Modular Coil Interface Hardware Outboard Bolted Joint FDR

Presented by
K Freudenberg, D Williamson
July 30, 2007

Review Charge

- Are the requirements defined? Does design meet requirements?
- Are the models/drawings complete?
- Is the analysis and R&D adequate? Documentation complete?
- Have prior design review chits been addressed?
- Have all technical, cost, schedule, and safety risks been addressed?

Scope

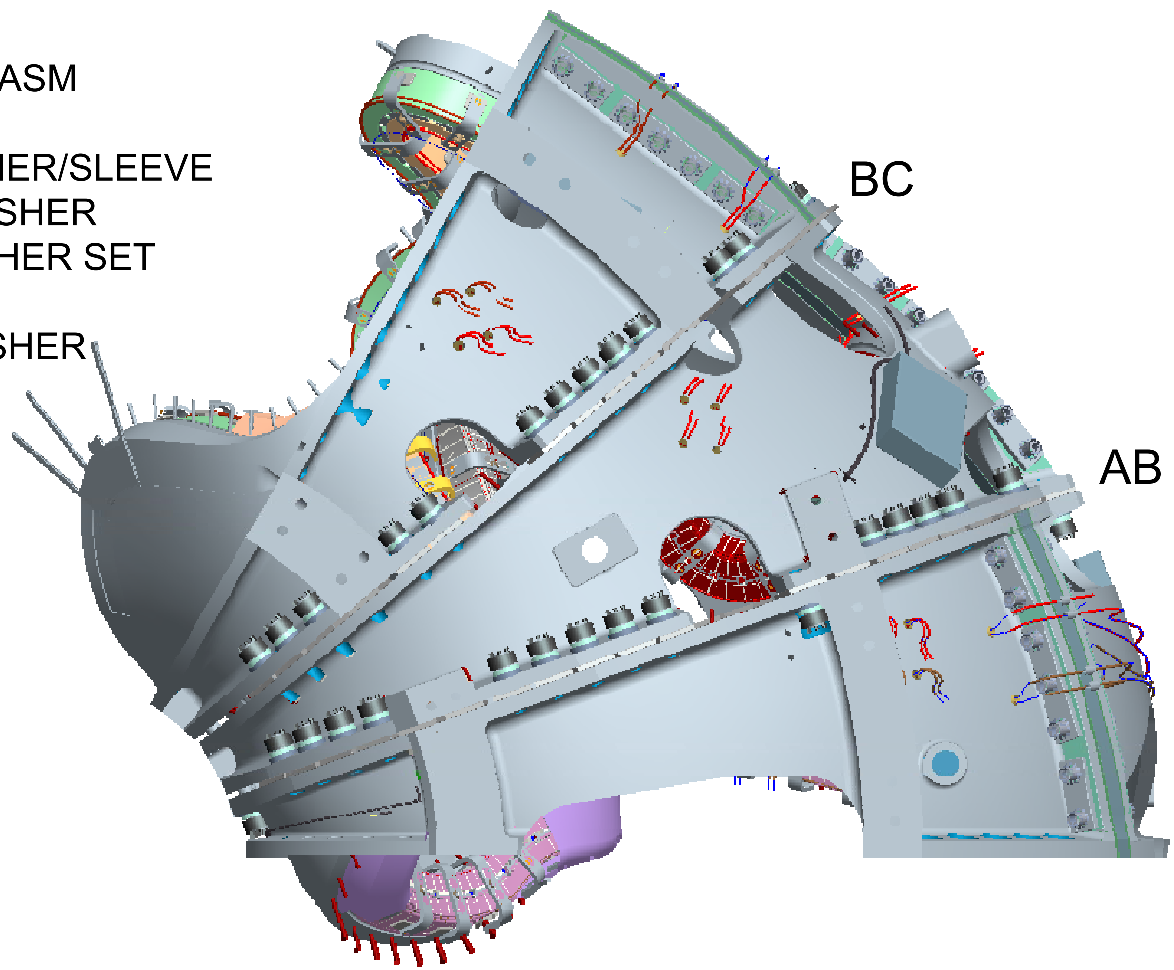
- This review-
  bolted joint assembly:

  SE140-190-R2, BOLT KIT ASM
  SE140-191-R1, STUDS
  SE140-192-R2, INS WASHER/SLEEVE
  SE140-193-R2, LOAD WASHER
  SE140-194-R1, SPH WASHER SET
  SE140-195-R0, BUSHING
  SE140-208-R0, FLAT WASHER
  SE140-040-R0, SHIM

- Upcoming reviews:

  AA/AB/BC Interface
  PDR 8/2/07
  FDR 9/4/07

  CC Interface
  PDR 8/7/07
  FDR 1/7/08



Requirements

Requirements are derived from the Modular Coil Asm Specification (NCSX-CSPEC-14-05-01) and the Station-2 Asm Specification (in progress).

Electrical

- Partial Toroidal electrical breaks shall be provided between adjacent modular coils within a field period (AA, AB, BC).
- Electrical breaks are required between adjacent modular coils in adjacent field periods (CC). [Ref. GRD Section 3.2.1.5.2b to be revised]
- Toroidal electrical breaks must be able to withstand an applied voltage of 150 V (ref. GRD Section 3.2.1.5.3.6).

Structural

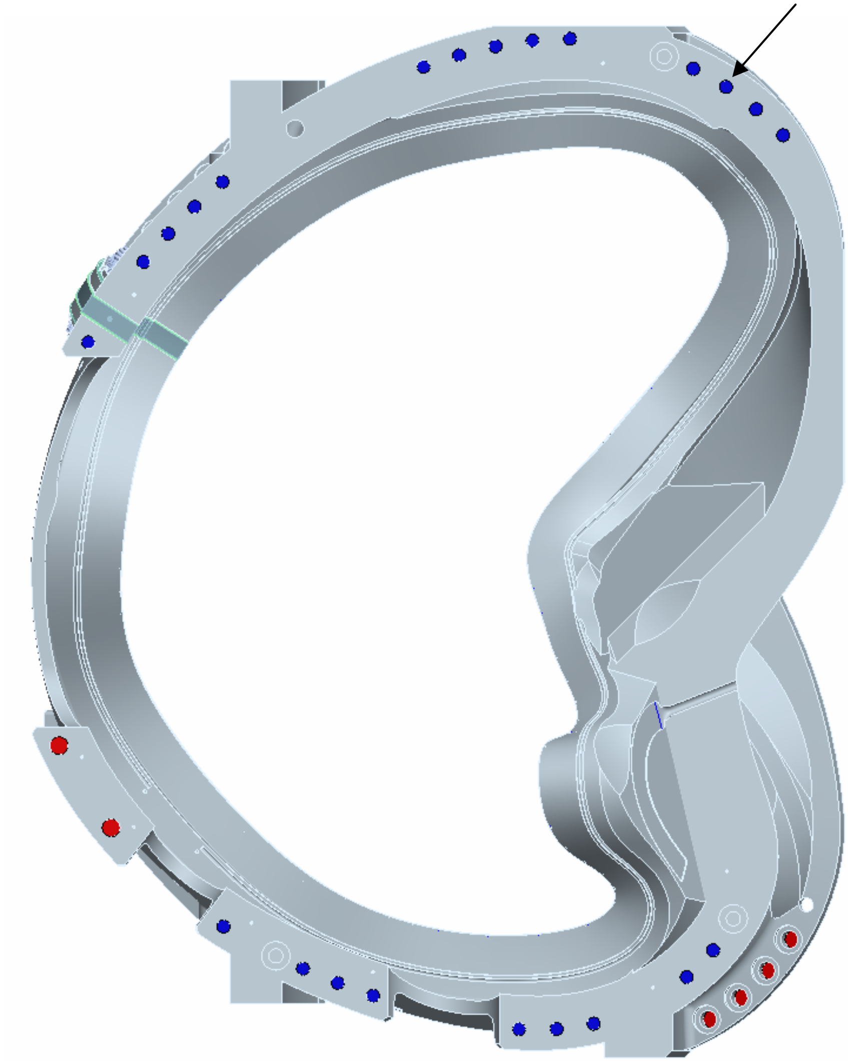
- Carry compressive loads
- Maintain a “no slip condition” under the bolts (friction joint)

Assembly

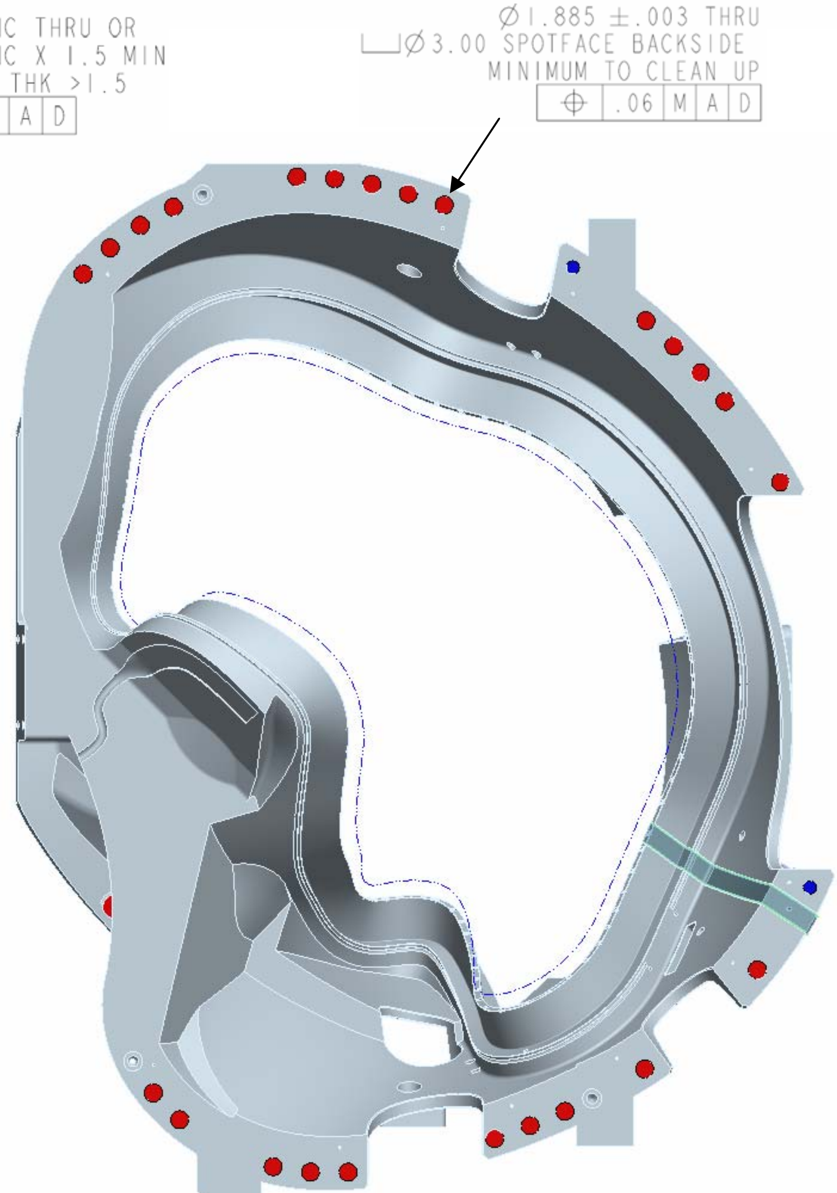
- Position the coils accurately
- Minimize gaps

Interface A-B

- 25 tapped holes, most on Type-A
- 1 through hole



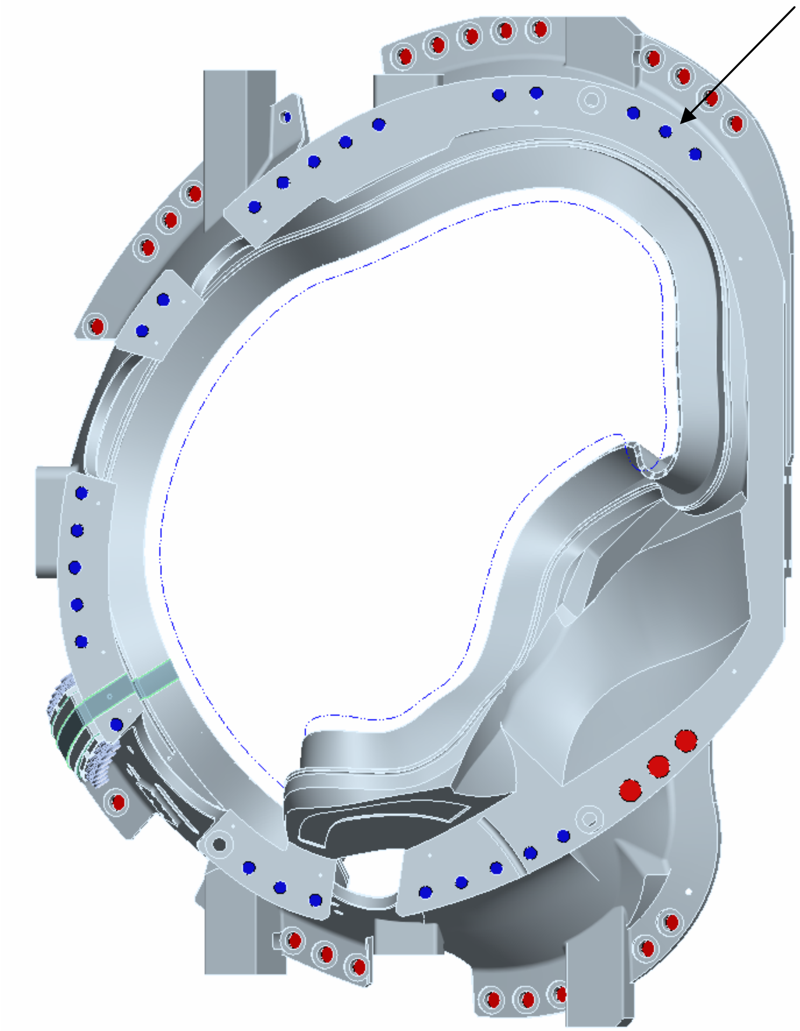
Type-A



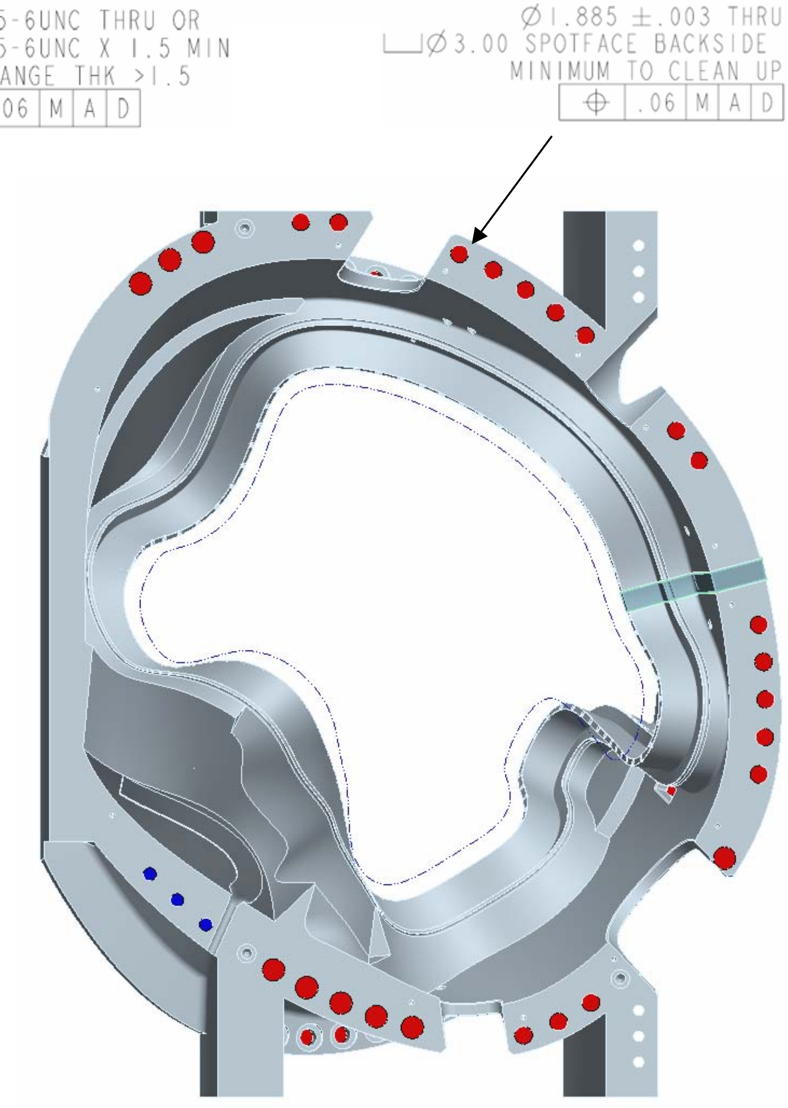
Type-B

Interface B-C

- 29 tapped holes, most on Type-B



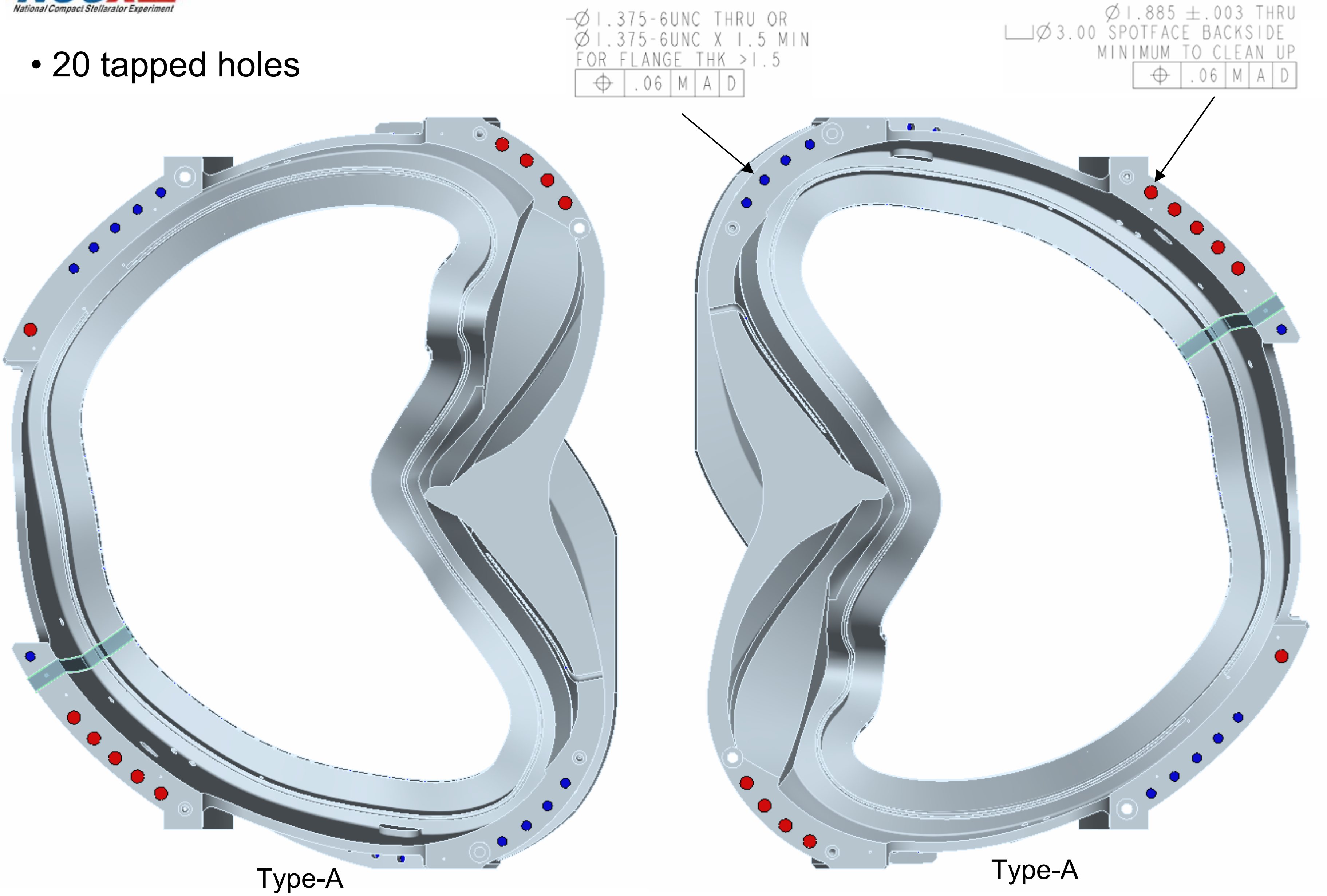
Type-B



Type-C

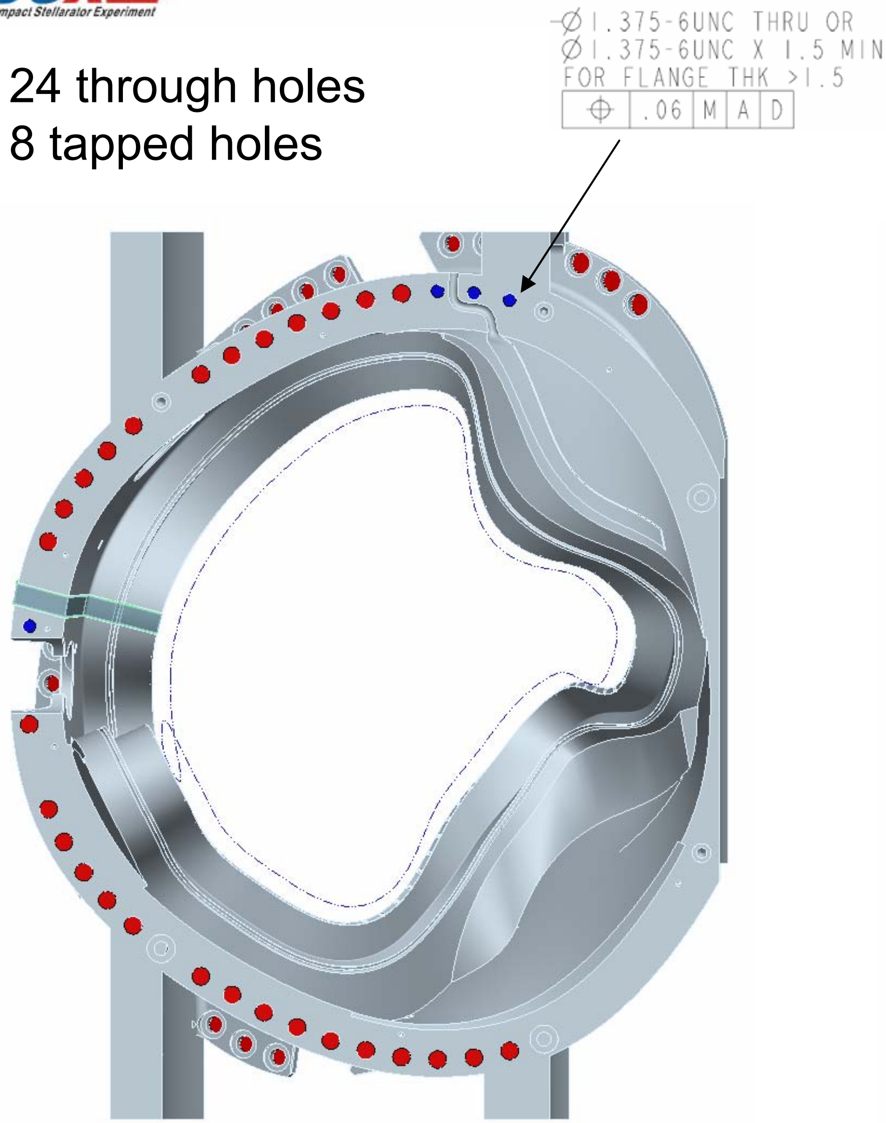
Interface A-A

- 20 tapped holes

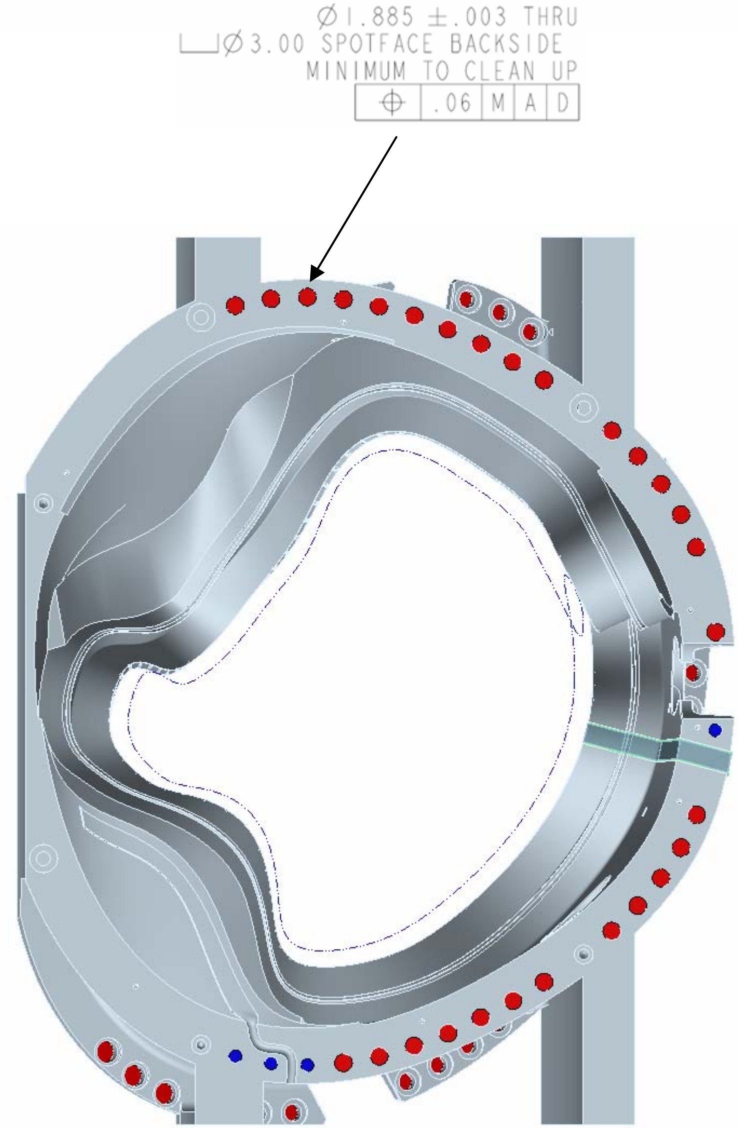


Interface C-C

- 24 through holes
- 8 tapped holes



Type-C



Type-C

Inventory of Tapped/Through Holes

No.	Interface	Typ	No. Tapped Holes	Total Tapped	No. Thru Holes	Total Thru	Total Fasteners
1	A-B	5	25	125	1	5	
2	A1-B	1	7	7	19	19	
3	B-C	6	29	174	0	0	
4	A-A	2	20	40	0	0	
5	A1-A	1	6	6	14	14	
6	C-C	3	8	24	24	72	
	Total	18		376		110	486

Bolted Joint Asm (SE140-190-R2)

NCSX National Compact Stellarator Experiment

- ECN-5244 MODIFICATIONS:

DESCRIPTION OF CHANGE: (state drawing no., zone. group, or list attachments)
SE140-190:
DELETED 12PT NUT AND SHIM BUSHING. ADDED SUPERNUT, F/N 11 AND WASHER, F/N 8. ADDED SLEEVE, F/N 6. ADDED ADHESIVE, F/N 16 AND INS SHEET. ADDED GRINDING NOTE AND ADDITIONAL INSULATEING METHODS ON SHT 2. ADDED OPTIONAL THRU BOLT CONFIGURATION.

SE140-191:
LENGTH 6.25 WAS 7.50, 8.00 WAS 10.50. CHANGED THREAD CLASS TO 2A. ADDED REQUIREMENT FOR ROLLED THREADS.

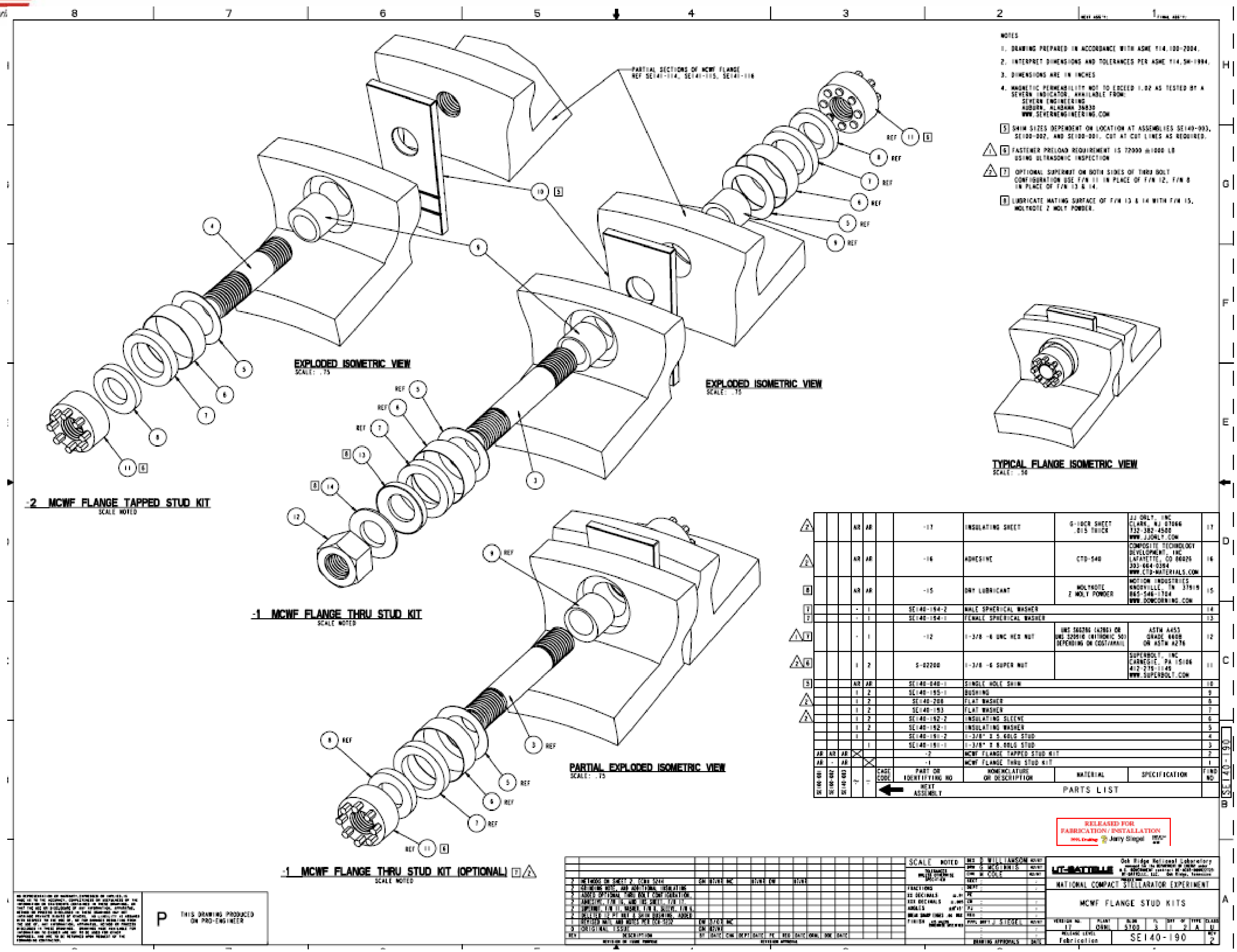
SE140-192:
ADD G-10CR SLEEVE F/N2 3.00OD X 2.875 ID TUBE

SE140-193:
REVISED MATERIAL FOR UNSN07718 OR UNS R56400

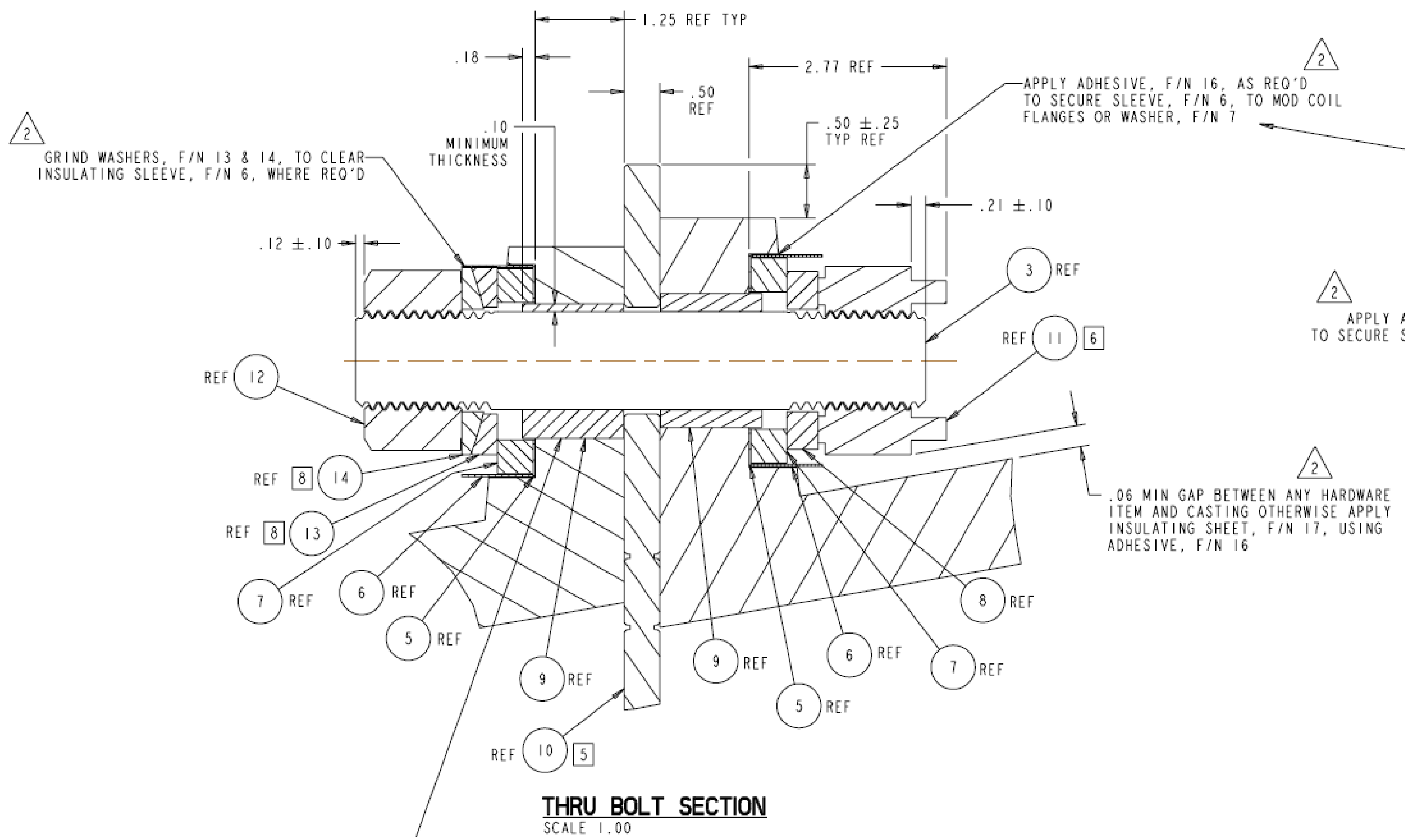
REASON FOR CHANGE:
FEEDBACK FROM FIELD MEASUREMENTS AND ASM TRIALS.

Bolted Joint Asm (SE140-190-R2)

NCSX
National Compact Stellarator Experi...



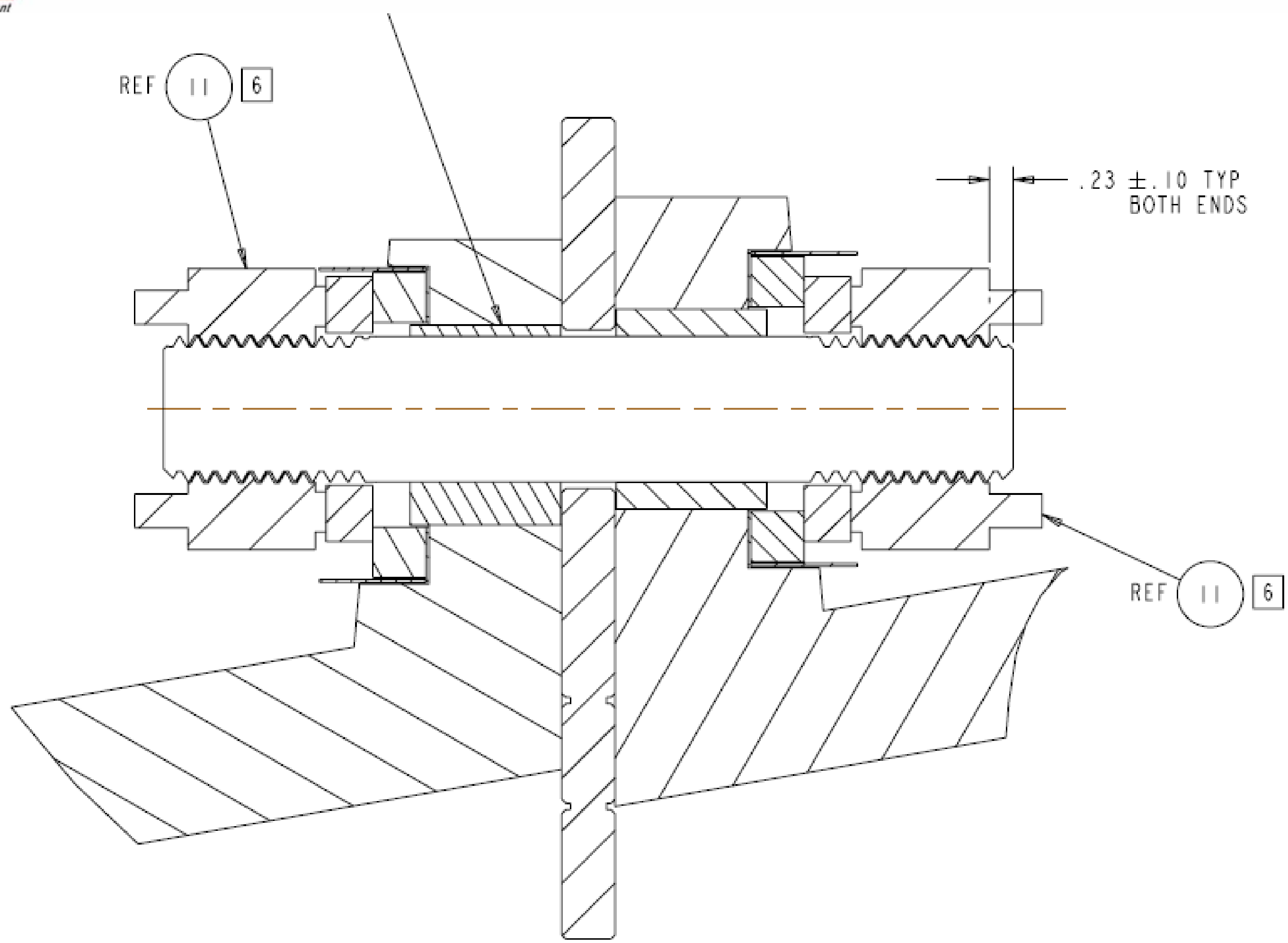
Bolted Joint Asm (SE140-190-R2)



THRU BOLT SECTION

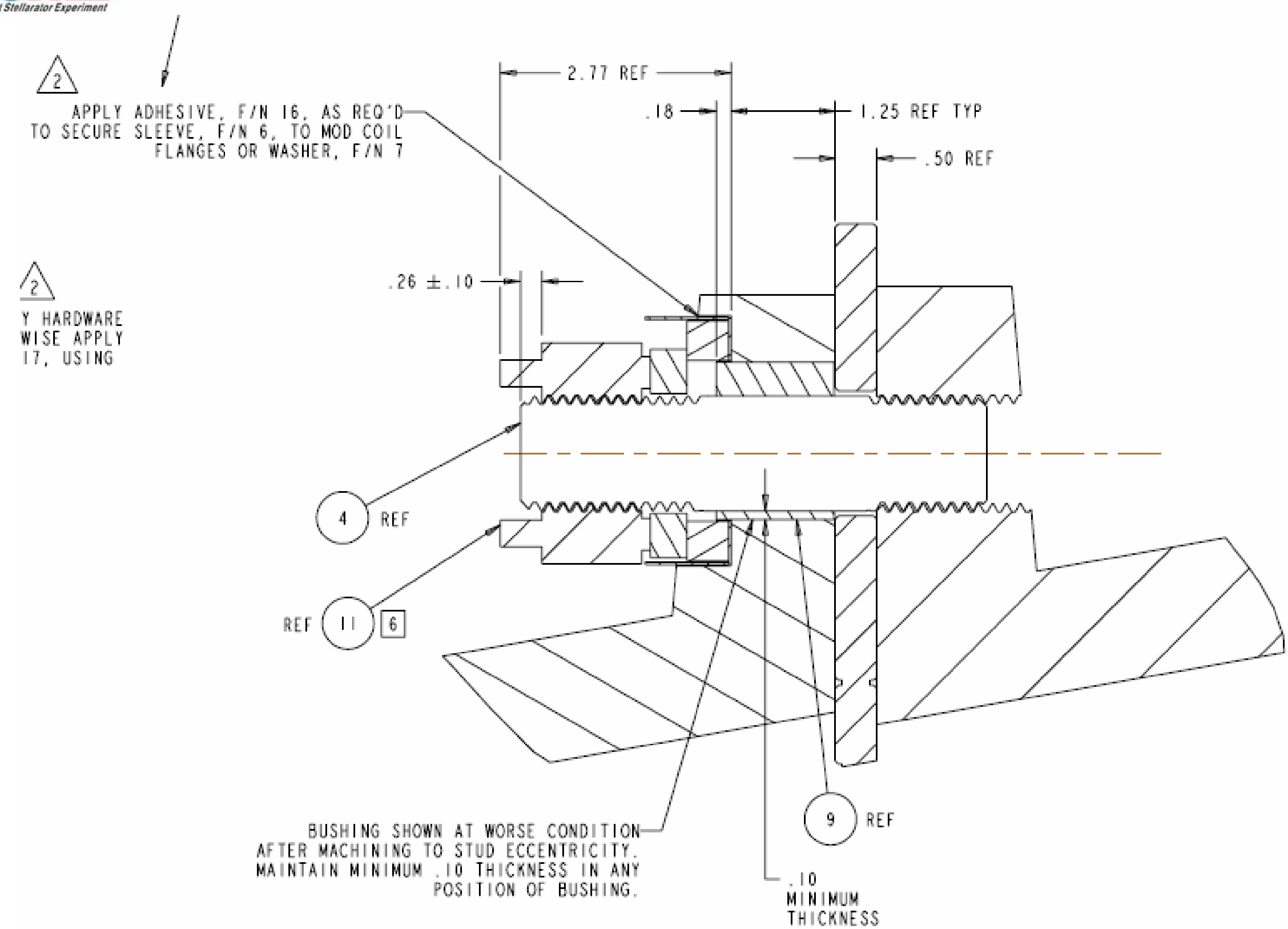
SCALE 1.00

Bolted Joint Asm (SE140-190-R2)



THRU BOLT SECTION (OPTIONAL) 7 2
SCALE 1.00

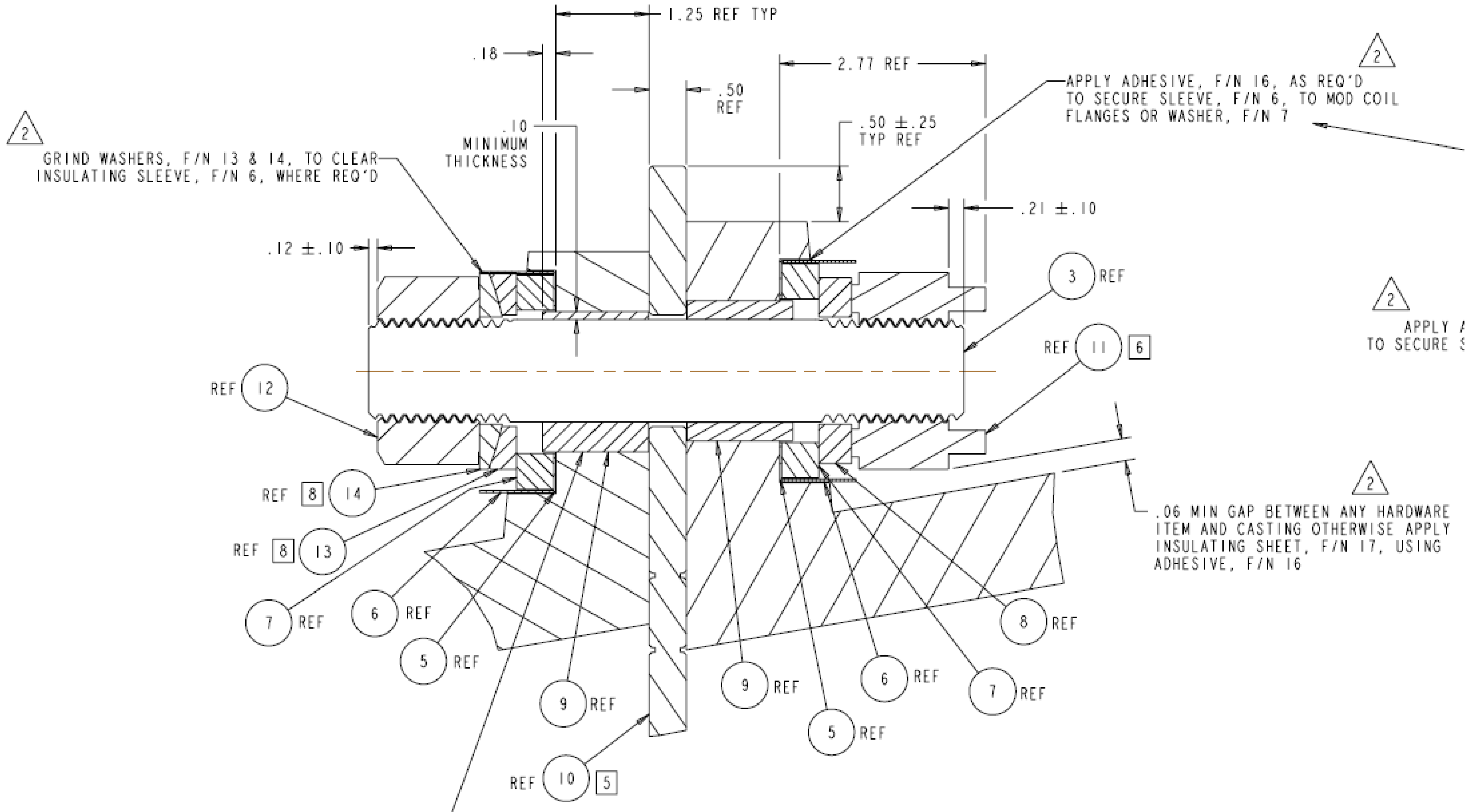
Bolted Joint Asm (SE140-190-R2)



TAPPED BOLT SECTION
SCALE 1.00

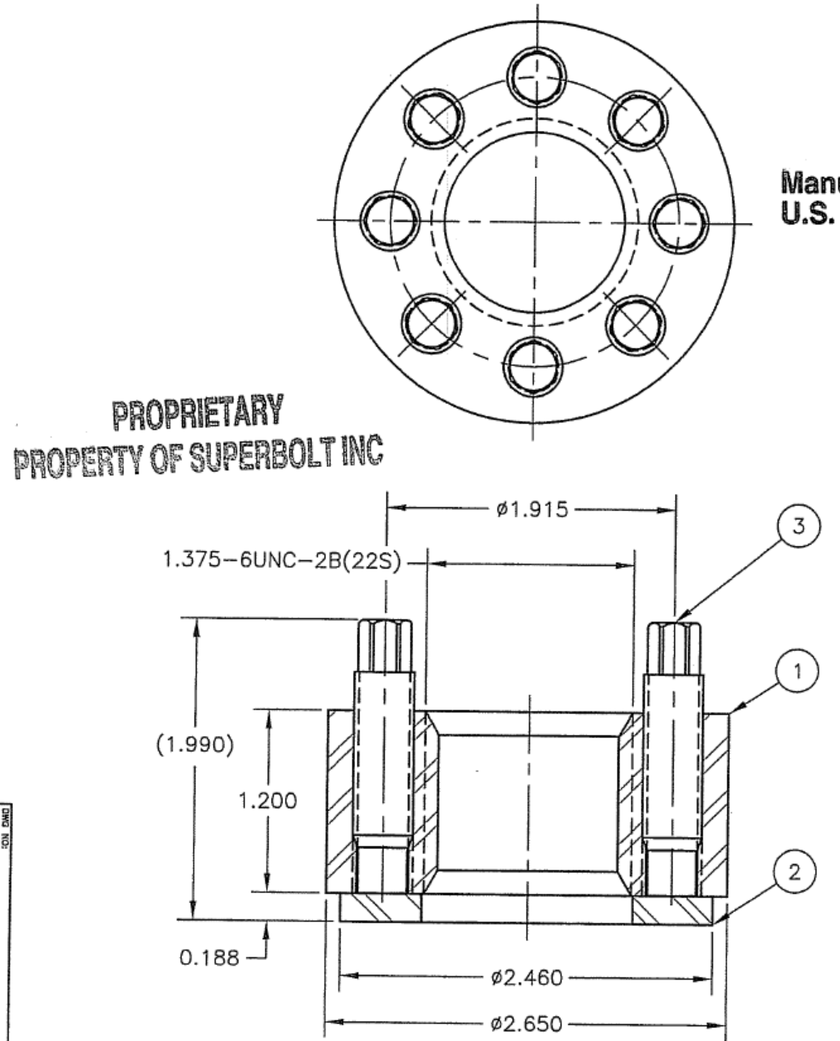
Bolt Preload

- Nominal preload of 73-kips based on 85% of A286 yield strength, permanent joint, 2% uncertainty w/ ultrasonic inspection
- Cool-down relaxation of assembly is -4% (Inconel washers)



THRU BOLT SECTION
SCALE 1.00

Supernut (P/N S-02200)



Manufactured Under U.S. Patent RE33490

PROPRIETARY
PROPERTY OF SUPERBOLT INC

NOTES:
1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN INCHES.
2. ALL DIMENSIONS ARE FOR REFERENCE ONLY.
3. STAMP PER 85–100–00.

ITEM/MATERIAL:
1. NUT BODY= 64–193–00
2. WASHER= 63–111–00, 70–302–00
3. JACKBOLTS= 63–111–00, 70–404–00

PRELOAD= 75,000 LBS
TORQUE= TBD (SUPERBOLT JL–G)
ESTIMATED TORQUE= 39 LBFT

ITEM	PART NUMBER	QTY	DESCRIPTION	WGH
3	JB–01997	8	JB, PINTLE, M10.0X1.25X1.458, 63, 5/16H	0.04
2	W–04616	1	WASHER, 1.400X2.460X0.188, 63	0.18
1	B–05556	1	NUT, 1.375–6, 2.650X1.200, 64	1.07

INTERPRET DIMENSIONS AND TOLERANCES PER ASME Y14.5M–1994, UNLESS OTHERWISE SPECIFIED

THIRD ANGLE PROJECTION

TOLERANCES, UNLESS OTHERWISE SPECIFIED:

LINEAR DIMENSIONS (INCHES)	< 8	≥ 8	≥ 12	≥ 24
X.X	±0.1	±0.1	±0.1	±1/8
X.XX	±0.02	±0.03	±0.05	
X.XXX	±0.005	±0.008	±0.015	

ANGULAR DIMENSIONS ±1°

SURFACE FINISHES 125 UNLESS OTHERWISE SPECIFIED

MANUFACTURED UNDER U.S. PATENT # RE33490

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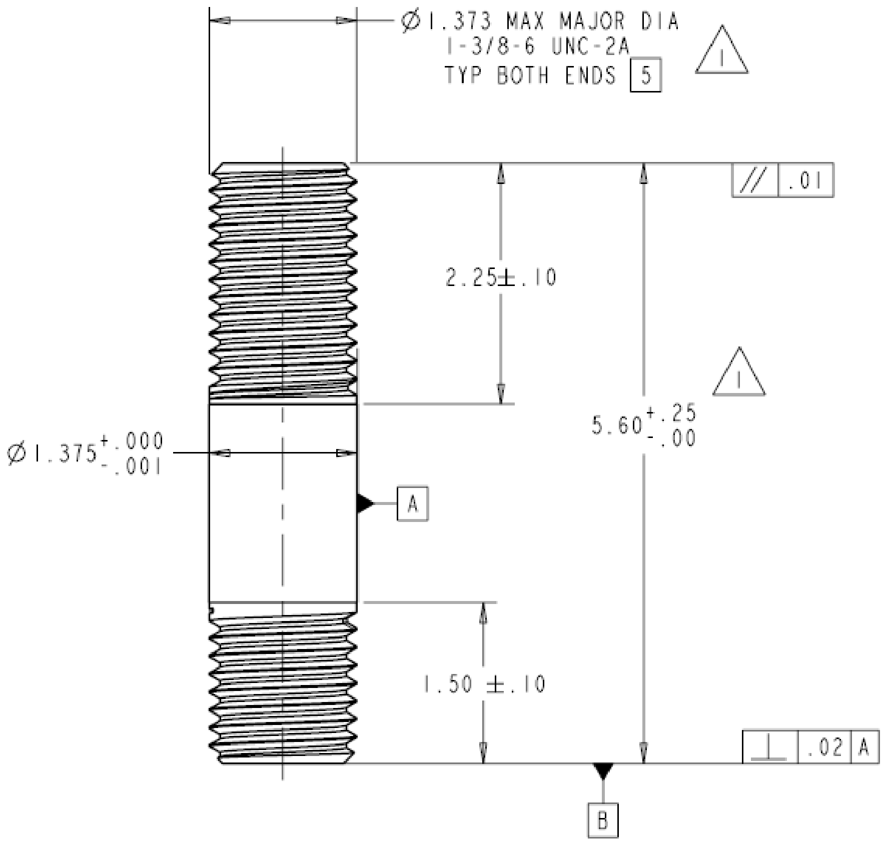
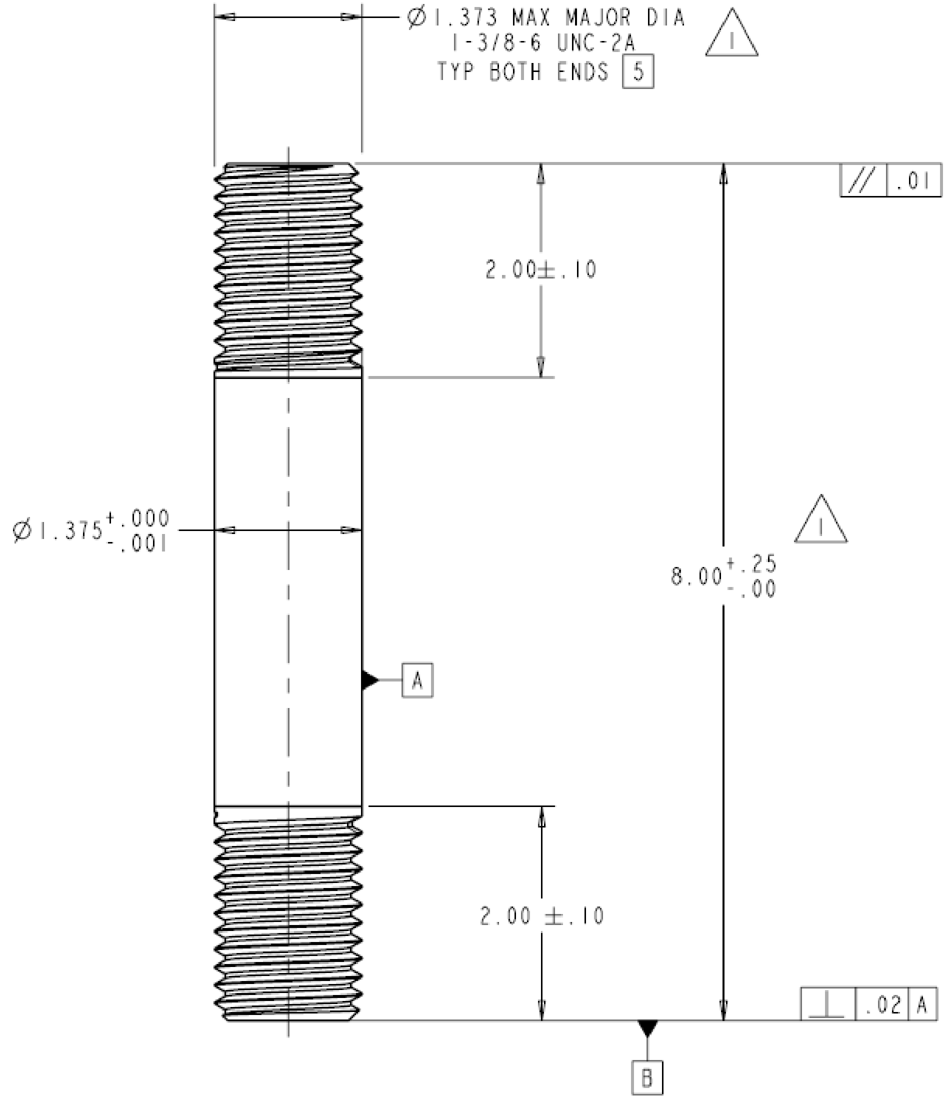
SUPERBOLT®
P.O. BOX 683
CARNEGIE, PA 15106
412–279–1149

DRAWN BY: JR Moss DATE: 3/28/07	S, ASSY., 1.375–6	WEIGHT: 1.57
CHECKED BY: DATE:	PRINCETON PLASMA PHYSICS LAB	SHEET: 1 OF 1
APPROVED BY: DATE: 4-2-07	SCALE: 1:1 DWG NO: S–02200	REV:

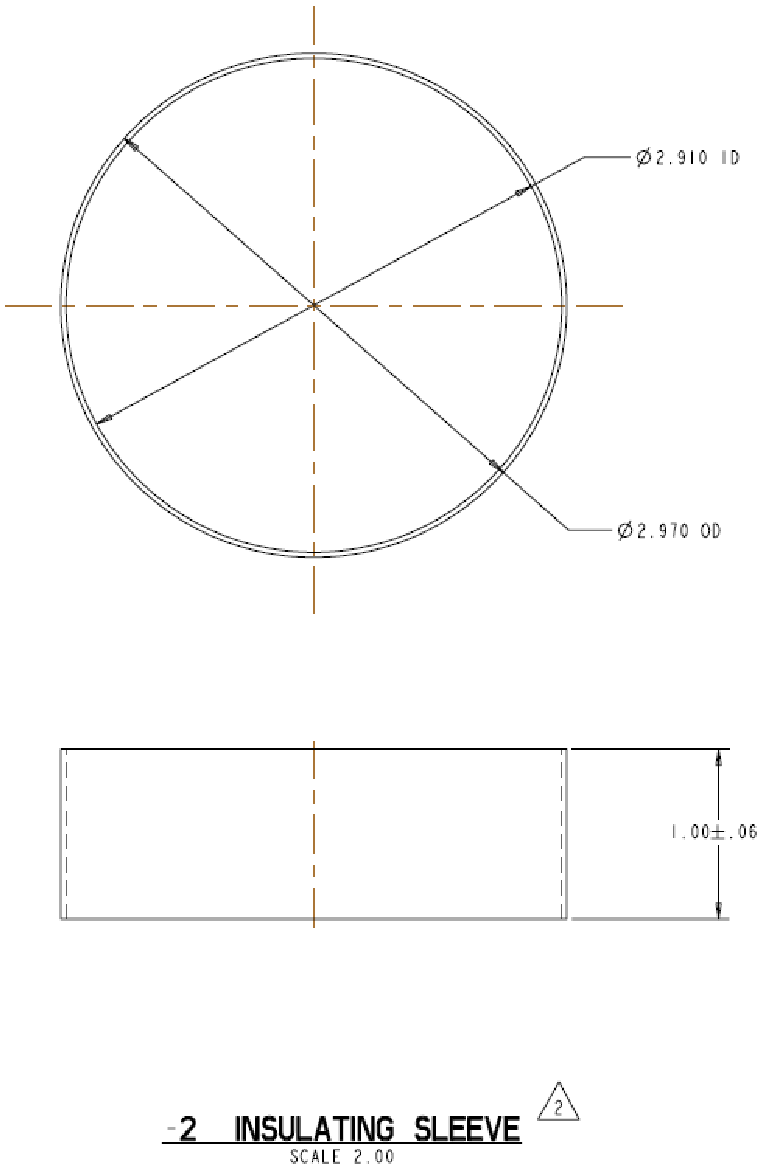
DWG NO: S–02200
SHEET: 1 OF 1

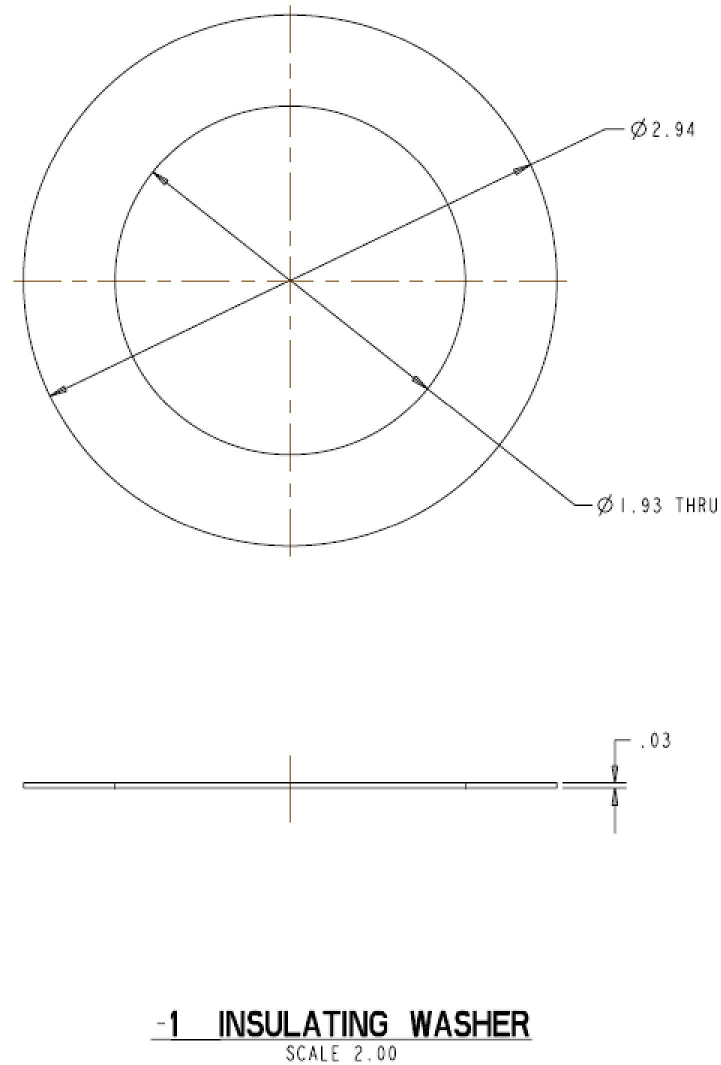
Studs (SE140-191-R1)





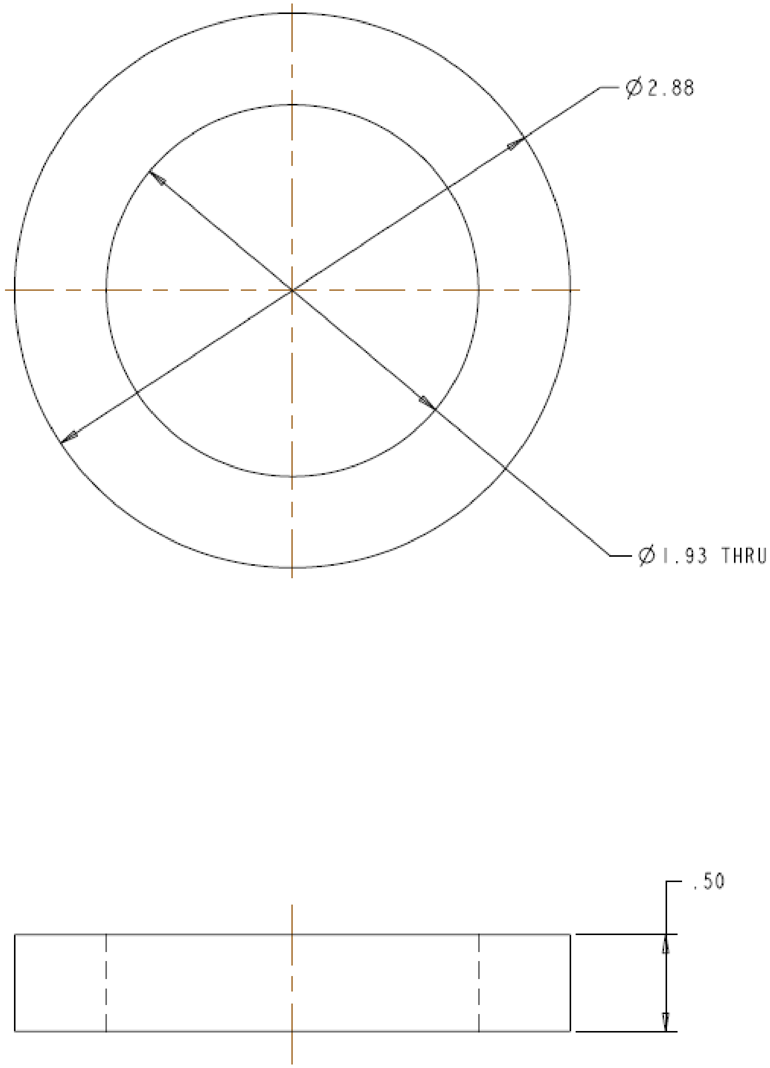
Ins Washer (SE140-192-R2)

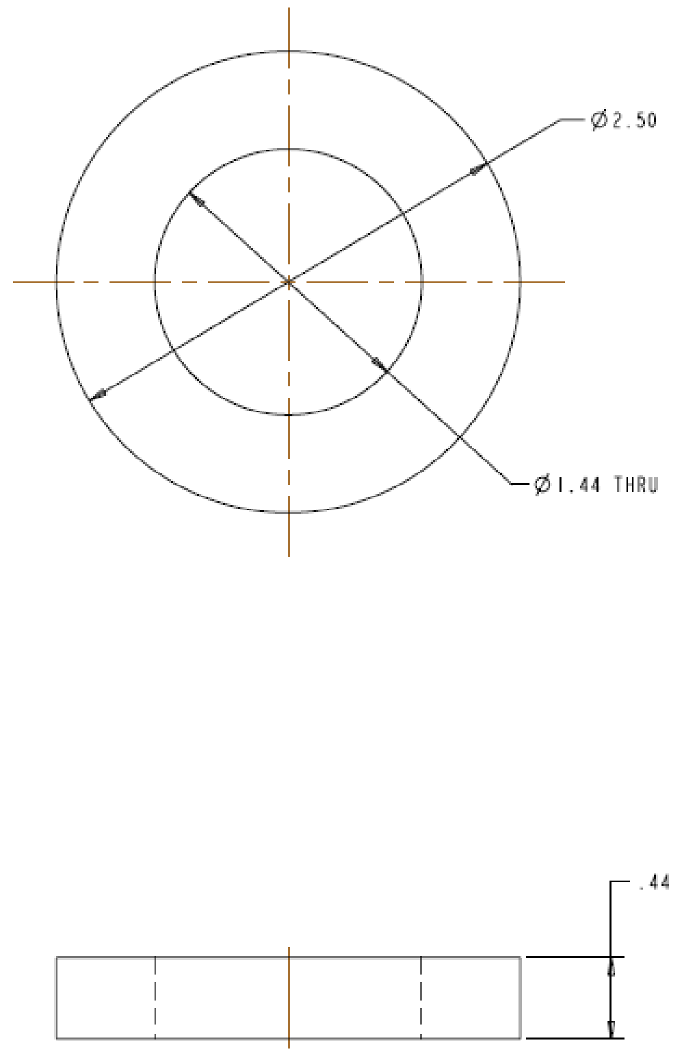




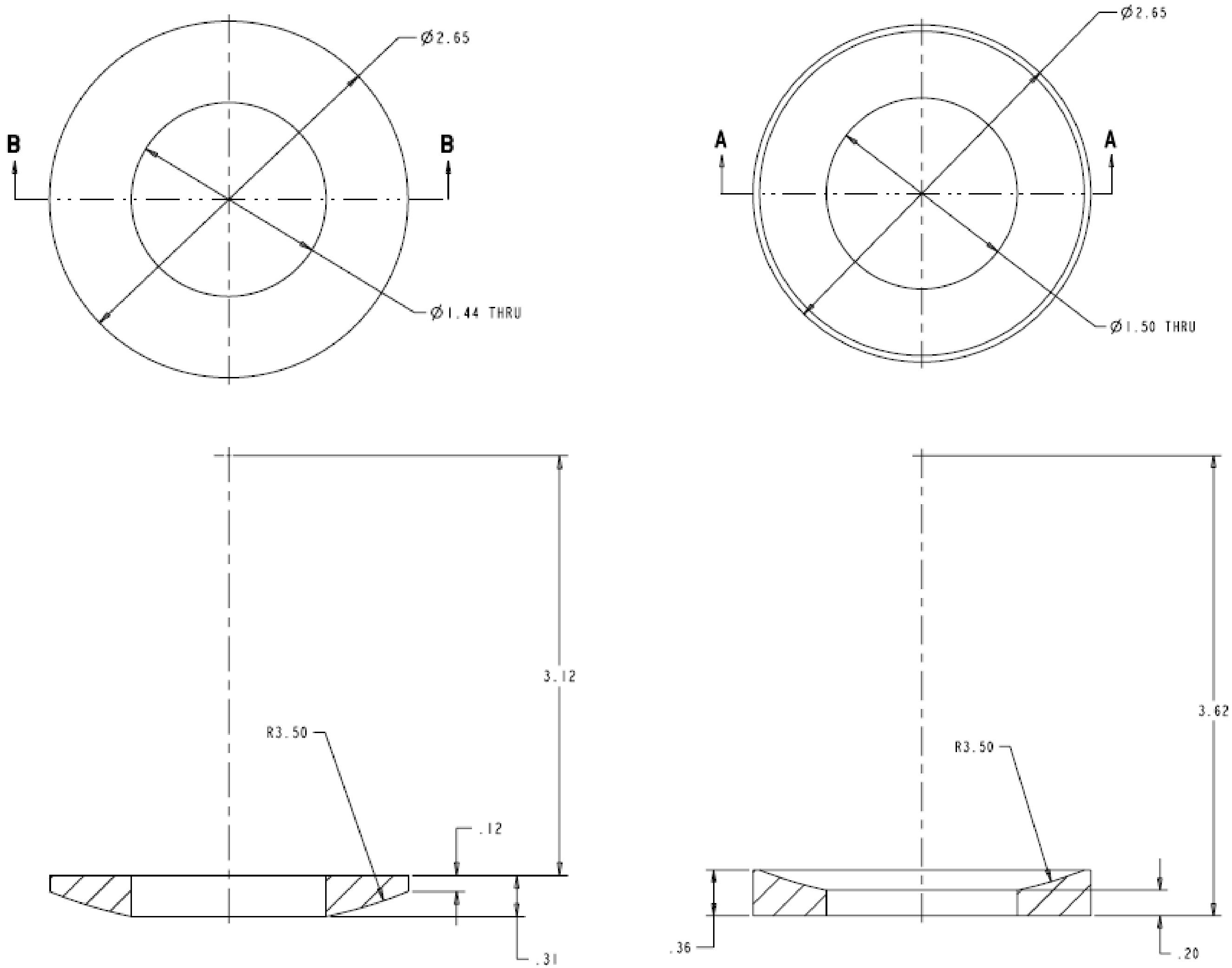
Load Washer (SE140-193-R2)

Flat Washer (SE140-208-R0)

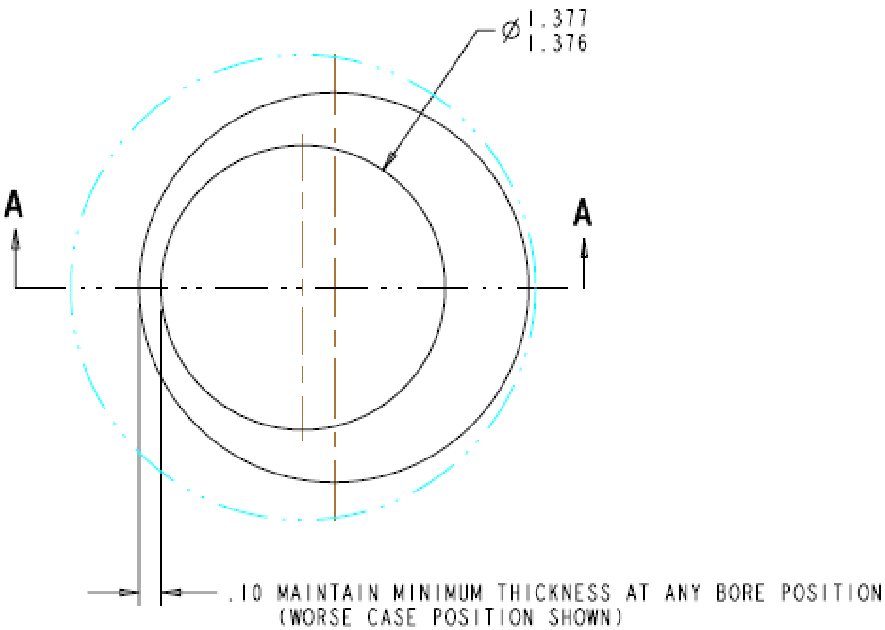


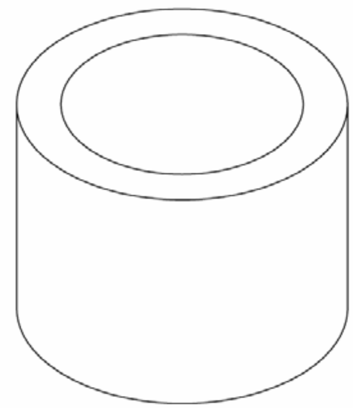


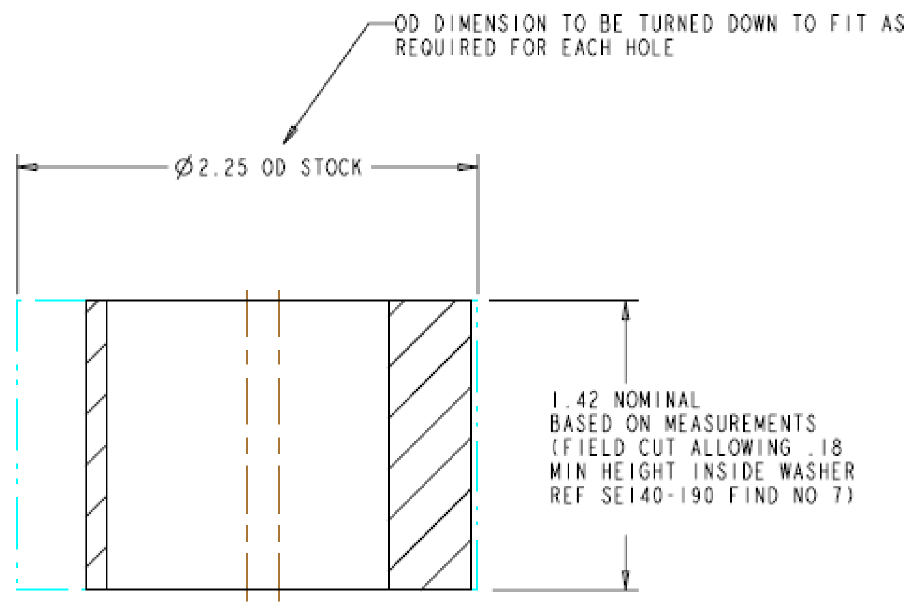
Sph Washer (SE140-194-R1)



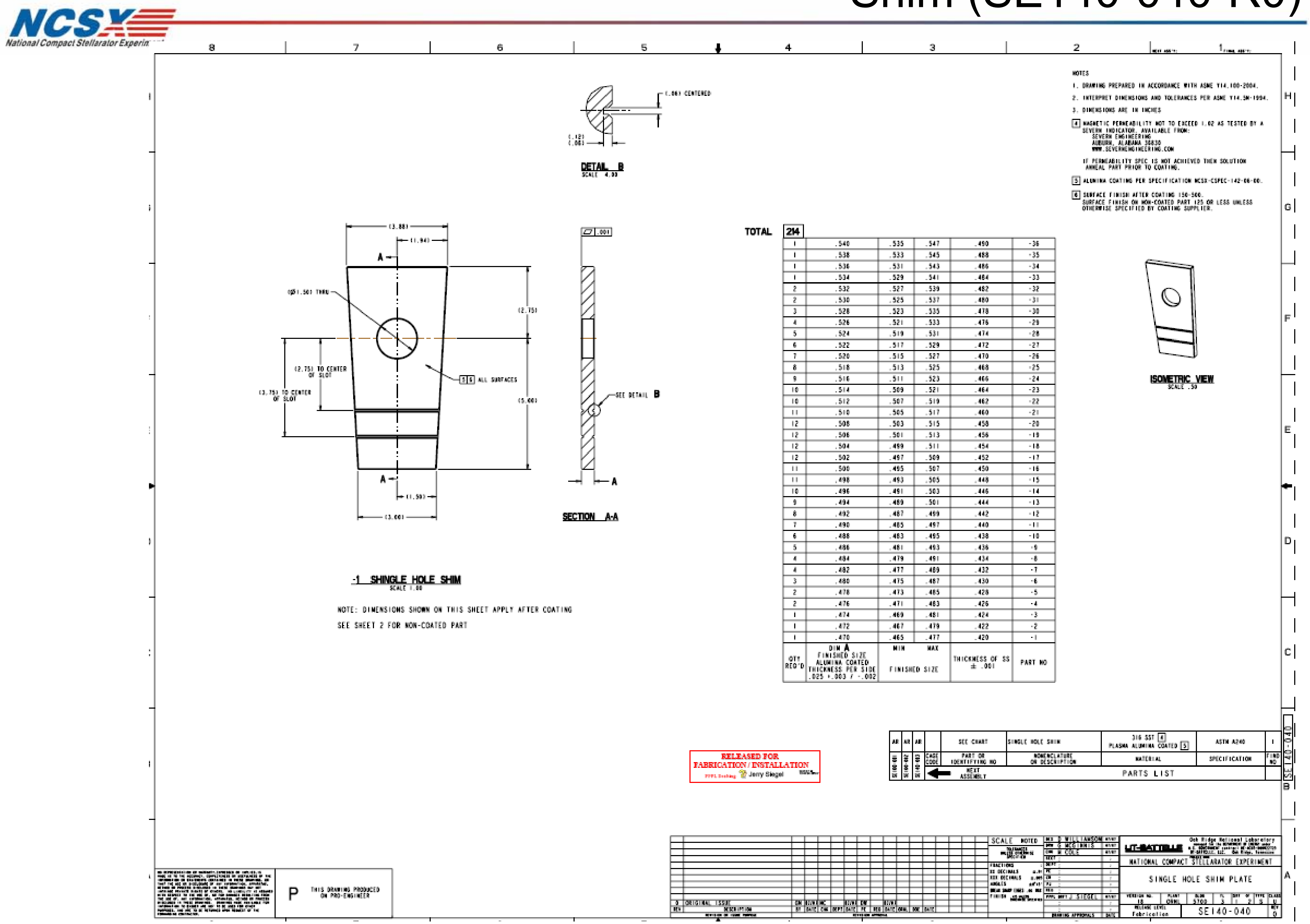
Bushing (SE140-195-R0)







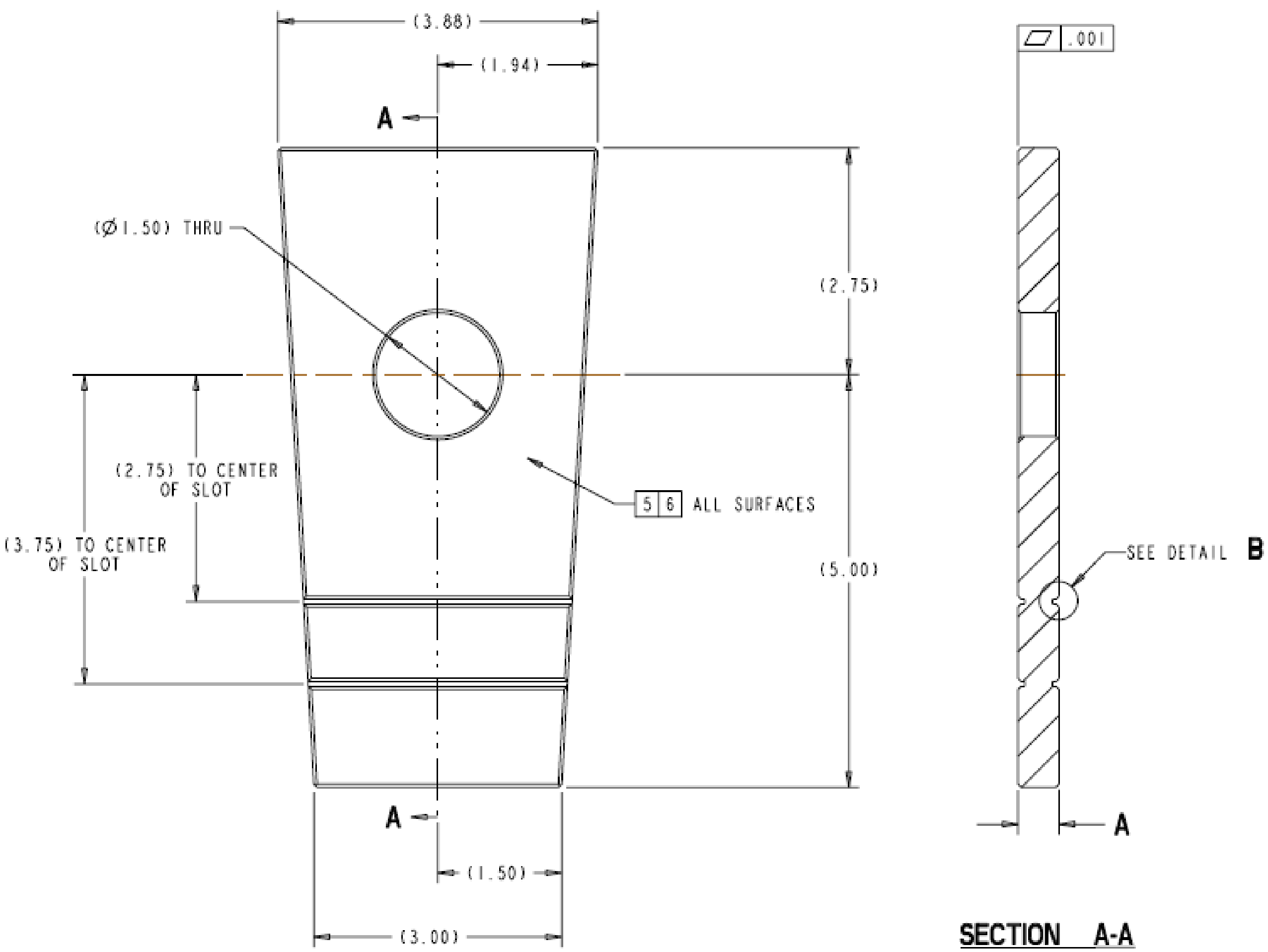
Shim (SE140-040-R0)



TOTAL 214

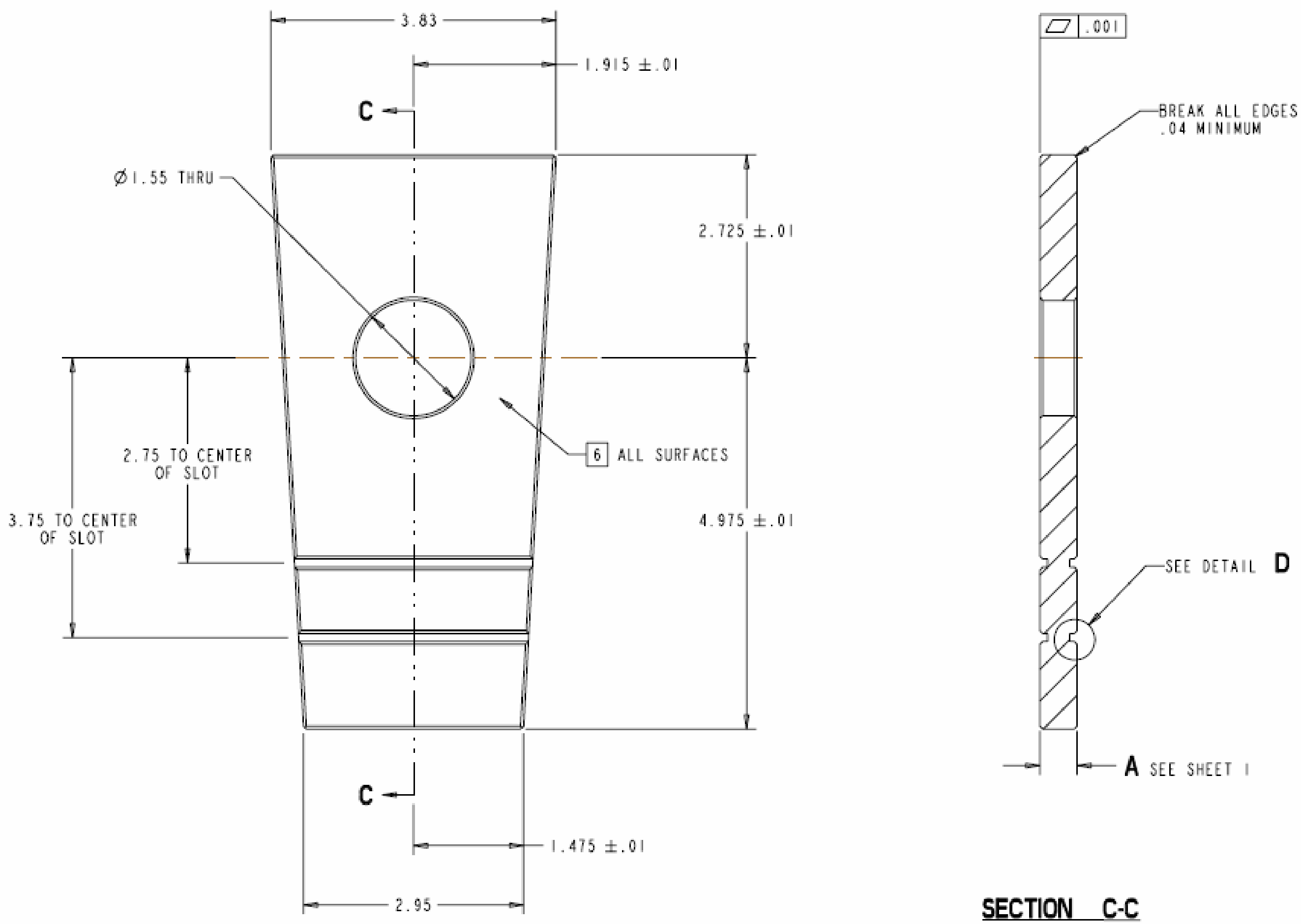
QTY REQ'D	DIM A FINISHED SIZE ALUMINA COATED THICKNESS PER SIDE .025 +.003 / -.002	MIN FINISHED SIZE	MAX FINISHED SIZE	THICKNESS OF SS ± .001	PART NO
1	.540	.535	.547	.490	-36
1	.538	.533	.545	.488	-35
1	.536	.531	.543	.486	-34
1	.534	.529	.541	.484	-33
2	.532	.527	.539	.482	-32
2	.530	.525	.537	.480	-31
3	.528	.523	.535	.478	-30
4	.526	.521	.533	.476	-29
5	.524	.519	.531	.474	-28
6	.522	.517	.529	.472	-27
7	.520	.515	.527	.470	-26
8	.518	.513	.525	.468	-25
9	.516	.511	.523	.466	-24
10	.514	.509	.521	.464	-23
10	.512	.507	.519	.462	-22
11	.510	.505	.517	.460	-21
12	.508	.503	.515	.458	-20
12	.506	.501	.513	.456	-19
12	.504	.499	.511	.454	-18
12	.502	.497	.509	.452	-17
11	.500	.495	.507	.450	-16
11	.498	.493	.505	.448	-15
10	.496	.491	.503	.446	-14
9	.494	.489	.501	.444	-13
8	.492	.487	.499	.442	-12
7	.490	.485	.497	.440	-11
6	.488	.483	.495	.438	-10
5	.486	.481	.493	.436	-9
4	.484	.479	.491	.434	-8
4	.482	.477	.489	.432	-7
3	.480	.475	.487	.430	-6
2	.478	.473	.485	.428	-5
2	.476	.471	.483	.426	-4
1	.474	.469	.481	.424	-3
1	.472	.467	.479	.422	-2
1	.470	.465	.477	.420	-1

Shim (SE140-040-R0)



DIMENSIONS AFTER ALUMINA COATING

Shim (SE140-040-R0)

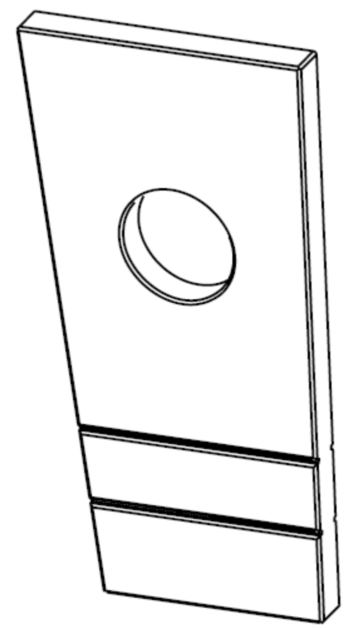


DIMENSIONS BEFORE ALUMINA COATING

Shim (SE140-040-R0)

TOTAL 214

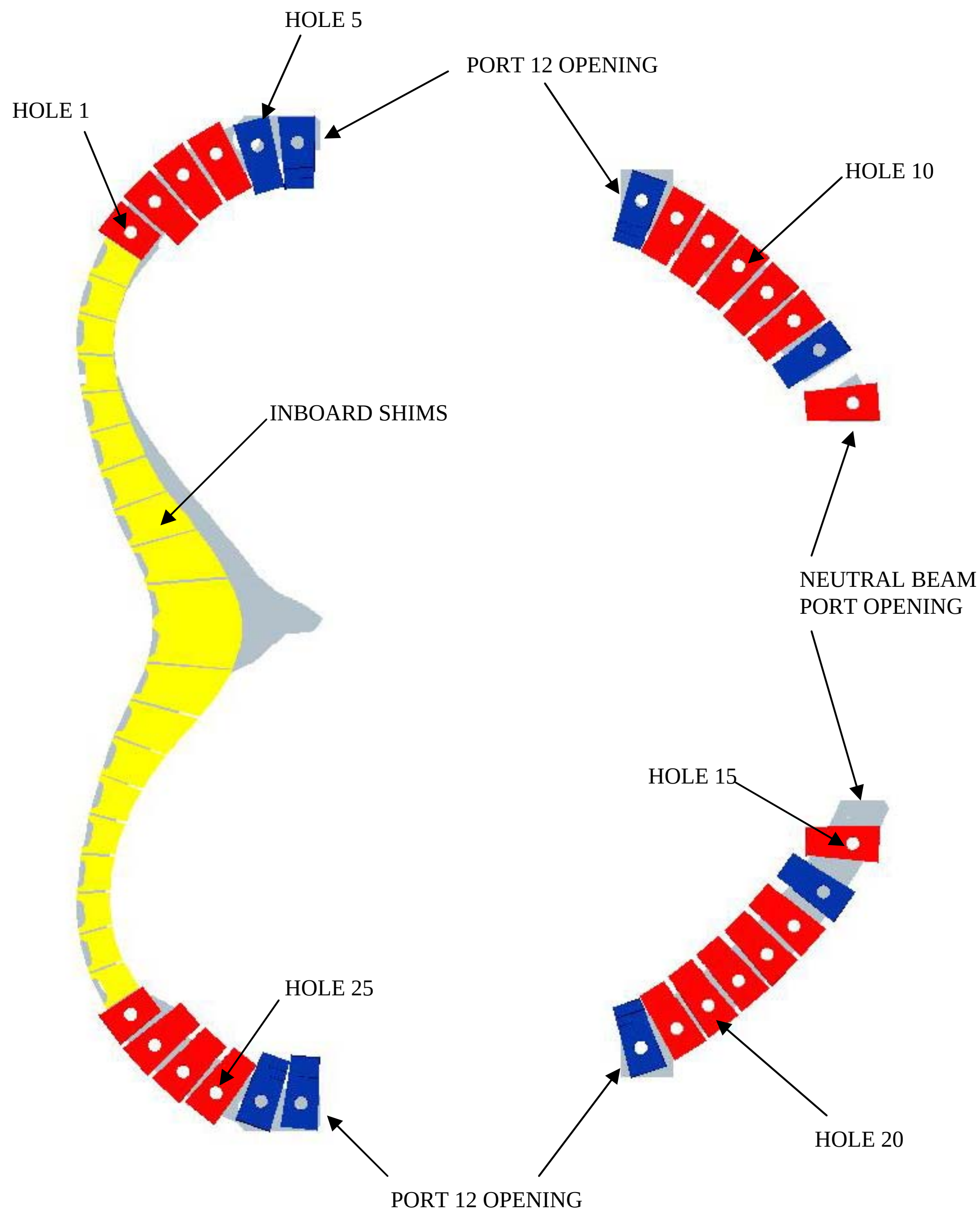
1	.540	.535	.547	.490	-36
1	.538	.533	.545	.488	-35
1	.536	.531	.543	.486	-34
1	.534	.529	.541	.484	-33
2	.532	.527	.539	.482	-32
2	.530	.525	.537	.480	-31
3	.528	.523	.535	.478	-30
4	.526	.521	.533	.476	-29
5	.524	.519	.531	.474	-28
6	.522	.517	.529	.472	-27
7	.520	.515	.527	.470	-26
8	.518	.513	.525	.468	-25
9	.516	.511	.523	.466	-24
10	.514	.509	.521	.464	-23
10	.512	.507	.519	.462	-22
11	.510	.505	.517	.460	-21
12	.508	.503	.515	.458	-20
12	.506	.501	.513	.456	-19
12	.504	.499	.511	.454	-18
12	.502	.497	.509	.452	-17
11	.500	.495	.507	.450	-16
11	.498	.493	.505	.448	-15
10	.496	.491	.503	.446	-14
9	.494	.489	.501	.444	-13
8	.492	.487	.499	.442	-12
7	.490	.485	.497	.440	-11
6	.488	.483	.495	.438	-10
5	.486	.481	.493	.436	-9
4	.484	.479	.491	.434	-8
4	.482	.477	.489	.432	-7
3	.480	.475	.487	.430	-6
2	.478	.473	.485	.428	-5
2	.476	.471	.483	.426	-4
1	.474	.469	.481	.424	-3
1	.472	.467	.479	.422	-2
1	.470	.465	.477	.420	-1
QTY REQ'D	DIM A FINISHED SIZE ALUMINA COATED THICKNESS PER SIDE .025 +.003 / -.002	MIN FINISHED SIZE	MAX FINISHED SIZE	THICKNESS OF SS ± .001	PART NO



ISOMETRIC VIEW
SCALE .50

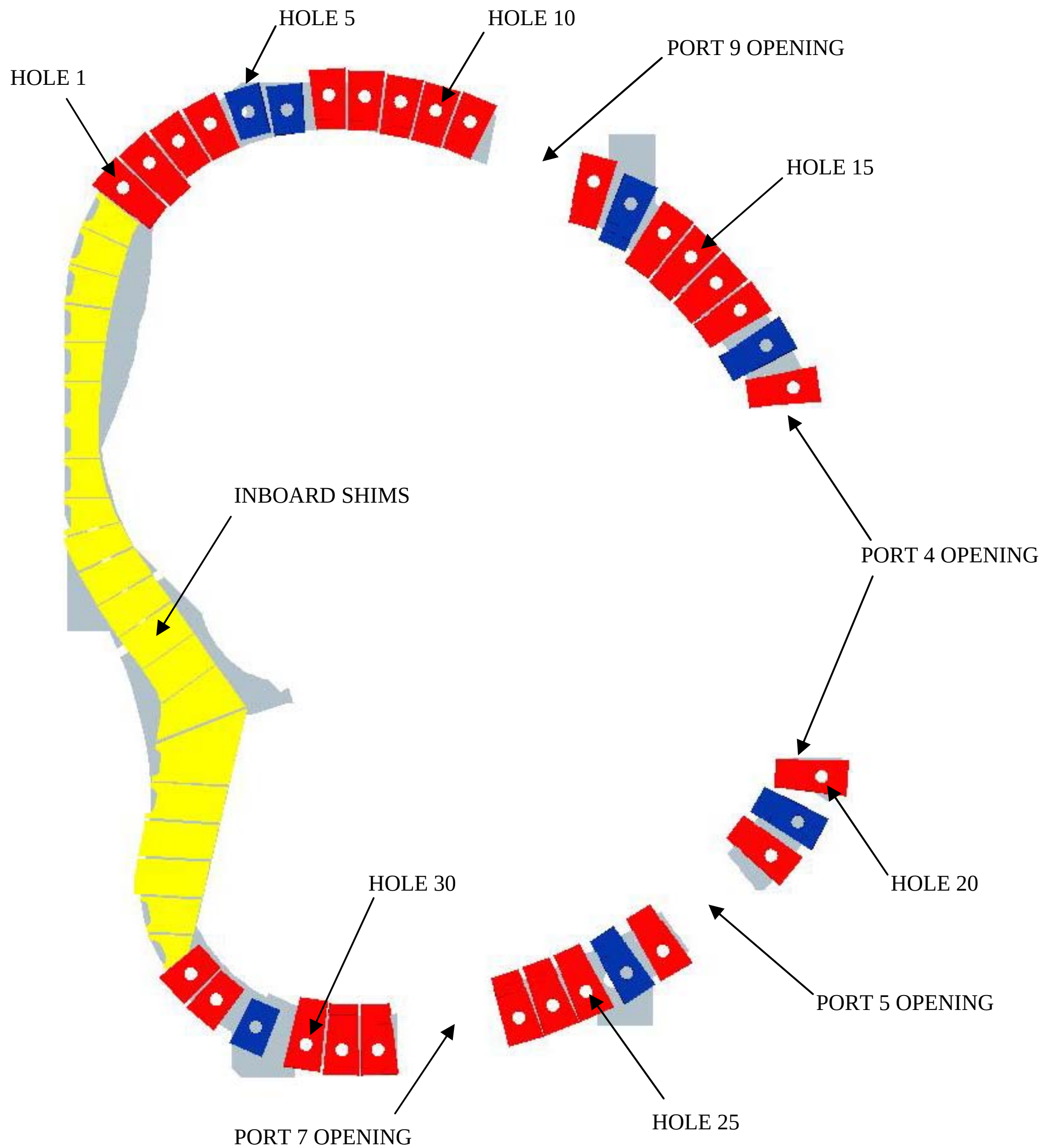
A-A FLANGE

AA Hole #	Shim Length Hole to Bottom	No Bolt Shim
1	2.75	
2	5.00	
3	5.00	
4	5.00	
5		5.00
6		5.00
7		5.00
8	5.00	
9	5.00	
10	5.00	
11	5.00	
12	5.00	
13		5.00
14	5.00	
15	5.00	
16		5.00
17	5.00	
18	5.00	
19	5.00	
20	5.00	
21	5.00	
22		5.00
23		5.00
24		5.00
25	5.00	
26	5.00	
27	5.00	
28	2.75	



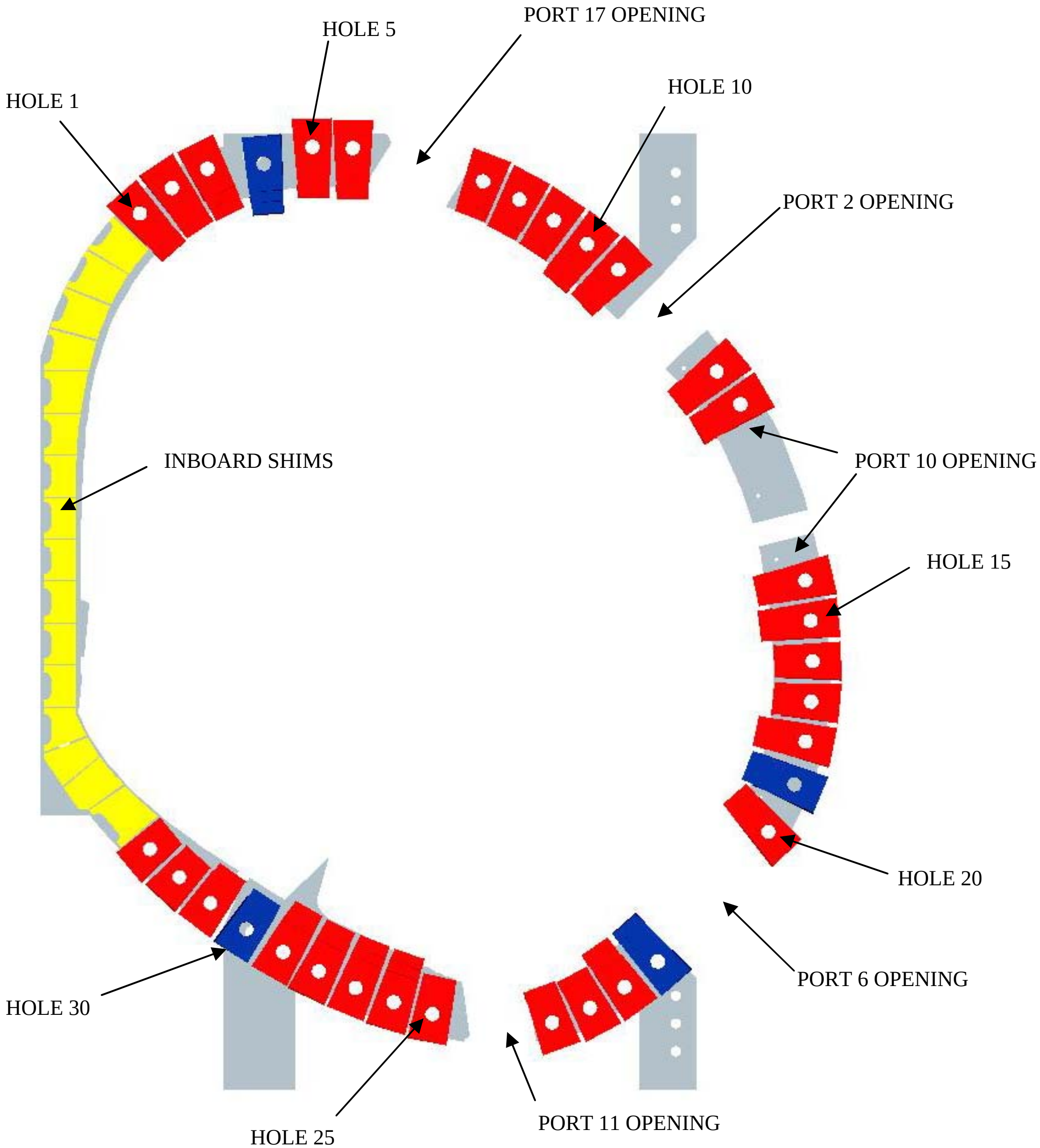
A-B FLANGE

AB Hole #	Shim Length Hole to Bottom	No Bolt Shim
1	5.00	
2	5.00	
3	3.75	
4	3.75	
5		2.75
6		2.75
7	3.75	
8	3.75	
9	3.75	
10	3.75	
11	3.75	
12	5.00	
13		5.00
14	5.00	
15	5.00	
16	5.00	
17	5.00	
18		5.00
19	5.00	
20	5.00	
21		5.00
22	5.00	
23	5.00	
24		5.00
25	5.00	
26	5.00	
27	5.00	
28	5.00	
29	5.00	
30	5.00	
31		2.75
32	2.75	
33	2.75	



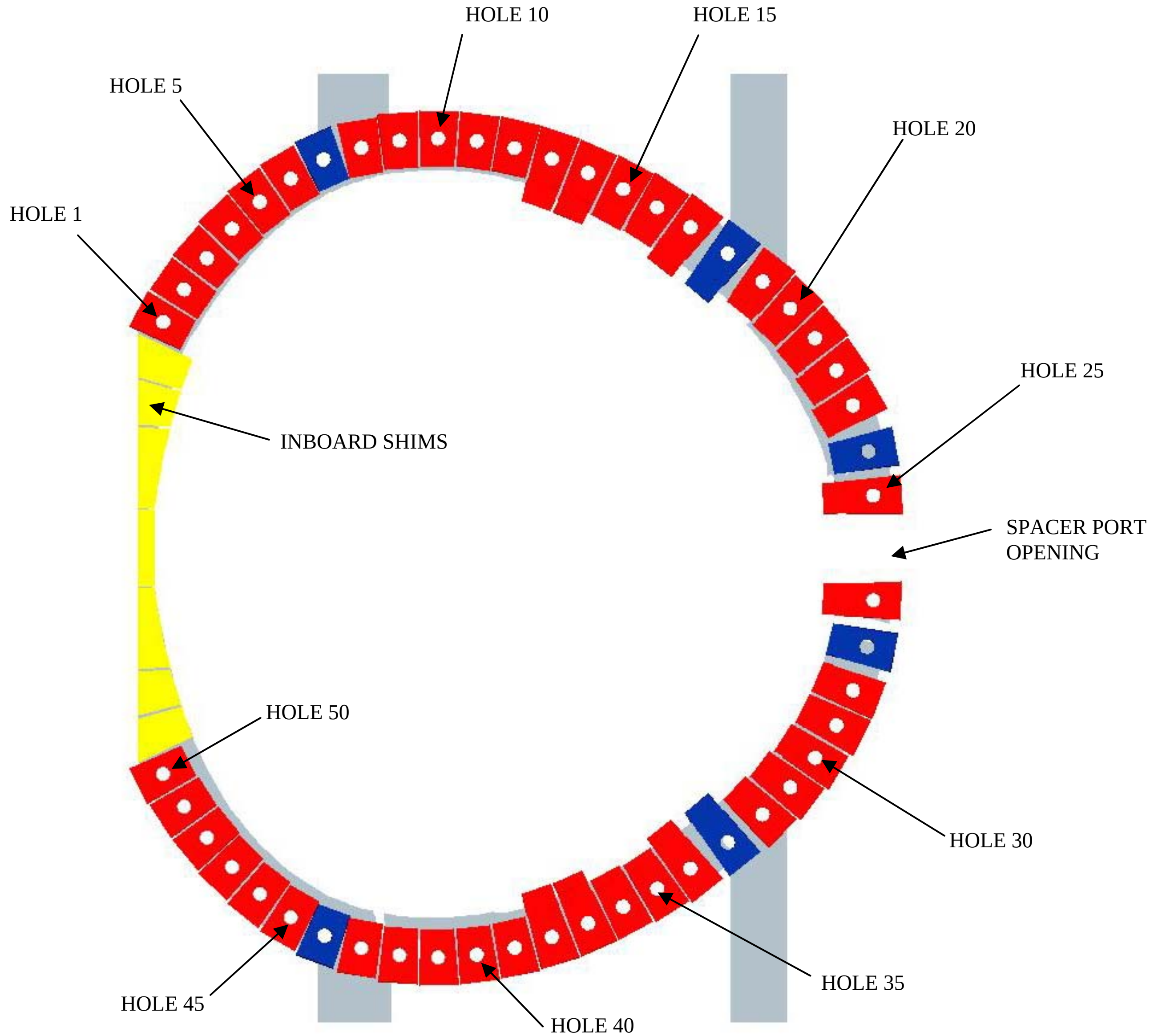
B-C FLANGE

BC Hole #	Shim Length Hole to Bottom	No Bolt Shim
1	5.00	
2	5.00	
3	5.00	
4		5.00
5	5.00	
6	5.00	
7	3.75	
8	3.75	
9	3.75	
10	5.00	
11	5.00	
12	5.00	
13	5.00	
14	5.00	
15	5.00	
16	3.75	
17	3.75	
18	5.00	
19		5.00
20	5.00	
21		5.00
22	5.00	
23	3.75	
24	3.75	
25	3.75	
26	5.00	
27	5.00	
28	5.00	
29	5.00	
30		3.75
31	3.75	
32	2.75	
33	2.75	



CC Hole #	Shim Length Hole to Bottom	No Bolt Shim
1	2.75	
2	2.75	
3	2.75	
4	2.75	
5	2.75	
6	2.75	
7		2.75
8	2.75	
9	2.75	
10	2.75	
11	2.75	
12	2.75	
13	5.00	
14	5.00	
15	3.75	
16	3.75	
17	5.00	
18		5.00
19	3.75	
20	3.75	
21	3.75	
22	3.75	
23	3.75	
24		3.75
25	5.00	
26	5.00	
27		3.75
28	3.75	
29	3.75	
30	3.75	
31	3.75	
32	3.75	
33		5.00
34	5.00	
35	3.75	
36	3.75	
37	5.00	
38	5.00	
39	2.75	
40	2.75	
41	2.75	
42	2.75	
43	2.75	
44		2.75
45	2.75	
46	2.75	
47	2.75	
48	2.75	
49	2.75	
50	2.75	

C-C FLANGE



No. Outboard Shims

SHIM LENGTH-HOLE TO BOTTOM	AA FLANGE	AB FLANGE	BC FLANGE	CC FLANGE	TOTAL
2.75	2	5	2	24	33
3.75		7	10	16	33
5.00 (UN-CUT)	26	21	21	10	78
TOTAL PER FLANGE	28	33	33	50	
TOTAL PER FIELD PERIOD	28	66	66		**160**
TOTAL PER MACHINE	84	198	198	150	**630**

Analysis Documentation

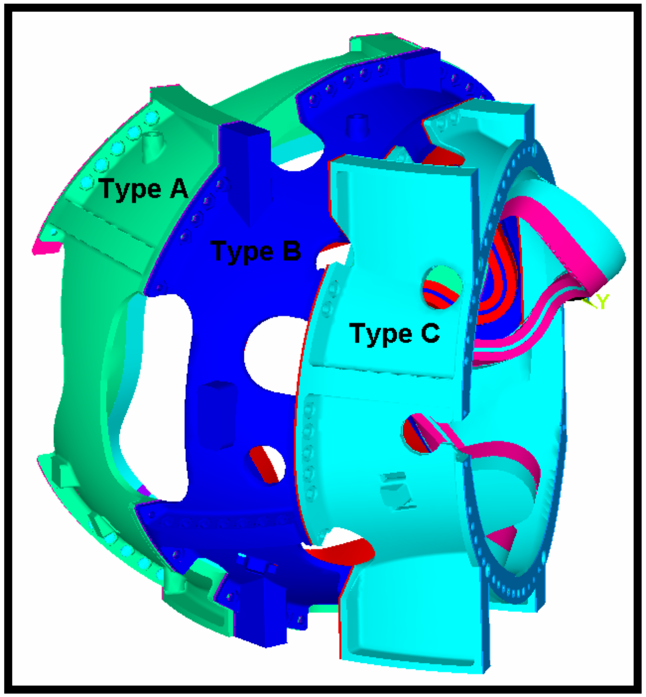
- Modular coil asm design basis is defined by 5 analysis reports:

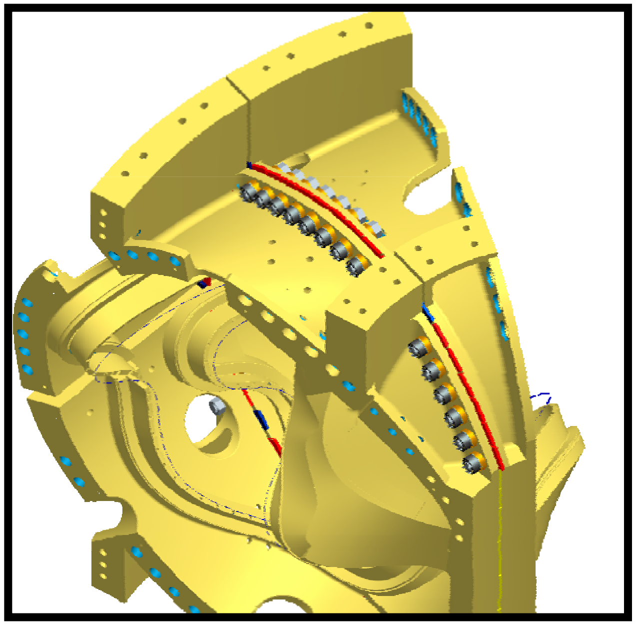
  HM Fan, Nonlinear Analysis of Coil and Shell Structure, NCSX-CALC-14-001, APPROVED
  HM Fan, Analysis of Integrated Structure, NCSX-CALC-14-003, APPROVED
  K Freudenberg, Modular Coil Thermal Analysis, NCSX-CALC-14-002, DRAFT
  K Freudenberg, Nonlinear Modular Coil Analysis, NCSX-CALC-14-004, DRAFT
  D Williamson, Modular Coil Failure Modes Analysis, NCSX-FMEA-14-002, DRAFT

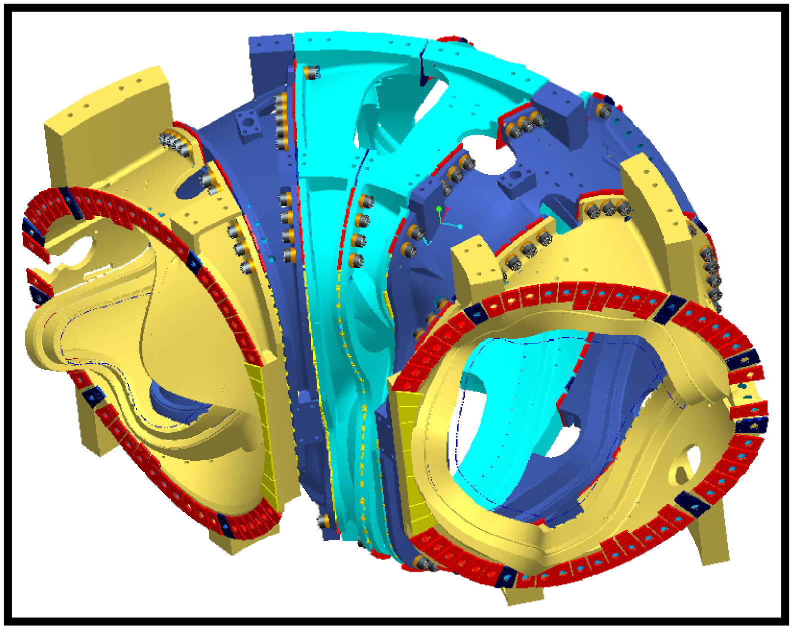
- Additional analysis reports are planned before Design Closeout:

  K Freudenberg, Outboard Bolted Joint Analysis, NCSX-CALC-14-006, DRAFT
  K Freudenberg, Inboard Welded Shim Analysis, IN PROGRESS
  D Williamson, Modular Coil Leads Structural Analysis, PLANNED

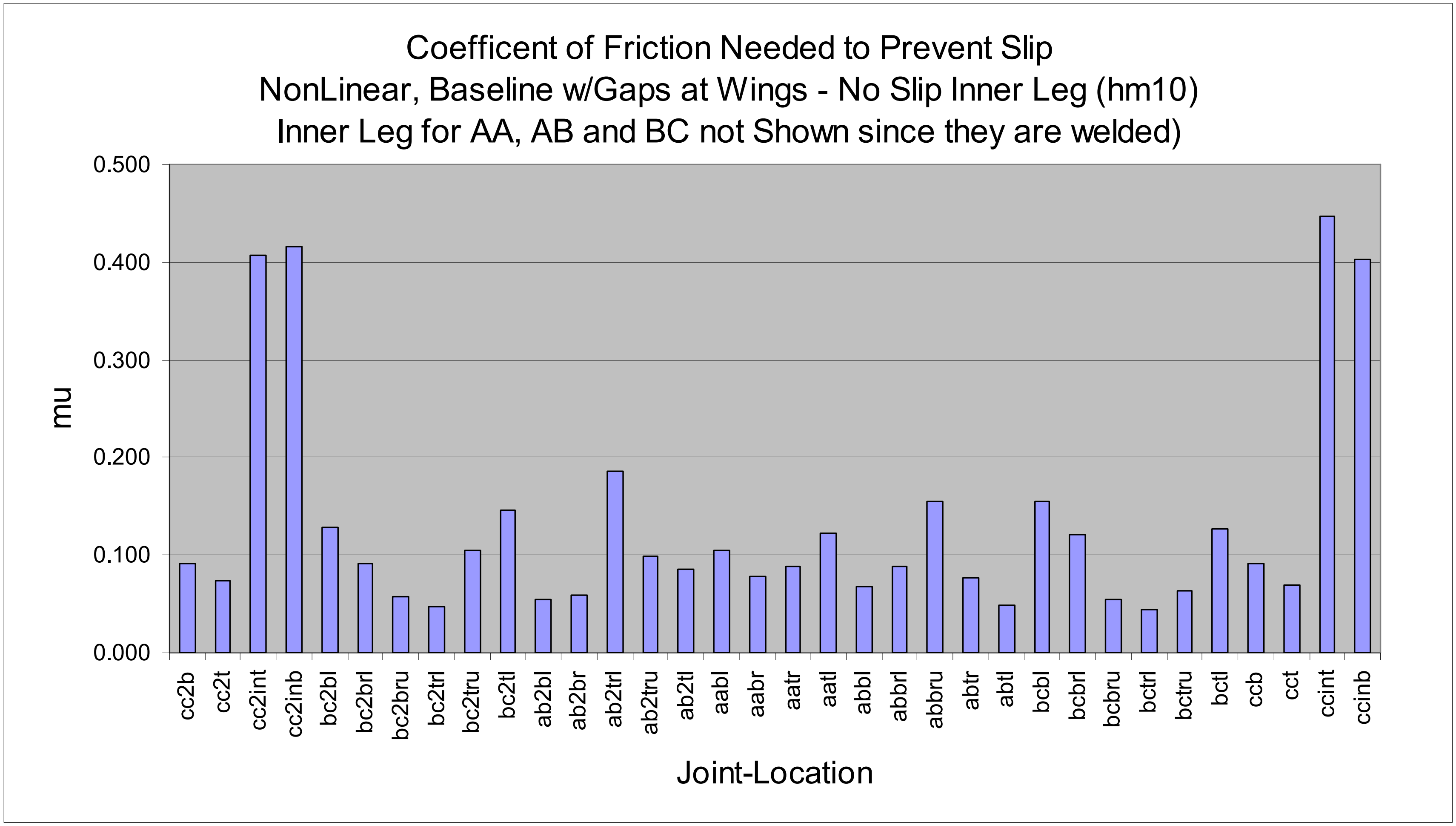
Finite Element Analysis







Linear Analysis for Friction coef.
- AVERAGES



From MCWF Toridal Joint Shear forces2.xls (H.M Fan and Art Brooks)

Inner Legs for AA, AB and BC not shown.

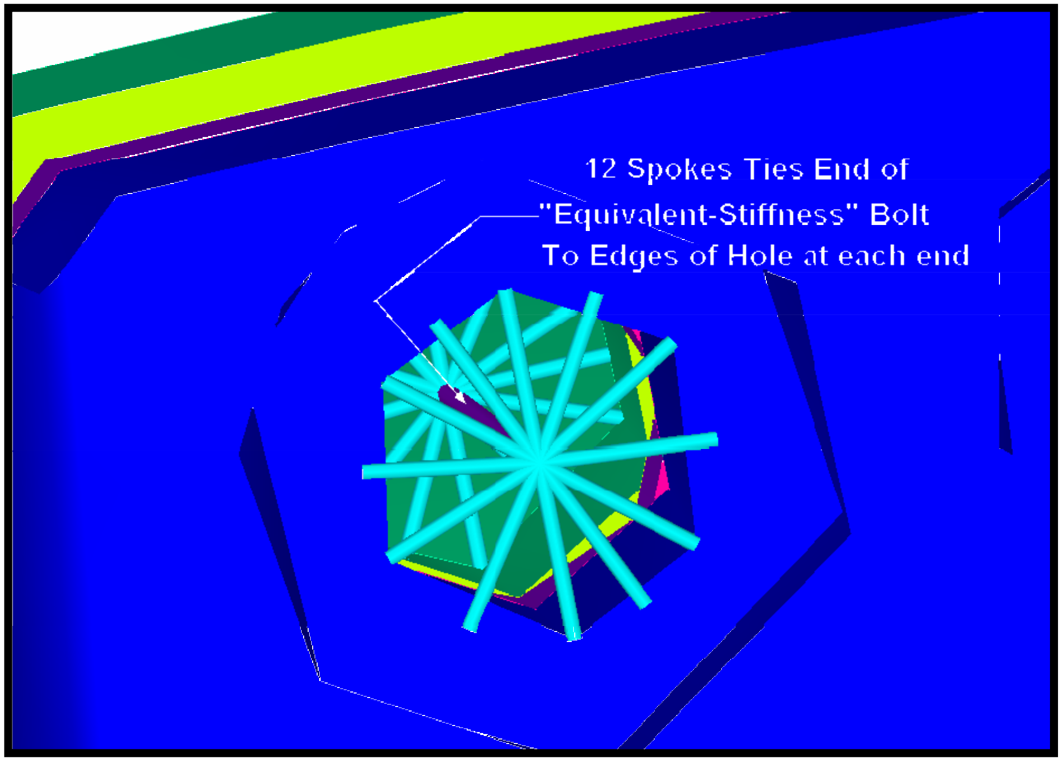
Analysis Assumptions

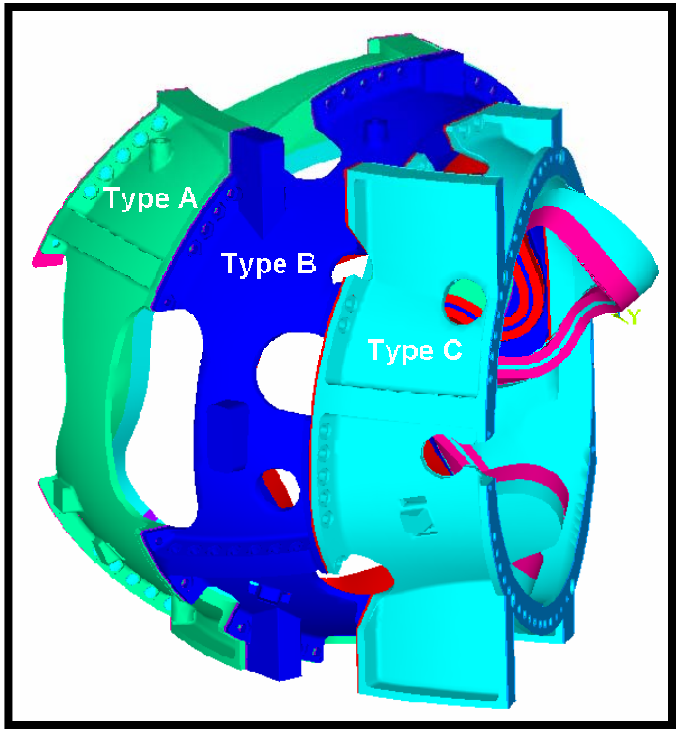
NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

- The non-linear (frictional) analysis of this structure is based on the half-field period model with anti-cyclic symmetric conditions on the end CC and AA flanges.
- The intent is to determine if the number of bolts is sufficient to prevent motion on the outboard side of the coils. Using discrete bolts instead of averages from a linear model gives a higher confidence.
- A friction factor of 0.4 used under all bolts and on the entire flange surface. This is derived from the approximate 0.6 average value seen in testing and a 1.5 reduction factor imposed.
- 2T high-β Magnetic loads, TF coil loads also applied.
- Preload compressive force of roughly 75 Kips applied to all bolts.

Bolt Modeling

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT





At one particular interface, pipe elements with appropriate section properties are used to represent the characteristics of a bolted interface. Contact elements at this interface are allowed sliding contact (no separation).

The other bolted interfaces are modeled with "Bonded Contact."“

**Any deflection of the top flange face (that connects to the bolt) relative to the bottom flange face or distortion of the hole itself could result in some minimal (usually less than 2 kips) shear in the bolt.

Global Results for 0.4 friction

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

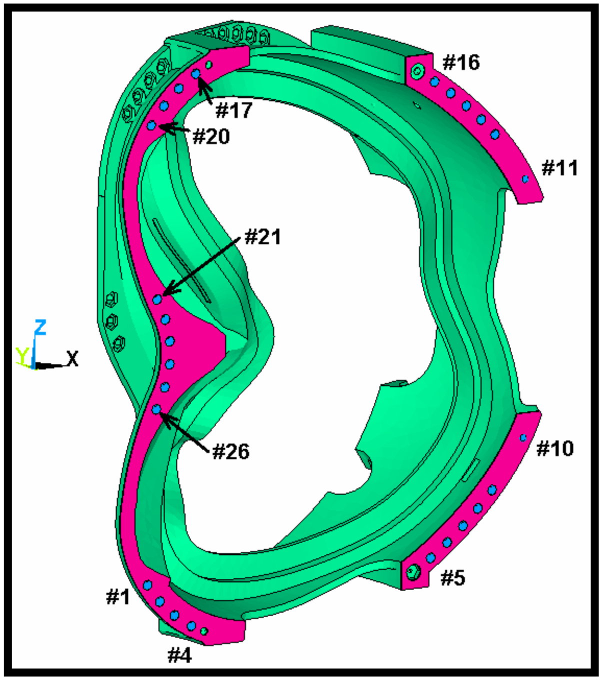
- **These models originated when the inner leg design was unsettled and inner leg bolts were placed on the AA, Ab and BC flanges.**
- **The design now calls for welding along the inner legs of three of the four joints.**
- **The analysis was performed with the out-dated inner leg bolts. However, the conditions on the outboard can be no worse than the condition presented. This is Conservative.**
- **The Table below indicates that there is very minimal slippage and bolt shear on the outboard region of the coils.**

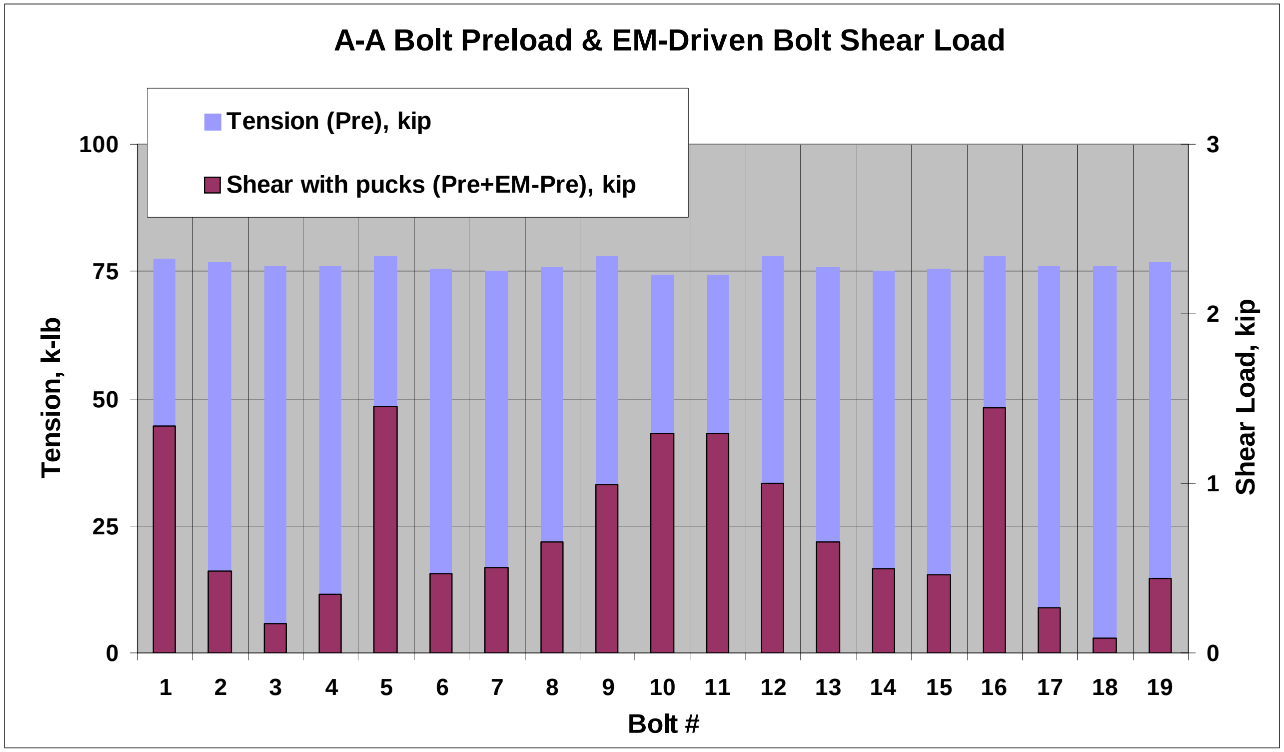
Flange Set	Max Bolt Shear, kip	Max Outboard Slippage mm
A-A	1.5	> 0.05
A-B	1.2	> 0.05
B-C	1.8	> 0.05
C-C	2.8	0.17

AA Bolt loadings (outboard)

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

Friction = 0.4 over the entire flange



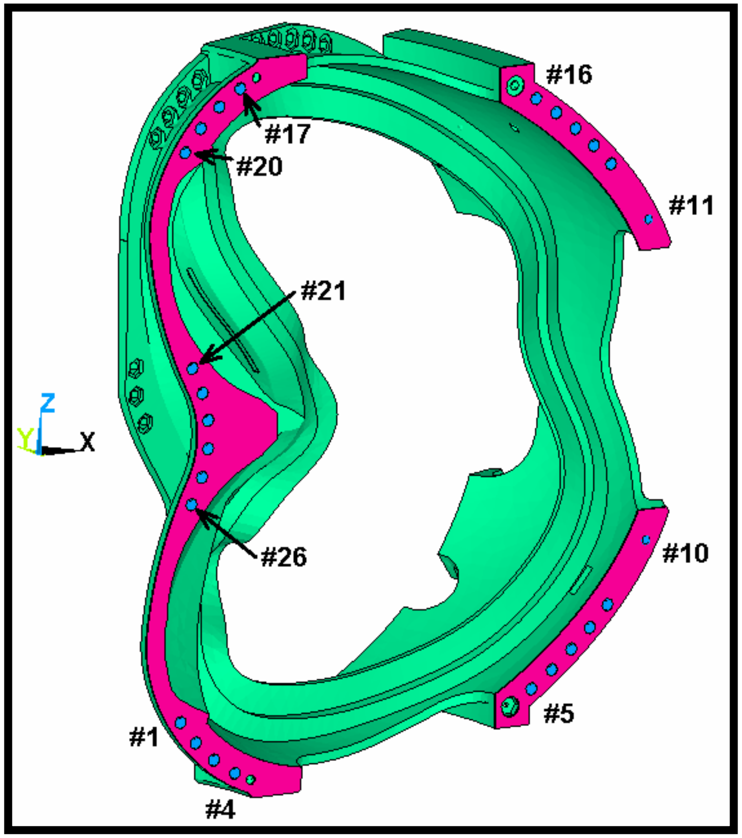


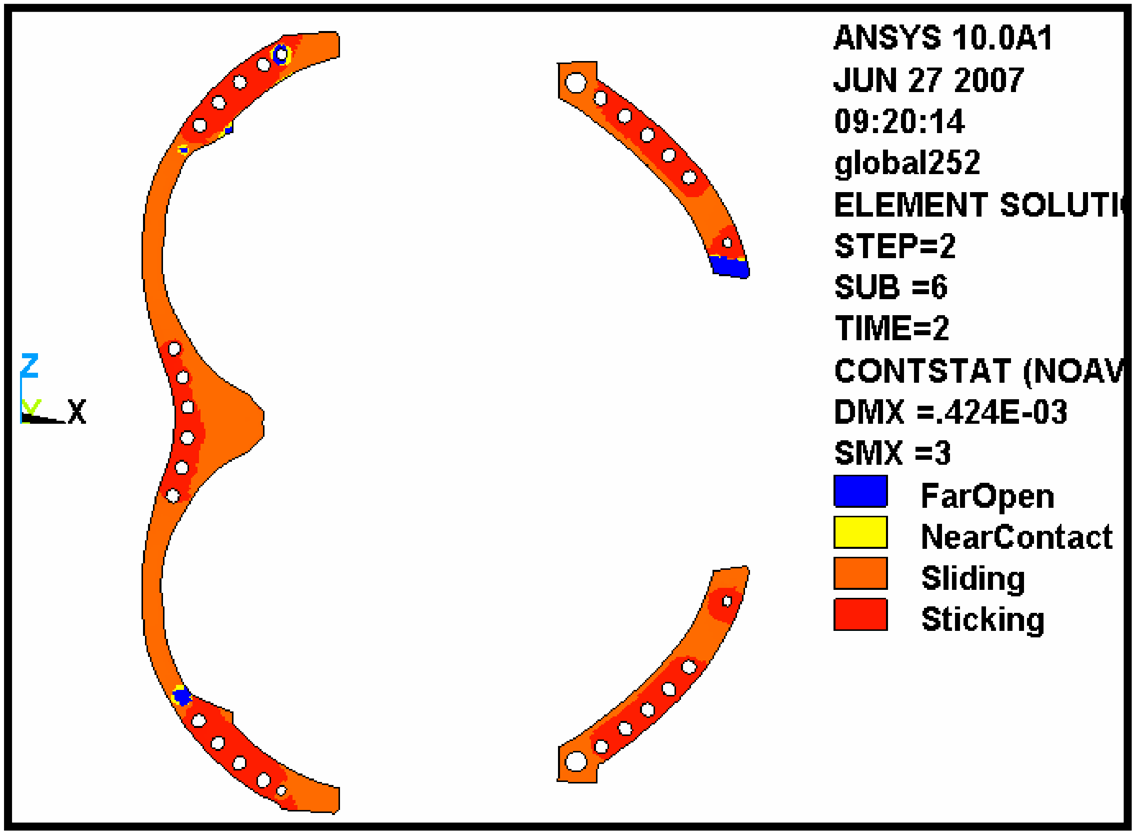
Bolts 21-26 are no longer in the design and are not presented.

AA Joint

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

Friction = 0.4 over the entire flange



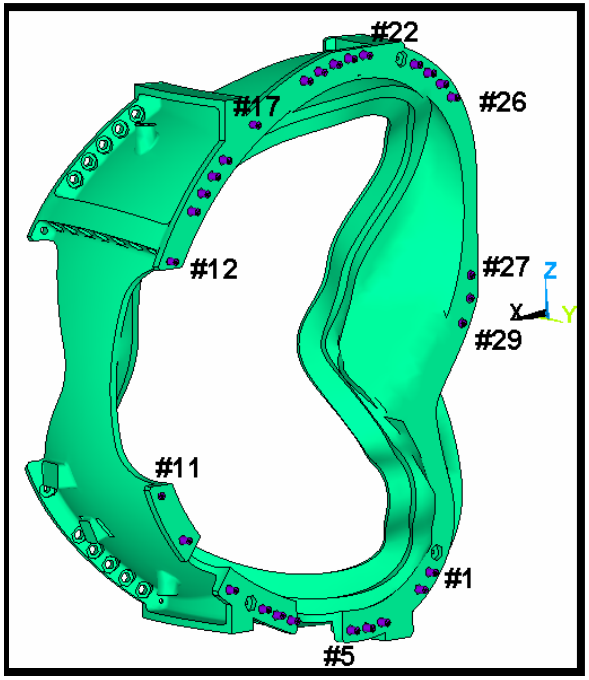


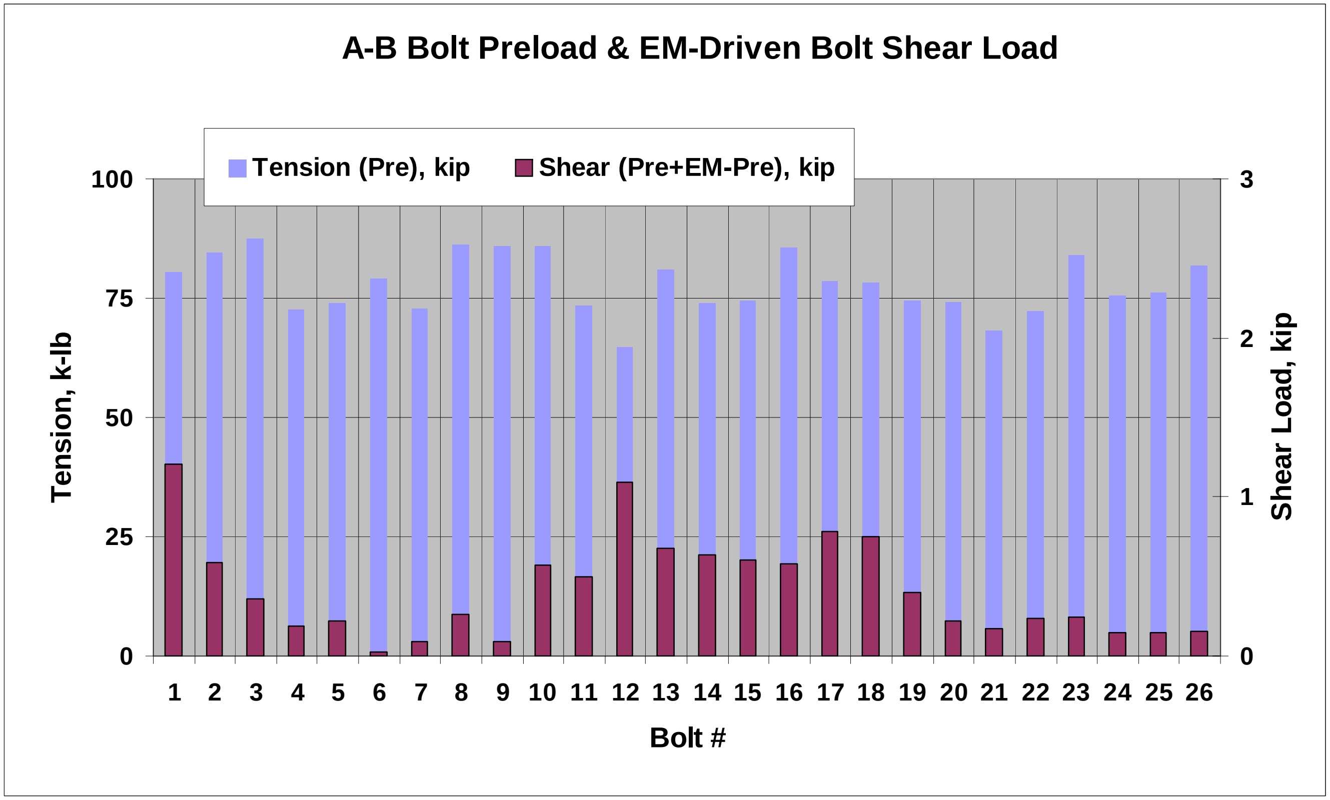
The Joint is stuck (red) under every outboard bolt.

AB joint

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

Friction = 0.4 over the entire flange



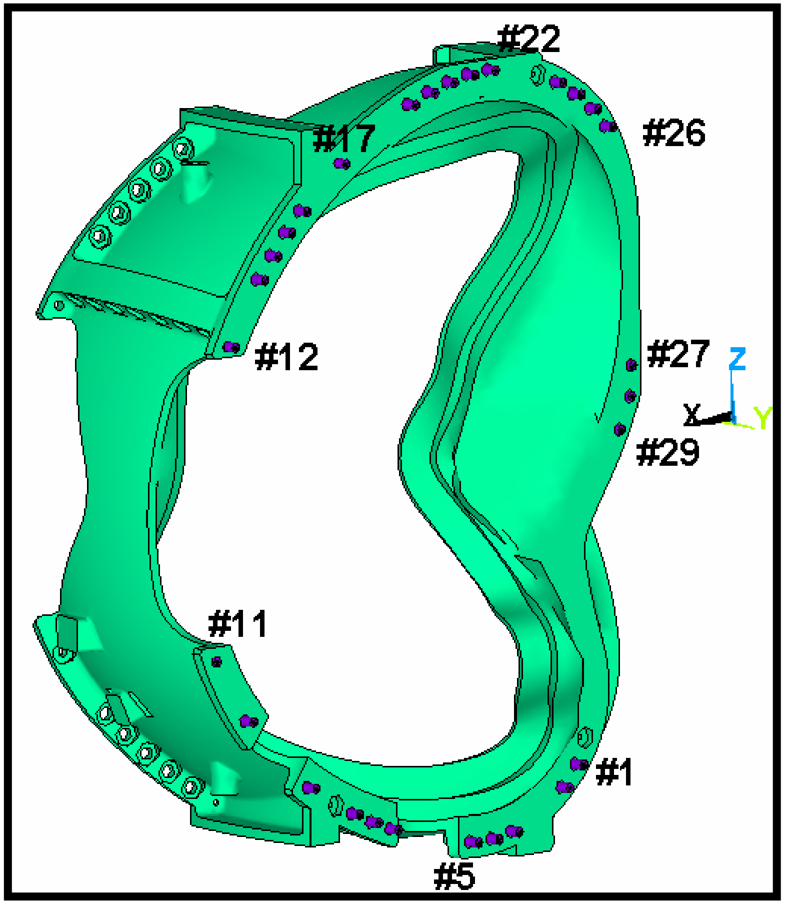


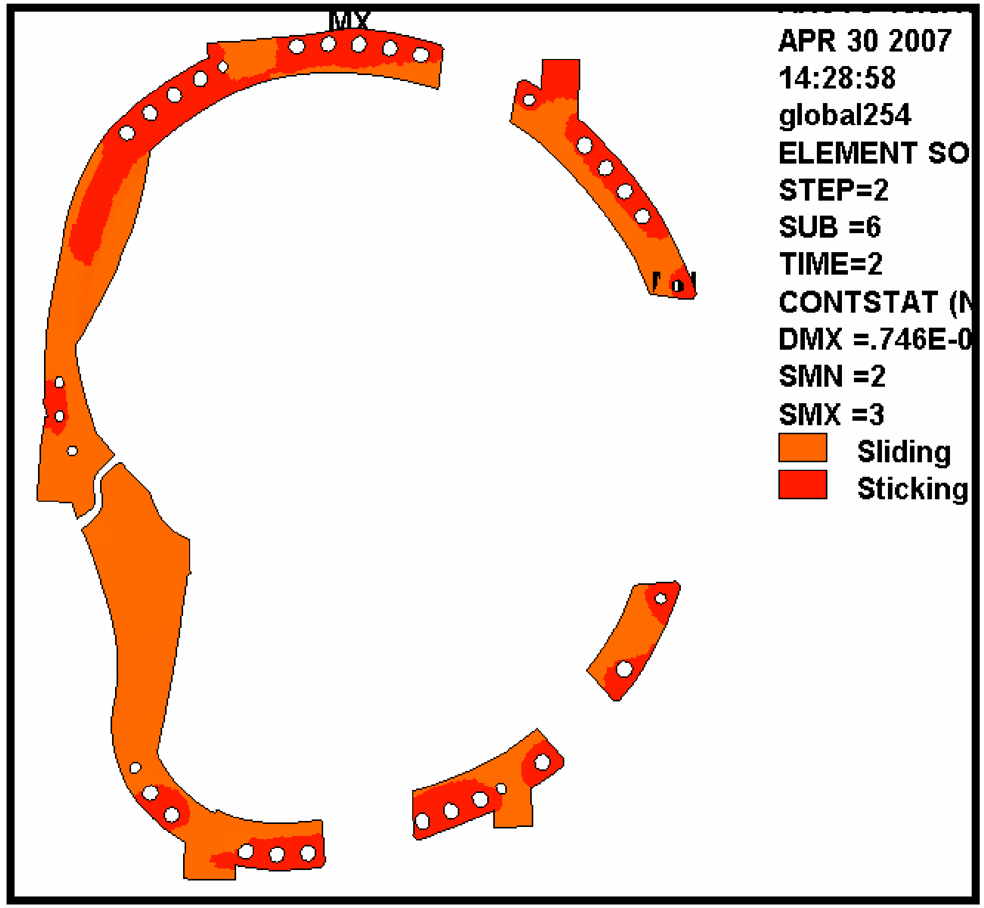
Bolts 27-29 are no longer in the design and are not presented in the table.

AB Joint

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

Friction = 0.4 over the entire flange



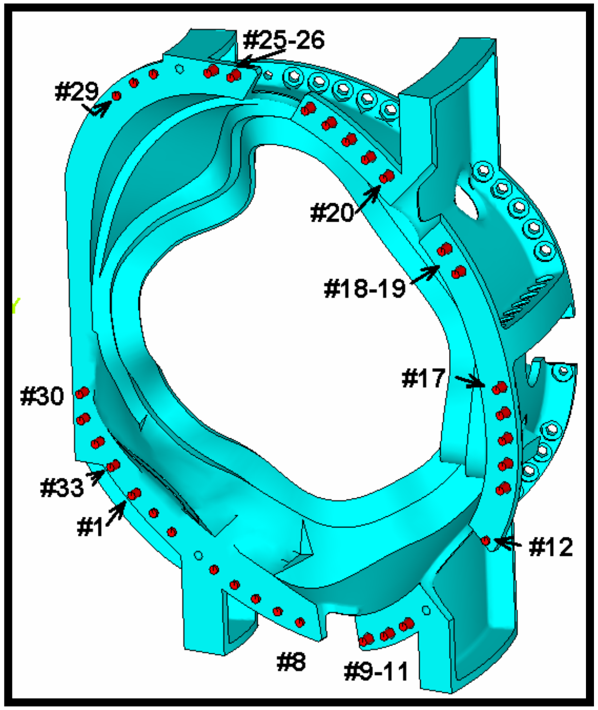


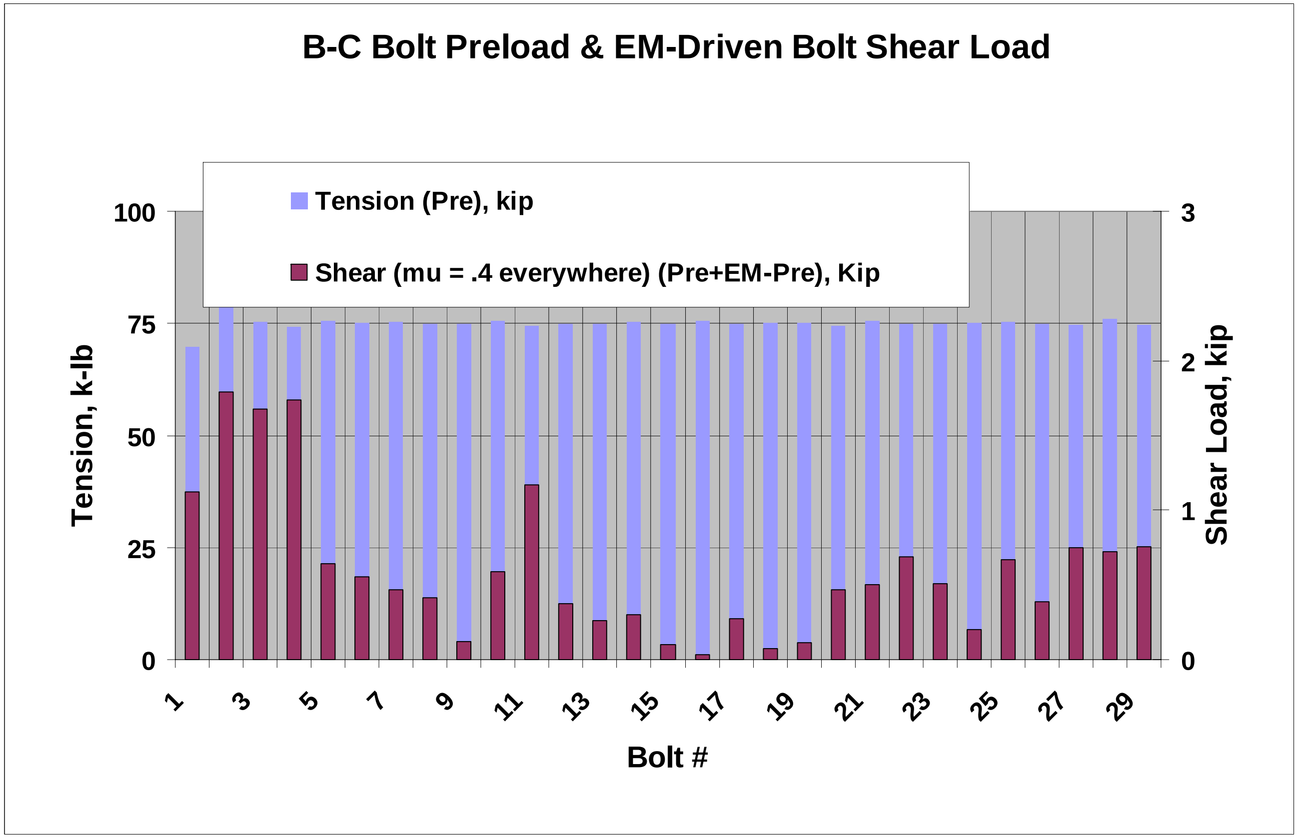
The Joint is stuck (red) under every outboard bolt.

BC Joint

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

Friction = 0.4 over the entire flange



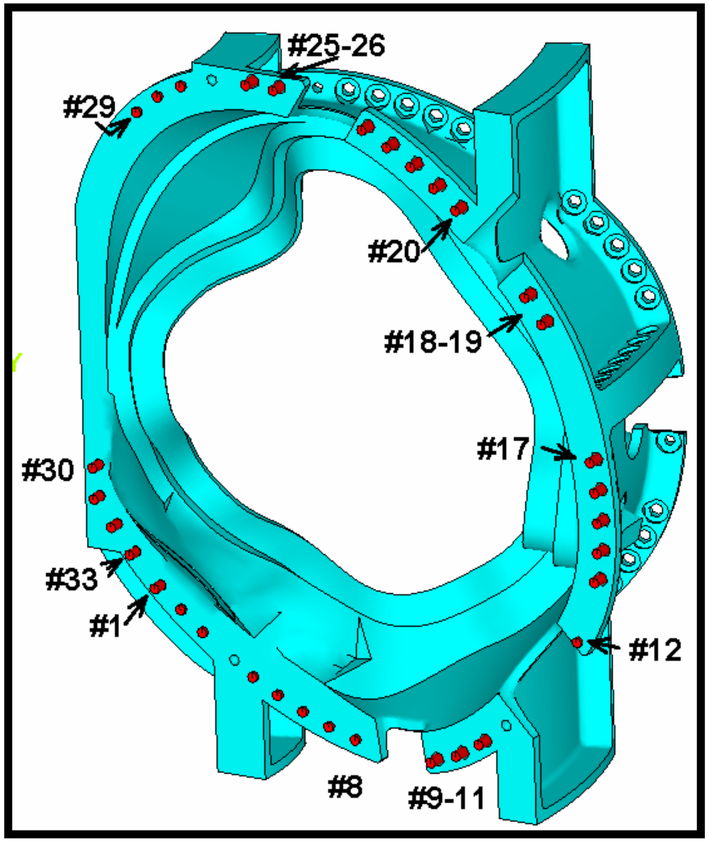


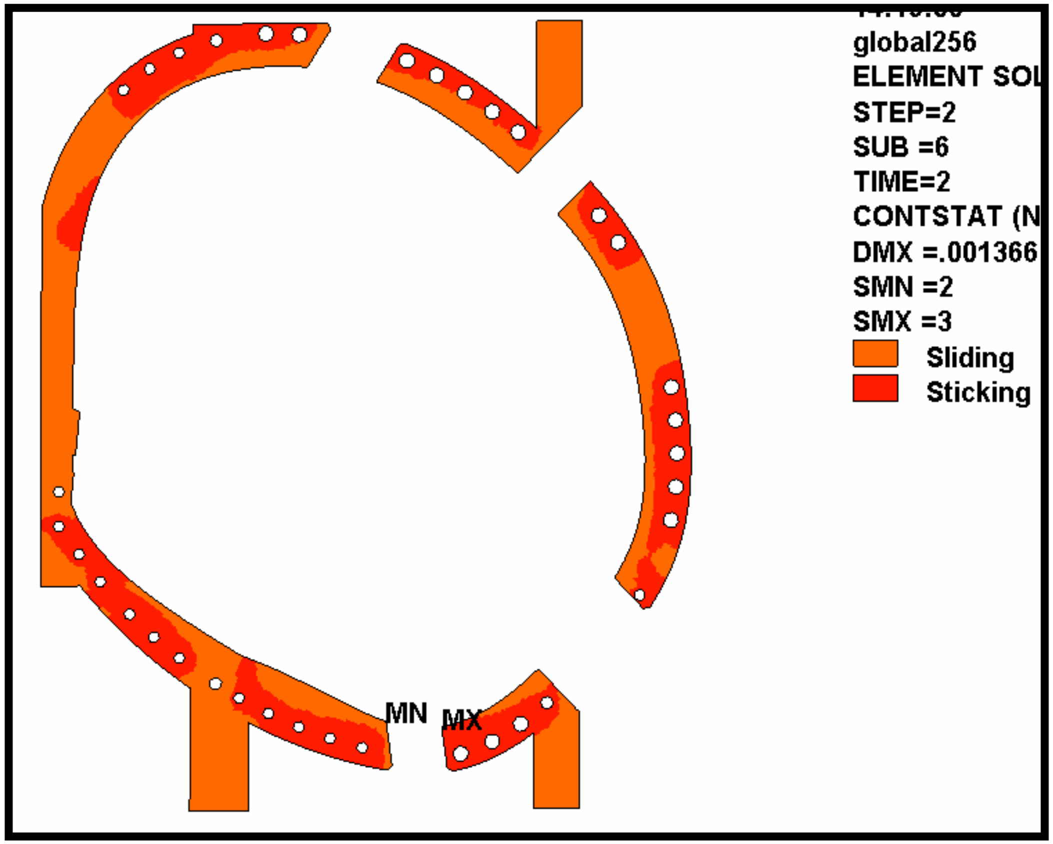
Bolts 30-33 are no longer in the design and are not presented in this table.

BC Joint

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

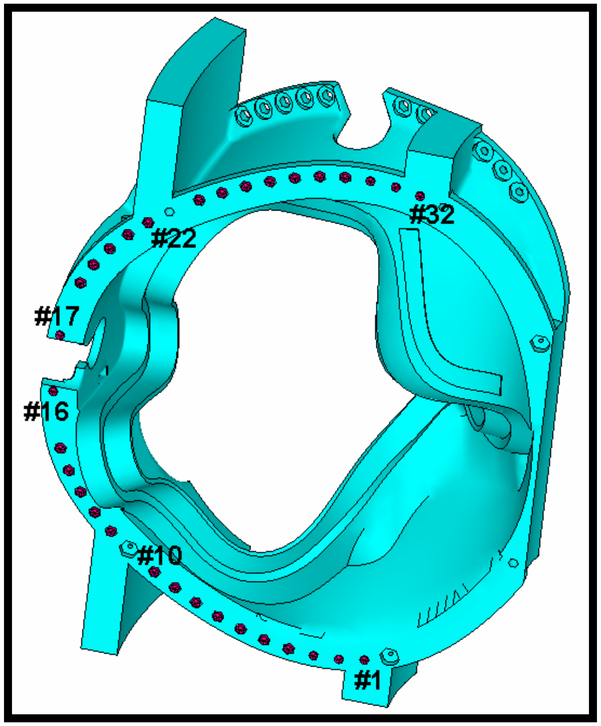
Friction = 0.4 over the entire flange

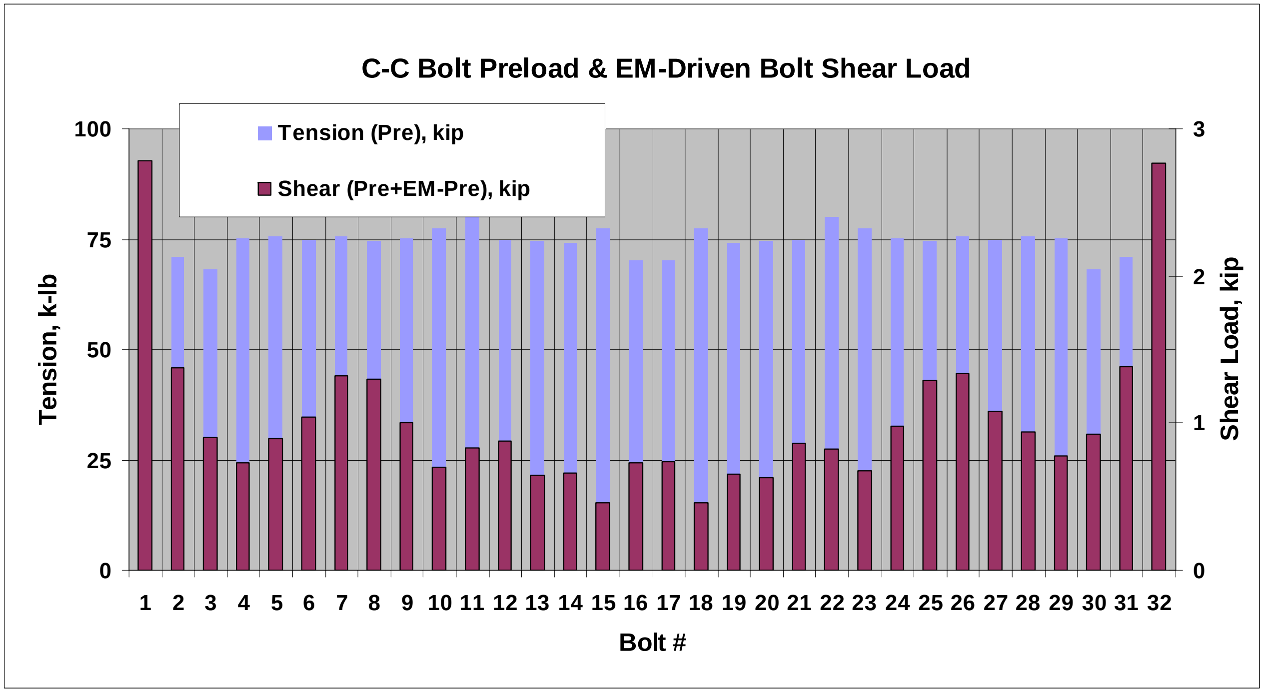




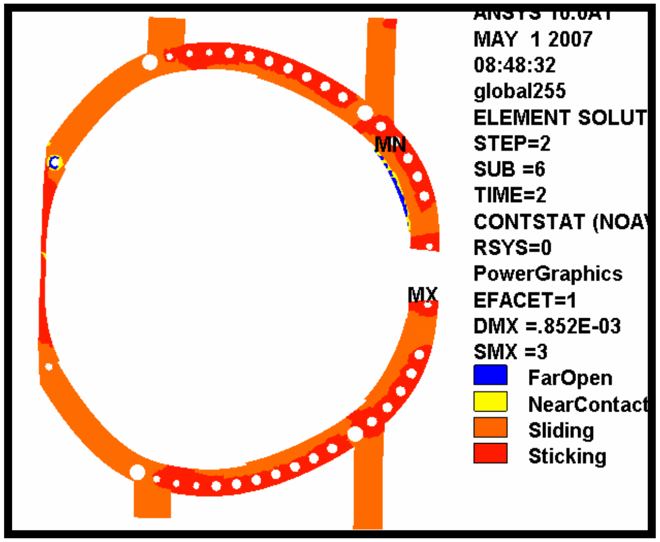
The Joint is stuck under every outboard bolt.

CC-Joint





- This joint has no weld on the inboard leg **or any inboard bolts**
- Model assumes 0.4 friction over the entire inboard leg. (**non-conservative** pending outcome of inner leg fix…next slides.)
- The last bolts (#1 and #32 are just beginning to slip a bit and pick up some very minimal shear)



CC Inboard possible solutions

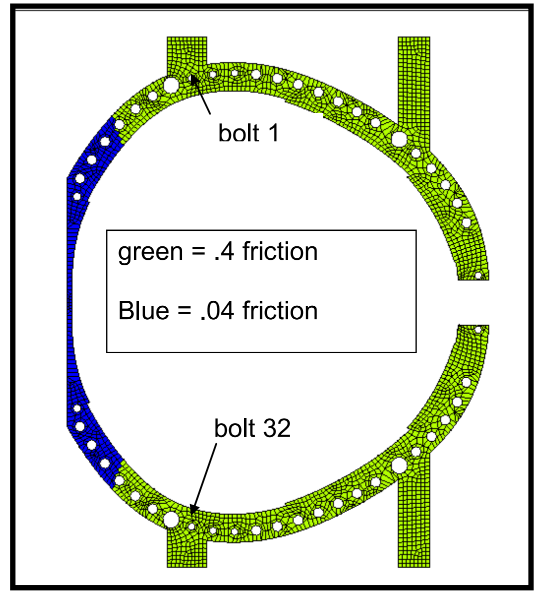
NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

Current Design is to add in board bolts (max possible of 12) to impart the shear load.

12 bolts holes added to the model and 6 or 12 were used with bolt connections

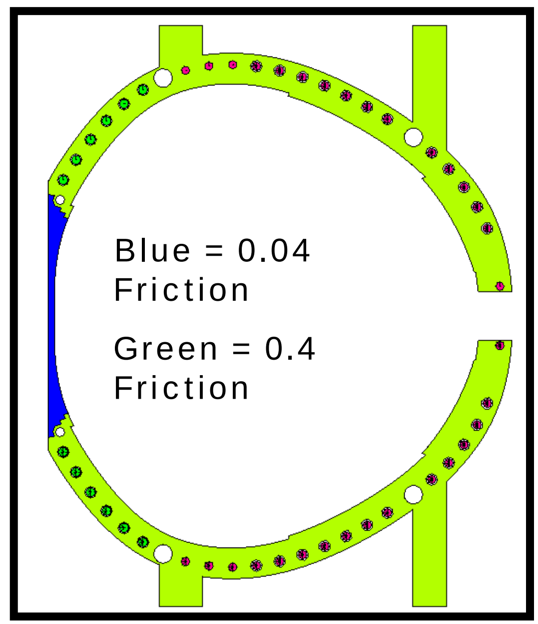
Friction on the innermost inboard unbolted region set to either 0.4 or .04

Contact Stiffness set of 0.5 e11 N/m^3 for all of these runs (results in slightly higher shear load)

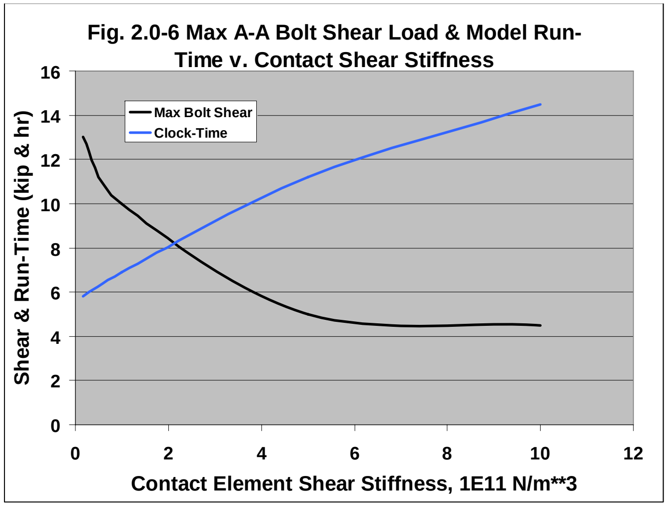


Inboard Friction	# of inboard bolts	Max sliding distance (in)	Max Shear Force (kips)
0.4	0	0.0065	2.8
0.4	6	0.0047	2.4
0.4	12	0.0011	2.7
0.04	0	0.0199	4.9
0.04	6	0.0143	4.5
0.04	12	0.0024	3.5
Imperfect Fit-up gap of .005" on unbolted region	0	0.0193*	3.3

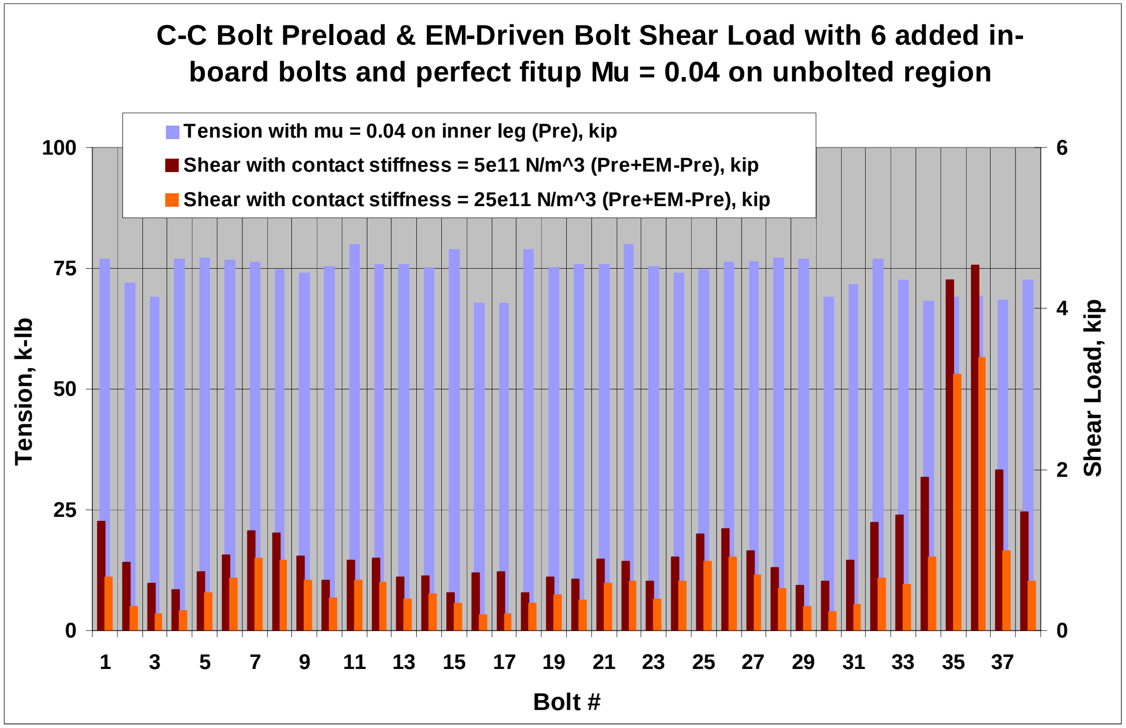
*sliding occurs after gap has closed



Contact Stiffness Problem



The default contact element shear stiffness (~0.17E11 N/m3) was found to be too soft, and flange faces slipped when they should have been stuck. A shear stiffness of 5E11 N/m3 seemed to provide a reasonable compromise in accuracy and run-time and was used throughout the analysis.



In the CC case, even the 5E11 N/m^3 value was too soft.

The Shear loading presented in the previous slides are likely overestimates.

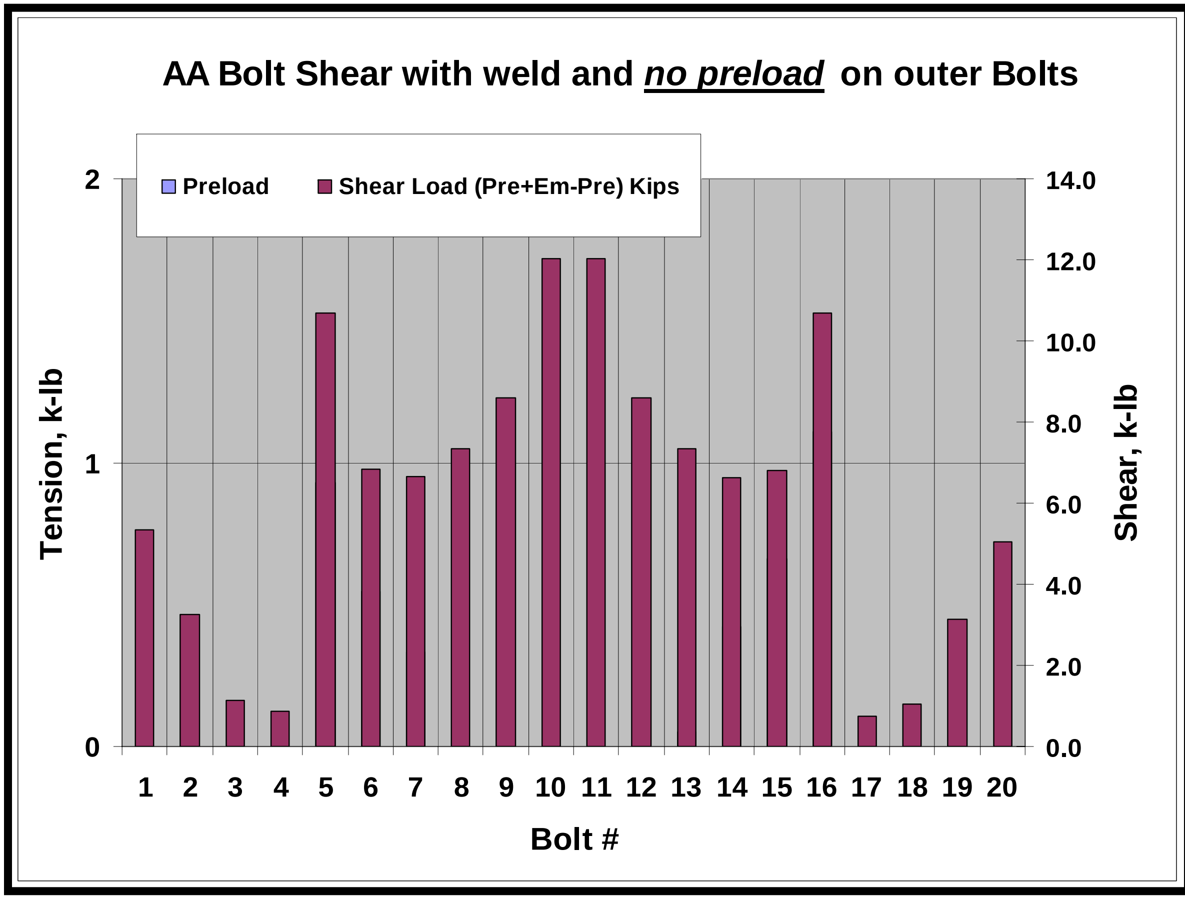
Still, even the high values pass the fatigue requirement of 9 Kips for the type 2 joint.

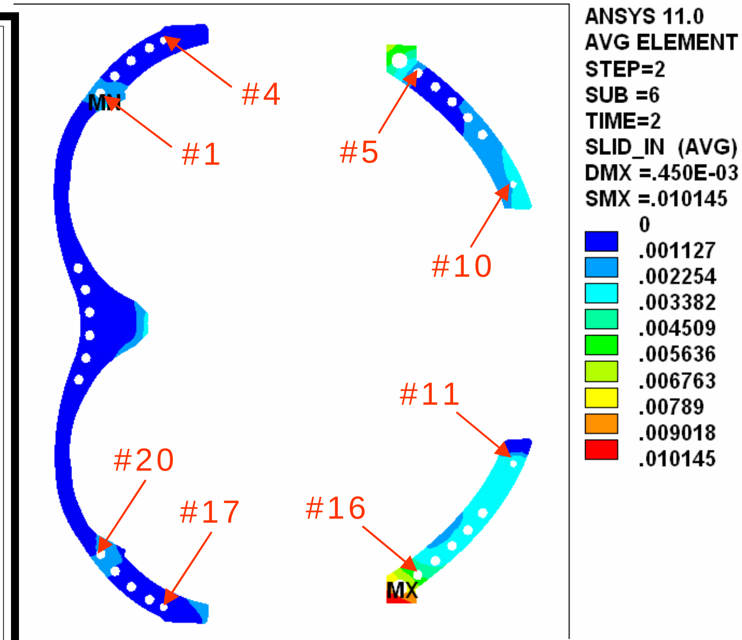
Preload Lost?

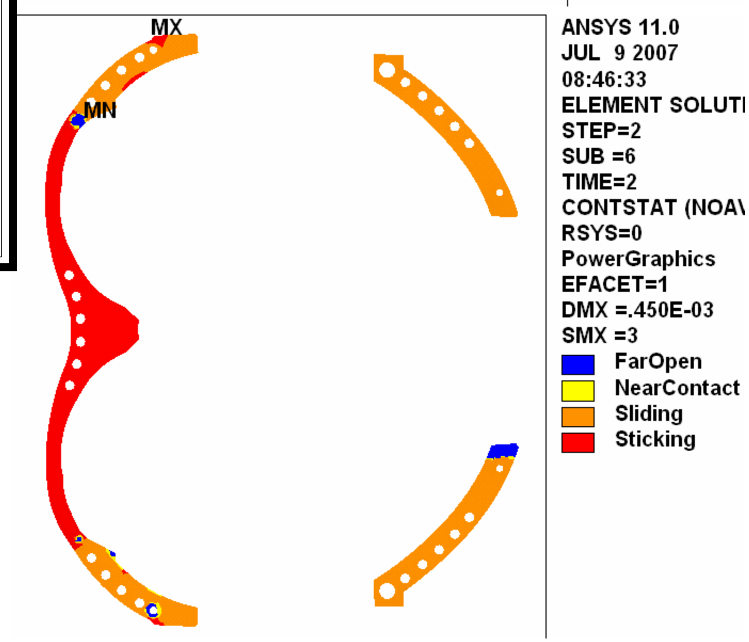
- What If Preload is lost on outer leg now that we are welding the inner leg?
- Which bolts should we be monitoring during operation (Strain gage candidates)? Are some more critical than others?
- The Next slides show the effect of bonding the inner leg (weld) and removing the preload on the outer bolts.

Interface Joint	Largest Shear Load (k-lb)	Number of Bolts Exceeding Fatigue Limit of 9 Kips	Max Slip (inches)
A-A	12	4	0.01
A-B	14	3	0.007
B-C	12	2	0.008
C-C	8	0	0.004

Outboard bolts Slipping A-A



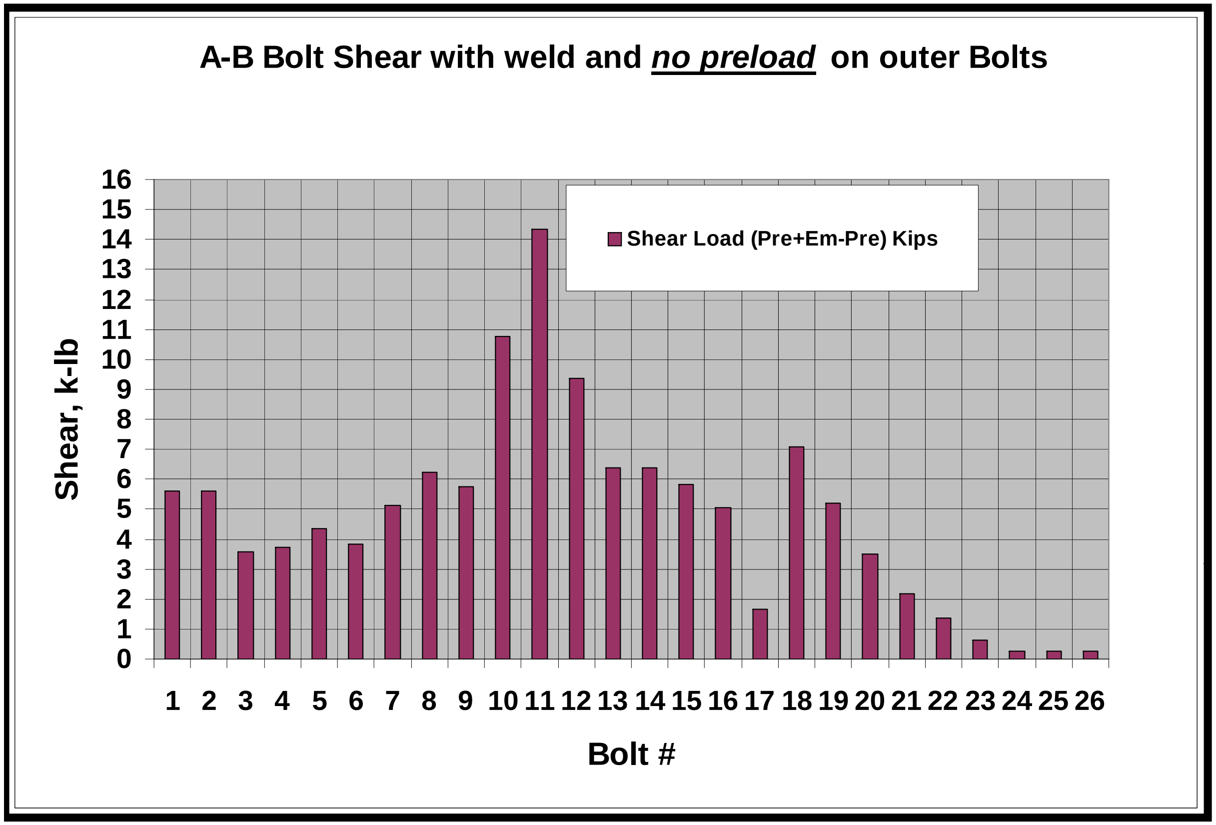


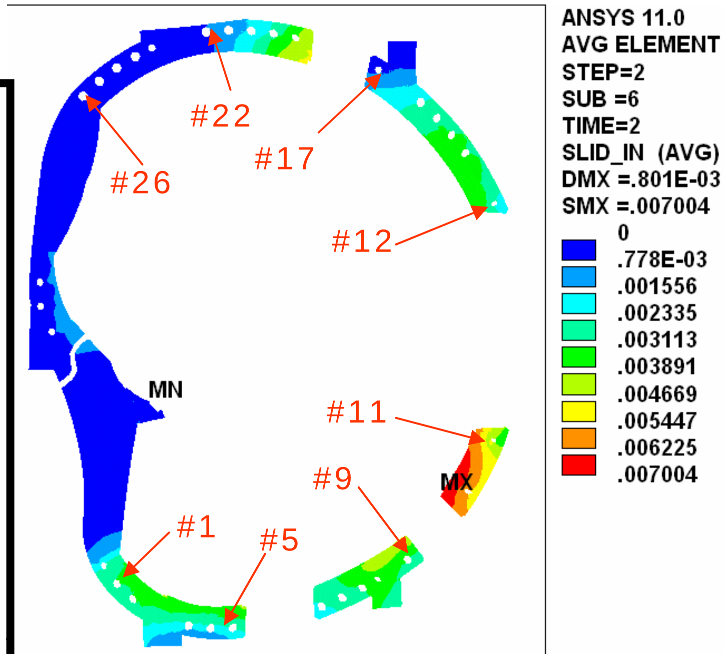


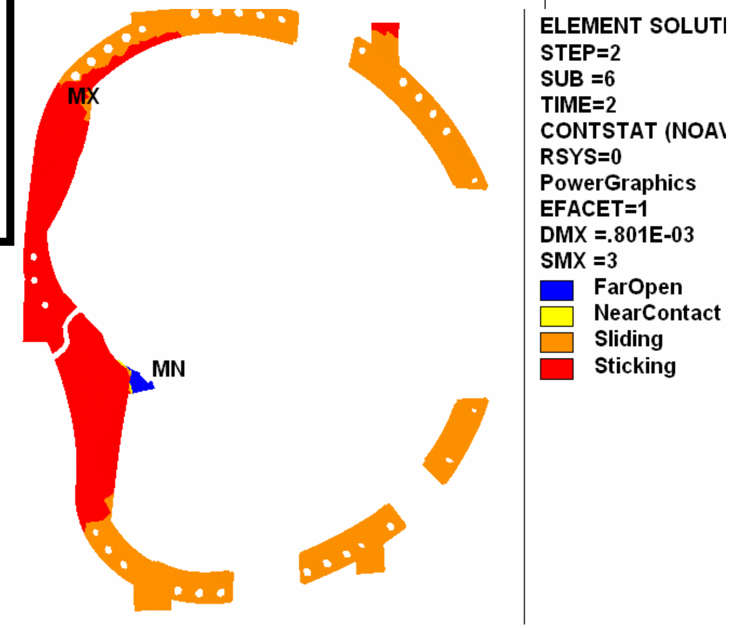
Bolts 5,10,11,16 have shear greater than 10 kips and should be monitored for preload during operation.

Preload is not really important in these plots and is only shown as a references aid.

Outboard bolts Slipping A-B



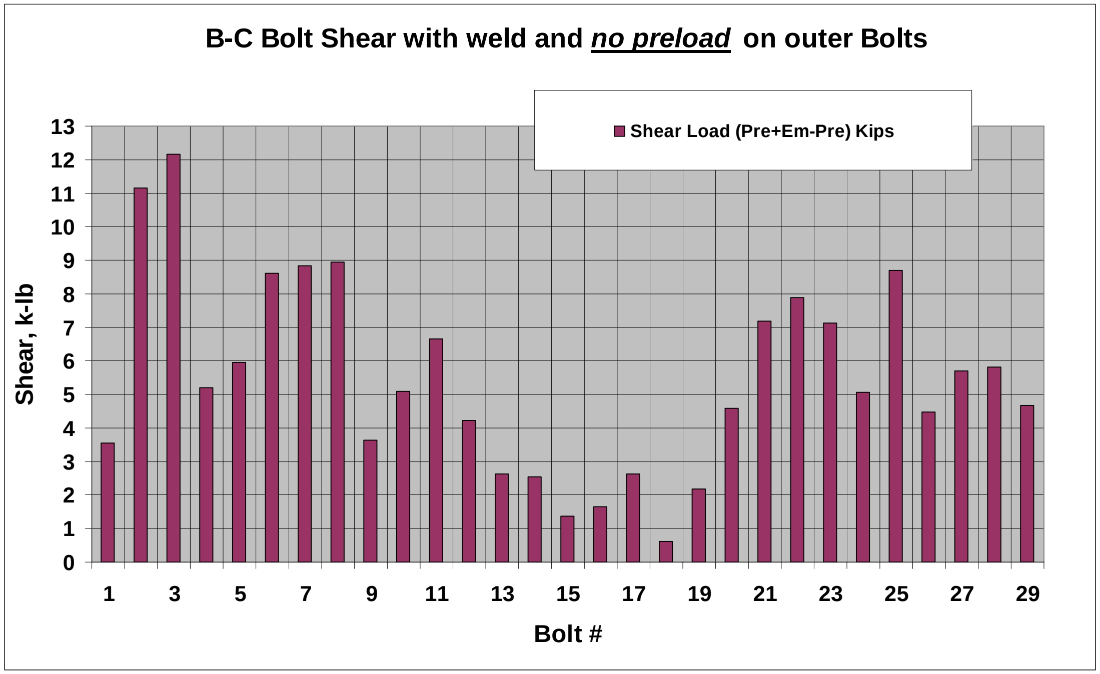


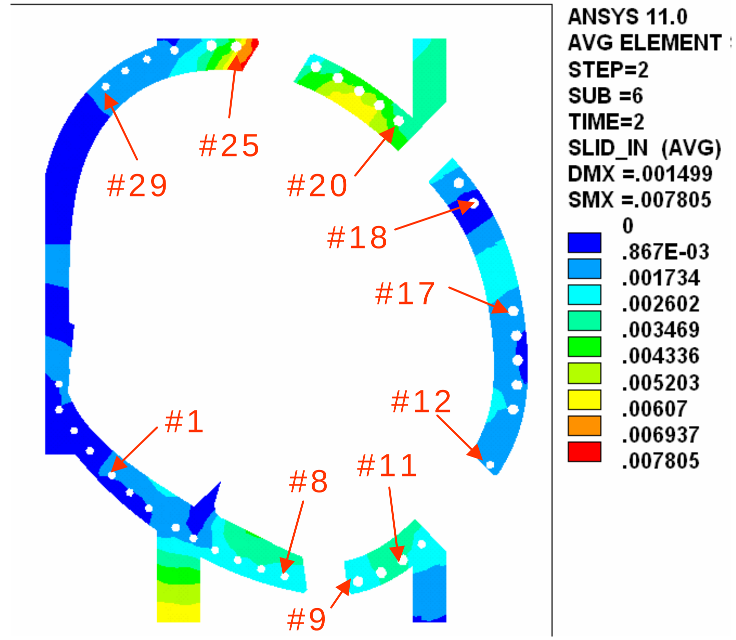


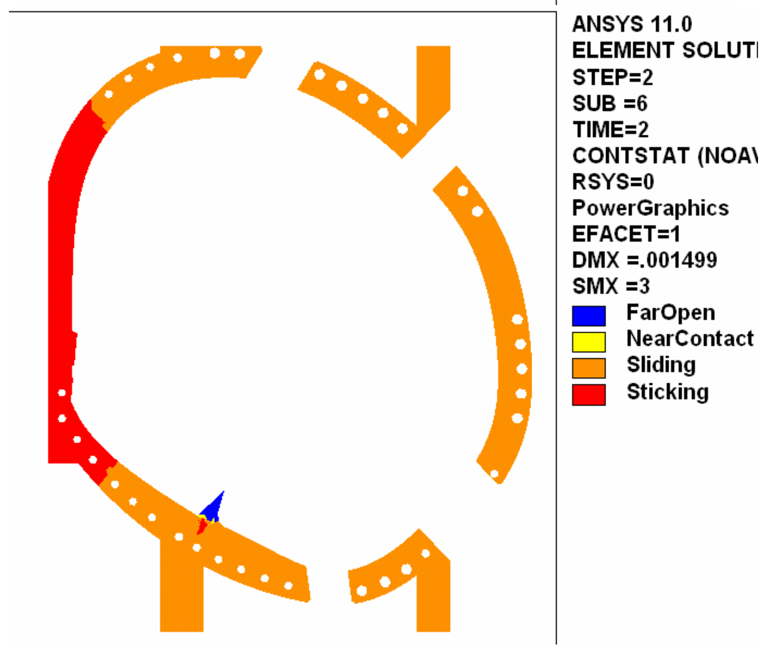
Bolts 10-12 have shear greater than 10 kips and should be monitored for preload during operation.

Outboard bolts Slipping B-C

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT





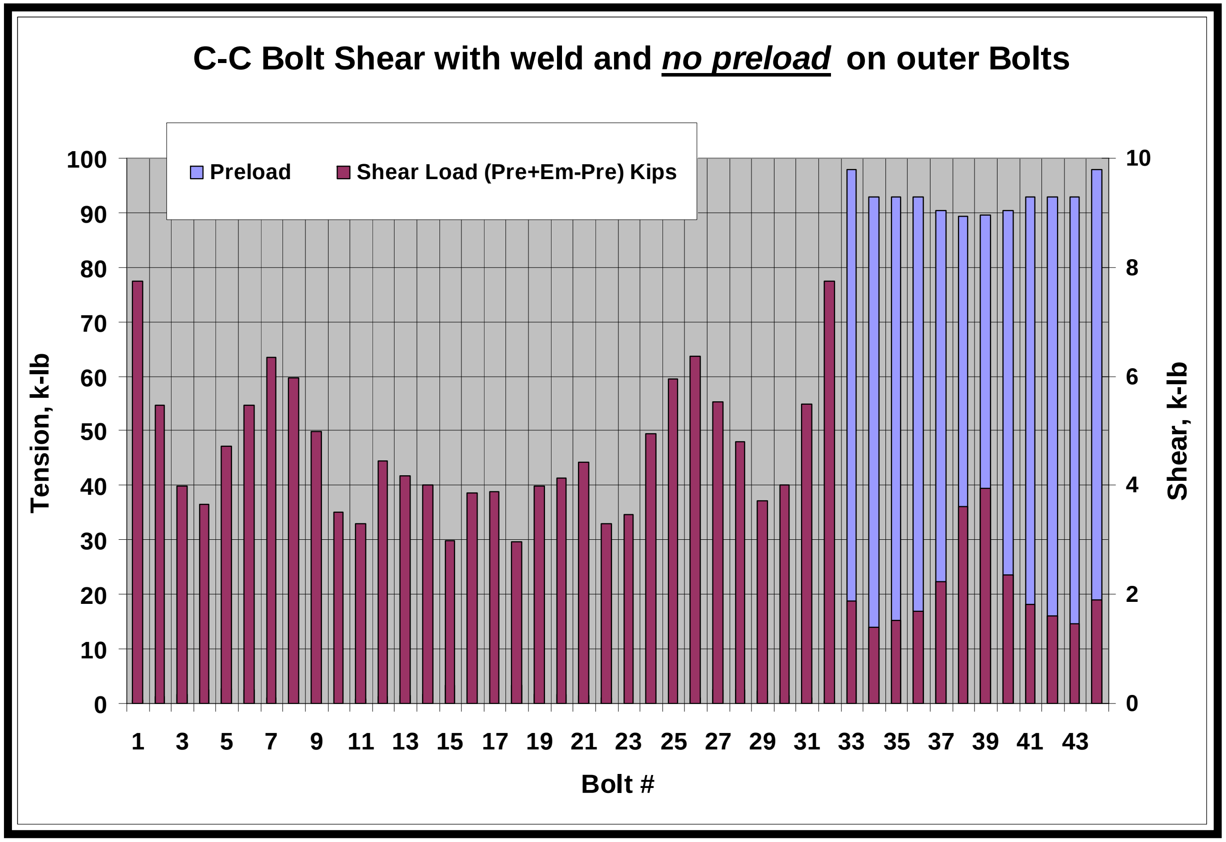


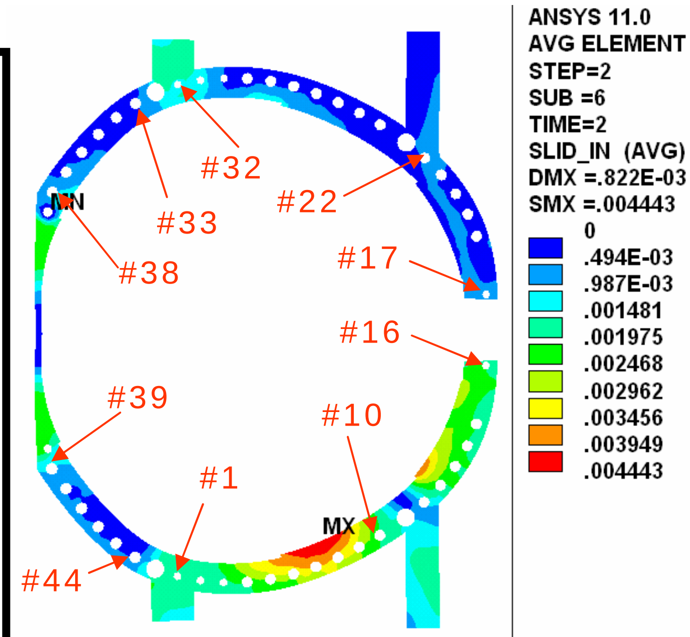
Bolts 2,3 have shear greater than 10 kips and should be monitored for preload during operation.

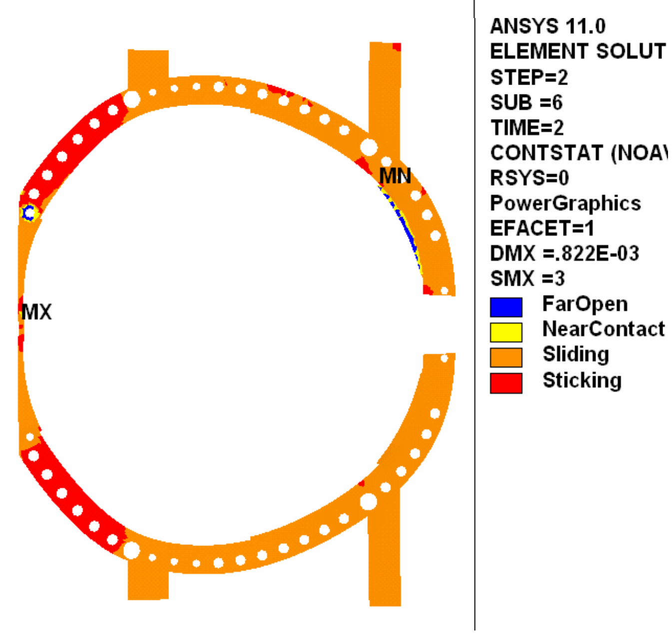
Although bolt 1 shows low shear, it should also be looked at since it is immediately adjacent to the weld and the weld may not be this close to the bolt.

The fact that bolts 2 and 3 see large shear but not sliding suggests that the flanges are tending to pull/twist way from each other here. (verified from deflection plots)

Outboard bolts Slipping C-C







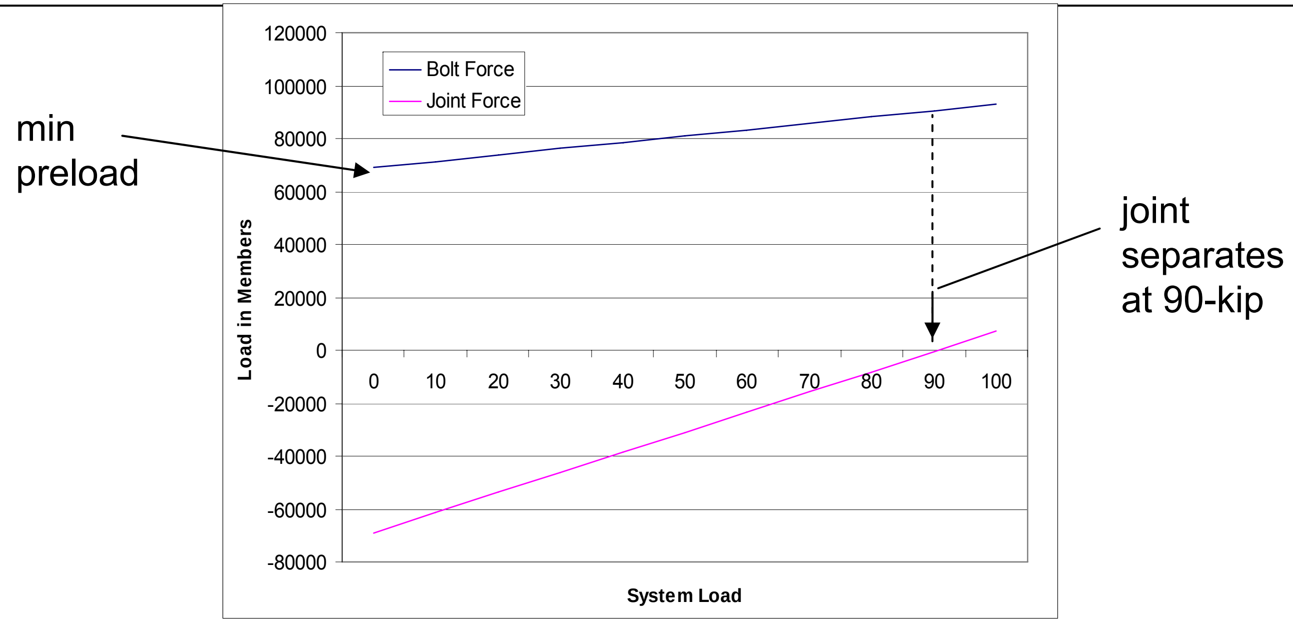
The Inner leg bolts Still have Preload and are larger (1.5”) here

No Outer bolts have shear greater than 10 Kips, but bolts 1 and 32 see shear of almost 8 Kips.

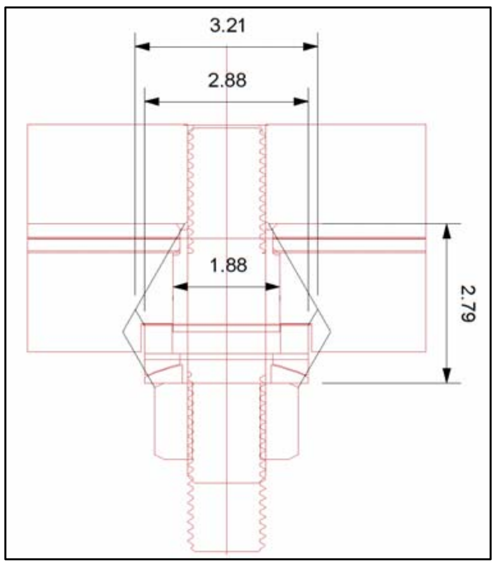
Individual Bolt Analysis

Joint Stiffness

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

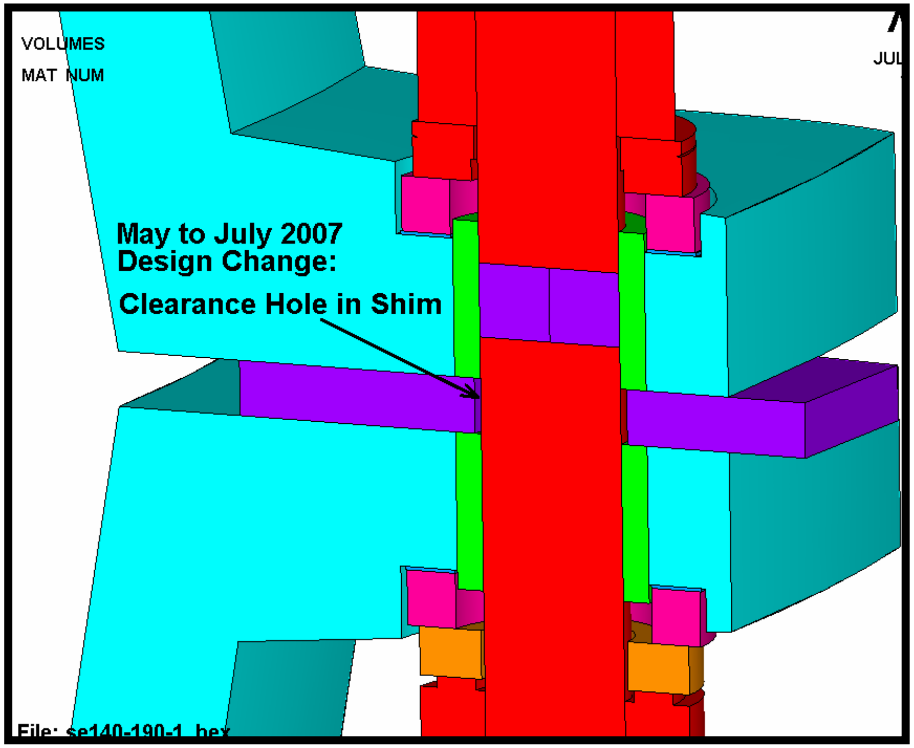


joint type			thru	tapped
effective clamp area	Ac	in2	8.3573	4.5063
washer area		in2	3.7385	3.7385
bolt stiffness	kb	lb/in	6599	12018
sph washer stiffness	k1	lb/in	211243	211243
flat washer stiffness	k2	lb/in	118136	118136
ins washer stiffness	k3	lb/in	336465	336465
flange stiffness	k4	lb/in	144414	144414
shim stiffness	k5	lb/in	471351	471351
equiv joint stiffness	ks	lb/in	20699	39656
kb/(kb+ks)			0.24	0.23
ks/(kb+ks)			0.76	0.77

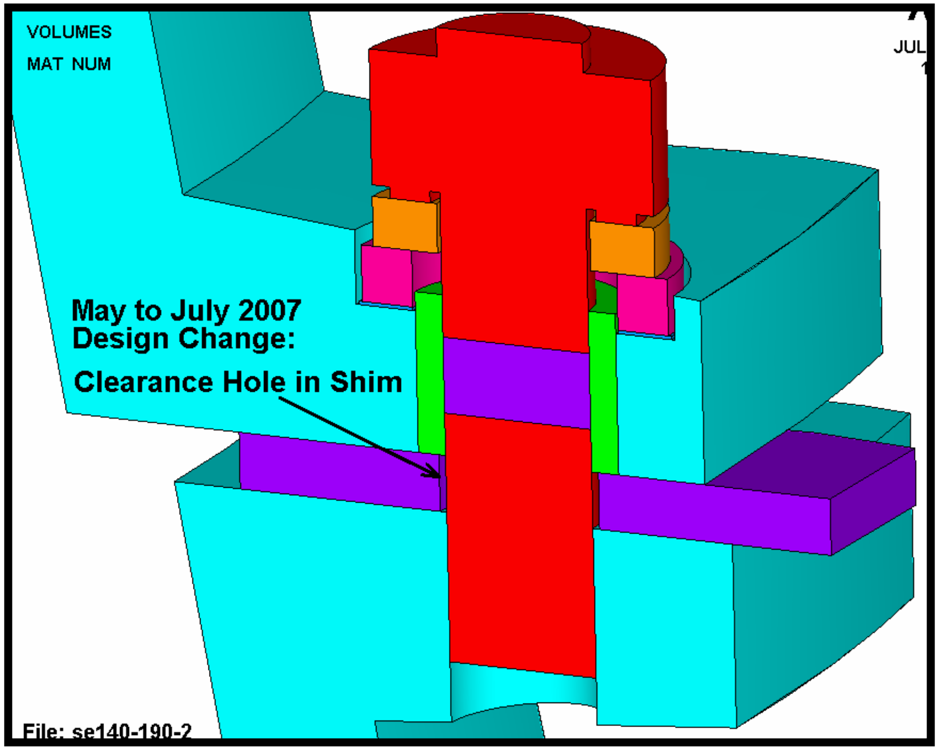


Individual Joint Analysis.

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT



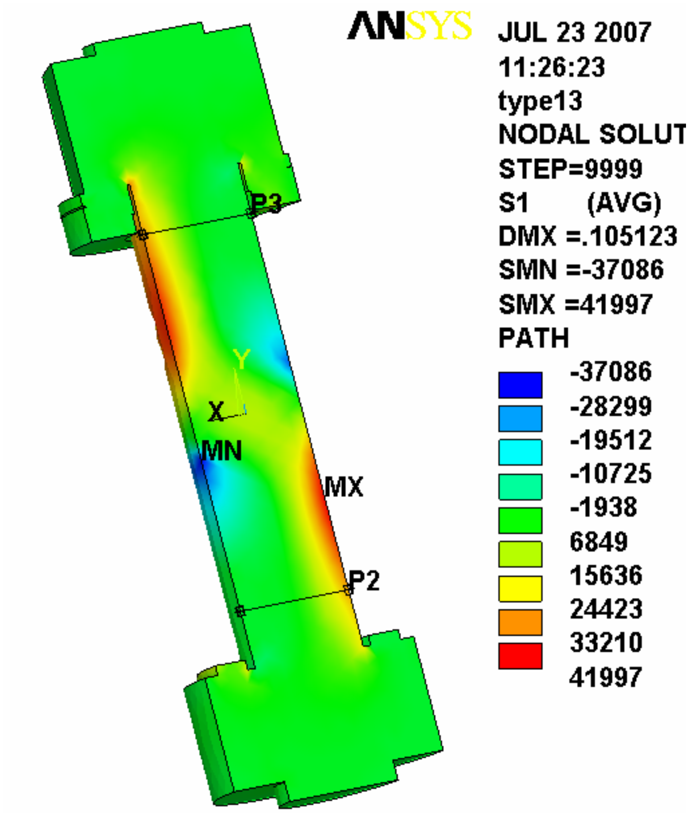
Type 1 Bolted Connection



Type 2 Bolted Connection

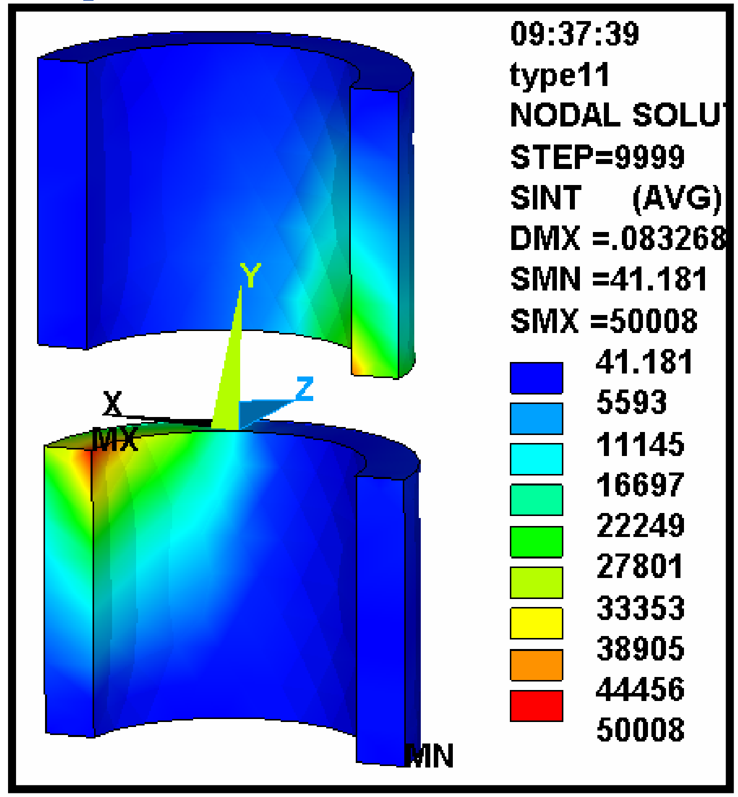
Individual Joint analysis (Type 1)

- **Load Step 1 (time=1.0): Bolt Preload ~72 kip, 0.0 kip Shear Load**
- **Load Step 2 (time=2.0): Bolt Preload plus 20 kip Shear Load**



G-10 Bushing

1st Principal Stress Range in Type 1 Bolt from 20 kip Shear Load



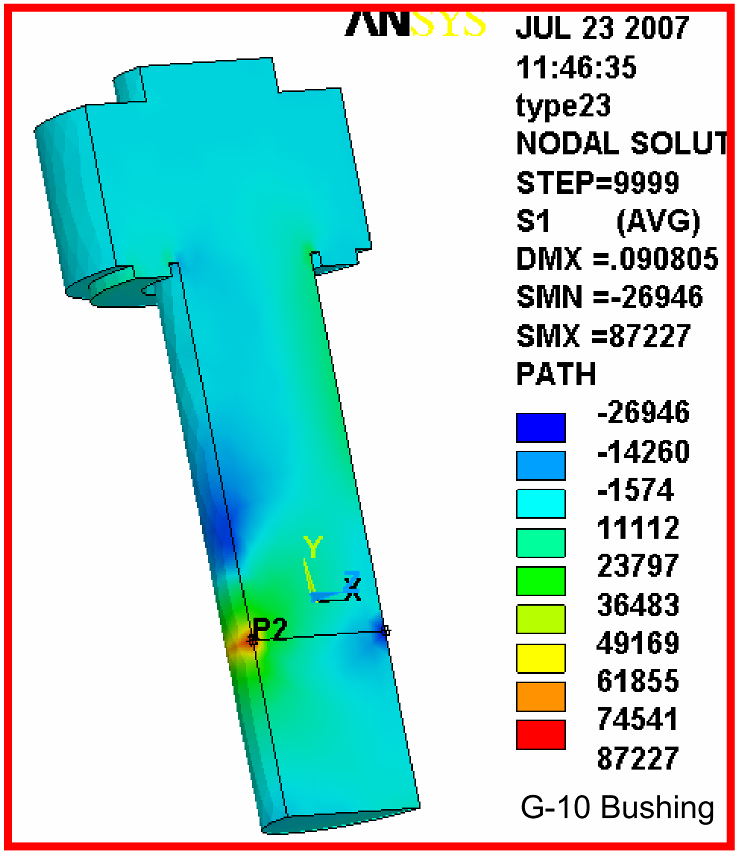
Stress Intensity of bushing

- Max bushing stress is 50-ksi
- Compare to bushing material:
  - Compressive strength = 60-ksi
  - Min bearing strength = 30-ksi
- **Max shear load = ~12-kip Static**

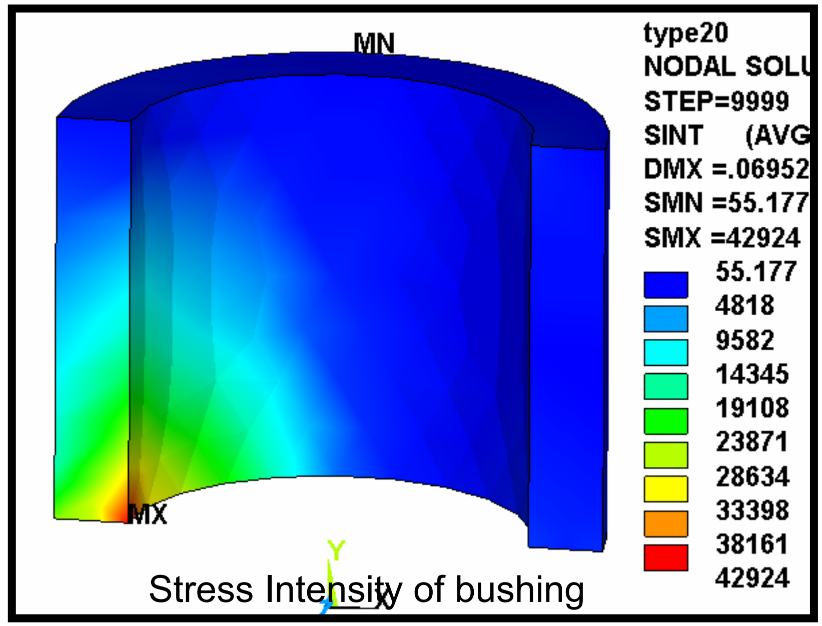
Stresses in threads are evaluated for fatigue (slides 27-30)

Individual Joint analysis (Type 2)

- **Load Step 1 (time=1.0): Bolt Preload ~72 kip, 0.0 kip Shear Load**
- **Load Step 2 (time=2.0): Bolt Preload plus 20 kip Shear Load**



1st Principal Stress Range in Type 2 Bolt
from 20 kip Shear Load

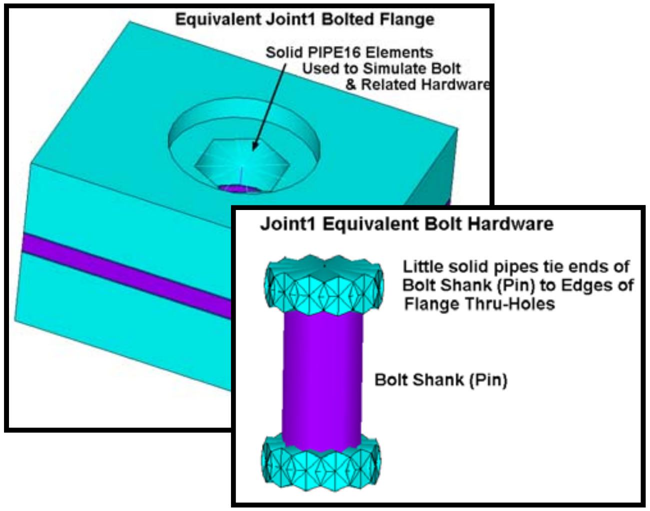


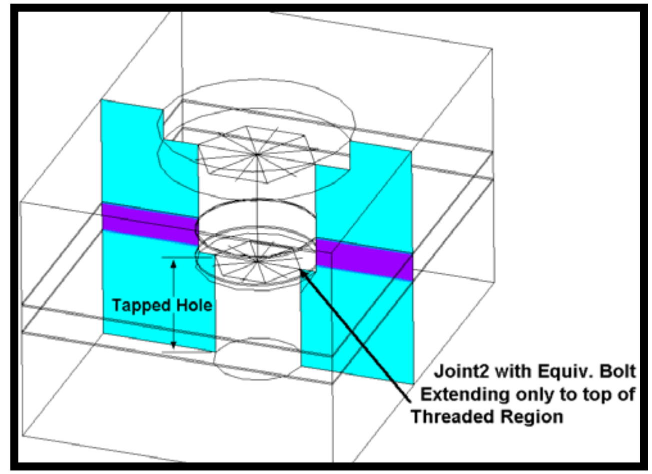
- Max bushing stress is -43 ksi
- Compare to bushing material:
  - Compressive strength = 60-ksi
  - Min bearing strength = 30-ksi
- **Max shear load = ~14-kip Static**

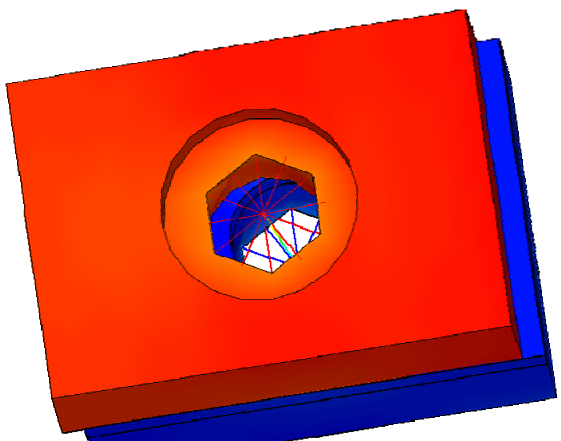
Stresses in threads are evaluated for fatigue (slides 27-30)

Equivalent Bolt Modeling

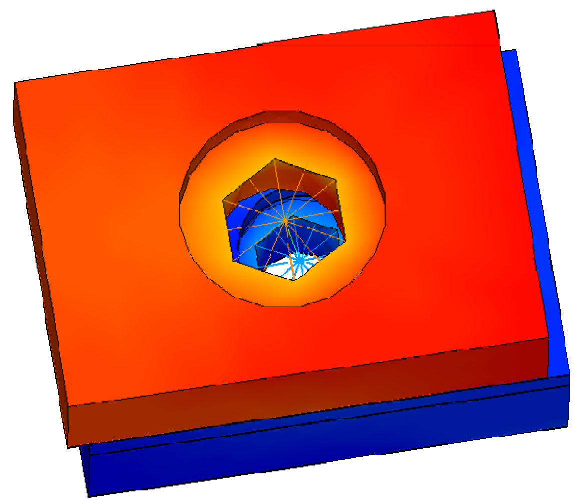
NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT







joint1 Lat Stiff Calc: k=1483838 lb/in at UZ=3 mils with 2.9" dia Bolt



joint2 Lat Stiff Calc: k=2583872 lb/in at UZ=3 mils with 2.75" dia Bolt

If the bolts are subjected to transverse slip, then the equivalent stiffness is like a 2.75" to 2.9" diameter rod in bending. If the joints are locked by friction, then the joint stiffness is determined by the actual bolt diameter (e.g., 1.375").

Tabular Result

from Individual bolt Study

Joint Type	Type 1	Type 2
Un-Intensified Stress Range, ksi	-35.4	-50.5
Thread Stress Intensification Factor	4	4
Peak Stress Range, ksi	-1.1	-40.0
Total Intensified Stress Range, ksi	143	242

Keep in mind that these values are based on a **20 kip unit shear load.**

- The stress profile indicates a predominantly Bending component (no surprise)
- The MEM+BEND stress and TOTAL stress are essentially the same for the Type-1 joint
- There is a significant PEAK stress component {TOTAL-(MEM+BEND)} in the Type-2 & 2a joints based on the bolt-hole geometric discontinuity.

Fatigue

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

- We need to amplify a particular stress component by the thread SIF.

  Amplifying SY is a logical choice since the thread concentration is normal to this stress component. However, amplifying S1 (max tensile stress) is also appropriate and conservative, if not essentially the same as SY. In addition, it would be difficult to ignore the Peak stress component that the model is able to capture, which also contributes to the total stress at this max stress location. Therefore, the total stress range which is used to evaluate the fatigue life of the bolts is defined as follows:

$$\Delta S_{tot} = (kthread)(\Delta S1) + PEAK$$

- Design basis fatigue Curve for A286 at 77K

  (Reference: N. Suzuki, "Low-Cycle Fatigue Characteristics of Precipitation-Hardened Superalloys at Cryogenic Temperatures," Journal of Testing and Evaluation, JTEVA, Vol. 28, No. 4, July 2000. pp. 257-266.).

NB-3230 NB-3000–DESIGN NB-3235

NB-3230 STRESS LIMITS FOR BOLTS

NB-3231 Design Conditions

(a) The number and cross-sectional area of bolts required to resist the design pressure shall be determined in accordance with the procedures of Appendix E, using the larger of the bolt loads given by the equations of Appendix E as a design mechanical load. The allowable bolt design stresses shall be the values given in Table I-1.3, for bolting materials.

(b) When sealing is effected by a seal weld instead of a gasket, the gasket factor, m, and the minimum design seating stress, y, may be taken as zero.

(c) When gaskets are used for preservice testing only, the design is satisfactory if the above requirements are satisfied for $m=y=0$, and the requirements of NB-3232 are satisfied when the appropriate m and y factors are used for the test gasket.

NB-3232 Normal Conditions

Actual service stresses in bolts, such as those produced by the combination of preload, pressure and differential thermal expansion may be higher than the values given in Table I-1.3.

NB-3232.1 Average Stress. The maximum value of service stress, averaged across the bolt cross-section and neglecting stress concentrations, shall not exceed two times the stress values of Table I-1.3.

NB-3232.2 Maximum Stress (Except As Restricted by NB-3232.3). The maximum value of service stress at the periphery of the bolt cross-section (resulting from direct tension plus bending) and neglecting stress concentrations shall not exceed three times the stress values of Table I-1.3. Stress intensity, rather than maximum stress, shall be limited to this value when the bolts are tightened by methods other than heaters, stretchers or other means which minimize residual torsion.

NB-3232.3 Fatigue Analysis of Bolts. Unless the components on which they are installed meet all the conditions of NB-3222.4*(d)* and thus require no fatigue analysis, the suitability of bolts for cyclic operation shall be determined in accordance with the procedures of the following subsubparagraphs.

(a) Bolting Having Less Than 100,000 psi Tensile Strength. Bolts made of materials which have specified minimum tensile strengths of less than 100,000 psi shall be evaluated for cyclic operation by the methods of NB-3222.4*(e)*, using the applicable design fatigue curve of Fig. I-9.4 and an appropriate fatigue strength reduction factor (see NB-3232.3*(c)*).

(b) High-Strength Alloy-Steel Bolting. High-strength alloy-steel bolts and studs may be evaluated for cyclic operation by the methods of NB-3222.4*(e)* using the design fatigue curve of Fig. I-9.4 provided:

(1) The maximum value of the service stress (see NB-3232.2) at the periphery of the bolt cross-section (resulting from direct tension plus bending) and neglecting stress concentration shall not exceed 2.7 S_m, if the higher of the two fatigue design curves given in Fig. I-9.4 is used. (The 2 S_m limit for direct tension is unchanged.)

(2) Threads shall be of a V-type having a minimum thread root radius no smaller than 0.003 in.

(3) Fillet radii at the end of the shank shall be such that the ratio of fillet radius to shank diameter is not less than 0.060.

(c) Fatigue-Strength-Reduction Factor (see NB-3213.17). Unless it can be shown by analysis or tests that a lower value is appropriate, the fatigue-strength-reduction factor used in the fatigue evaluation of threaded members shall not be less than 4.0. However, when applying the rules of NB-3232.3*(b)* for high-strength alloy-steel bolts, the value used shall not be less than 4.0.

(d) Effect of Elastic Modulus. Multiply S_{alt} (as determined in NB-3216.1 or NB-3216.2) by the ratio of the modulus of elasticity given on the design fatigue curve to the value of the modulus of elasticity used in the analysis. Enter the applicable design fatigue curve at this value on the ordinate axis and find the corresponding number of cycles on the axis of abscissas. If the operational cycle being considered is the only one which produces significant fluctuating stresses, this is the allowable number of cycles.

(e) Cumulative Damage. The bolts shall be acceptable for the specified cyclic application of loads and thermal stresses provided the cumulative usage factor, U, as determined in NB-3222.4*(e)(5)* does not exceed 1.0.

NB-3233 Upset Conditions

The stress limits for Normal Conditions (see NB-3232) apply.

NB-3234 Emergency Conditions

The stress limits of NB-3232.1 and NB-3232.2 apply.

NB-3235 Faulted Conditions

The limits of NB-3225 apply.

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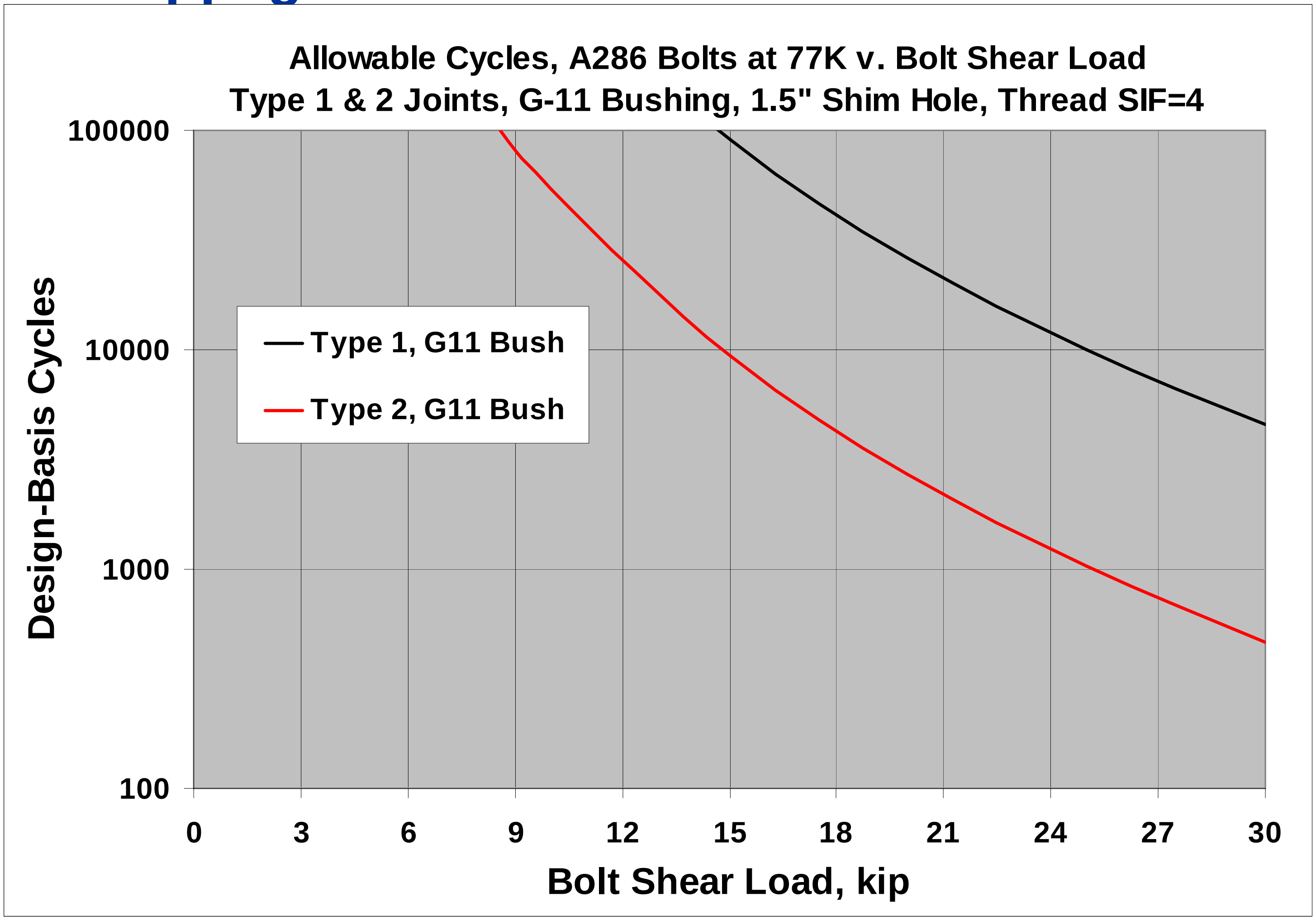
ASME Code Base Thread Stress Intensification Factor (NB-3232.3 (c))

Fatigue Curves for outboard bolts:

should slippage occur

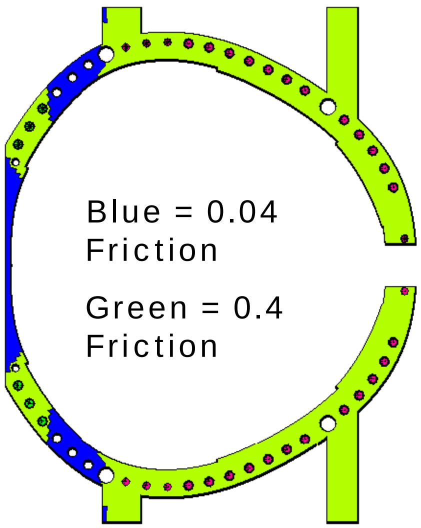


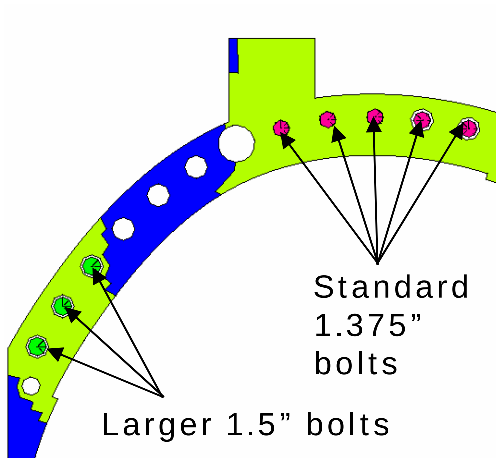
Maximum fatigue loading of type 2 with G11 = 8.8 kips

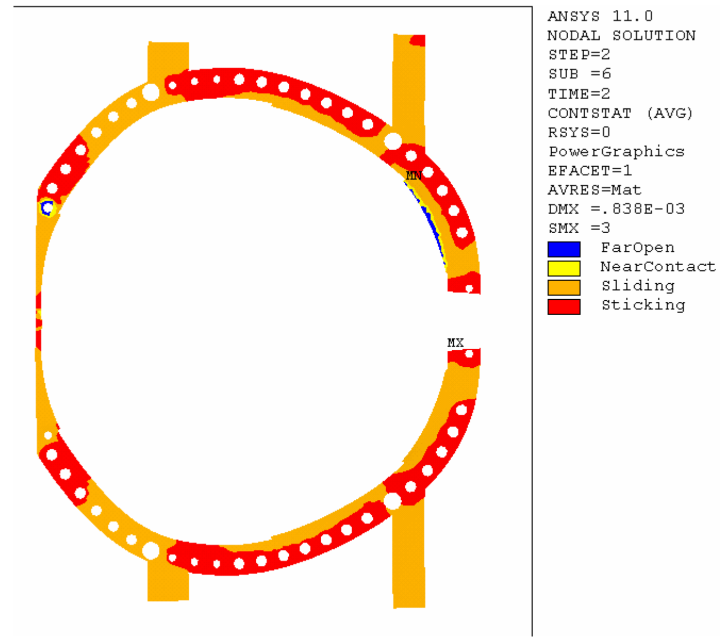
Maximum fatigue loading of type 1 with G11 = 14.8 kips

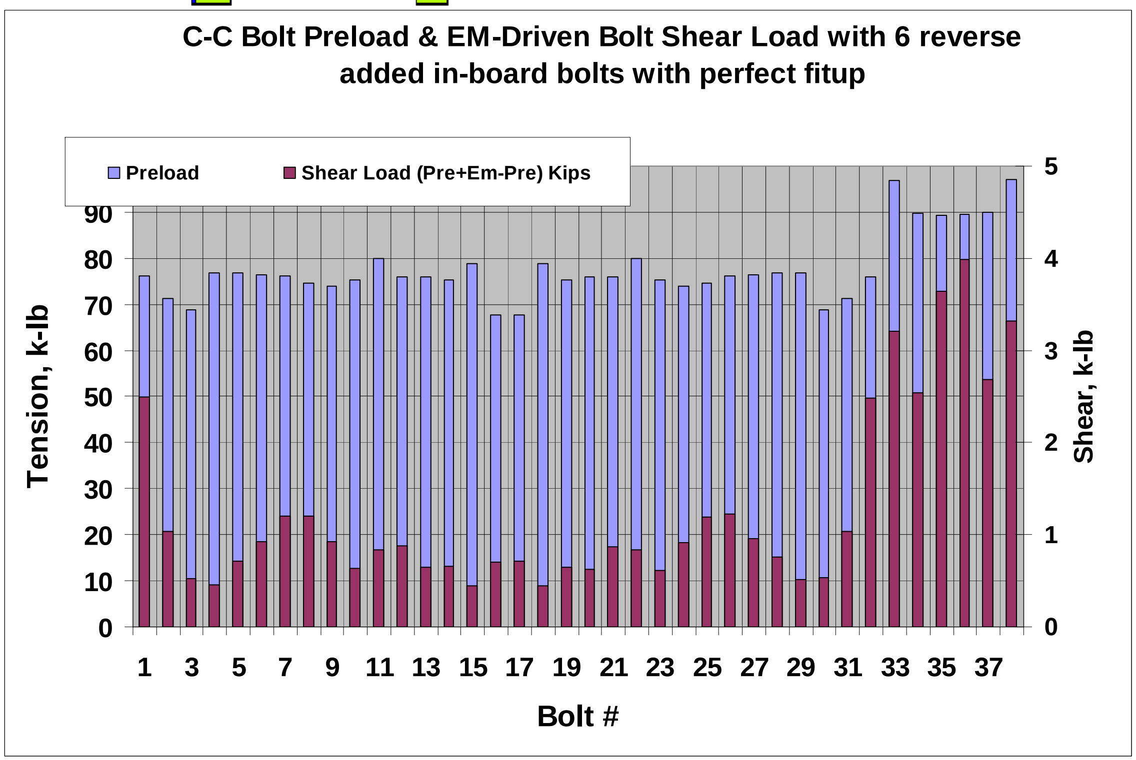
Appendix A: Extra slides on inboard bolts of CC set to 1.5”

Only inner most bolts are needed







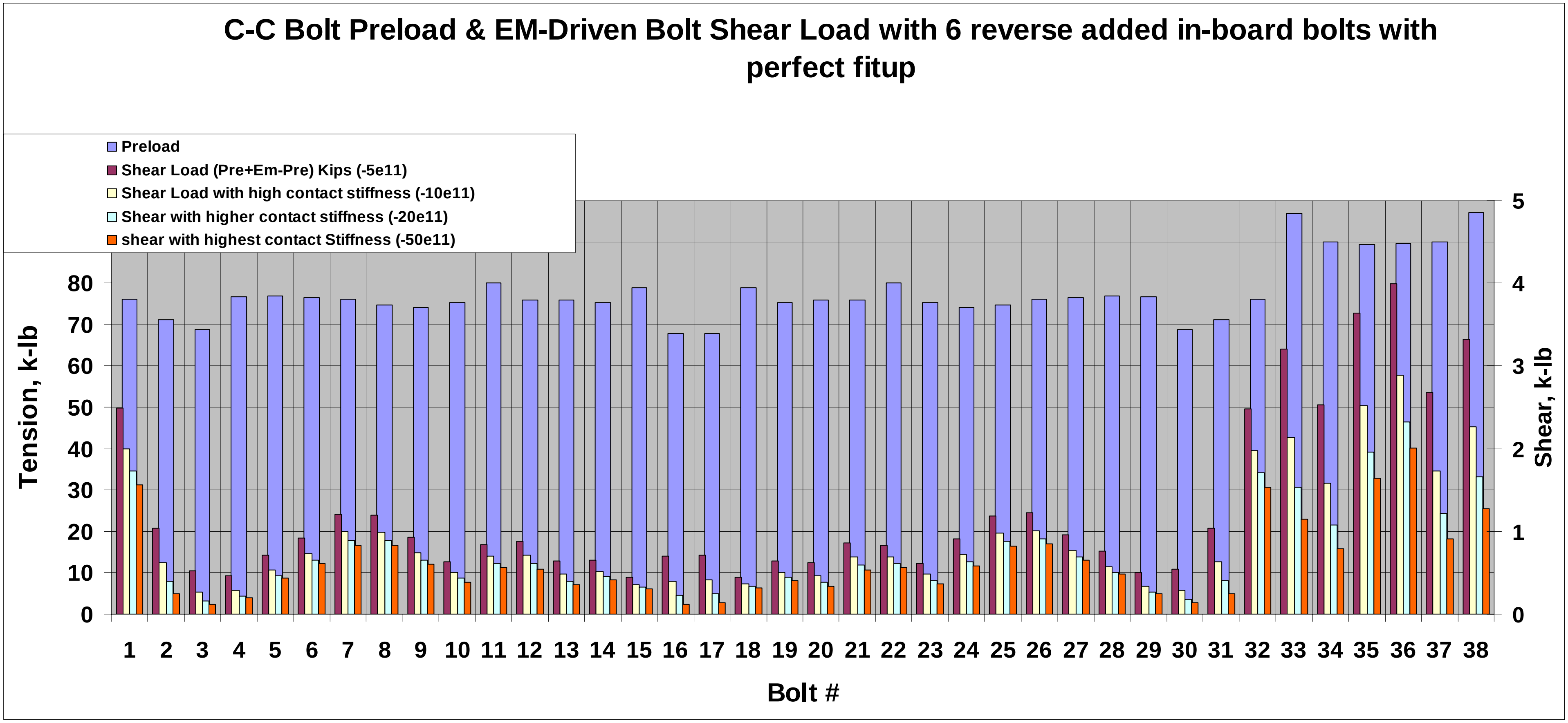


1.5” bolts were used in this particular run.

Shear loads are overestimated on inboard due to low contact stiffness. (next slide)

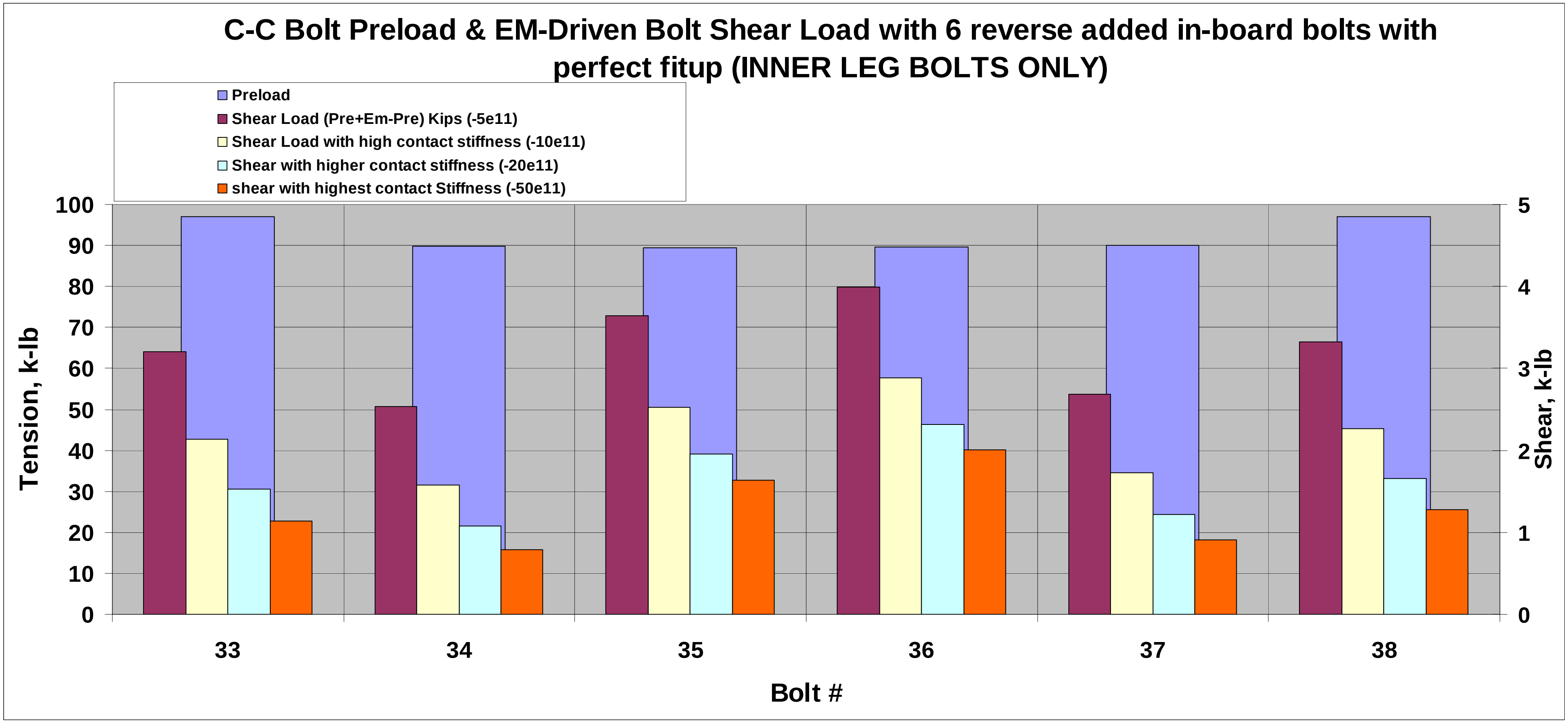
Study on the Inner Leg of CC

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT



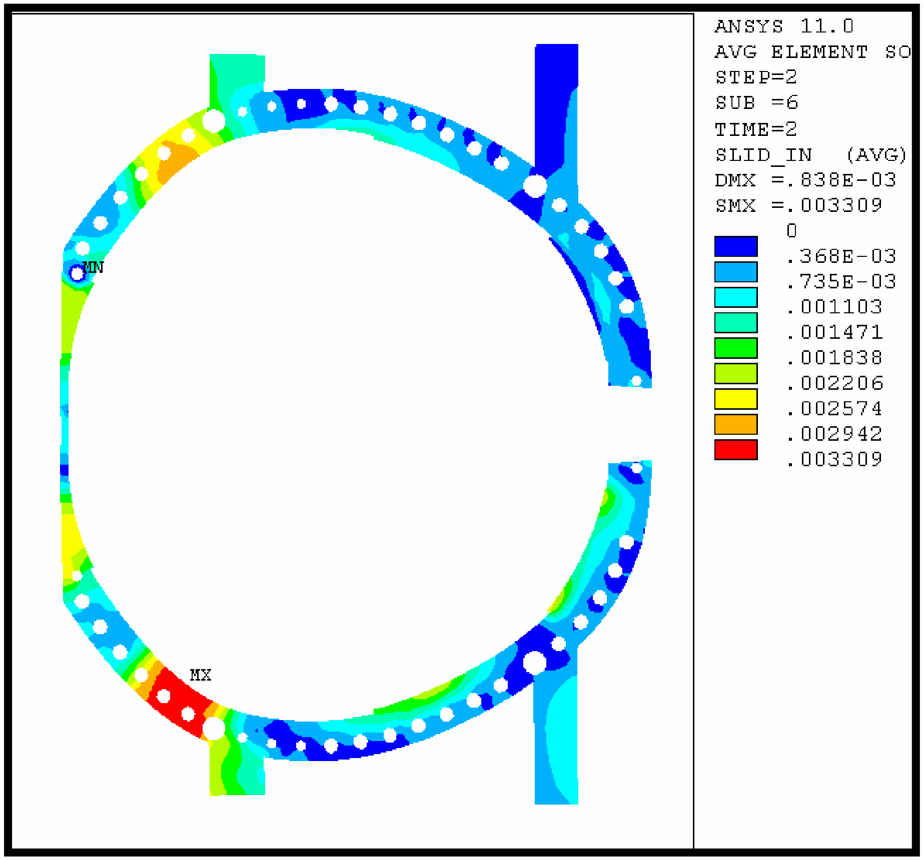
1.5” inner bolts

Inner Leg Bolts Only

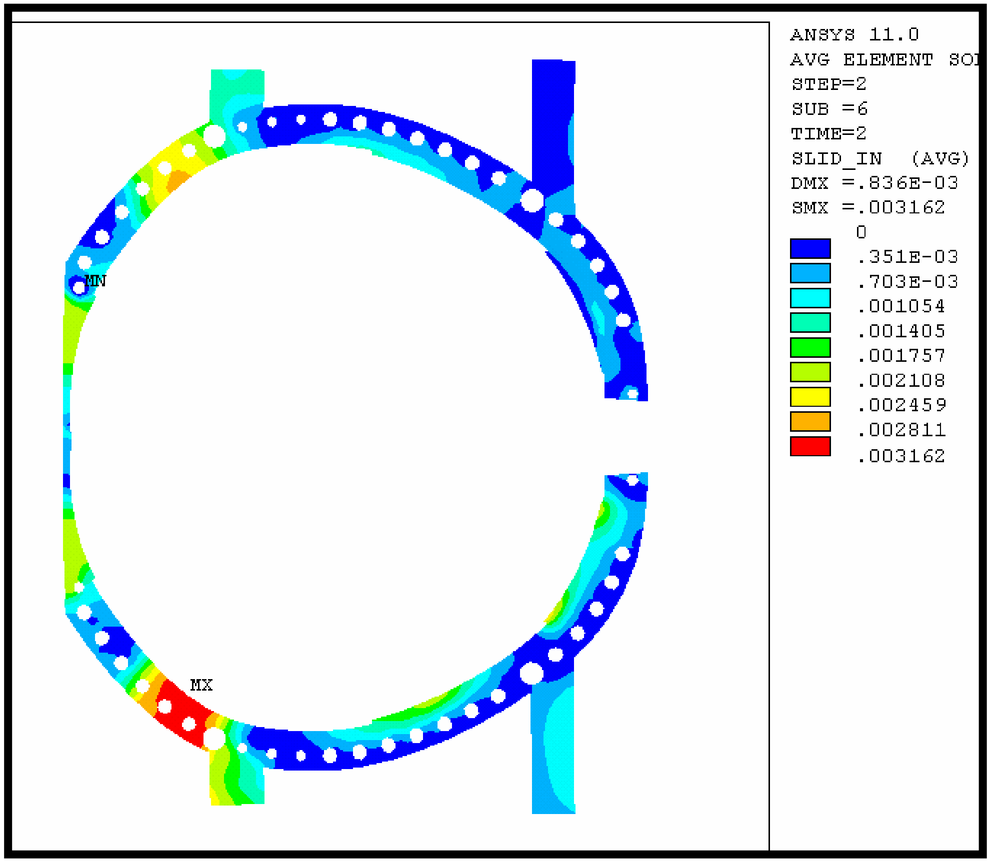


1.5” inner bolts

Contact Slip Plots



Stiffness = -5e11 N/m^3

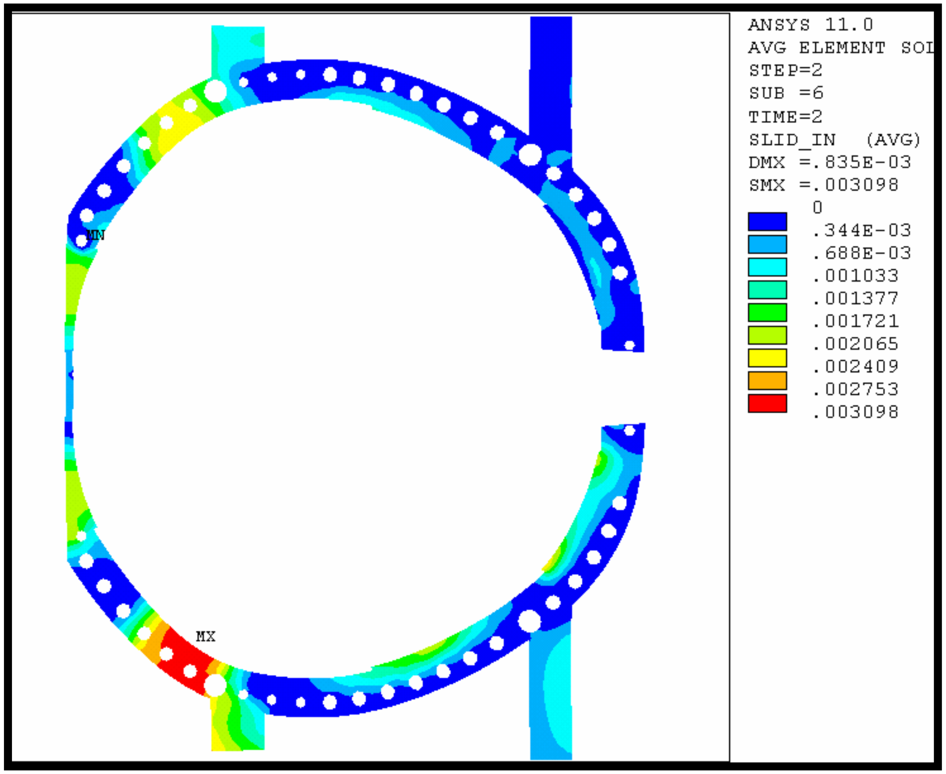


Stiffness = -10e11 N/m^3

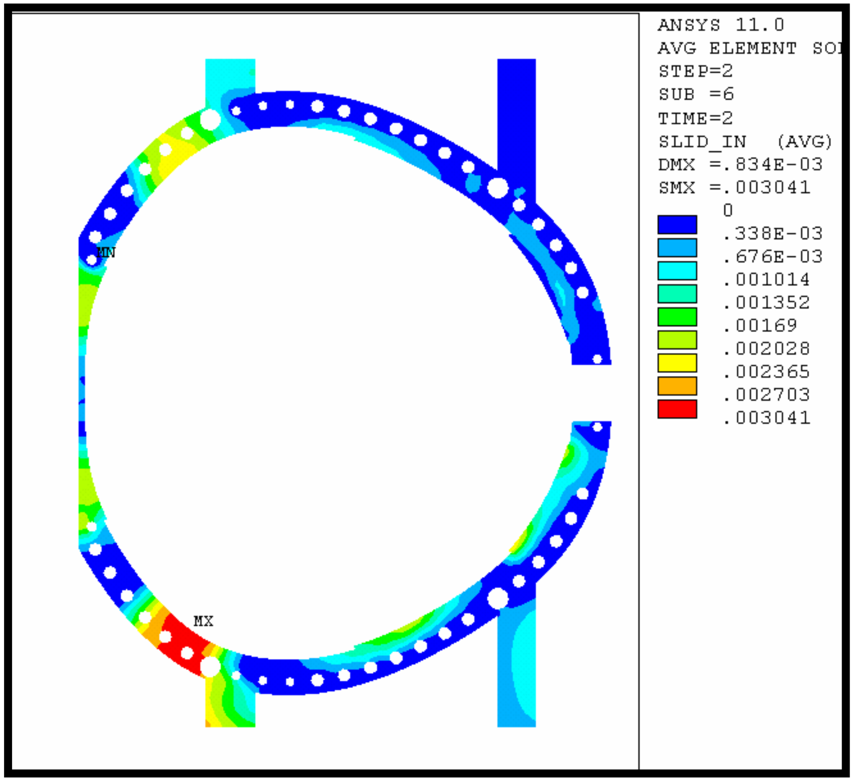
1.5” inner bolts

Contact Slip Plots

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT



Stiffness = -20e11 N/m^3



Stiffness = -50e11 N/m^3

1.5” inner bolts

What does this mean?

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

- Increasing the stiffness has a profound effect on bolt load (reduced by 2X) but a minimal impact on sliding. (as expected)
- Slippage and contact status plots from before for the inboard region on CC are still valid.
- Shear loads are overstated by approximately 2X.
- This suggests that using the 1.375” bolts was ok, and there is little advantage to using the larger diameter as the shear loads just simply aren’t there in magnitude to do anything.
- Slippage of the Inner leg (where and if there are no bolts) is still chief concern.

Appendix B: slides of H.M's work on joint.

Combined shear and preload

Fan single bolted joint analysis

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

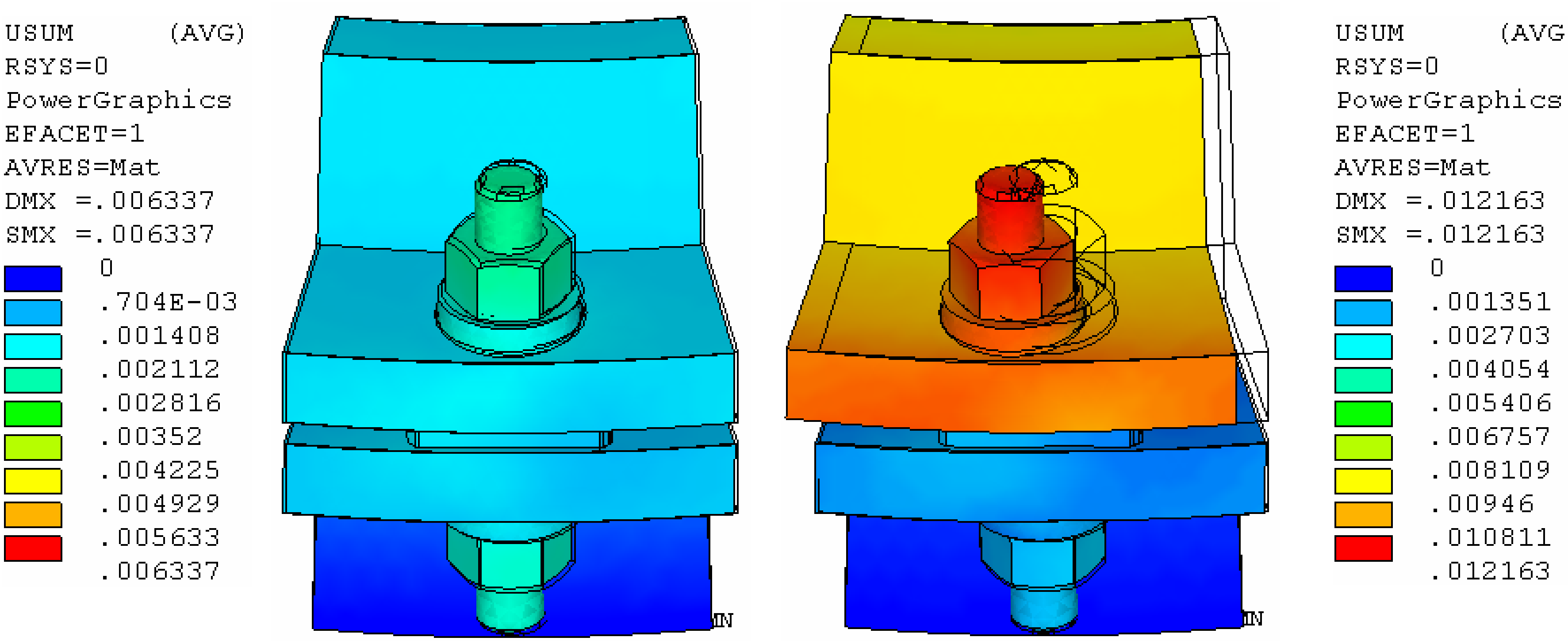
Combined 60 kip preload, 15 kip shear

In bonded case, dominant deformation is bolt shortening due to preload (6 mils)

In frictionless case, lateral deflection is dominant (12 mils)

Bonded

Frictionless

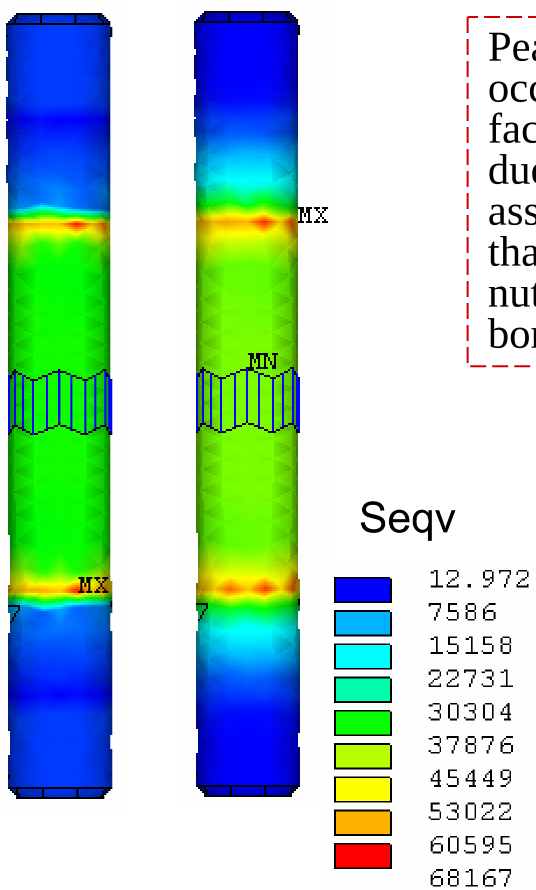


Fan single bolted joint analysis

Combined 60 kip preload, 15 kip shear

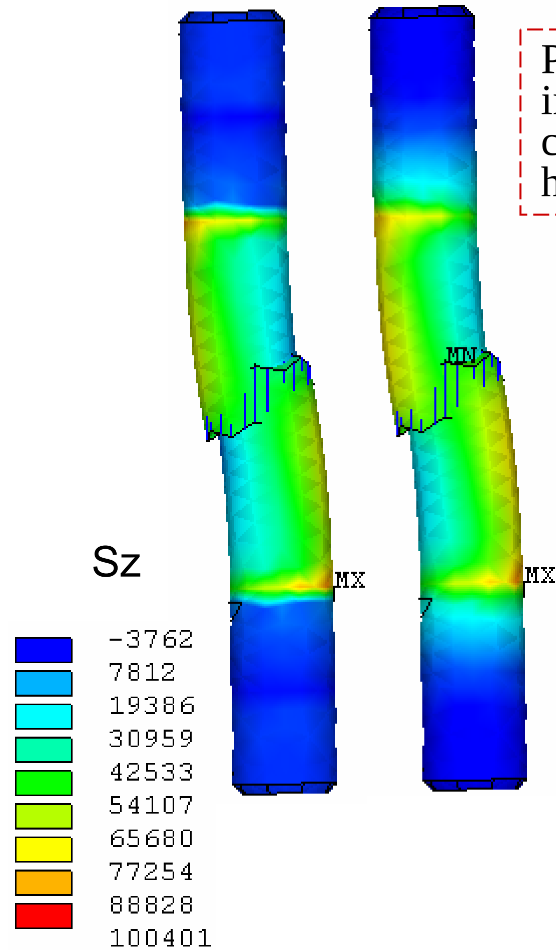
Average tensile stress due to 60kip preload is 40ksi

Bonded

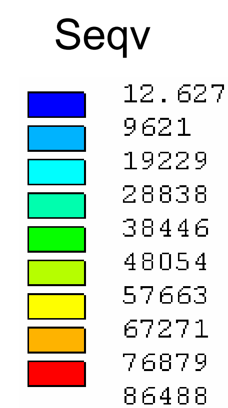


Peak stresses occur at the faces of nuts due to the assumption that stud and nut are bonded

Frictionless



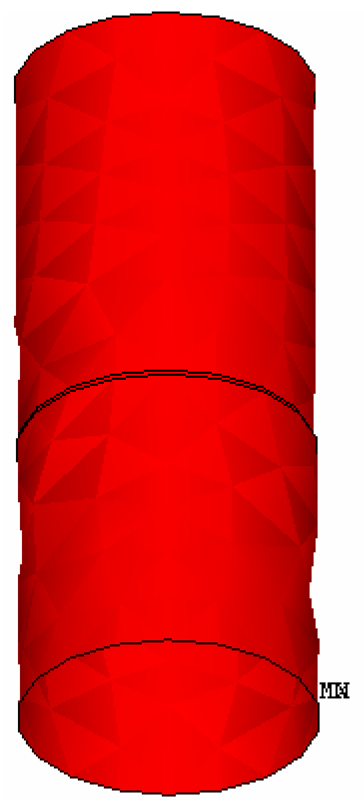
Peak stresses in frictionless case are 27% higher



Fan single bolted joint analysis

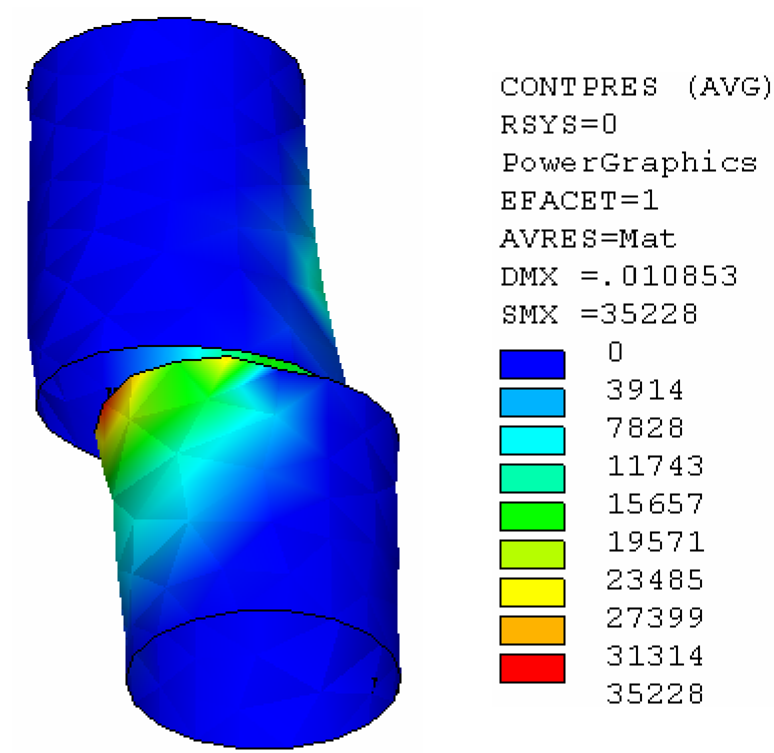
Combined 60 kip preload, 15 kip shear

Bonded



No contact pressure on bushing due to Poison’s effect of the preload on bolt and small shear displacement

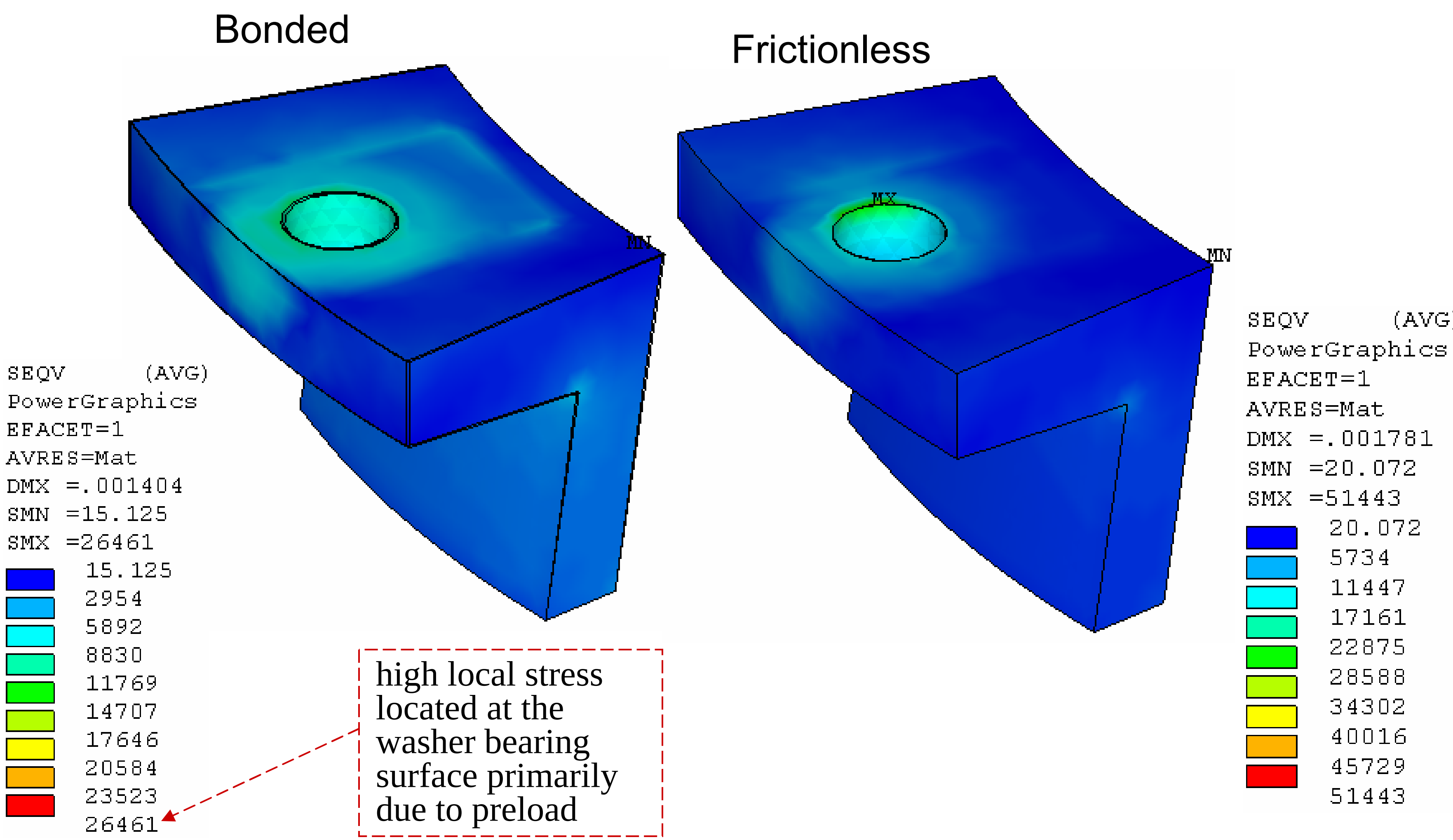
Frictionless



Fan single bolted joint analysis

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

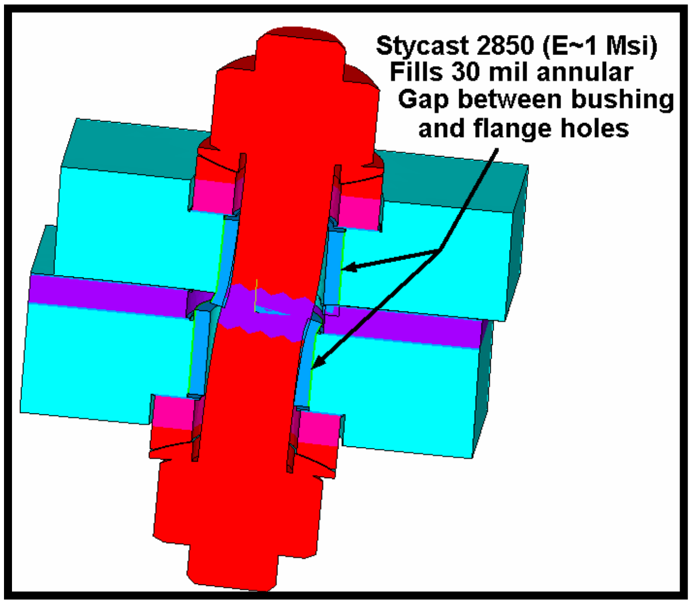
Combined 60 kip preload, 15 kip shear

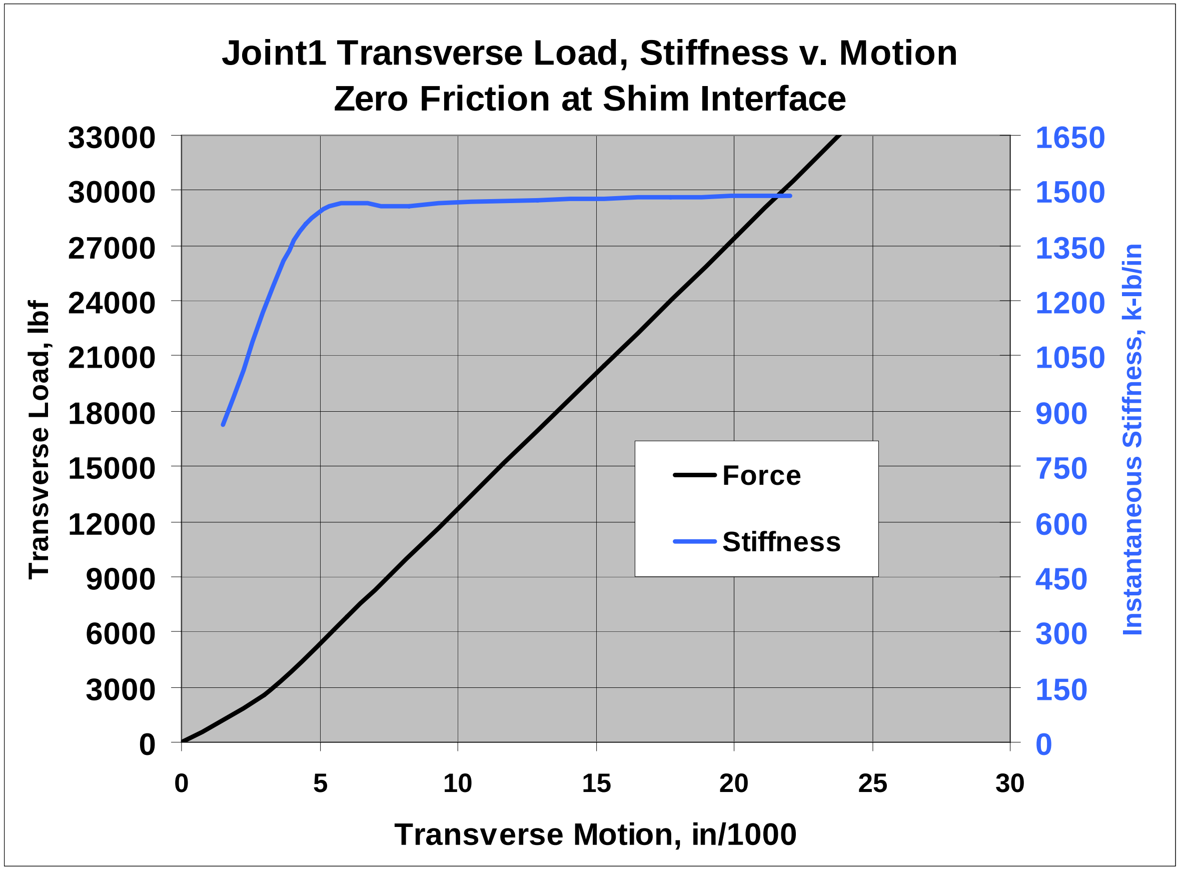


Myatt analysis on 1/2/07

Frictionless single bolted joint

15 kip lateral load results in 12 mil lateral deflection with zero friction.
Consistent with Fan's later calculations.



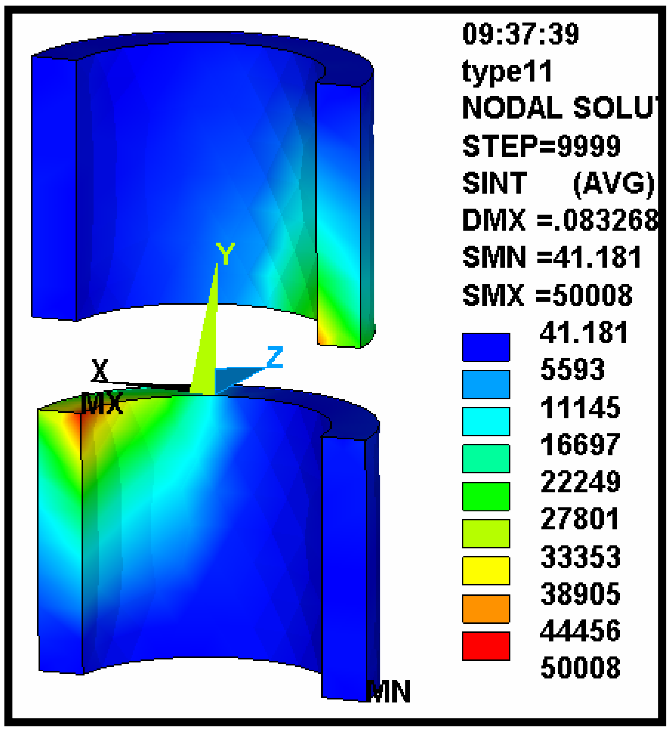


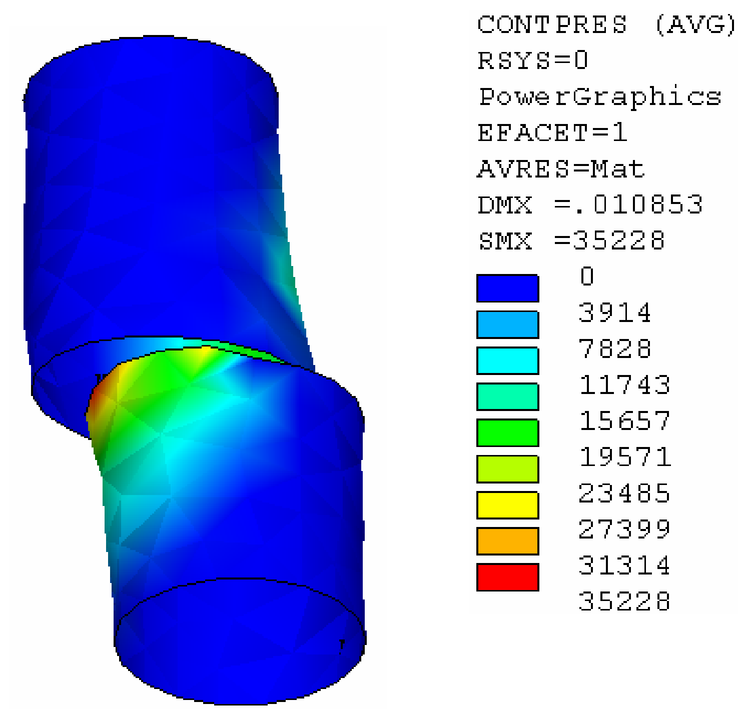
Myatt analysis Frictionless single bolted joint

Bearing stresses on the bushings are also consistent with Fan's later calculations.
Provides confidence in Fan/Myatt models of single bolted joint.

20 kip lateral load
Max bearing stress is 67ksi
2.50 ksi/kip

15 kip lateral load
Max bearing stress is 35ksi
2.35 ksi/kip



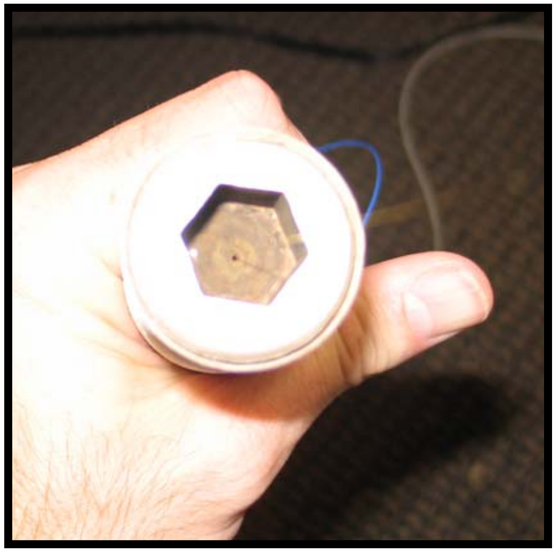


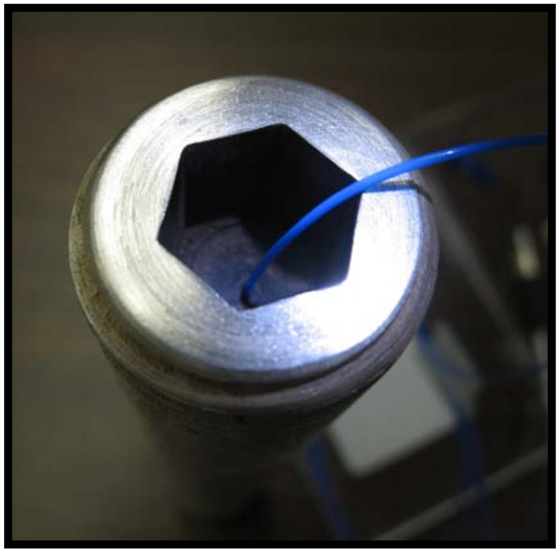
Confirmatory Experimental Testing

Measurement of preload

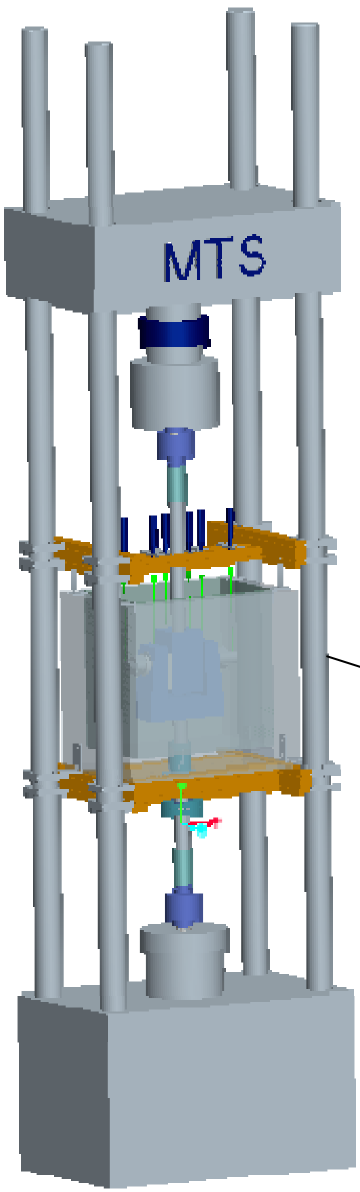
NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

- Fiber optic gages (which can be calibrated before installation!!) can be installed in a number of bolts to monitor preload during life.
- The gages would indicate when to re-torque when and if the preload lessons.
- Largest obstacle (drilling a 0.02” hole through a 9” long stud has been achieved.)
- Gages have been shown to give highly repeatable data.

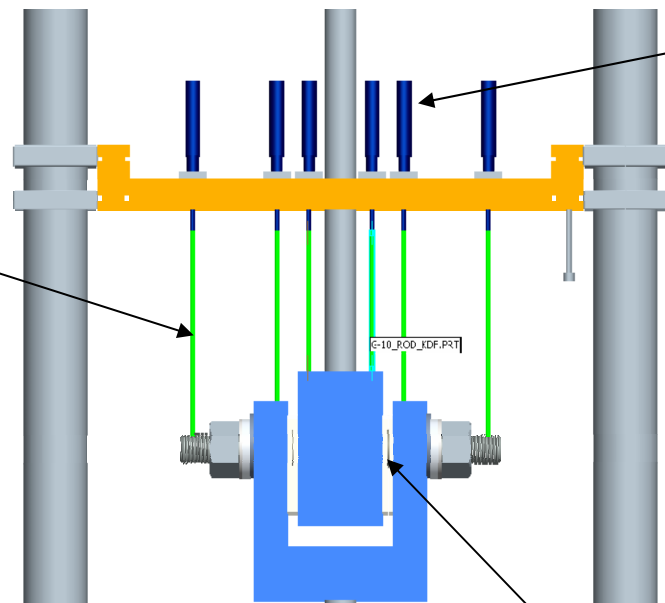




Shear Testing at ORNL



- Minimum friction condition (mu=0.4) does work for all outboard bolts and both analyses indicate that the friction coefficient seen in testing is more than adequate
- Tests of bolted joint mockups in LN2 (static and cyclic) are planned and will use the strain gage in a bolt concept to monitor preload.
- Status: All Load-train and LN2 tank parts manufactured, awaiting bolts and shims (mid July)



Chits Status- Interface Hardware PDR, Feb07

NCSX National Compact Stellarator Experiment

#	Chit/Audit Finding [Originator]	Project Disposition	Status
1	Consider a "Plan B" for the possible condition of inadequate fit-up which might require additional machining of the shims. [Reiersen]	1. Worst case fitups are being analyzed. May preclude using constant thickness shims everywhere. (Brooks) 2. Production prototype (A1:A2) will determine whether contoured shims are required. If so, use of a high friction foil or a spray application of alumina can be done post-machining.	Pre-assembly tests show that adequate asm tolerances can be achieved with constant thickness shims.
2	Identify if any of the existing holes need to be worked on. [Cole]	Holes should be examined and cataloged as to whether any re-work is required. Bushing OD could be determined at the same time.	Cataloging complete. Rework in progress. Drawing for A1 mods in progress.
3	What are tolerance requirement for the half-period assembly? Need to consciously define. Needs more attention. [Cole]	Requirements for positioning the coil current centers will be provided in the Station 2 assembly specification. (Cole) Input to be provided by Brooks.	Half-period and asm of two half-periods=.010-in, for total of .020-in per field period. Ref Dimensional Control Plan by Bob Ellis (to be issued)
4	Establish criteria for adequate fit-up of the shims [Cole]	1. FEA analysis indicates that maximum deflections will be on the order of 1 mil (Fan) 2. Joint tension tests will measure deflections upon tensioning the bolts (Gettelfinger) 3. Approach to finalize fit-up criteria is TBD	Ref Dimensional Control Plan by Bob Ellis (to be issued)
5	Do ultrasonic testing during tension test. [Cole]	UT will be performed during tension test	UT will be employed during confirmatory tests to verify joint behavior.

Chits Status- Interface Hardware PDR, Feb07

NCSX National Compact Stellarator Experiment

#	Chit/Audit Finding [Originator]	Project Disposition	Status
6	Measure μ at LN temperature with Stellalloy. Since Stellalloy seems stronger at LN temperature than standard stainless and since the failure seems to be destruction of the SS surface the maximum μ may be higher with Stellalloy. [Zarnstorff]	Stellalloy and SS316LN have very comparable strength properties. There are no plans to machine Stellalloy test pieces out of the prototype casting for friction tests.	Shim material selected based on cost/schedule considerations.
7	I recall Gettelfinger getting μ ~ 0.7 in one of his tests at very high clamping shims to increase pressure (~ 7000 PSI?). Consider understanding shims to increase pressure to obtain this high μ.	Friction testing will be performed over a representative range of pressures.	Done.
8	Tabulate deflection and bolt shear loads in case without additional inner leg bolts with ~ no friction on inner leg region. Consider if this is a more attractive solution than added bolt design. [Zarnstorff]	The overloading of the bushings on the A-A flange will be resolved by adding additional bolts.	Analysis complete. End bolt shear loads and motion was high. Welding selected as preferred configuration.
9	Shims must protrude beyond flange or have a handle for insertion and positioning. [Viola]	A handling feature for the shims will be added.	Shims protrude beyond flange edge.
10	Eliminate spherical washers! Unnecessarily costly and potential loss of preload. [Viola]	1. Loss of preload will be tested in bolt tension tests with spherical washers and flat washers. Test will also provide cost data. 2. Design solution may be to use only where necessary to save cost. Spherical washers are needed where stud is not normal to spotface.	Supernuts selected as preferred configuration, do not require spherical washers for asm. Hex nuts w/ spherical washers to be used on one end of through bolts only.
11	The concern is do we have a pre fit-up of the MC before the diamond coated shims are installed? [Brown]	The assembly sequence will be worked out on the production protoype (A1:A2)	Diamond coating rejected.

Chits Status- Interface Hardware PDR, Feb07

NCSX
National Compact Stellarator Experiment

#	Chit/Audit Finding [Originator]	Project Disposition	Status
12	Make as many similar parts as possible i.e. all shims have same shape. [Viola]	Plan is to minimize the number of different parts	Universal shim with cutoff lengths will minimize qtys.
13	In place of planned " welded threaded hole adapters" use A286 nuts and washers. Use box wrench to resist rotation during tightening operations. [Heitzenroeder]	A1 adapters to replace through holes with tapped holes will be replaced with standard nuts	Drawing for A1 in progress.
14	Expedite completion of coil-to-coil assembly prototyping to resolve issues that cannot be otherwise addressed. [Reiersen]	Daily meetings are being held at 3:45 to review daily progress and make plans for the following day.	Daily meetings continue.
15	Need to establish acceptable fit up requirements for the shim. Also, determine where the preferred contact area is [Reiersen]	1. See Chit 4 re fit-up criteria. 2. Good fit-up around the stud is seen as important to provide a good load path for the bolt preload. The impact of not having good fit-up in the shell region will be investigated.	Fitup testing w/ Fuji film performed to determine acceptable fitup.
16	Need to finalize shim area. Fit up favors a smaller area. Shear is the glass epoxy favors a larger area. [Reiersen]	See chits 12 and 15.	Universal shim selected.
17	Load washer may have to be modified to accommodate hydraulic tensioners. [Reiersen]	Interface with hydraulic tensioners will be investigated.	Supernut configuration adopted

Chits Status- Interface Hardware PDR, Feb07

NCSX National Compact Stellarator Experiment

#	Chit/Audit Finding [Originator]	Project Disposition	Status
18	Resolve issue of what the stress allowables should be in the G-11 bushing. [Reiersen]	Stress allowaqbles will be reviewed and set per the NCSX Structural and Cryogenic Design Criteria.	Friction joint design developed. Bushings serve as aid to positioning, electrical isolation, secondary structural elements only.
19	Send analysis results to Fan for checking. [Reiersen]	Analyses will be documented and provided for proejct review.	Analysis of various options documented, final analysis pending. Independent checking of design basis analyses is still required.
20	Finalize location of bolts to resolve peak bushing stress concerns especially on A-A [Reiersen]	Adding more bolts on A-A will be investigated for reducing peak bushing stresses.	Welded joint configuration under development
21	Confirm that single shear test setup is OK. If not, consider setting it up a a double shear test. [Reiersen]	Double shear setup is being considered.	Test setup revised, fabrication complete, asm in progress.

Chits Status- Shims FDR, Jun07

NCSX National Compact Stellarator Experiment

Design Review [Cog Engr/RLM/Chair]	Rvw Date	#	Chit Finding [Originator]	Status
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	1	Verify that the loads carry through the washers without significant deformation and yield which would compromise tension over time. [Viola]	Open.
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	2	Are the variations in shim thicknesses accommodated by the threaded length of studs? Especially where studs threads impede screwing into flange. [Viola]	Stud length is being evaluated.
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	3	What is the minimum wall thickness allowed on bushings? [Viola]	Min wall thickness = 0.1-in.
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	4	Solution anneal shims after all grinding and maching is finished if required to meets mu X 1.02 requirements. [Heitzenroeder]	Incl in procedure.
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	5	Add a flatness callout of 1 mil on the shim. [Reiersen]	Revise due to cost?
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	6	Load washer material needs to be changed from T1 to Inconel (to match what was delivered) [Dudek]	Inconel is ok.
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	7	Aluminia coating should be specified as 0.025" + 0.003"/-0.002" with a surface roughness [Gettelfinger]	Specified on shim drawing, SE140-040.
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	8	Complete confirmatory tests (shear, tension, cycle, edge loading) prior to installation. [Reiersen]	Testing scheduled to be complete in mid-Oct. FPA begins late Oct.
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	9	Determine max depth of spot face before setting height of insulation rings. [Reiersen]	Ring height changed to 1-in, cut as required.
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	10	Address issue of Inconel v titanium load washer. Titanium is specified, Inconel was purchased. [Reiersen]	Inconel load washer is ok.
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	11	Re-evaluate installation cost of bushings based on Edwards/Fogarty timeline and re-visited fit requirements use opportunity presents by upcoming weld test in using winding joints. [Reiersen]	Assembly tests in progress.

Chits Status- Shims FDR, Jun07

Design Review [Cog Engr/RLM/Chair]	Rvw Date	#	Chit Finding [Originator]	Status
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	12	Define where instrumented studs should be used. [Reiersen]	Inboard leading bolts for interfaces, C-C flange new bolts. Tot=15*4+3*12=96
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	13	Higher the 1.02 magnetic permeability needs Brooks concurrence that it is ok. [Reiersen]	Concur.
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	14	Determine whether edge loading (time contact) of the alumina shims is a problem or not. If so, it may be necessary to undercut the edge or radius it. [Reiersen]	Open.
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	15	For the thru-hole configuration with a hex-hut, there should be a mechanism to secure the hex-nut from turning under cyclic load. [Zarnstorff]	Use welded locking tab, same as clamps.
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	16	Need to review effect of material choice for washers (T2 or Inconel) on bolt pre-load at LN temperature and effect on shear load capability before changing spec. [Zarnstorff]	Slight relaxation with Inconel washers compared to Titanium.
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	17	Please place note on drawing specifying minimum clearance between spot face ID and load and spherical washer OD. Also, allow grinding at washer OD. [Viola]	Note added to bolt asm drawing, SE140-190.
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	18	Please change the ID of the shim hole to provide 1/16" diametral gap between stud and alumina coated ID. [Viola]	Specified on shim drawing, SE140-040.
Outboard Bolted Joints Shims FDR Williamson, Nelson, Reiersen	6/29/2007	19	For shims secure with 1/16" thick minimum securing to adjacent shims on both sides. [Viola]	Incl in FPA asm spec.

Conclusion

- Are the requirements well defined?
  Coil asm spec is approved, FPA Station-2 spec in progress
- Does the design meet the requirements?
  Outboard shim, bolt asm details unaffected by remaining inboard interface work.
- Is the design adequately underpinned by analysis and testing
  Documented analysis is being checked. Confirmatory tests planned.
- Are the drawings complete and ready to be released for fabrication?
  Drawings have been issued for fabrication.
- Have chits from previous MC design reviews been addressed?
  Open chits to be resolved by asm and welding trials, FPA Station-2 specification.
- Have technical, cost/schedule, safety risks been addressed?