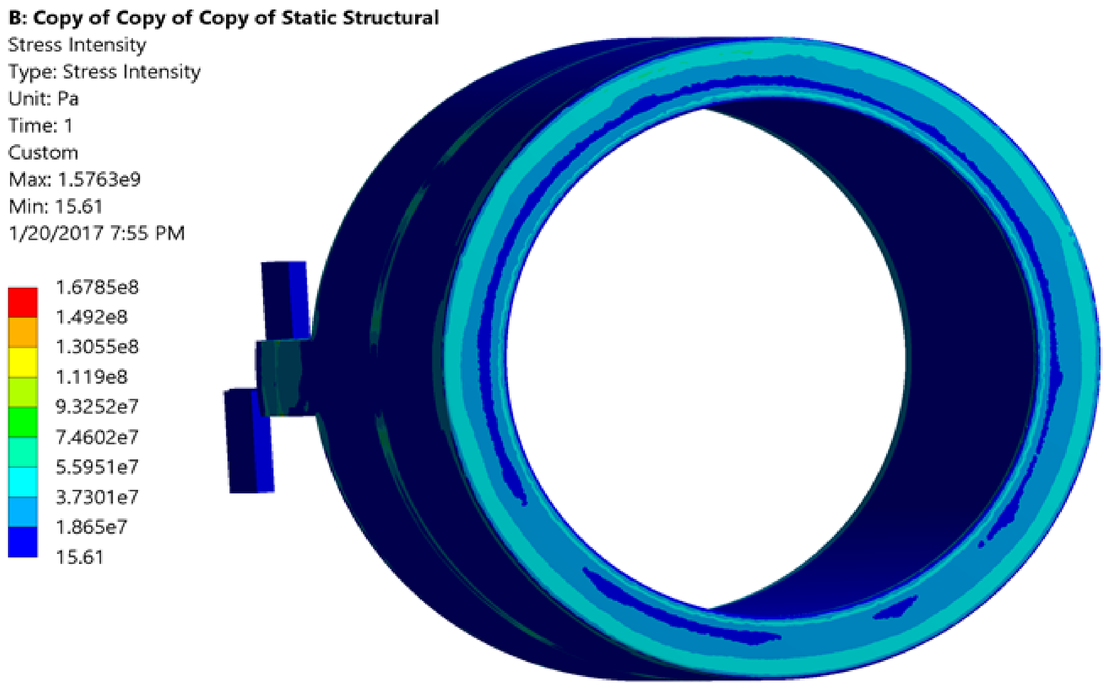


Figure 16.2-4 3D model of PF1a Coil End Face Tresca Showing Variation due to Ramps and Fillers

In figure 16.2-4, the Tresca stress in the end face of the coil is plotted The end view of the coil at the left shows no severe hard point that concentrates too much load inventory on the lower extremities of the winding/transition pattern.

17.0 Coil Elastic-Plastic Response with Lorentz and Cooldown
17.1Chaboche Multi Cycle Analysis

New conductor with a minimum yield of 9ksi has been purchased intending to achieve 12 ksi as wound. Cooldown is expected to yield the conductor and we have to demonstrate that the purchased conductor will cycle acceptably and not strain the insulation any more than we have qualified for the OH glass and Kapton CTD 425 system. This effort has required a re-calculation of the cooldown behavior and sophisticated elastic –plastic analysis in order to demonstrate that the cyclic behavior "shakes down" and the behavior of the conductor is repetitive and does not grow. The cyclic stresses will need to be qualified for fatigue and that is done in section 18.0 .

Elastic Plastic analyses have utilized multi kinematic hardening models – for the winding simulation, and Chaboche models for the cyclic simulation. Three Copper Chaboche models have been considered. The first two sets of data are derived from research done for the CIT project at MIT-PSFC in 1989 [28]. The third is from published data for a copper lined rocket nozzle [27]

Art's interpretation of the Chaboche parameters from the CIT J Chen MIT-PSFC data is included in Appendix A. His results from a simple segmented cylinder are presented below. This is for the higher yield version of the copper stress strain curve for which Art developed Chaboche parameters. The higher yield version has a yield of 100 Mpa, or 14.5 ksi – larger than the target in the purchase spec of 12 ksi.

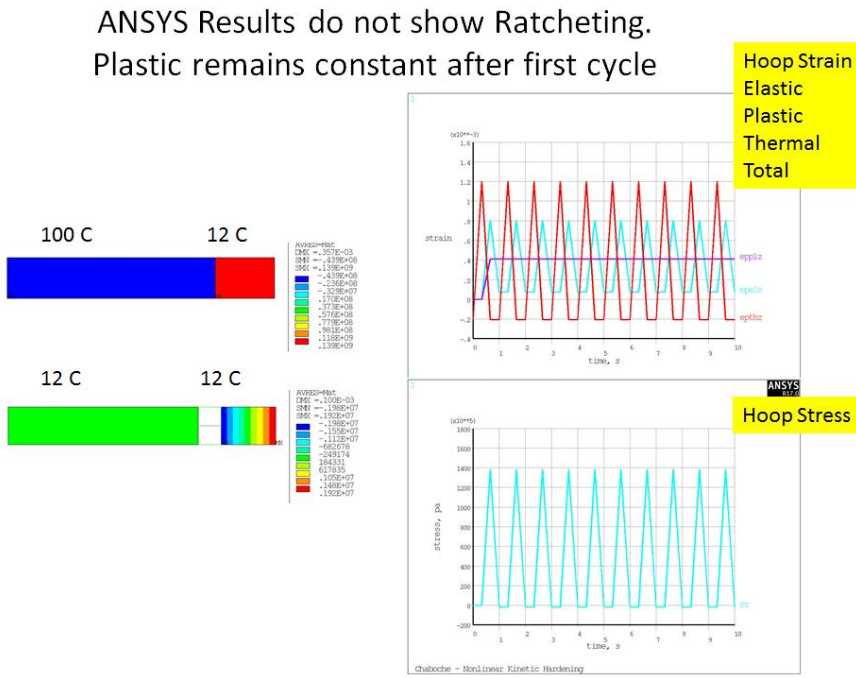
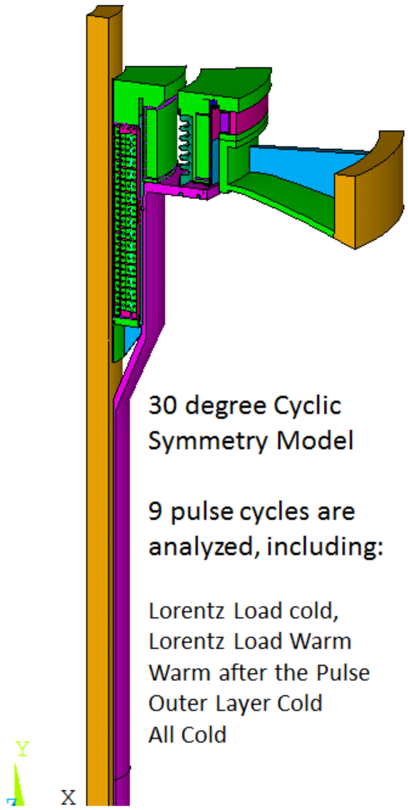


Figure 17.0-1 Results for thermal cycling of a nested cylinder.

One important conclusion from Art's simulation is that after the first plastic deformation, the cycles progress elastically. There is no ratcheting. This will be an important characteristic needed from the new coil. Once it experiences a cooldown from the max temperature, the coil should experience no changes in its "at rest" geometry.

In Appendix A, Art considers a second set of Chaboche parameters for a lower yield in which the cyclic behavior does not "shake-down" . This will require more investigation, but the "rocket nozzle" data is based on a 70 MPa yield and may be more representative of the copper purchased for the new PF1a coil.




```
*do,numpulse,1,9,1

/title, PF1a at 20C + Lorentz Shot #%numpulse%
esel,mat,17
nelem
nrsel,x,0,.38
f,all,fx,390442/12/.2248/(16*4*76*30)
f,all,fz,-95770/12/.2248/(16*4*76*30)
eall
nall
solve
save

/title, PF1a at 88C + Half Lorentz Shot #%numpulse%
esel,mat,17
nelem
nrsel,x,0,.38
f,all,fx,.5*390442/12/.2248/(16*4*76*30)
f,all,fz,.5*(-95770/12/.2248/(16*4*76*30))
esel,mat,17
easel,mat,5
nelem
bf,all,temp,88
Eall $nall
solve
save

/title, PF1a at 88C + Lorentz Shot #%numpulse%
esel,mat,17
nelem
nrsel,x,0,.38
f,all,fx,390442/12/.2248/(16*4*76*30)
f,all,fz,-95770/12/.2248/(16*4*76*30)
esel,mat,17
easel,mat,5
nelem
bf,all,temp,88
Eall $nall
solve
save

/title, PF1a After  Pulse at 88C No Lorentz  Shot #%numpulse%
esel,mat,17
easel,mat,5
nelem
bf,all,temp,88
nall
eall
esel,mat,17
nelem
nrsel,x,0,.38
f,all,fx,.000001
f,all,fz,.000001
Nall $eall
solve
save
/title, PF1a Outer Layer at 12C Inner Layers at 88C No Lorentz  Shot #%numpulse%
esel,mat,17
easel,mat,5
nelem
bf,all,temp,88
esel,mat,7
nelem
enode
nelem
enode
nelem
enode
nelem
bf,all,temp,12
Nall &eall
solve
save
/title, PF1a All cooled to 12C Shot #%numpulse%
esel,mat,17
easel,mat,5
nelem
bf,all,temp,12
Nall $eall
solve
save
*enddo
```

Figure 17.0-1 Model and Loading for the Cyclic Simulation.

In the rocket nozzle Chaboche model, the yield is 70 MPa or 10 ksi The purchase spec is for 12 ksi but this is for a .5% offset (this is used for copper vs. a .2% offset for steel.) The 12 ksi at .5% offset yield spec is probably closer to the 10 ksi used in the Chaboche model

Table 1 Chaboche and Voce parameters of copper alloy

Parameters	Test temperature (K)					
	300	673	773	823	873	900
Chaboche						
σ_o	70	66	62	56	50	45
C_1	3994330	1,009,000	2,635,464	109,100	999,100	5,294,330
γ_1	4,630,000	11,260,000	2,020,000	101,000	991,000	3,945,000
C_2	132,726	47,868	32,080	15,100	20,100	4533
γ_2	1110	1110	1110	1110	2110	888
C_3	2455	1100	1010	800	200	491
γ_3	9	100	9	9	50	9
Voce						
k	70	66	62	56	50	45
R_o	0	0	0	0	0	0
b	10	24	5	19	12	15
R_∞	140	64	40	18	20	10

γ_3 is relatively higher at 673 and 873 K than at other temperatures, which indicates a faster saturation of strain hardening in region III. This could be due to cyclic characteristics of the material, which is indicated by a relatively higher γ_1 as well, at these temperatures

Figure 17.0-2 Tabulated Chaboche Data from [27]

!Mat 17, Copper   From Run cool05.txt   - "Rocket Nozzle Data"
pex=118660e6

```
 YIELDSTR = 70.00e6     !Yield Strength of Material
! YIELDSTR = 100.00e6     !Yield Strength of Material
 POISS = .3            !Poisson's Ratio for the material
 alpx,17,17e-6
 MP,EX,17,pex ! ELASTIC CONSTANTS
 MP,NUXY,17,POISS
 TB,CHAB,17,1,3 ! CHABOCHE TABLE
 TBDATA,1,YIELDSTR,399433,4630000
 tbdata,4,132726,1110
 tbdata,6,2455,9
```

The behavior of the outer layer of the coil depends on the degree to which the insulation system can support transverse tension. For the Kapton-Glass interleaved system, the tensile capacity is near zero because of the parting-plane behavior of the Kapton. The layer to layer insulation plane between layers 3 and 4 is modeled with a very soft material that develops minimal tension and gap elements that support compression when the outer layer is cooled.

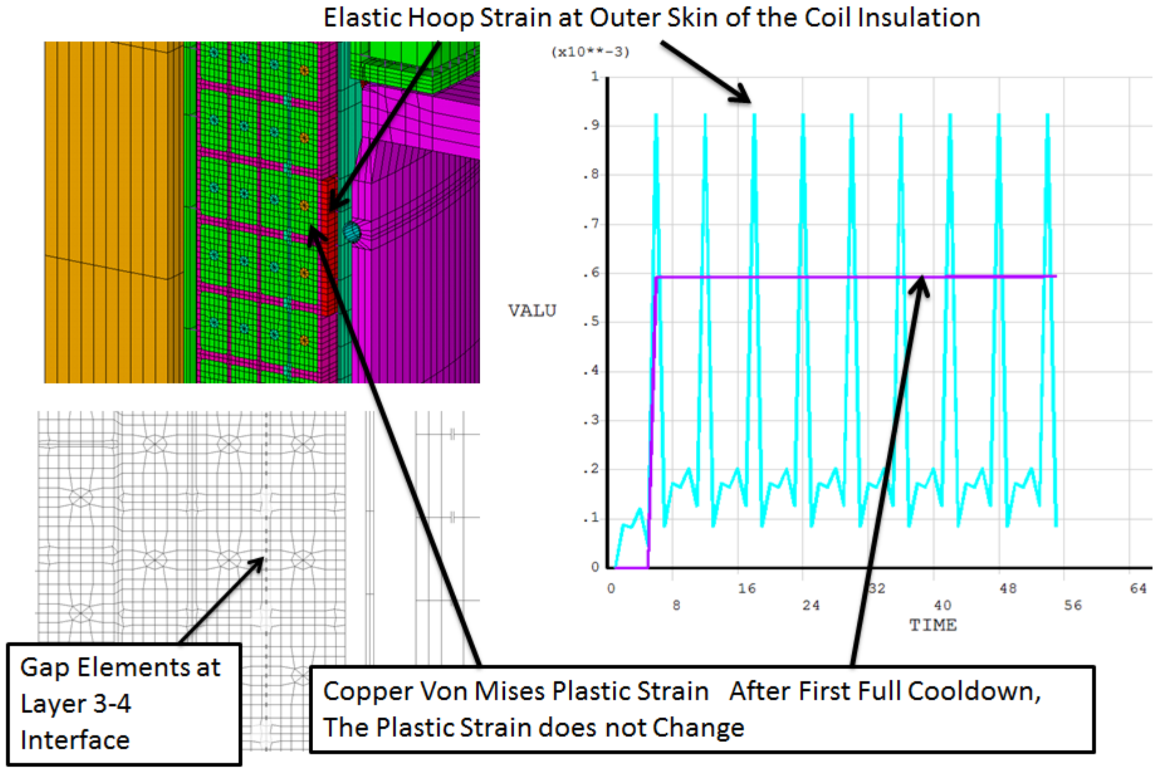


Figure 17.0-3 Results with the 3 to 4 layer insulation modulus of 20e8 MPa

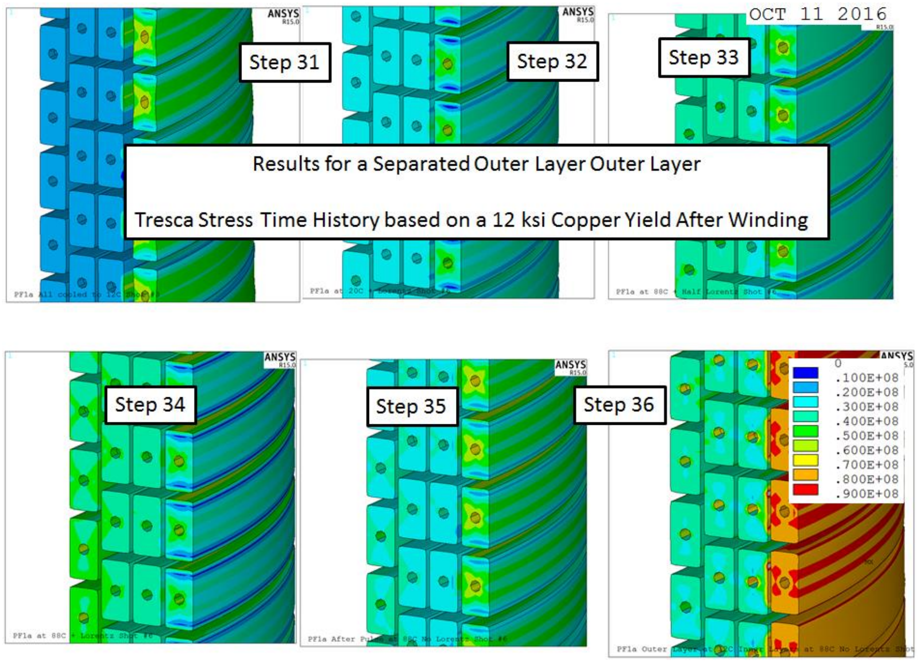


Figure 17.0-4 Results with the 3 to 4 layer insulation modulus of 20e7 MPa

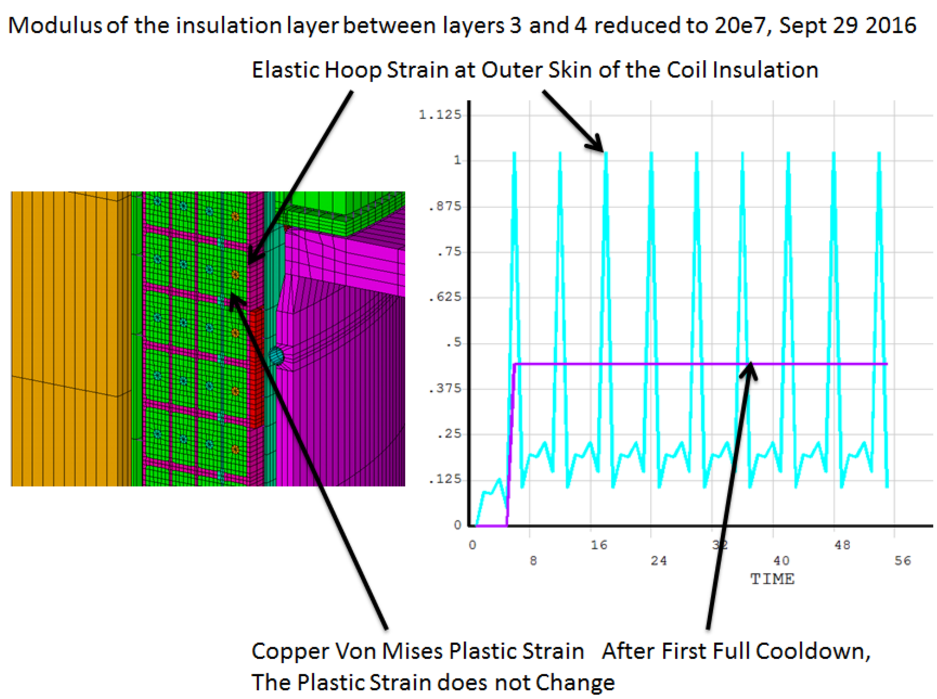


Figure 17.0-5 Results with the 3 to 4 layer insulation modulus of 20e7 MPa

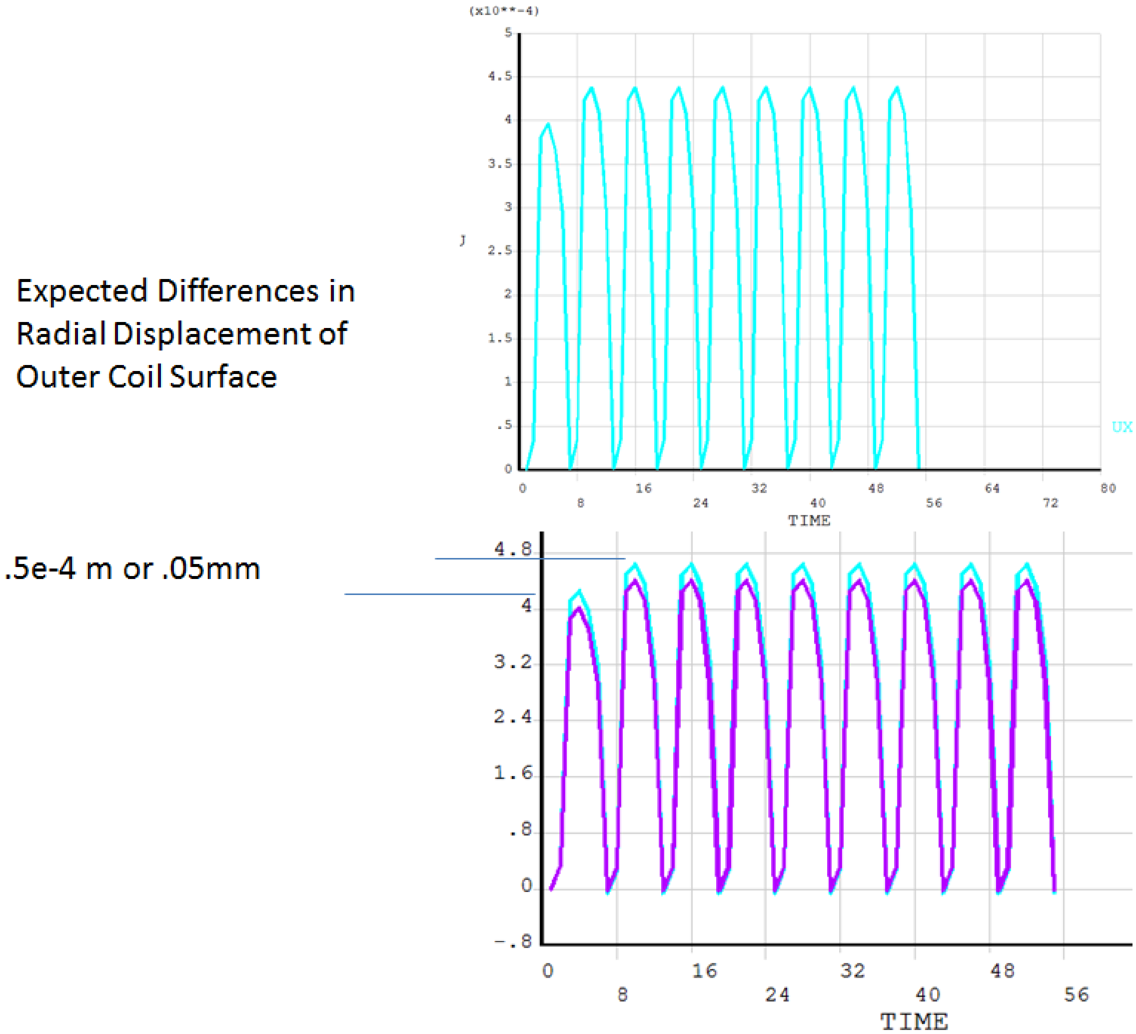


Figure 17.0-6 Displacement Results with the 3 to 4 layer insulation modulus of 20e6 MPa

The model was run with the CIT based CHABOCHE date. The APDL materials input is listed below: It is based on a 105 MPa or 15 ksi yield, so it is above the specified yield for the new conductor

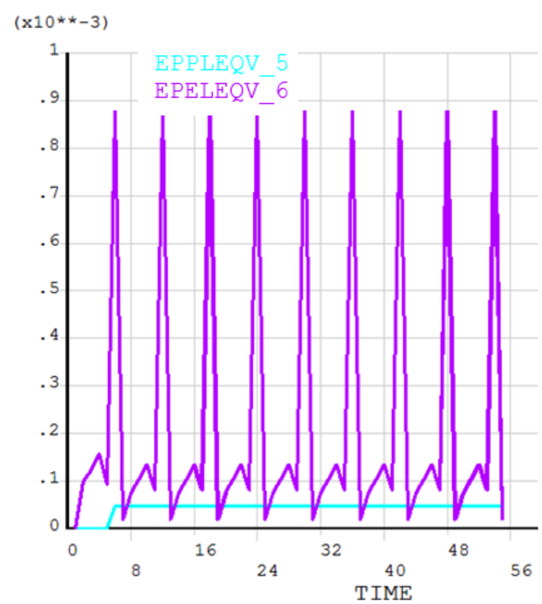
```
chaboche_1d_strain2.txt - fit to CIT data
  Ex=122.5e9  ! Elastic Modulus
  !Et1=110.e9  ! Tangent Modulus1 - small strain
  Et2=7.e9  ! Large strain tangent modulus
  Sy=105.e6  ! Yield Stress
  Slim=77e6 ! Limiting Stress = C1/G1 (from C1 = dS/de = d(Slim*(1-exp(-G1*e)))/de = Slim*G1)
  !C1=Ex*Et1/(Ex-Et1)  ! Plastic Tangent modules1 (?)
  !G1=C1/Slim
  G1=667
  C1=Slim*G1
  C2=Ex*Et2/(Ex-Et2)
  G2=0

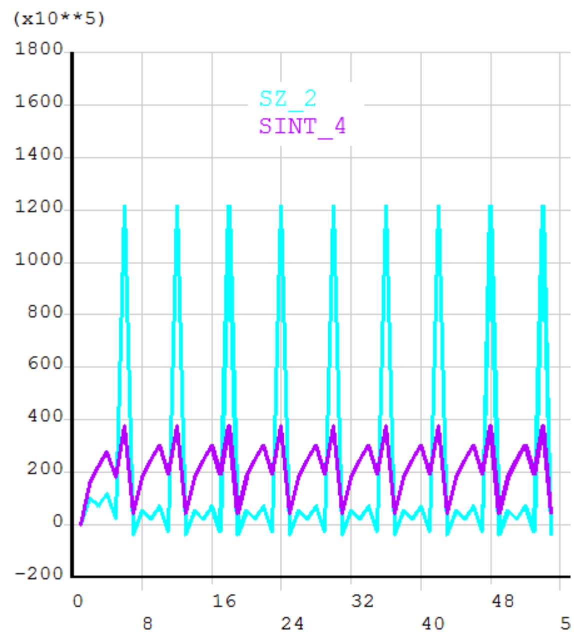
!Mat 17, Copper
pex=ex
```

```
YIELDSTR = Sy   !Yield Strength of Material
 POISS = .3          !Poisson's Ratio for the material
 alpx,17,17e-6
 MP,EX,17,pex ! ELASTIC CONSTANTS
 MP,NUXY,17,POISS

 TB,CHAB,17,1,3 ! CHABOCHE TABLE
 TBDATA,1,YIELDSTR,C1,G1
 tbdata,4,C2,G2
```

Based on Art's Development of Chaboche parameters from the CIT J Chen MIT-PSFC data in Appendix A , in P. Titus's model





This plot is useful to evaluate whether the planned test can be instrumented adequately to measure the geometric change of the coil due to plastic strains. It is hard to imagine an LVDT could measure the .05mm growth of the coil, and separate it from other motions of the coil. It is expected that measuring the strain at the outside surface of the coil, is probably the best approach to see the shake-down behavior.

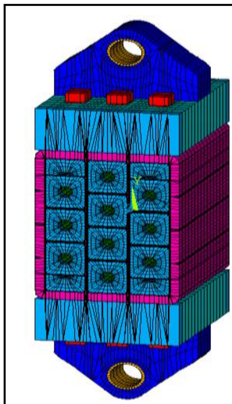


Figure 17.2-1 Model of the Strain Controlled Specimen

17.2 Assessment of Insulation Strains

There will be a growth of the outer layer of the coil away from the rest of the coil build . In actuality the behavior will not be limited to layer 4 but will occur to lesser degrees in the inner layers. The intention of the interleaved Kapton-glass system is to provide some tolerance to local strains in the coil. Multiple Kapton wraps are usually used around the terminals to provide insulation integrity if the terminal move under Lorentz loads or thermal motions. Kapton has a very large % elongation before it will break and can stretch and bridge epoxy cracks. But excessive motion of the insulation system during cooldown can damage the Kapton tape or propagate cracks. This issue came up with the OH coil and the approach was to test the insulation system in strain controlled tests that enveloped the cooldown wave behavior and in parallel design a warming system for the OH cooling water that would produce a more gradual distribution of thermal strains in the coil. CTD was contracted to do the tests. The fixture and test specimen are shown in Figure 17.2-2 The CTD Test specification and test report are references [23] and [24]

Table 4.0-1 Tensile Strains from Analyses and Test in [21] OH Cooldown System and Preheater, NSTXU CALC-133-17-0

Location	No Preheater Figure or [21] Section	No Preheater	With Preheater Figure	With Preheater
CTD Test SOW	Reference [23]	4.0e-4		
CTD Actual Test	[21] 4.0-14	~6.0e-4		
NSTXU Cooling Wave	[21]Figure 8.0-3	2.56e-4	8.0-3	7.5e-5
NSTXU Cooling Wave	[21]9.0-1	4.07e-4	9.0-4	1.3e-4
NSTXU Base	[21]11.8, 11.9			3.37 to 4.1e-4

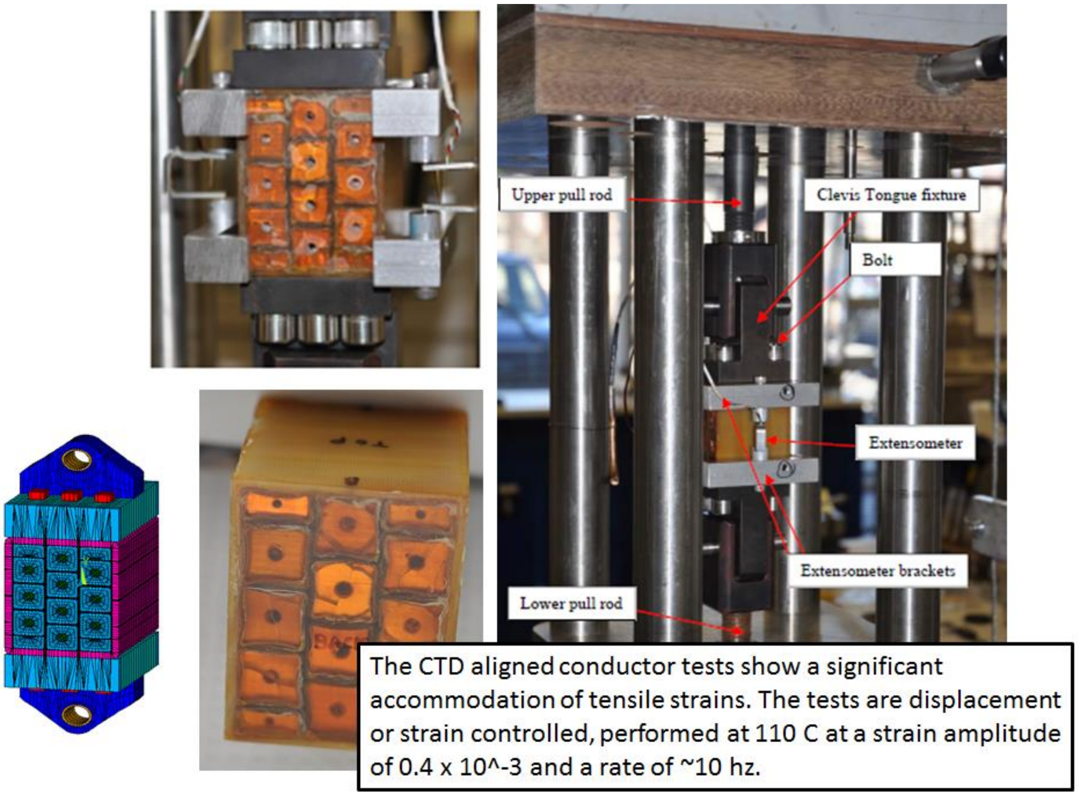


Figure 17.2-2 Array Test Samples and Fixtures from [23]

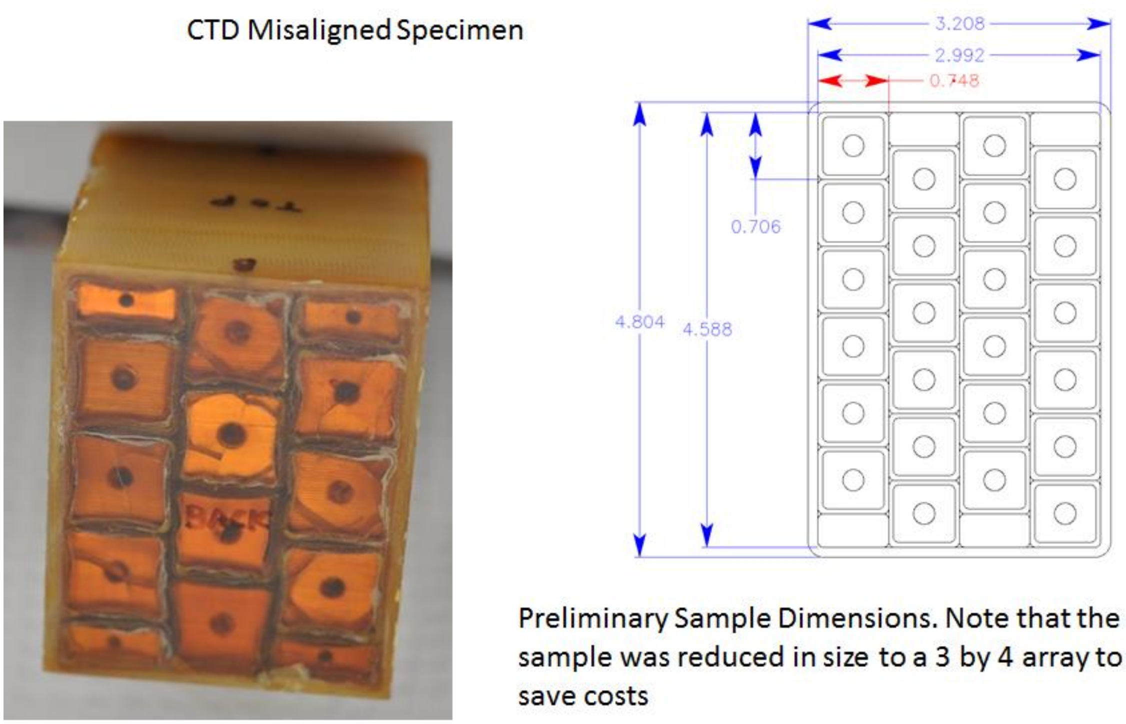
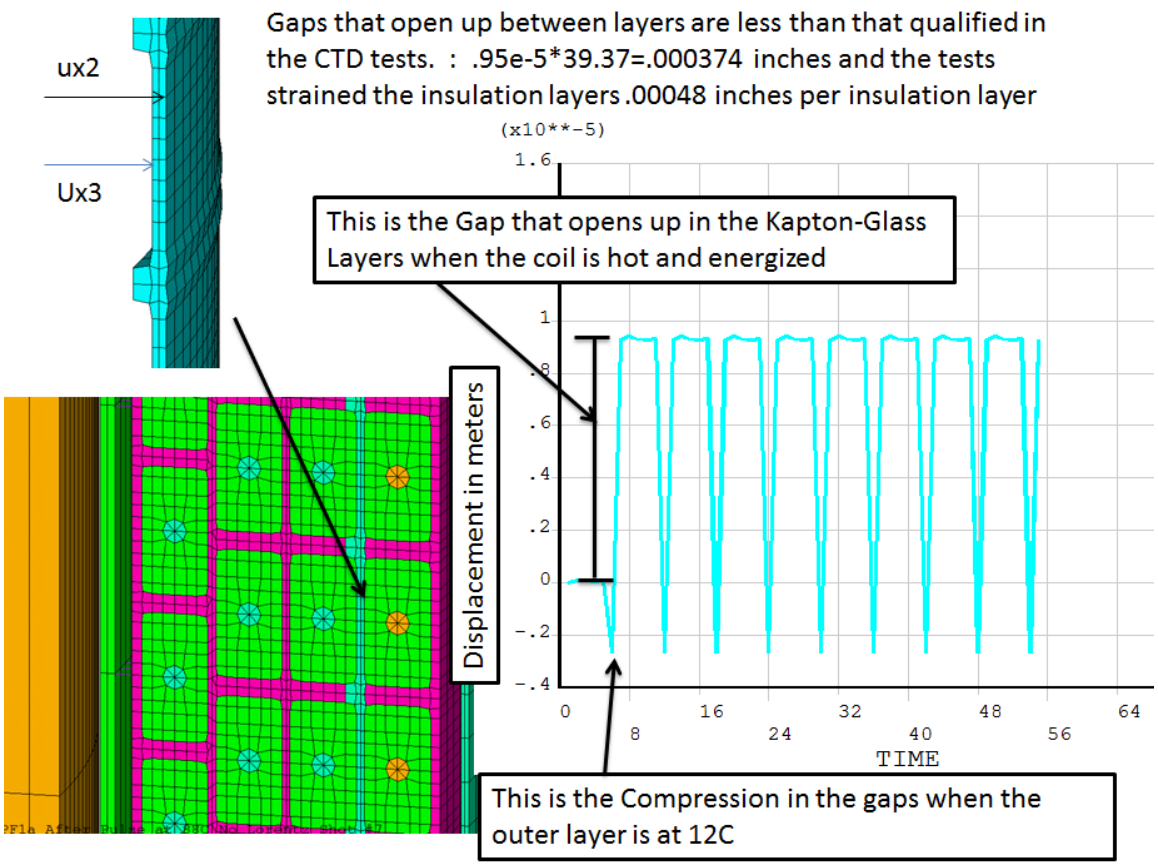


Figure 17.2-3 Array Test Sample from [23] (The sample at left was shortened in the actual tests)

The CTD aligned conductor tests show a significant accommodation of tensile strains. The tests are displacement or strain controlled, performed at 110 C at a strain amplitude of 0.4 x 10^-3 and a rate of ~10 hz. A full discussion of these tests and their application to the OH can be found in [21] While the electrical behavior did not degrade, there were indications that the modulus was changing, after 30,000 cycles. Indicating the insulation system was de-bonding.

Imposed strain during the test was 4e-4 as a requirement. The actual test imposed 6e-4. Based on the sample in the figure above, the displacement of the insulation system would be 6e-4*4.804 inches = .00288 inches. 6 layers or .00048 inches per insulation layer



The simulation produces .9e-5m gap or .000374 inches , less than .00048 gap in the test a test gap

18.0 Assessment of Copper Fatigue

18.1 SN Based Fatigue Assessment

For PF1a and the other inner PF coils, fatigue damage is more significant for the stress level imposed during cooldown than for the Lorentz loading. This is an important distinction when compared with the fatigue damage in the OH coil. The OH is double swung, and its cyclic requirements are basically two times the design number of full power pulses – or 60,000 based on the original 30,000 full power pulse specification – or 40,000 based on the later GRD pulse spectrum which has been simplified to 20,000 full power pulses.

Criteria Document
Mean Stress Effect:

$$\mathbf{Seq} = \frac{\mathbf{Salt}}{\mathbf{1 - (Smean/Su)}}$$

where Su = tensile strength

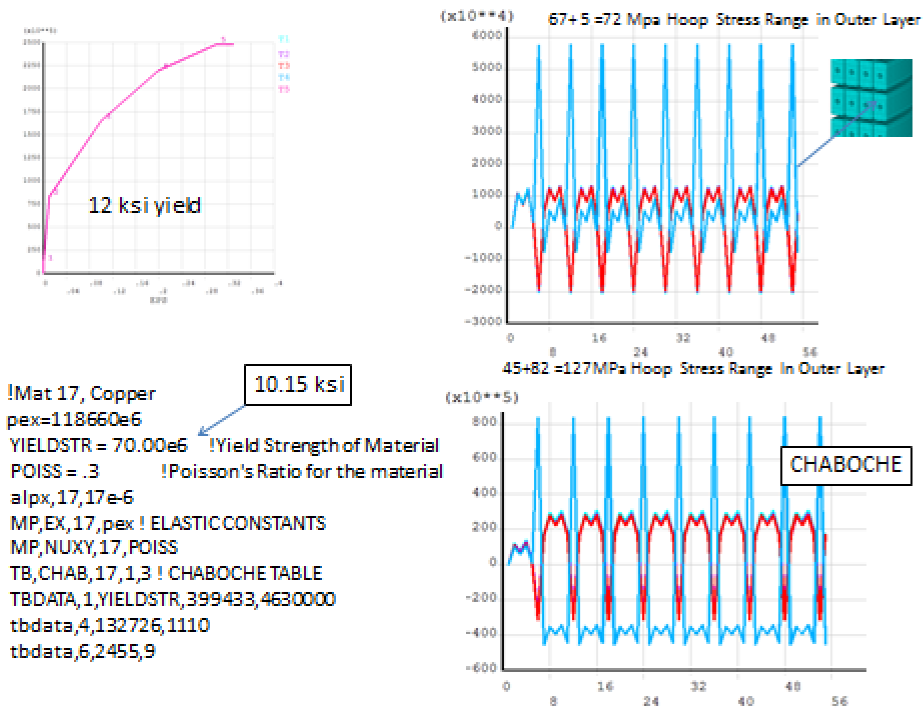


Figure 18.0-1 Stress Range for the Fatigue Assessment

For +80 MPa to -45 MPa, the mean is 17.5, the Alt is 62.5 so the equivalent R=-1 stress is= 62.5/(1-17.5/300)
= 66 .37 MPa

The equivalent R=0 stress is 2*66.37/(1+66.37/300) = 108.7 MPa. This is appropriate for a comparison with a Tresca based S-N evaluation. For the project this was set at 125 MPa and so the cyclic stress in PF1a primarily due to cooldown is satisfied

For a fracture mechanics calculation, the crack will close under compression, so only the tensile part of the stress cycle is pertinent.

18.2 Fracture Mechanics Assessment of 1mm crack

The fatigue limit established for the copper conductors used in the upgrade was set at 125 MPa [10] This was based on the specification for the conductors that set a limit of 0.7mm crack size. Luvata took exception to this and countered with a claim that if the tails of the conductor run showed no Cuprous Oxide, then the probability of any flaw was near zero. Luvata – when it was Outokompu - did 100% NDE on the full length and could guarantee no flaws greater than 0.7 mm. This approach is taken by Wieland in their production, but they can't guarantee anything better than 1mm. The original conductor specification was intended to satisfy mainly the requirements for the OH coil, and the inner PF coil conductors were added to the purchase spec. The inner PF coils are not nearly as highly stressed as the OH coil.

As a first cut on the effect of the larger flaw, the OH calculations were modified adding the larger crack. The NSTX-U Structural Design Requirements Document[11] establishes levels of conservatism for fracture mechanics. These are a factor of 2 on flaw size, a factor of 1.5 on fracture toughness, and a factor of 4 on cyclic life. So the Paris integral that had been run for 1.4 (two times 0.7mm) was re-run for 2mm and the data added to the stress vs. cycle plot for the OH conductor. This is shown in figure 18.2-1. This analysis used the OH conductor parameters, and a program by Jun Feng for the Paris Integral. PF1a is not double swung, and experiences one cooldown stress per cycle, so the required cycles for the PF1a coils is half that for the OH. The results show that when the lower total number of cycles is considered, even with the larger crack size, the allowable stress is increased over the 125 MPa.

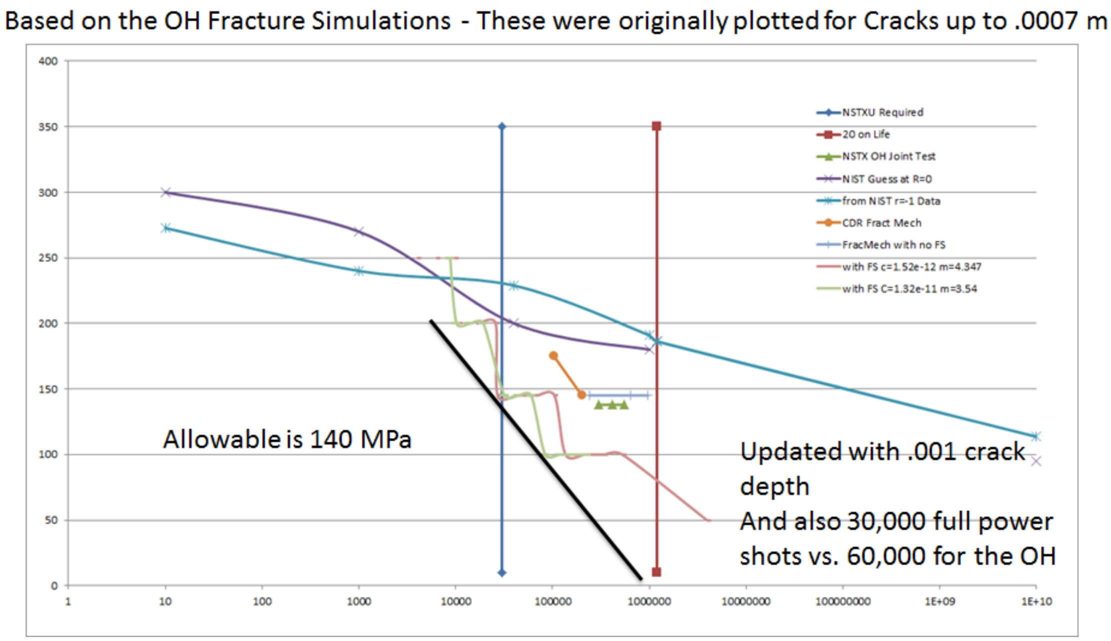


Figure 18.2-1 Updated SN Curves with .001 mm flaw Size and OH Conductor Characteristics

A new program that accommodated the PF1a conductor geometry and stress intensity values calculated from ANSYS KCALC calculations is also used in this section. This allows a more readily understood consideration of the specifics of the PF1a conductor. In this program a handbook stress intensity function for a circular embedded crack was used which produced unacceptable life. The simpler function was then replaced with stress intensities from ANSYS KCALC calculations.

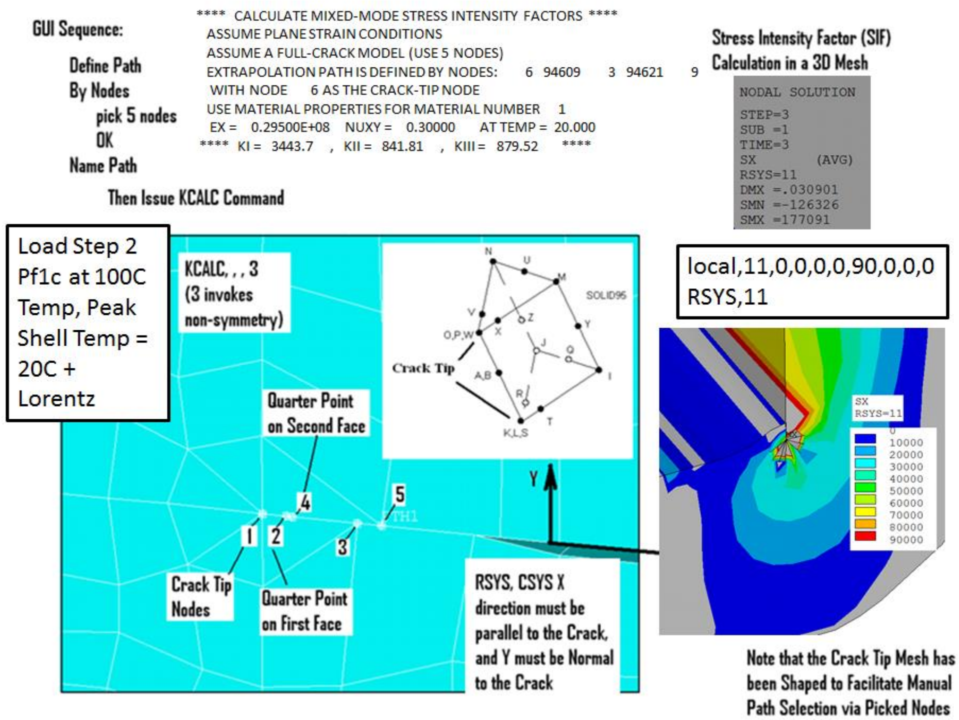
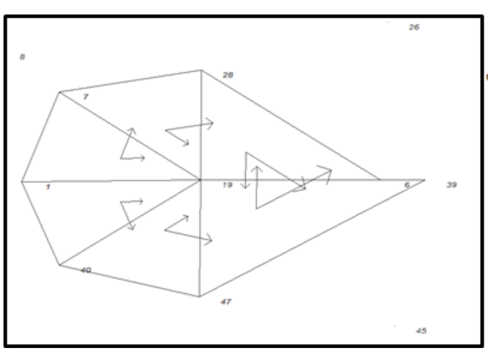


Figure 18.2-2 Methodology of Using KCALC feature of ANSYS

For a crack in the conductor that is positioned pessimistically near the cooling channel, the crack would conservatively appear as an embedded or surface crack perpendicular to the conductor axial stress. Handbook treatments of the geometry can approach that in the conductor. In the simplified code (Appendix F) the handbook treatment was considered load controlled and the tensile stress was adjusted for the loss in cross section to the crack area. In actuality, especially for the thermal stress loading, the behavior is more like a displacement controlled loading. This is the modeling used in the KCALC calculations. There is a release of stress in a displacement controlled loading situation that will mitigate the stress intensity (SIF) vs. crack depth. To calculate the SIF, the ANSYS crack tip element is used. Solid 90 elements with mid side nodes are used for the model. Wedge elements are arrayed around the crack tip. The midside nodes of the crack tip elements are positioned 1/4 of the length of the side. This causes a singularity that can be used by the KCALC ANSYS command to calculate the stress intensity factor (SIF), KI for a mode one crack, (and KII and KIII for the other modes) from a finite element model of a component including the crack tip. Higher order, 20 node elements must be used and the mid-side node of the elements at the crack tip must be positioned at one quarter the element edge length to force the appropriate discontinuity at the crack tip. Collapsed nodes must be at the crack tip.

A routine in NTFTM2 takes an 8 node brick mesh and writes 20 node elements for input to ANSYS. Type 16 elements are written as crack tip elements with their collapsed nodes and ¼ point midside nodes positioned properly.



```
0
 El   typ mat rel    n1     n2     n3     n4     n5     n6     n7     n8
   13  16   7   0     1      7     19     19      0      0      0      0
  0.0000000E+00  0.00000000000000E+000
   14  16   7   0     7     28     19     19      0      0      0      0
  0.0000000E+00  0.00000000000000E+000
   15  16   7   0    28      6     19     19      0      0      0      0
  0.0000000E+00  0.00000000000000E+000
   34  16   7   0    47     39     19     19      0      0      0      0
  0.0000000E+00  0.00000000000000E+000
   35  16   7   0    40     47     19     19      0      0      0      0
  0.0000000E+00  0.00000000000000E+000
   36  16   7   0     1     40     19     19      0      0      0      0
  0.0000000E+00  0.00000000000000E+000
```

Figure 18.2-3 Typical Crack Tip Mesh in NTFTM2 Before Conversion to Solid 90 with Mid Side Nodes

To evaluate the stress intensity factor, a path is defined that describes the crack tip location. This is then used by ANSYS using the KCALC macro – accessed from the nodal operations entry in the postprocessor GUI. This was done for a 3 dimensional model of the PF1c Case (For a 3 dimensional model the APDL command is KCALC,,,3). The mesh must be re-generated for each crack depth to obtain the stress intensity factor a function of the crack depth.

The PATH command is used to define a path with the crack face nodes (NODE1 at the crack tip, NODE2 and NODE3 on one face, NODE4 and NODE5 on the other (optional) face). A crack-tip coordinate system, having x parallel to the crack face (and perpendicular to the crack front) and y perpendicular to the crack face, must be the active RSYS and CSYS before KCALC is issued. This is summarized in figure 18.2-2.

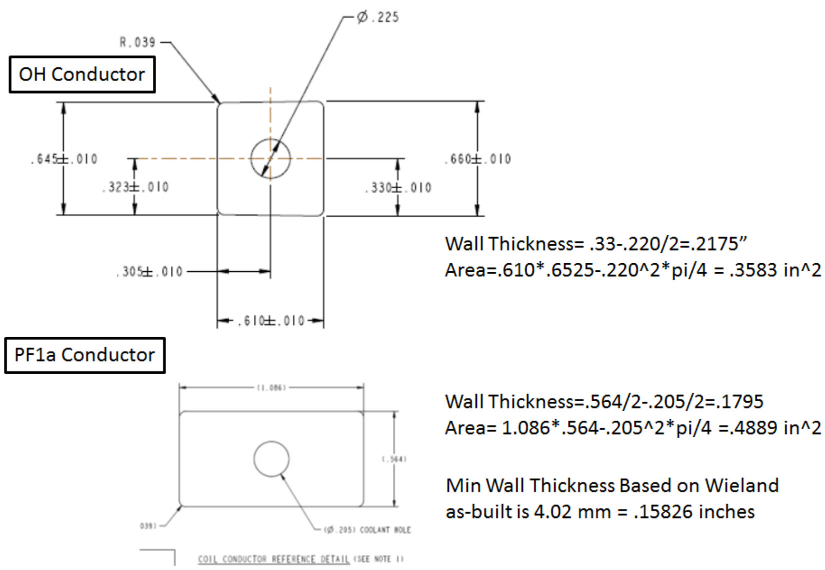


Figure 18.2-2 Conductor Cross Sections – OH (on Top) for Comparison and PF1a (Bottom)

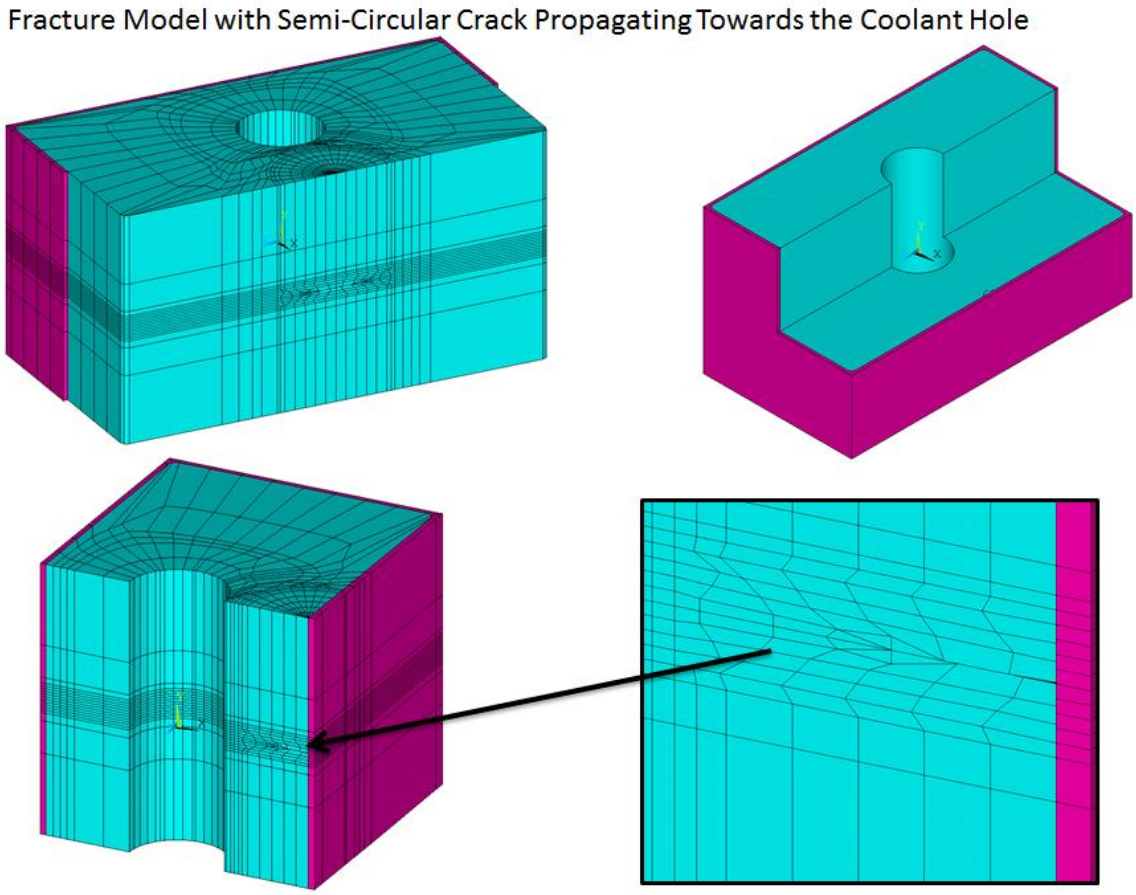


Figure 18.2-3 Fracture Model

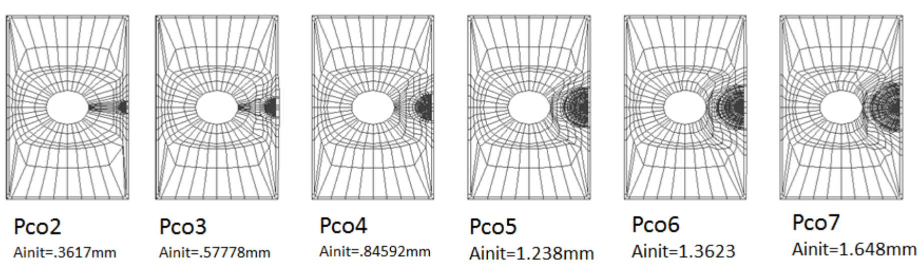


Figure 18.2-3 Progression of Models with Varying Crack Depths

These meshes are created by progressively distorting (and correcting) an original mesh

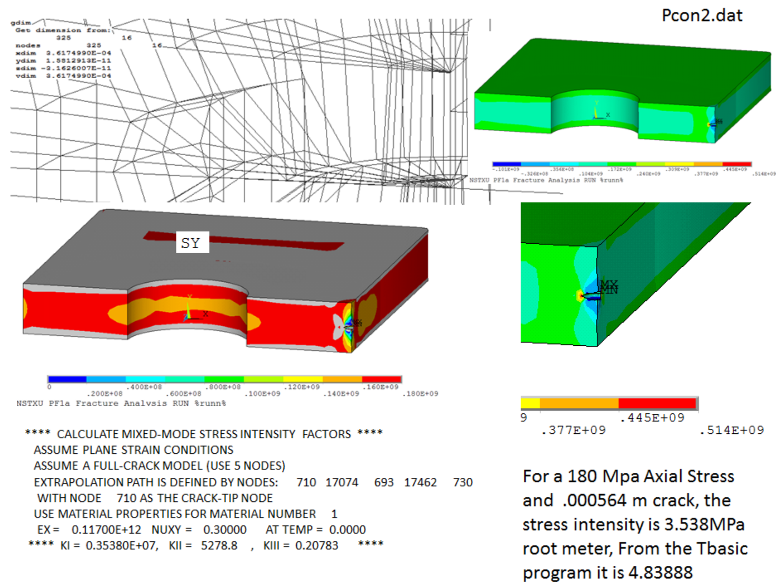


Figure 18.2-4 Model and Results with a .36174mm Initial Crack Depth

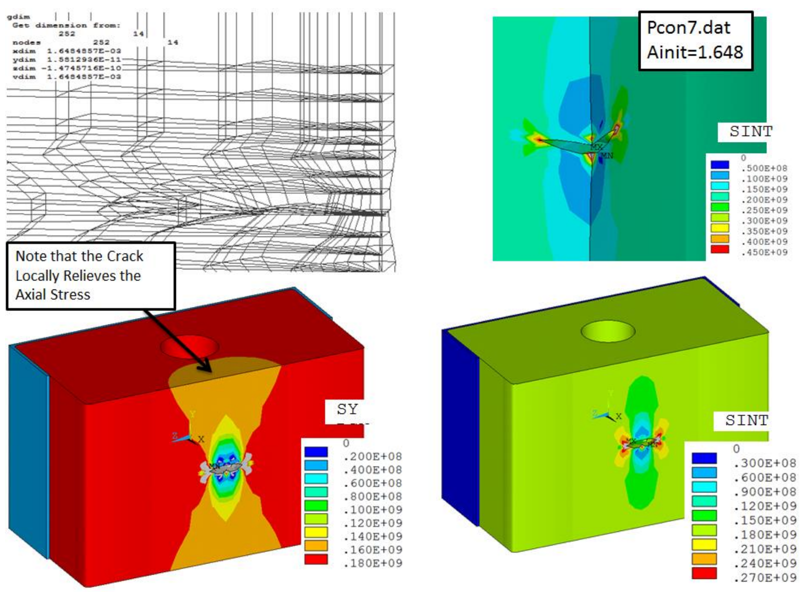


Figure 18.2-5 Model and Results with a 1.648mm Initial Crack Depth

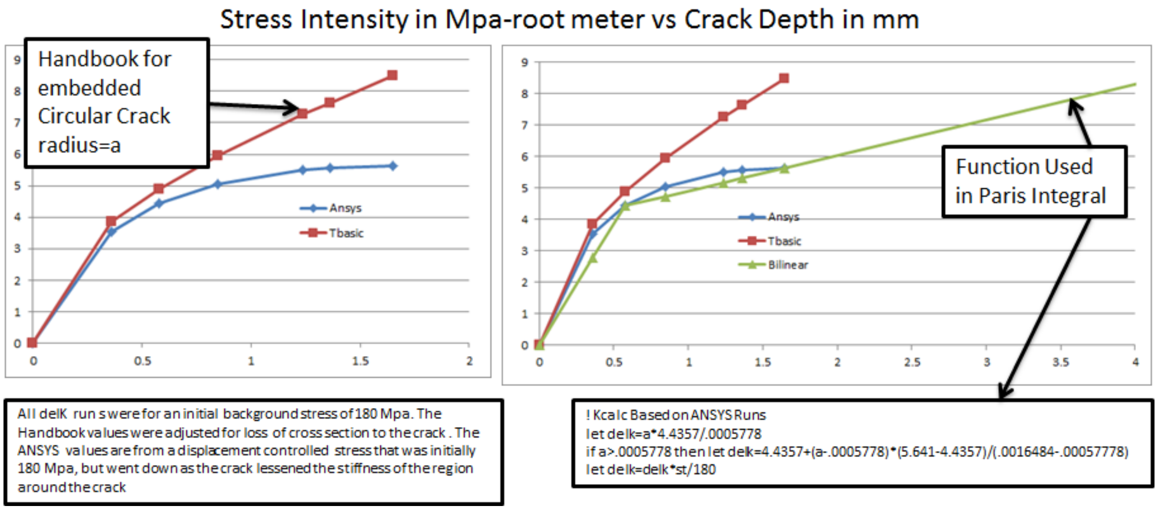


Figure 18.2-6 Stress Intensity vs. Crack Depth

A simple Pasic integral was programmed with True Basic (See Appendix F). This was used to generate the stress intensity vs. crack depth for the handbook solution, and with the bilinear approximation of the ANSYS KCALC derived stress intensity value, it was used to calculate life.

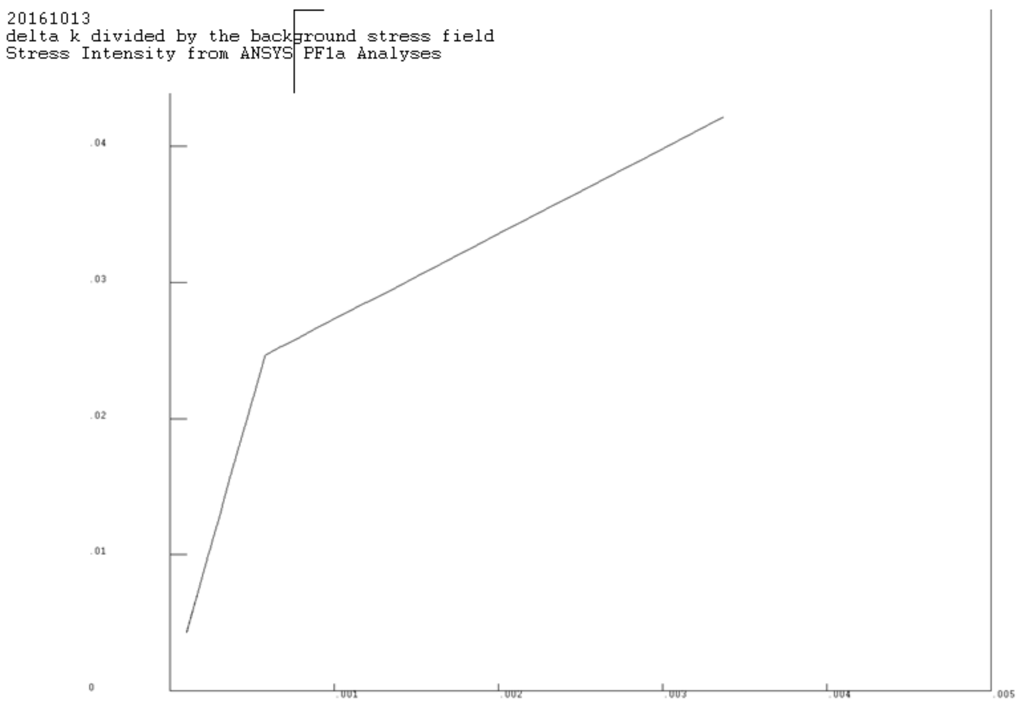


Figure 18.2-7 Bilinear Stress Intensity vs. Crack Depth Based on ANSYS KCALC

The Paris integral s based on twice the guaranteed maximum flaw of 1 mm – or 2mm and a minimum wall thickness to develop a leak of 4.02 mm. The 4.02 mm minimum wall thickness is based on as-produced conductor tolerances and comes from an email from Mike Kalish, reference 8, Appendix B.

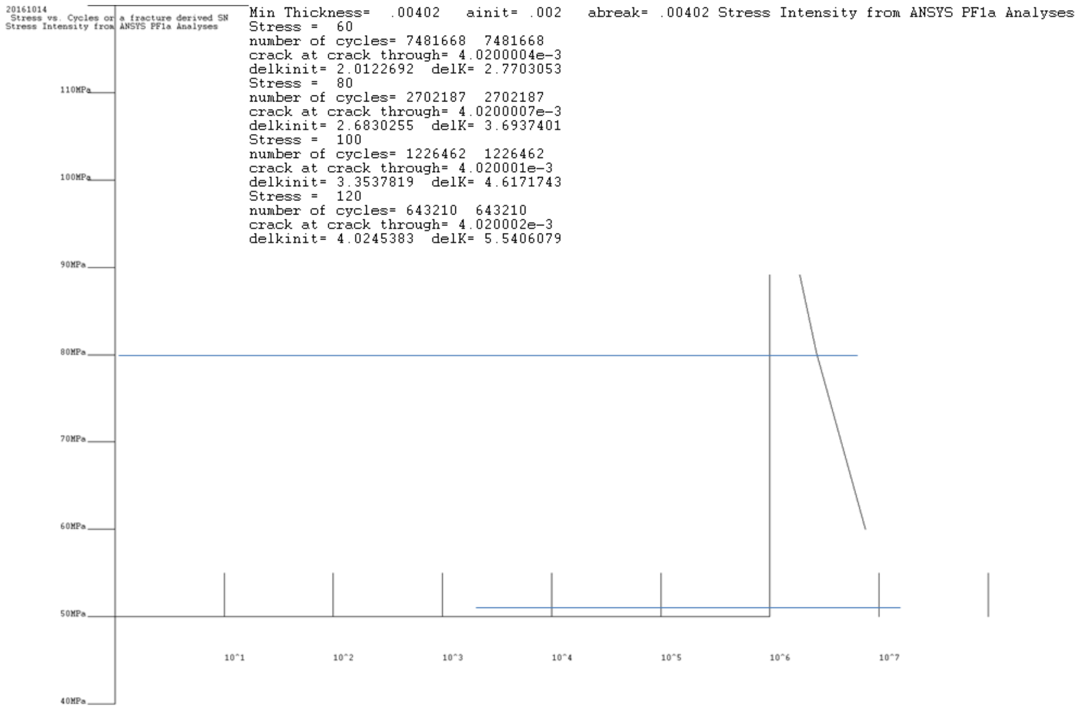


Figure 18.2-8 Life vs. Background Stress for 2mm crack, 100 MPA root-meter Fracture Toughness, .00402m min wall thickness at the cooling hole, Based on ANSYS KCALC.

For the tensile range of 80 MPa ,taking credit for compressive crack closure, the life is 2.7 million cycles. This must be divided by 4 to satisfy the Structural Design Criteria or 675,000 allowed cycles. If the tensile stress range shifts to 120 MPa, because the elastic-plastic analysis is not accurate or not conservative, then the allowed cycles is 643210/4=160802 cycles – well above the required 20 to 30,000 full power cycles.

19.0 Mandrel Stress
19.1Analysis with Thinner Inner and Outer Shell

The nominal original mandrel thickness is .25 inches and the vertical steel outer bands are 1/8"– see Figure 6.3-7. With proposed added insulation wraps and a bit more clearance at the ID for assembly, the intention is to thin the inner mandrel to about 3/16". The outer bands may be thinned as well. As of this writing, the thickness is uncertain. Consequently this analysis assumes a minimum thickness of .125 for the inside and 1/16" for the bands. In the original qualification calculation, the bands were not intended to take the primary vertical loading from the coil. They were added to aid centering of the coil. The bending of the lower flange ledge was taken by stresses in the inner shell. To allow the thinning of the shells, the vertical steel bands will be included as necessary structural elements.

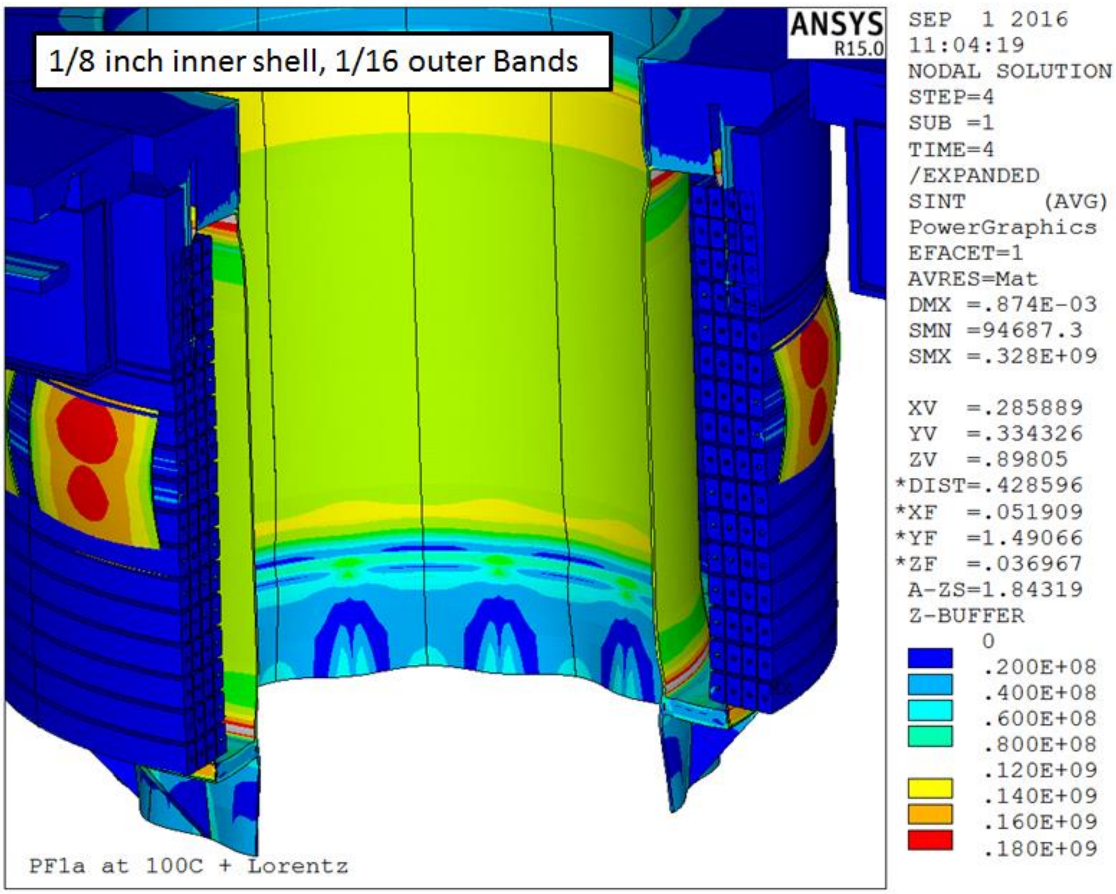


Figure 19.0-1 Stress with 100C Coil Temperature and Full Lorentz (Vertical and Radial) Loads

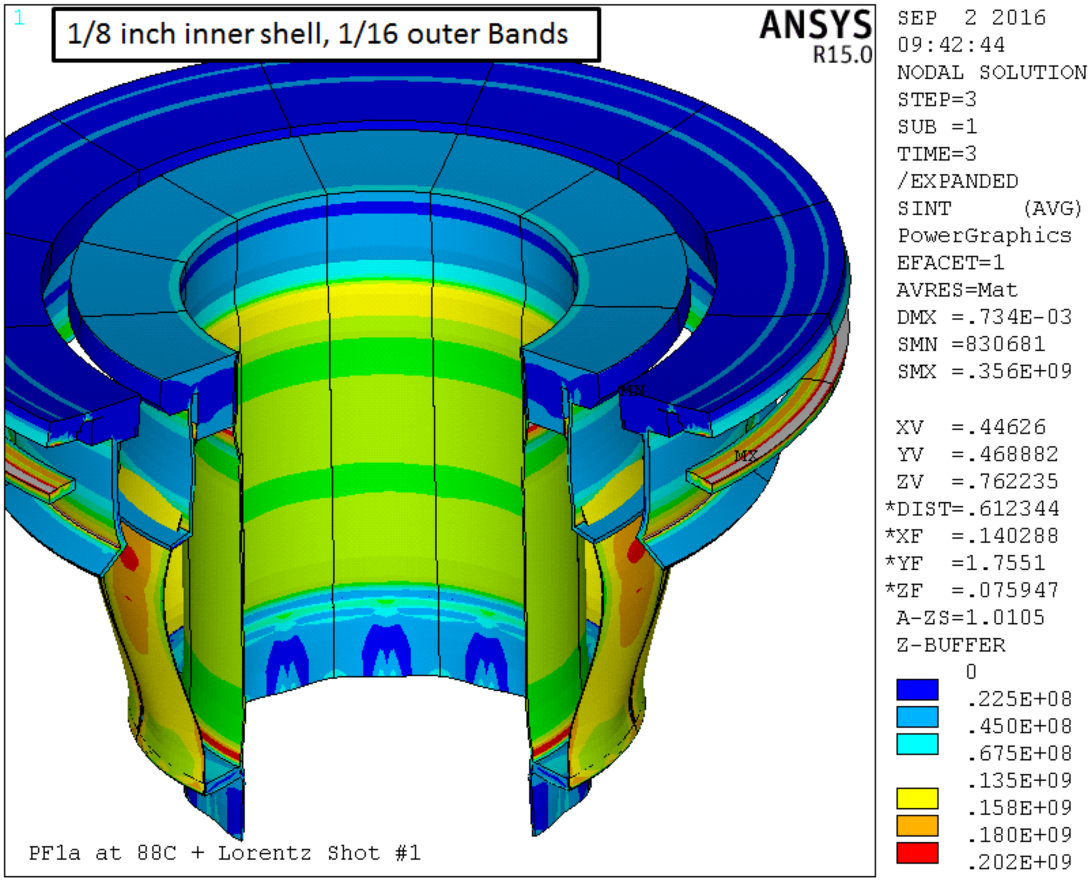


Figure 19.0-2 Stress with 88C Coil Temperature and Full Lorentz (Vertical and Radial) Loads

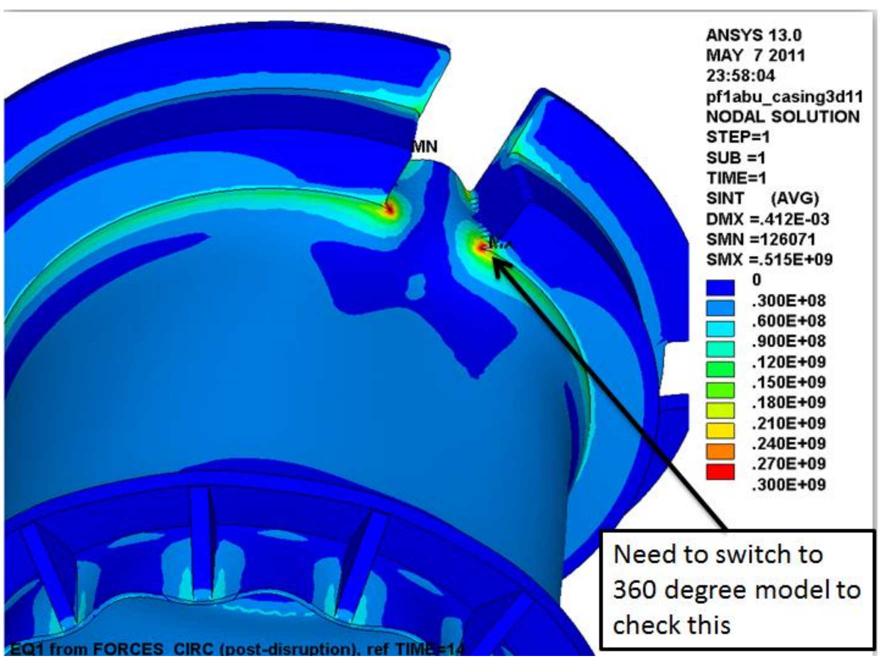


Figure 19.0-3 Mandrel Stress From Original Qualification Calculation

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)

Figure 19.1-4 Table from Section 6.4

The square notch at the terminal break-out has a significant concentration that will require a radius or relief. The flange is very heavy and can be undercut to get a smooth transition that will improve the fatigue performance.

19.2 Stresses and Displacements on Mandrel Due to Winding

The new mandrel will have a thinner shell than the present one. This to make room for more insulation than in the existing coil. The loads on the inner shell might deform or over stress the mandrel This section of the calculation addresses the winding loads. One intent of this calculation is to decide if additional internal support is needed. The issue is moot however because a support fixture was designed to support the mandrel during machining and this is planned for use during the winding process.

Applied various loads were applied to the PF1A mandrel to determine needed support configuration. It is Supported on 1" thk – 32" dia winding plate at one end, with (6) 2.5" dia collars w/ ½" dia bolts

Boundary Conditions:
Assumed bonded union of collars to mandrel face and support plate, Support plate rear face fixed

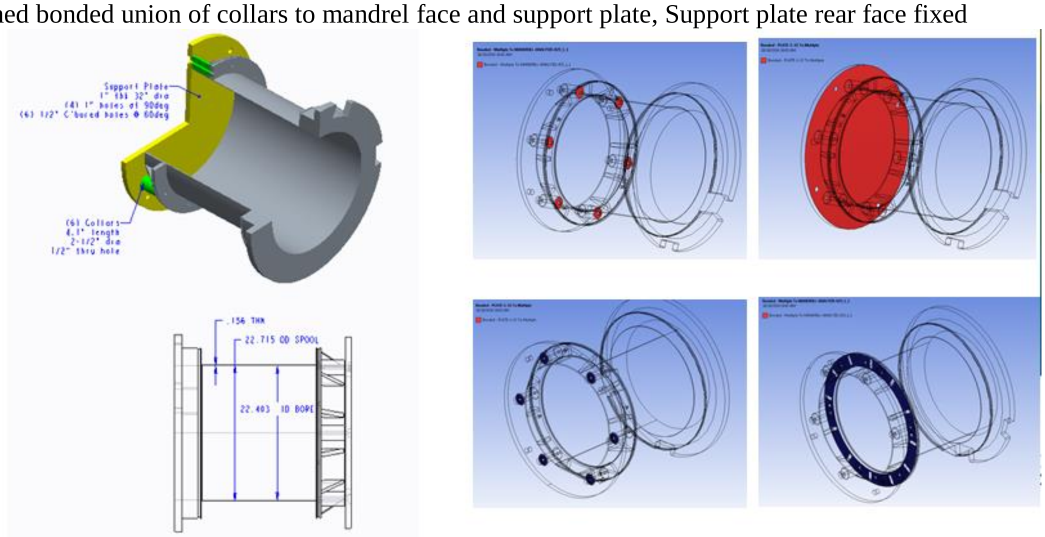


Figure 19.2-1

All material 316SS @ RT
Static loads
Evaluated (4) load cases all with same BC's:

1) Combined loads: a) torsional force (1000 lbs), b) flange vertical load (1000 lbs) & spool diameter center load (1000 lbs)
2) Combined loads: a) torsional force (1000 lbs) & b) flange vertical load (1000 lbs)
3) Single load: a) torsional force (1000 lbs)
4) Single load: b) flange vertical load (1000 lbs)

Case	Peak Deflection (in)	Peak VM Stress (KSI)
1	0.007	11.2
2	0.002	6.0
3	0.002	4.7
4	0.001	3.9

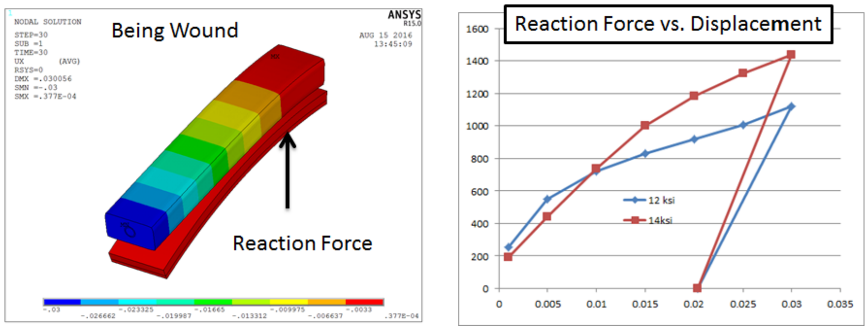
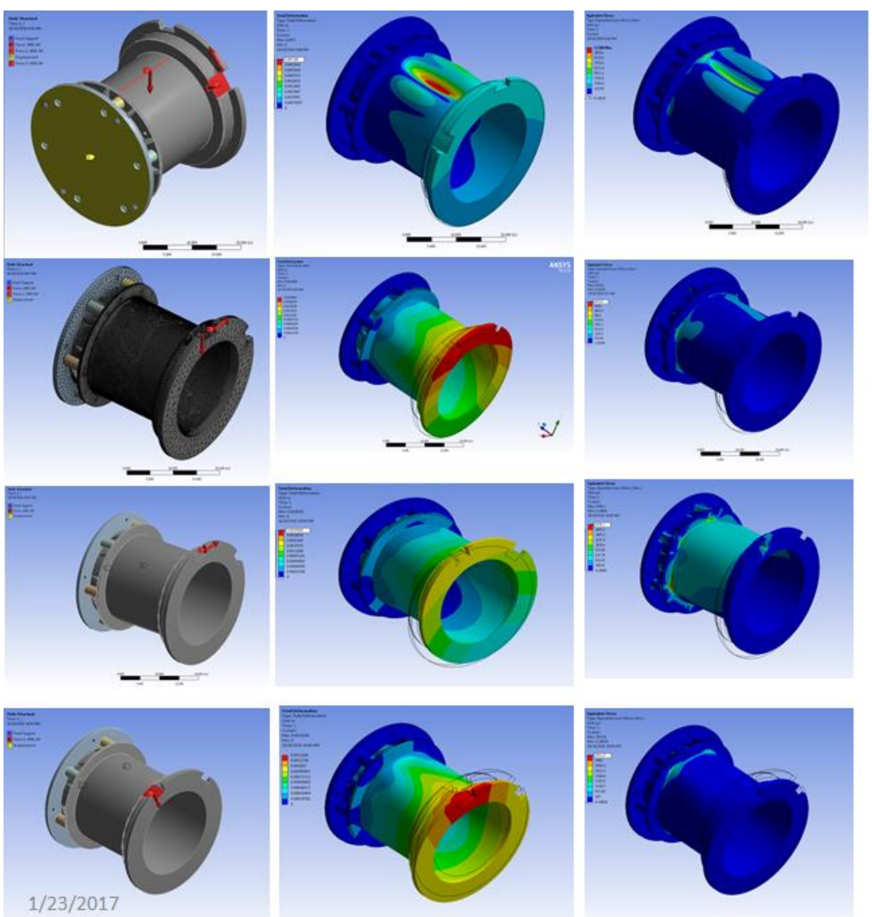


Figure 19.2-2 Winding Load Estimate from Section 15.0



Case 1)

Case 2)

Case 3)

Case 4)

Figure 19.2-3

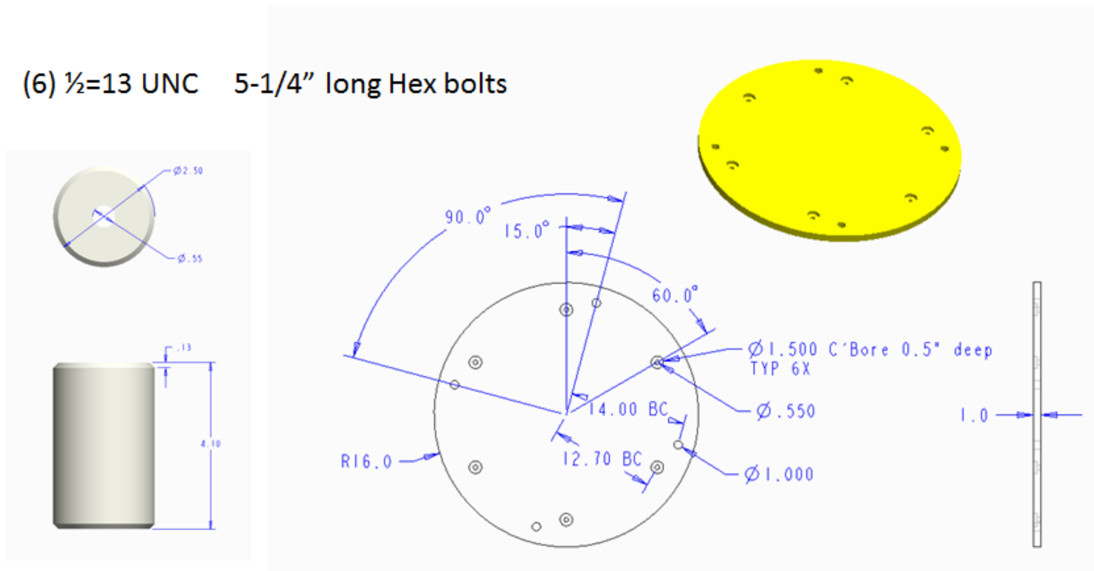


Figure 19.2-4 Mounting Plate to WindingTable

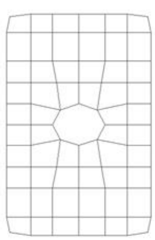
20.0 Acceptance Test

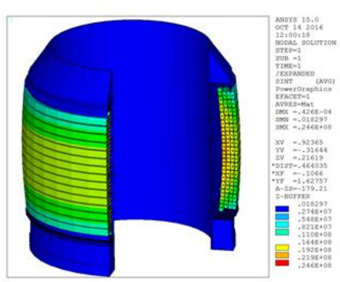
The current plan is to perform a “full performance” test on the new coil, to qualify it’s use in the machine. Full current of 19 kA is planned and 20 full j^2*t heat-up pulses with cooldown will be included. PF1a lower will be available for test first. Testing this coil to full performance can qualify it for re-installation into NSTXU and/or build confidence in the quality of the PF1b and c coils, and help determine if PF1b, and c U&L should be re-manufactured. The planned test will be conducted in the FCPC on a fixture mounted to the floor. Using the existing bus bars that have been taken out of the machine, will eliminate one fabricated component and add some confidence that the leads and bus bar connections used in the machine are acceptable. The connection to flex cables will also be as is used in the machine. . The bus support brackets that connect to the umbrella structure could also be used. As of this writing the plan is to use an existing bus bar connection. Loading of the bus bar connections to the free standing coil will be less than they experience in the machine due to the lack of toroidal field and background field from the rest of the poloidal field coils

C. Neumeyer mentioned that his simplified stress model produced 40 MPa stress. A check of the free standing coil stress is presented here. The free standing 19 kA case produced a 24 MPa peak Tresca Stress around a coolant hole. My guess is that Charlie Neumeyer’s simplified calculation assumes the field in the bore is the same through the build. The folks at MIT (Bob Pillsbury and Joel Schultz) used to make that assumption because it was conservative and more appropriate for a nested coil set or a PF coil set. The average field in the build should be used or the stress should be divided by 2 for a free standing coil. -

NTFTM2 Analysis of Lorentz Forces

19 kA/conductor 56
elements total =339.28
amps per element





```
zero
read
p1a9
merge
0,.002
redu
ecor
seal
0
smat
6,6
smat
66,66
stype
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smat
17,17
smat
5,5
smat
55,55
smat
15,15
smat
40,40
secoor
0,14.5,100,-100,100,-100,100
gerase
0
redu
chkg
gerase
99
gerase
98
gerase
97
redu
```

```
snal
0
seal
0
conv
0,1
smat
17,17
grpr
17,17
r
17,1,339.28
smat
17,17
snel
17,17
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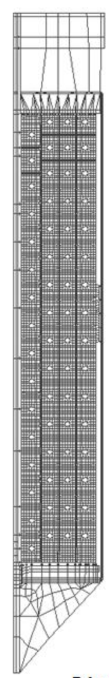


P1a9.dat

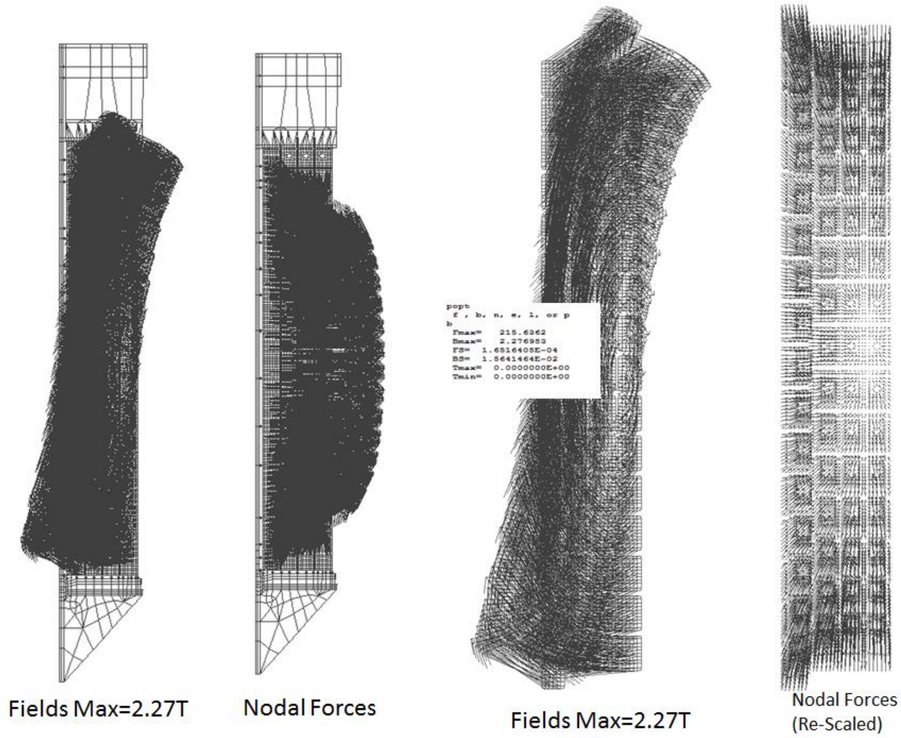


Figure 20.0-2 Fields and Forces on the Free Standing PF1a Coil

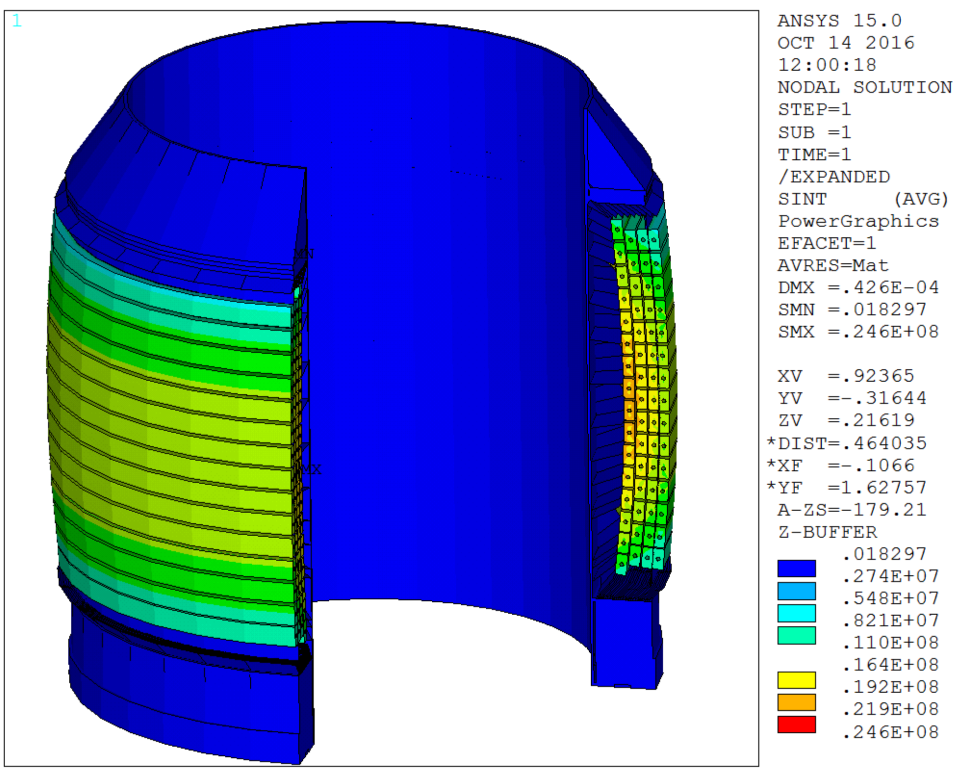


Figure 20.0-3 Tresca Stress in the conductor in the Free Standing PF1a Coil

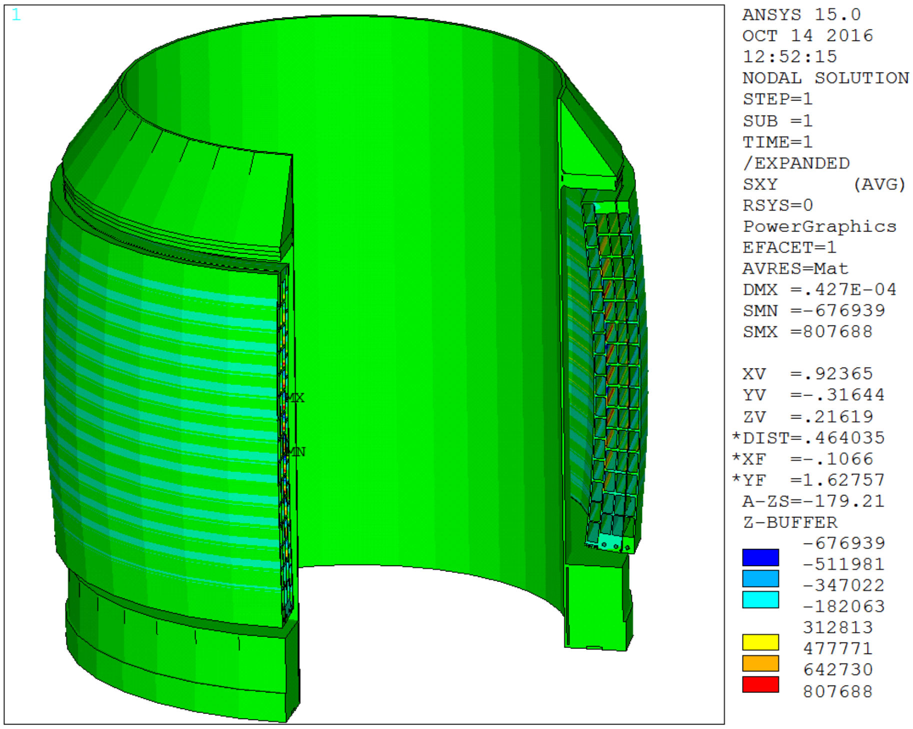


Figure 20.0-4 Shear Stress in the Insulation in the Free Standing PF1a Coil

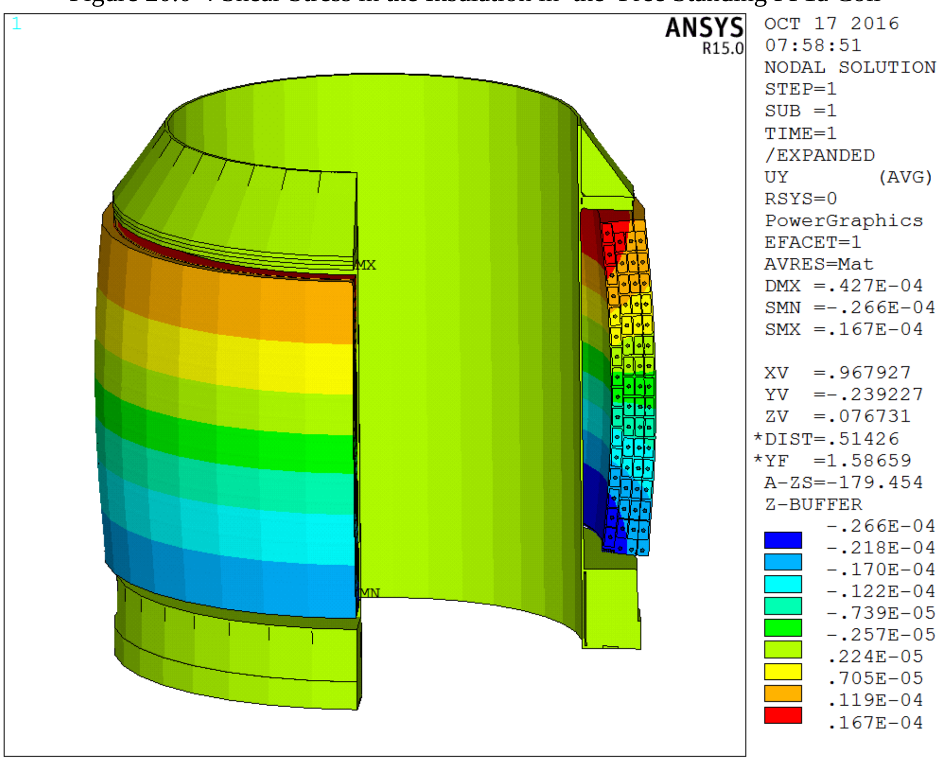


Figure 20.0-5 Axial or Vertical Displacement – Lorentz Forces Only in the Free Standing PF1a Coil Test

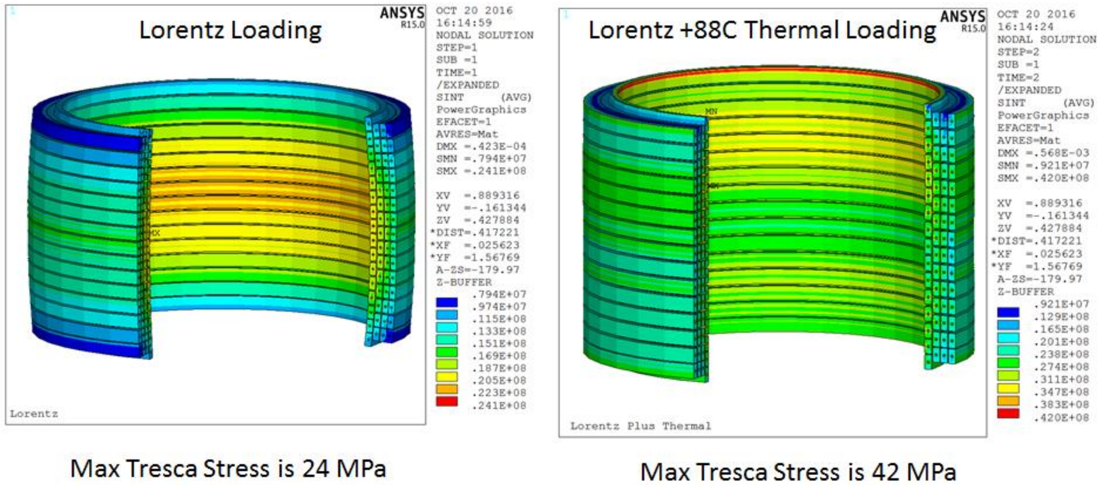
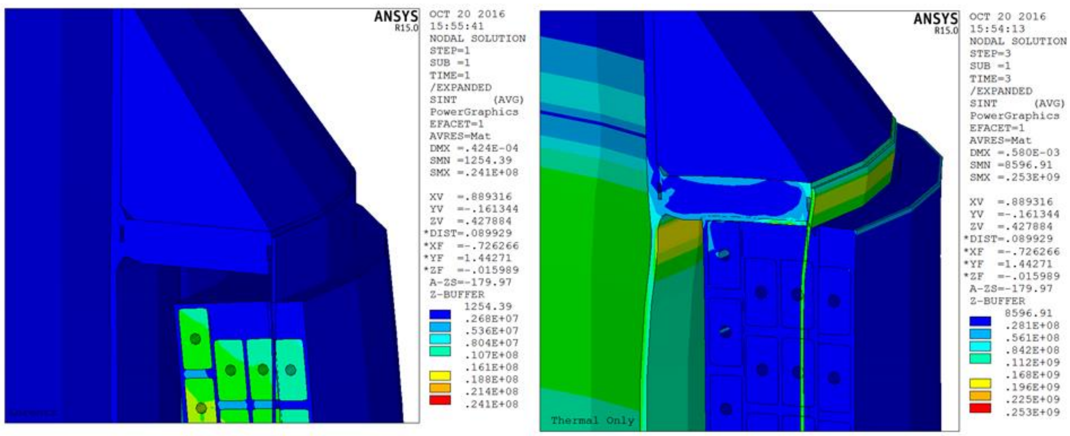


Figure 20.0-6 Tresca Stress – Lorentz Forces Only at Left and with Thermal Loads at Right Free Standing PF1a Coil Test



3

Figure 20.0-7 Mandrel Stresses During the Test Loading – Left is the Lorentz Loading and at Right is the Thermal Loading

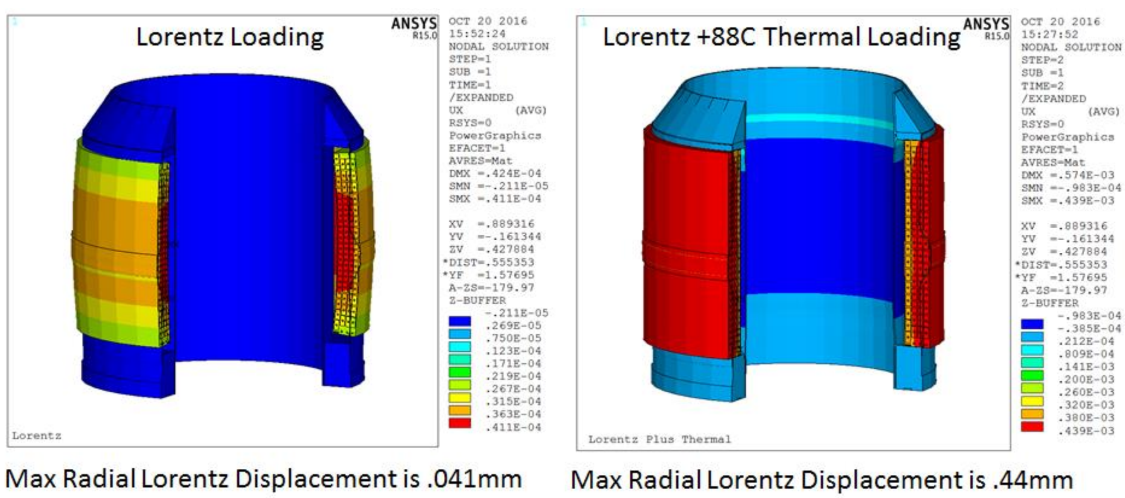


Figure 20.0-8 Radial Displacement during the Test Loading – Left is the Lorentz Loading and at Right is With the Thermal Loading

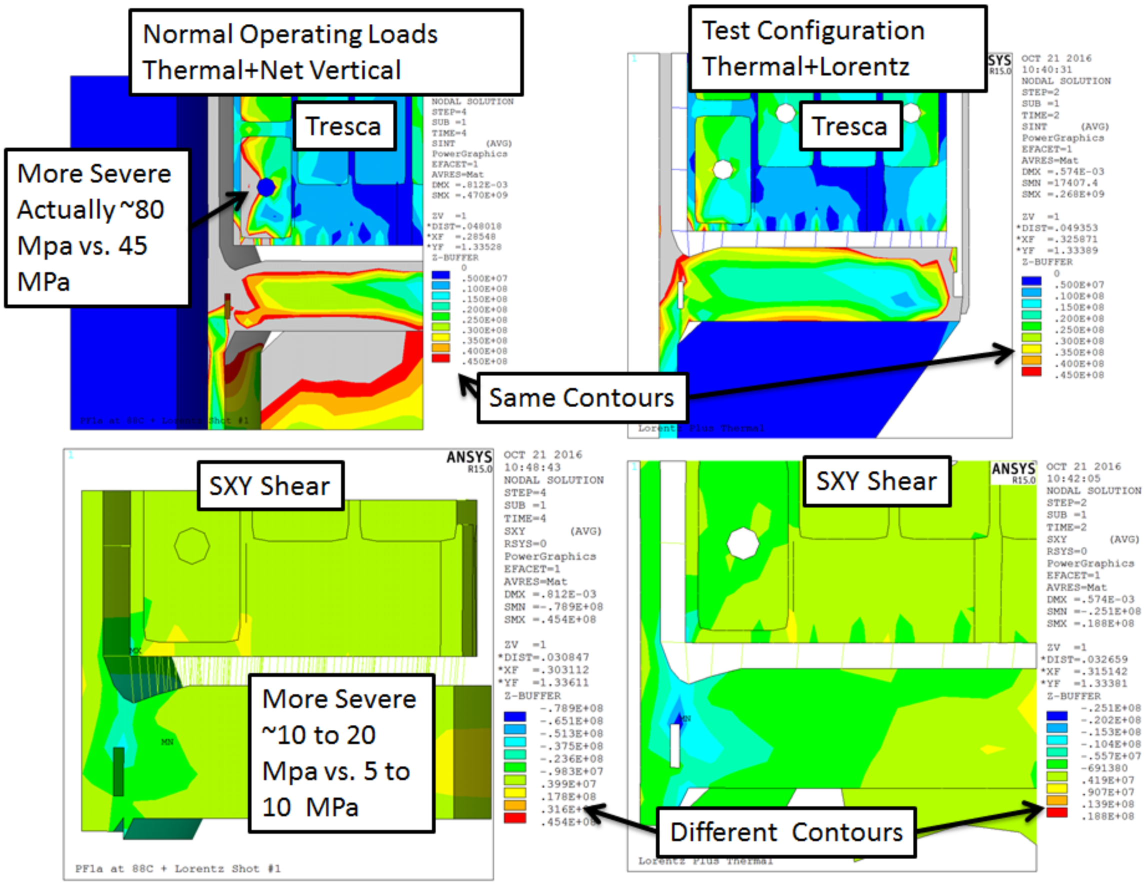
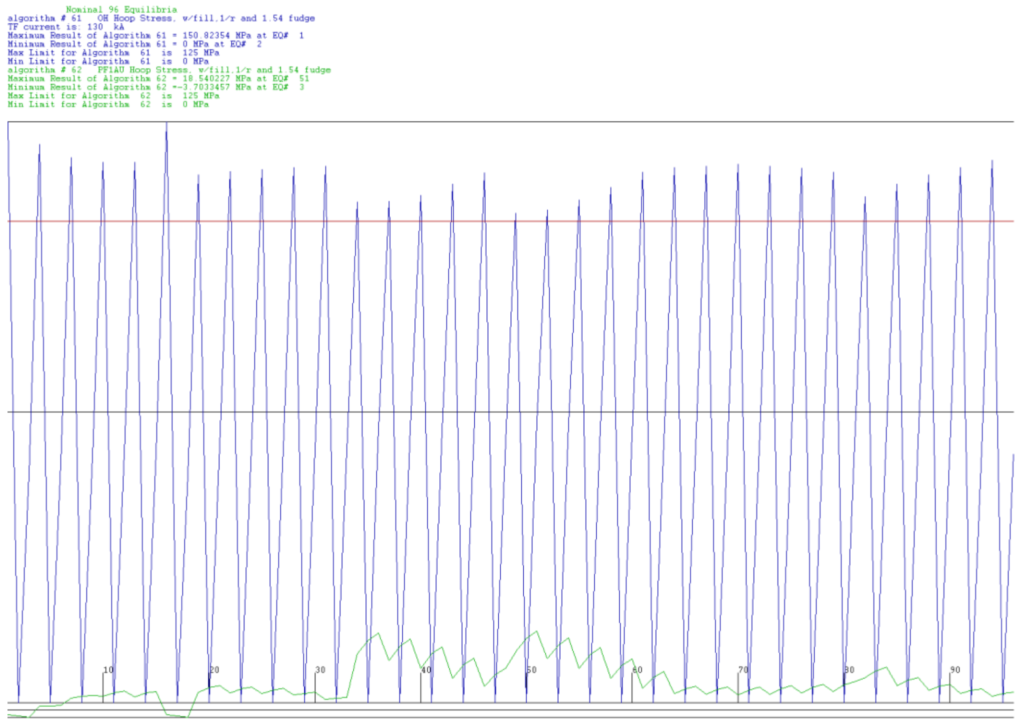


Figure 20.0-9 Comparison of the Nominal Corner Stress and Test Corner Stress

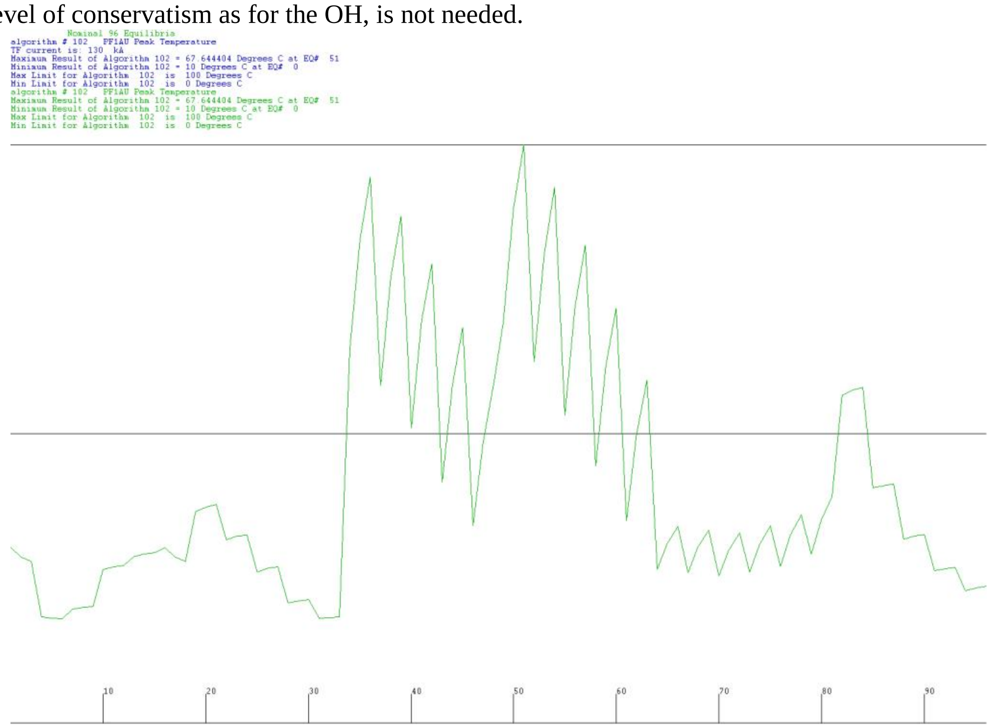
The proposed test will not include the 95770 lbs vertical load on the coil from the interaction with the rest of the PF coils. This is a significant driver in the local insulation stress as it concentrates on the corners due to the flange flexure. . However the restraint of thermal expansion is an even larger source of corner compressive stress and this will be included in the tests. Normal operating corner stress is about twice that in the test at 80 MPa Tresca and 10 to 20 MPa Shear. The insulation system is strong in compression , > 400 MPa for G-11 used for the ramps and fillers. The CTD 425 system compressive strength isn't known but I will be well above the 80 MPa experienced in the corner. Compression augments the shear capacity. G-11 strengths are included in Table 6.4.1.2 -2 and [15]. Corner insulation integrity will rely on the integrity and plasticity of the Kapton Tapes around the conductors and in the ground wrap.

21.0 Cooling System – Evaluation of Necessity

Cooldown insulation strains are similar between the OH and PF1a and this invites the question as to why a recommendation could be made to use an elaborate system of temperature "shock" mitigation for the OH [21] and not for PF1a. Both coils would benefit from limiting the exposure of the coil to instantaneous flow of 12C water into a warm coil. In the first year of operation, the OH operated successfully up to about 80C without the benefit of the new preheater system. The negative effects of the cooldown cycles are a result of the difference in coil temperature and 12C, and the number of cycles the coil is exposed to the abrupt thermal changes. The coil Lorentz stresses also contribute to coil fatigue

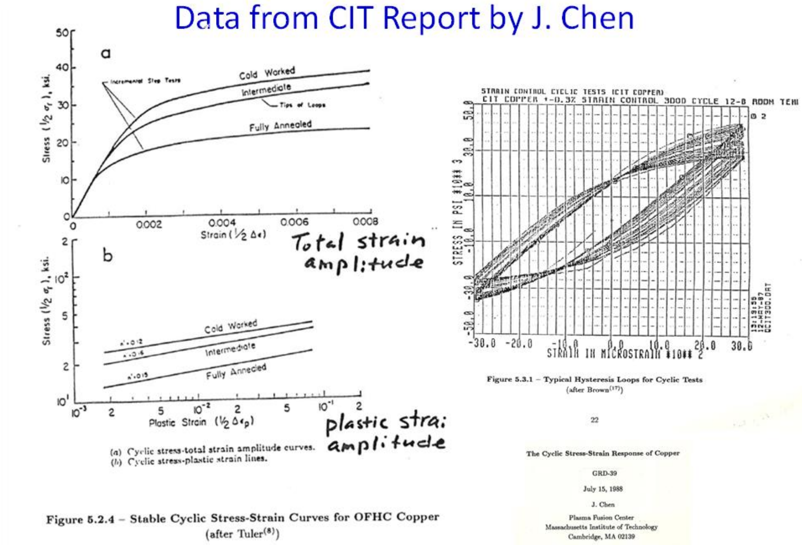


Based on the Lorentz stress in the coil, the OH is loaded much more significanly than PF1a. This is true of the thermal loads of the coils as well. Significant OH currents are needed for every shot to drive plasma current. PF1a Upper and lower are not big actors in every shot. Based on the insulation strain testing, It was found that thermal strains would be within the acceptable test levels for the OH, but for an added level of conservatism and to treat the OH coil as gently as possible, the OH preheater system has been retained and is being implemented. The OH has been exposed to hundreds of thermal cooldown cycles from about 80C to 12C, without the preheater, and shows no signs degradation. The judgement for the PF1a coils is that the same level of conservatism as for the OH, is not needed.



Appendix A
Development of Chaboche Parameters from CIT –Jim Chen[28] Data
Presentation by A. Brooks

Data from CIT Report by J. Chen



Overlay of Stress-Strain Curve on Strain Cycling

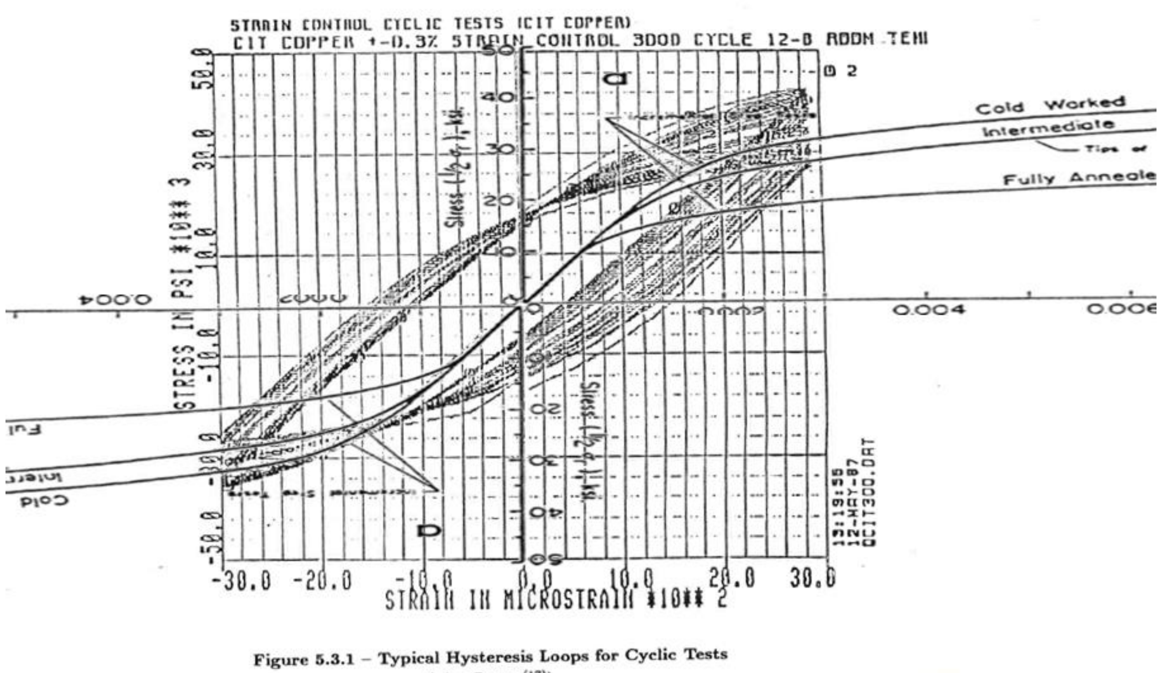
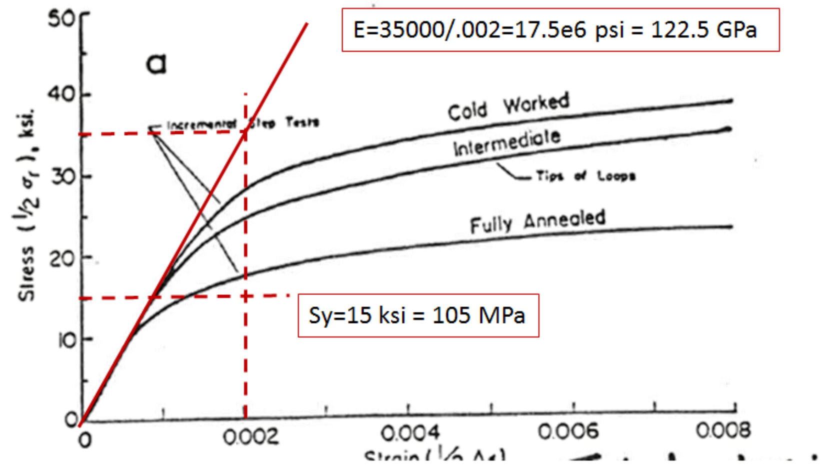


Figure 5.3.1 – Typical Hysteresis Loops for Cyclic Tests (after Brown(17))

22

Use "Intermediate" Curve to Calculate Chaboche Parameters

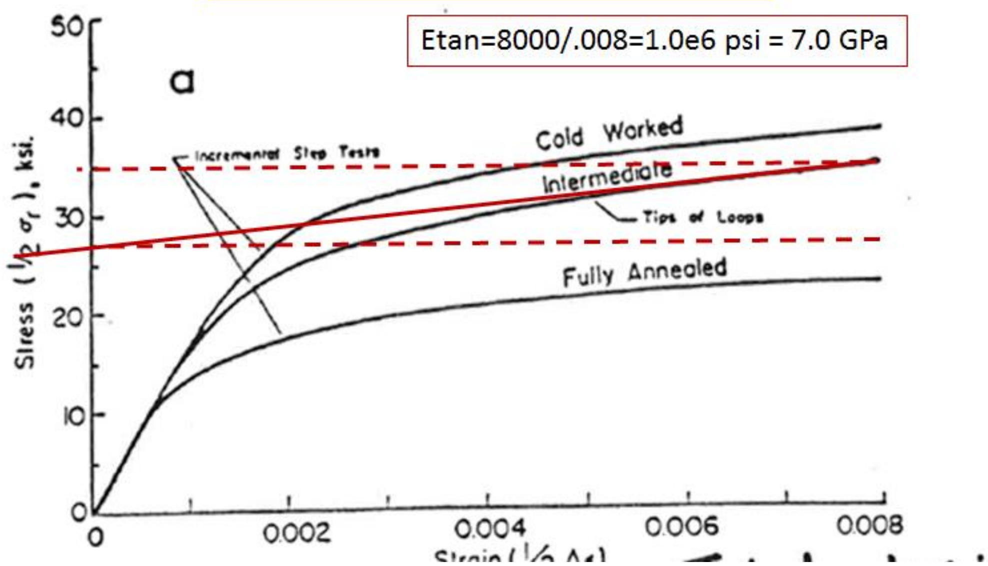
First, get Elastic Modulus and Yield



Sy is actually the end of the elastic region, not .2% strain

Use "Intermediate" Curve to Calculate Chaboche Parameters, Continued

Next, get Tangent Modulus at large strain

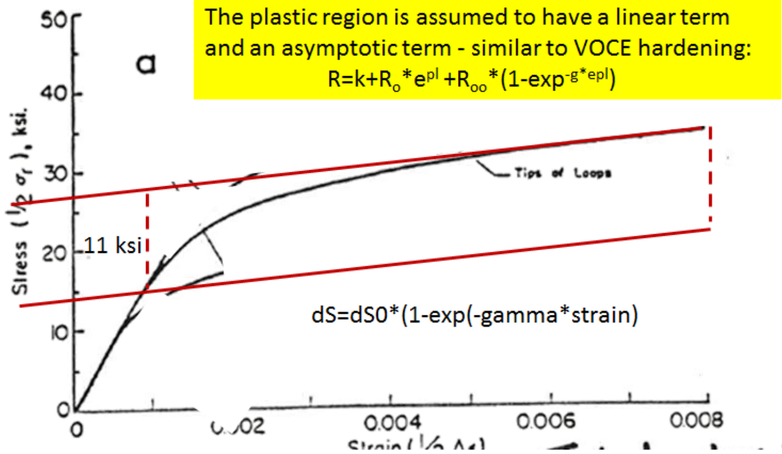


Use "Intermediate" Curve to Calculate Chaboche Parameters, Continued

Finally, get Gamma – back stress parameter

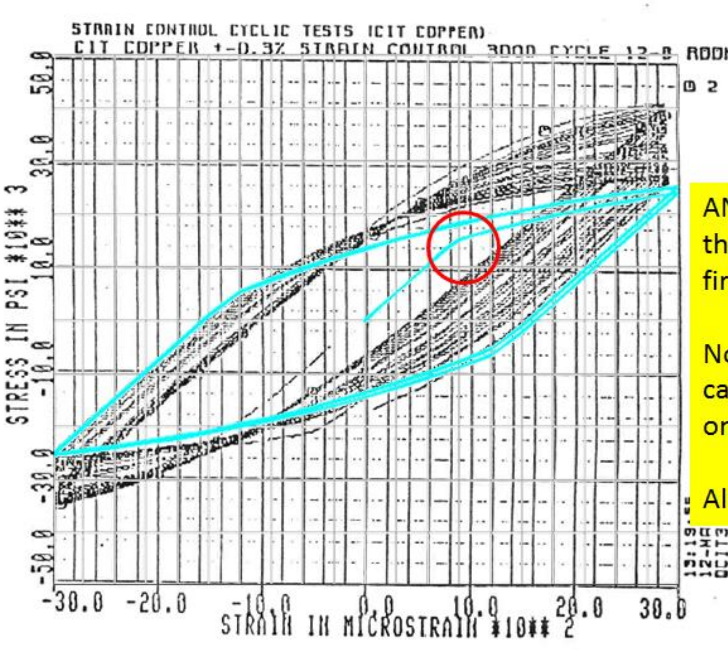
The plastic region is assumed to have a linear term and an asymptotic term - similar to VOCE hardening:

$$R=k+R_o*e^{pl}+R_{oo}*(1-exp^{-g*epl})$$



Gamma ~ 1/.0015= 667

Comparison with ANSYS Chaboche Model Results



ANSYS run for 10 cycles that overlay after the first

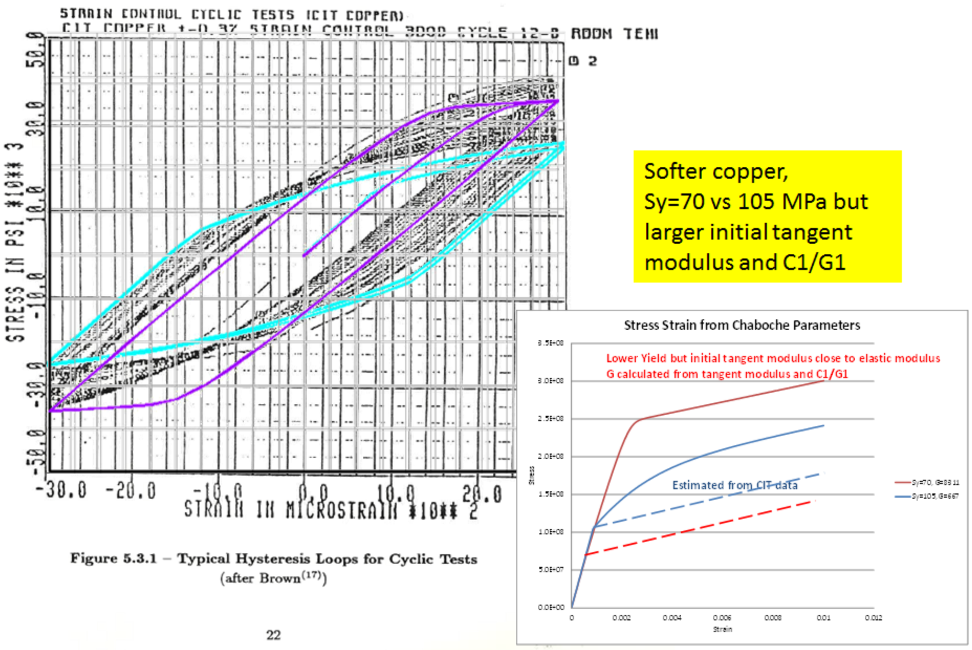
Note: ANSYS can't capture strain softening only strain hardening

Also,

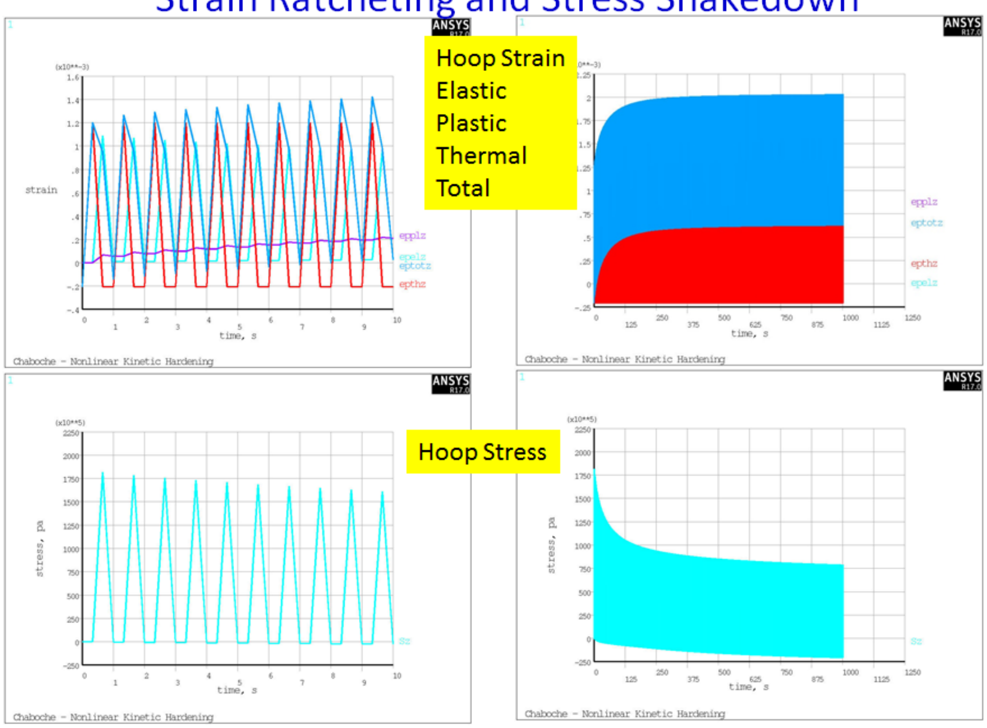
Figure 5.3.1 – **Typical Hysteresis Loops for Cyclic Tests**
(after Brown[17])

22

Alternate Chaboche Material Model



Modified Parameters lead to Strain Ratcheting and Stress Shakedown



Comments

- Without multiple equilibrated strain cycling tests at different strain magnitudes Chaboche parameters are only initial estimates
- ANSYS Simulations show very different behavior with two different sets of Chaboche parameters

Appendix B
Emails

Email from Mike Kalish, Weiland Forwarded October 24th
Dear Mike,

attached you find our results after respooling.
We packed Coil No. 1 , 2 and No. 4 for shippment but we want to wait until all testresults finished.
Coil No 3 is very short as you can see in the table but meets the required 143,5 m
If you want to have this spool also we have to order extra packing material for shippment.

Results after respooling

Coil No.	Rp0,2 [MPa]	Rp0,5 [MPa]	Rm [MPa]	A5 [%]	Remarks	Meters	kg
Coil 1	75	82	213	56	Coil 1 A start after winding on diameter 600 mm	143,5 + 3,5 m	484 kg
Coil 1	78	84	212	55	Coil 1 E end after winding on diameter 1200 mm		
Coil 2	81	87	211	52	Coil 2 A start after winding on diameter 600 mm	143,5 +2 m	479 kg
Coil 2	81	90	211	52	Coil 2 A start after winding on diameter 1200 mm		
Coil 2	77	83	212	54	Coil2/E end after winding on diameter 1200 mm		
Coil 3	76	83	210	54	Coil3/A start after winding on diameter 1200 mm	143,5 m + 0,5 m	474 kg
Coil 3	75	81	212	54	Coil3/E end after winding on diameter 1200 mm		
Coil 4	79	86	212	54	Coil4/A start after winding on diameter 1200 mm	143,5 + 5 m	489 kg
Coil 4	79	86	212	54	Coil4/E end after winding on diameter 1200 mm		

October 10 2016 email from Mike Kalish
Pete,
fyi... I'm resending the email I sent last week with the Wieland conductor test results. This will be useful for your 1mm crack calculation.
Note that in the attachment the wall thickness on the drawing is 4.31mm +/- .89mm or

3.42mm minimum wall thickness required
The wall thickness in the inspection report attached is 4.31mm - .293mm =

4.02mm minimum wall thickness as built
The yield strength test results are also included in the attachments.

-Mike Kalish

	length	windings	UT- Testing	H2 -embrittlement - Testing	visual inspection
spool 1	>143,5 m	waste, see picture of coil 1	--	--	
spool 2	>143,5 m - 148m	40 single layer windings = 148 m + 1 second layer winding ~ 2 m for testing	100%	good	good
spool 3	>143,5 m - 148m	41 single layer windings = 148 m + 1 second layer winding ~ 2 m for testing	100%	good	good
spool 4	>143,5 m - 148m	42 single layer windings = 148 m + 1 second layer winding ~ 2 m for testing	100%	good	good

Arthur Brooks <abrooks@pppl.gov>

Attachments   Jul 13,2016

to me

Peter,

Attached is an Acool plot of a full power pulse just to give you a sense of how the turns cool down. It is long enough (or has a small enough cooling hole) to show a cooling wave. I haven't gotten the actual flow velocity but assuming it was the same as the OH (2.12 m/s) produces a similar trace to the measured data so I think its close.
Art
Arthur Brooks <abrooks@pppl.gov>
AttachmentsAug 11

to me

Peter,
I programmed the cool down to limit the temperature difference in the coil to 40 C to keep the stresses less than 80 MPa. The attached shows the outcome. The cool down is initially linear since it is controlled by the mdot*Cp*dT of the water which is held constant. The cooling slows, decaying exponentially, once the Tout-Tin falls less than 40 C. After 40 minutes the coil is down to ~18 C.
To achieve this requires a variable control value controlled by the outlet water temperature readings.
Art

Reference [22]
James Chrzanowski <jchrzano@pppl.gov>
11/7/11
to me, Lawrence, Philip, Michael
Pete
Below are the copper conductor strength values that Luvata can provide the OH conductor. Please review let me know whether I can move forward with this order.

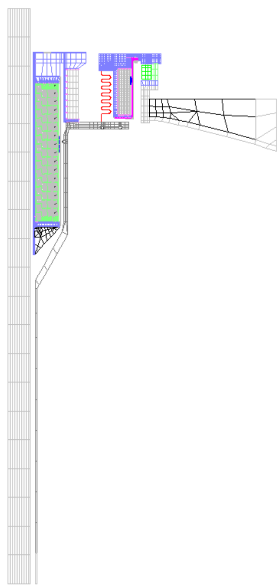
Jim
Tensile Strength min. PPPL requested: 36-38 ksi / Luvata Proposal: 33 000 psi (min. 227 N/mm2)
Yield 0,5 % Strength: PPPL Requested: 28-30 ksi / Luvata Proposal: 29 000 - 36 000 psi (200-250 N/mm2)
Elognation A 5 min 25 %
Hardness max.: PPPL Requested: 60-70 HRF / Luvata Proposal ; 81 HRF (max. 90 HV)

Appendix D

Free Standing Coil NTFTM and ANSYS Files

```
zero
read
p1a9
seal
0
smat
17,17
smat
5,5
secoor
0,14.2,100,-100,100,-100,100
gerase
0
stype
2,2
gerase
2
redu

merge
0,.0001
redu
snal
0
seal
0
conv
0,1
smat
17,17
grpr
17,17
r
17,1,339.28
smat
17,17
snel
17,17
egrp
7
ngrp
7
ccur
17,1,2,3,4,0,0,0,0
styp
7,7
grprel
7,17
repla
tmod1
!read
grid
plce
```



P1a9.dat

```
/batch
/prep7
et,1,42,,,1
et,2,52
ex,17,117.0e9
ex,6,200.0e9
ex,2,200e9
ex,5,20.0e9
ex,15,10e9
ex,40,200e9
ex,55,20e6
r,2,1e9
r,1,1e9
r,22,1e9
/input,p1a9,mod

esel,mat,40
nelem
!nasel,y,1.605,1.609
d,all,uy,0.0
nall
eall
save
fini
/solu
fscale,2*3.1416
solve
save
/exit
```

```
pl
sfield
17
stype
7,7
gerase
7
mfor
17,1,2,3,4,0,0,0,0
repla
tras
egrp
0
exit
```

Appendix F
Paris Integral True BasicProgram

```
! Simple da/dn integral for PF1a Coil
dim stinit(200), life(200),keff(100000),crack(100000)
let t=.2175/39.37
let t=.00402    ! Minimum Wall Thickness near the Cooling hole
let w=.66/39.37
let f=1      !Factor not used
let xarea=.4889/39.37^2
let ainit=.002
let abreak=t
let kopt=1
if kopt=1 then let kopt$="Stress Intensity from ANSYS PF1a Analyses"
if kopt=2 then let kopt$="Internal circular flaw"
if kopt=3 then let kopt$="Finite Plate uniform uniaxial stress, center crack"
print "Min Thickness= ";t;"  ainit=";ainit;"  abreak=";abreak; kopt$
let m=3.54              ! Reference Jun Feng vs copper calculation Dec 2009
let c=1.32e-11          ! Reference Jun Feng vs copper calculation Dec 2009
!let m=4.347
!let c=1.52e-12
let fractTough=100    ! with factor of safety of 1.5

let j=0
let smax=120
for s=60 to smax step 20
let j=j+1
let stinit(j)=s
next s
let jmax=j

for j=1 to jmax
let a=ainit
let i=0

let counter = 0
let l=0

do
if kopt=1 then
! Kcalc Based on ANSYS Runns
let st=stinit(j)
let delk=a*4.4357/.0005778
if a>.0005778 then let delk=4.4357+(a-.0005778)*(5.641-4.4357)/(.0016484-.00057778)
let delk=delk*st/180
end if

if kopt=2 then
! Circular Crack in a uniform uniform stress field
!Adjust stress for the area lost to the crack
let st=stinit(j)*(xarea/(xarea-pi*a^2))
let delk=f*2*st*(a/pi)^.5
end if

if kopt=3 then
! Finite Plate uniform uniaxial stress, center crack
```

```
!let delk=st*(pi*a)^.5* ((1-a/w+.326*(2*a/w)^2)/(1-2*a/w)^.5)
end if


if kopt=3 then
! Crack 2*a wide in an infinite plate
let delk=st*(pi*a)^.5
end if

if kopt=4 then
!Adjust stress for the area lost to the crack
let st=stinit(j)*(xarea/(xarea-pi*a^2))
!deltak is From an equation for a compact tension specimen
let aoW=a/t
let faW=(2+aow)/(1-aow)^1.5*(.886+4.64*aow-13.32*aow^2+14.7*aow^3-5.6*aow^4)
let delK=faw*st*(t^.5)
end if

let i=i+1
let counter=counter+1
let dadn=c*delK^m
let a=a+dadn

if counter = 10000 then
let l=l+1
!print i;",";st;",";delk;","; a
let keff(l)=delk/st
let crack(l)=a
let counter = 0
end if

if a>abreak or delk>fractTough then exit do
if i=1 then let delkinit=delk
loop

let lmax=l
let life(j)=i
print "Stress = ";stinit(j)
!print "Cracked Through"
print "number of cycles=";i; life(j)
print "crack at crack through=";a
print  "delkinit=";delkinit;" delK=";delk

next j
get key kinp
clear

!set window -1000,1e8,40,110
set window -1,8,40,smax
print date$
print " Stress vs. Cycles or a fracture derived SN"
print kopt$
for i=1 to 20
plot i,50;i,55
plot text, at i,45: "10^"&str$(i)
next i
```

```
for i=1 to 20
plot -.25,i*10;0,i*10
plot text, at -.5,i*10: str$(i*10)&"MPa"
next i
!plot 0,50;1e6,50;1e6,100;0,100;0,0
plot 0,50;6,50;6,smax;0,smax;0,0
for j=1 to jmax
plot log10(life(j)),stinit(j);
!print log10(life(j)),stinit(j)
next j

get key kinp
clear
print date$
print "delta k divided by the background stress field"
print kopt$
set window -.001,.006,-.01,.05
plot 0,0;.005,0;.005,12;0,12;0,0
!       Xaxis
for i=.001 to .005 step .001
plot i,0;i,.0005
plot text, at i,-.0005: str$(i)
next i
!       Yaxis
for i=0 to .1 step .01
plot 0,i;.0001,i
plot text, at -.0005,i: str$(i)
next i
plot ainit,delkinit;.005,delkinit
for j=1 to lmax
plot crack(j),keff(j);
next j

end
```

Appendix G
Emails

Subject: RE: Dielectric Strength of CTD-425

Date: December 14, 2016 at 10:33:50 AM EST

To: "Charles L. Neumeyer" <neumeyer@pppl.gov>

Hi Charlie,

No problem with the question. I'm happy to help if I can.

I don't really see an issue with the G-10 being included in the 170C cure. Yes, the service temperature is 140C or thereabouts, but really, that just refers to the glass transition temperature (Tg). At 170C, the epoxy in the G10 will NOT start breaking down. I would not think there would be any contamination to the CTD-425 since the G10 should not break down chemically.

Really, nothing much should happen except a slight softening of the G10 at that cure temperature. I do suppose that depending on the types of loads that are applied to shims, things could move slightly when the G10 softens, but that is about all I can think of that might be detrimental. Therefore, in the future, if you're going to use shims to hold things in place and locations are critical, I would recommend using shims made of materials that have a Tg higher than 170C.

Hope that helps.
Best regards,
Paul

Paul E. Fabian

VP of Operations
Composite Technology Development, Inc.
2600 Campus Drive, Suite D
Lafayette, CO 80026
Phone: 303-664-0394 x103
Fax: 303-664-0392

John Mitchell <jmitchel@pppl.gov>
Attachments10/10/16
to me, Steve

Pete,
attached is the IGES of the coil.
E-dc11023-1_10_10_16.igs