Modular Coil Assembly Outboard Bolted Joint FDR 6/29/07

Presented by the ORNL/PPPL Design team

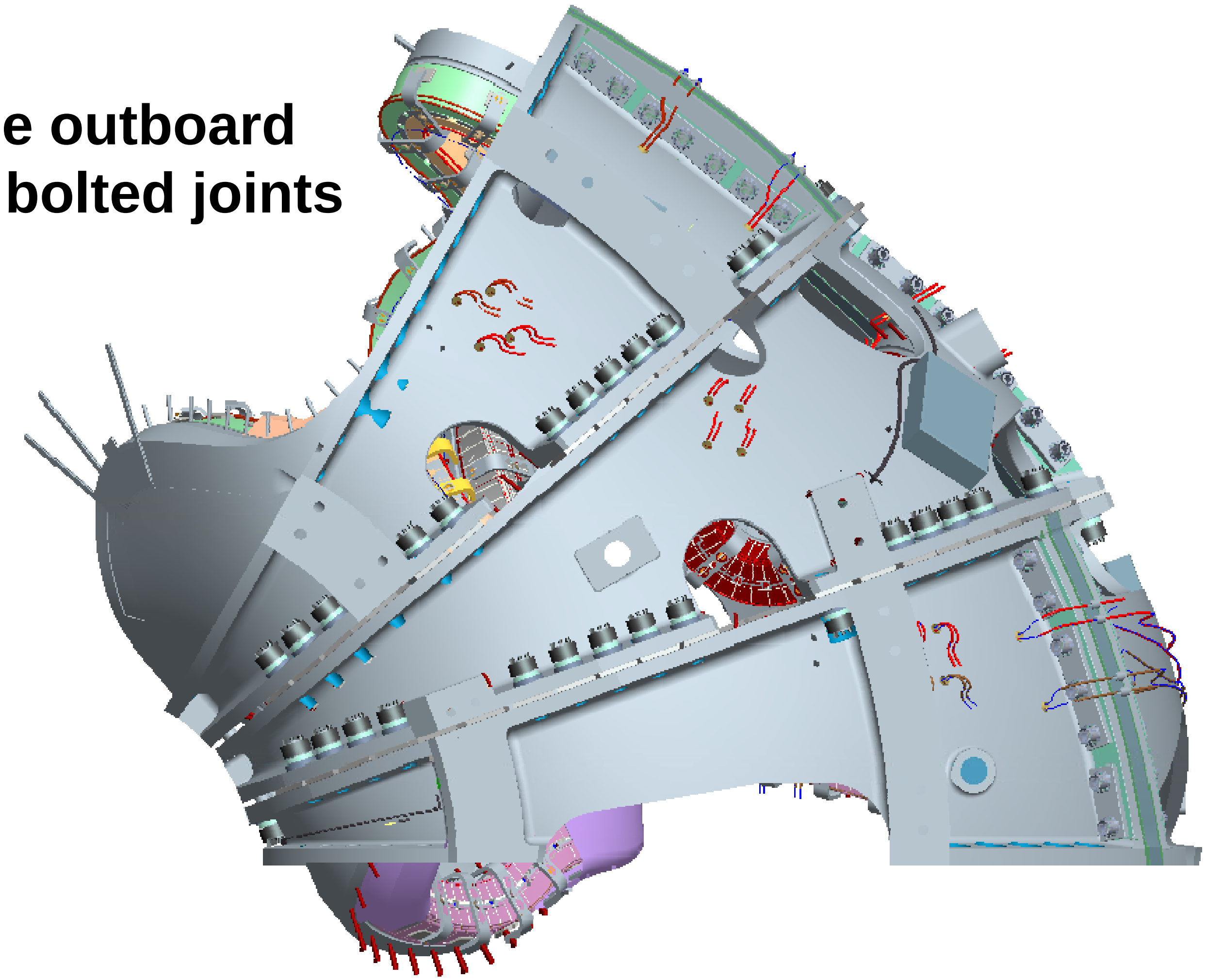
Charge

- **Are the requirements well defined?**
- **Does the design meet the requirements?**
- **Is the design adequately underpinned by analysis and testing?**
- **Is the shim friction testing sufficient to proceed with procurement of coated shims?**
- **Is the shim coating spec complete?**
- **Are the drawings complete and ready to be released for fabrication?**
- **Have all relevant chits from previous MC design reviews been adequately addressed?**

Scope

This review covers the outboard shims for all existing bolted joints in the design.

The inboard shims (including the welds and added bolts on C-C joint) will be addressed at a later review.



Requirements

Requirements are derived from the coil assembly specification and the station 2 assembly specification.

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

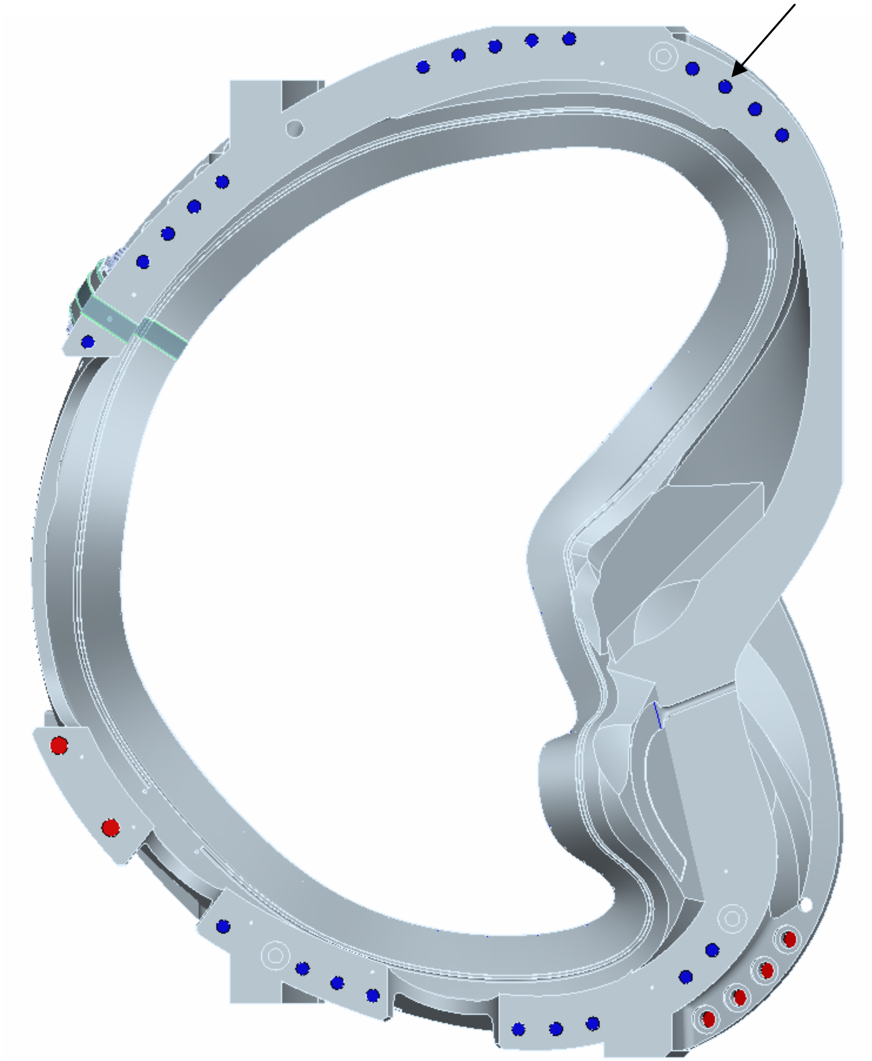
- Carry compressive loads
- Maintain a “no slip condition” under the bolts (friction joint)

Assembly

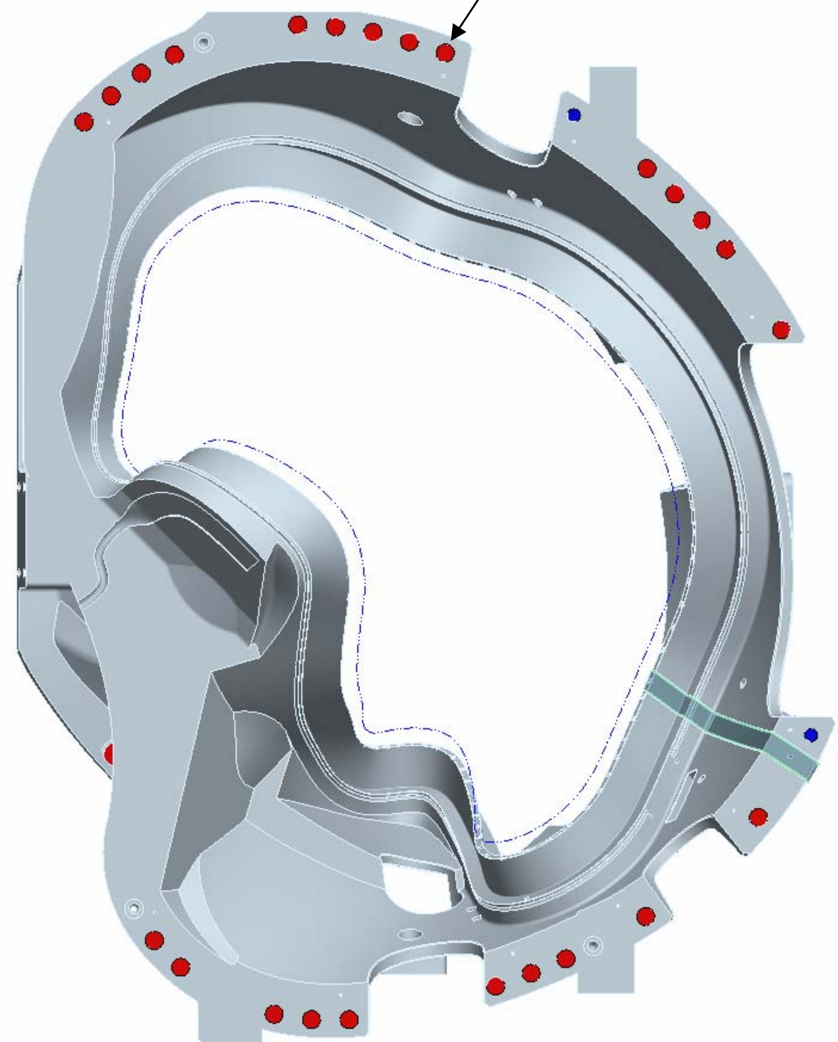
- Position the coils accurately
- Minimize gaps

Interface A-B

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



Type-A



Type-B

Interface B-C

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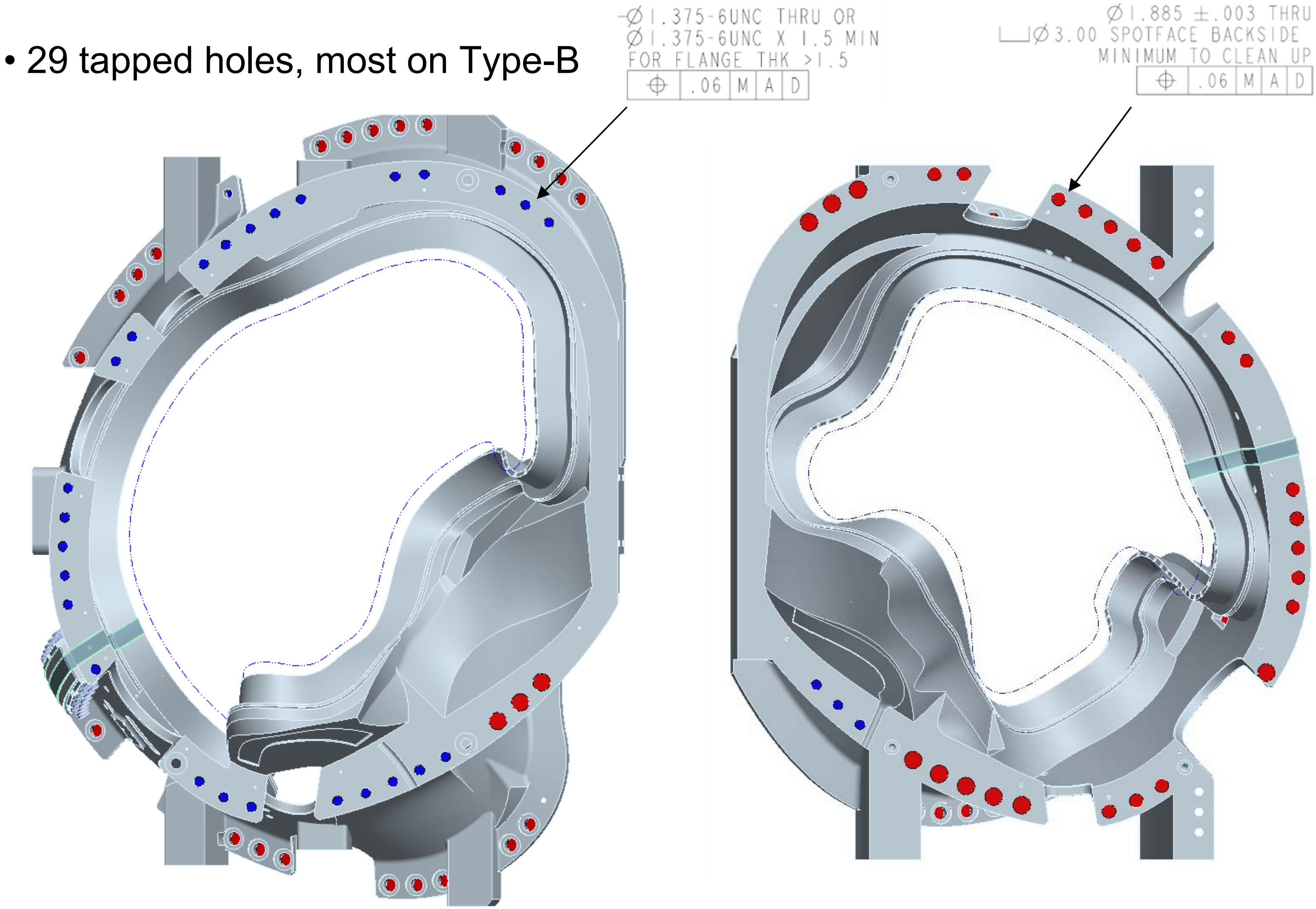
- 29 tapped holes, most on Type-B

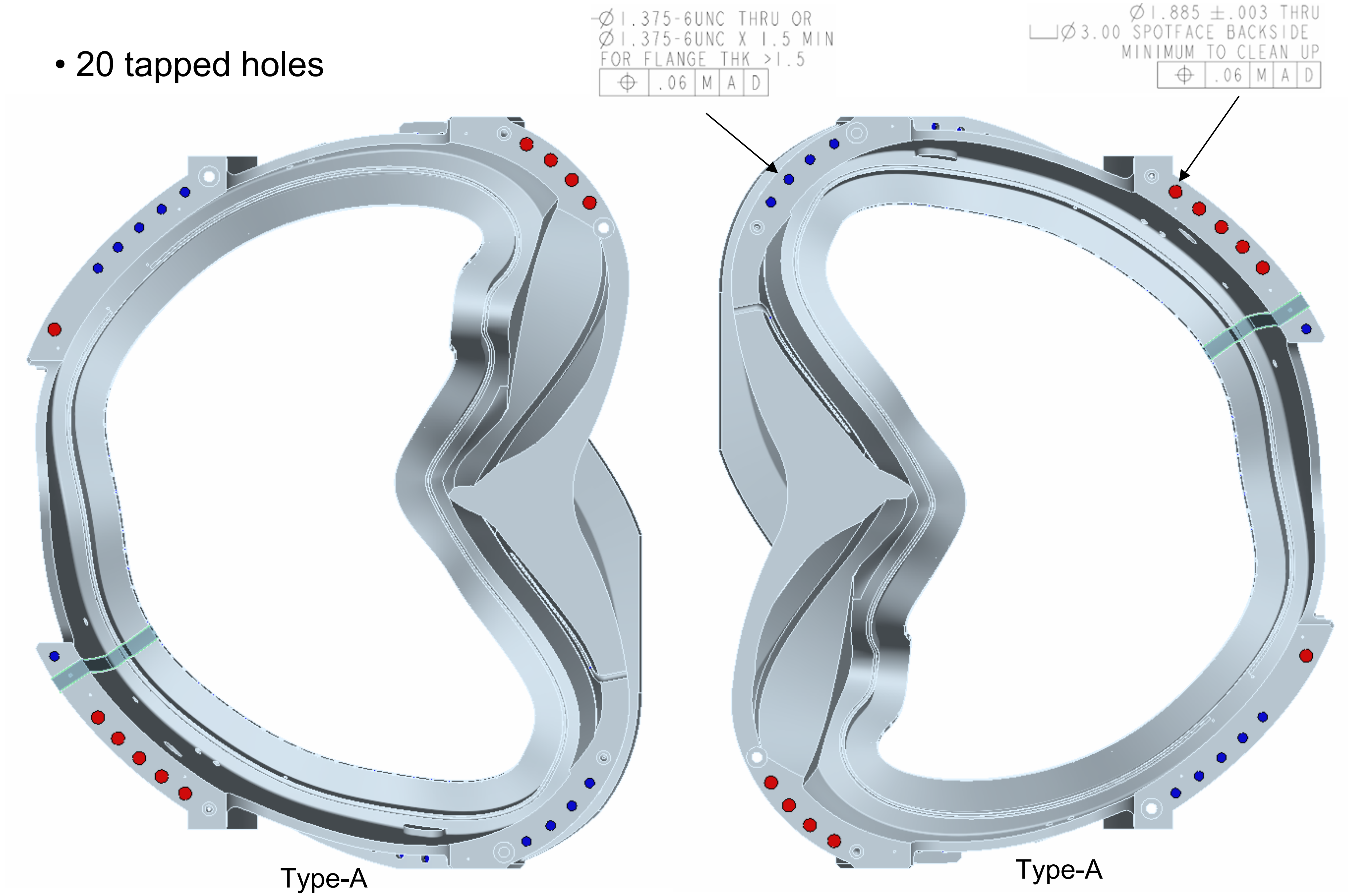


Type-B

Type-C

Interface A-A

• 20 tapped holes



Interface C-C

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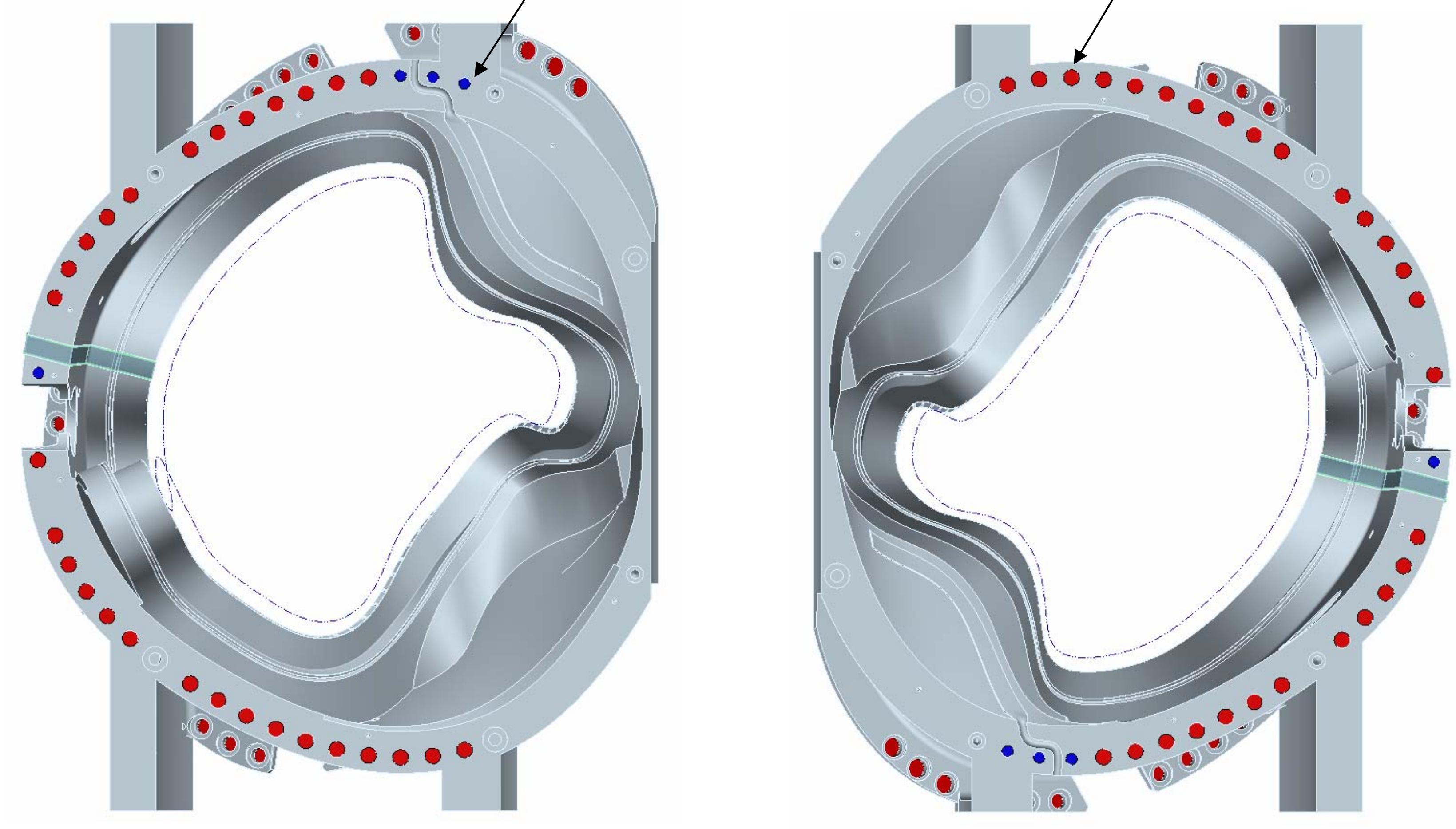
- 24 through holes
- 8 tapped holes

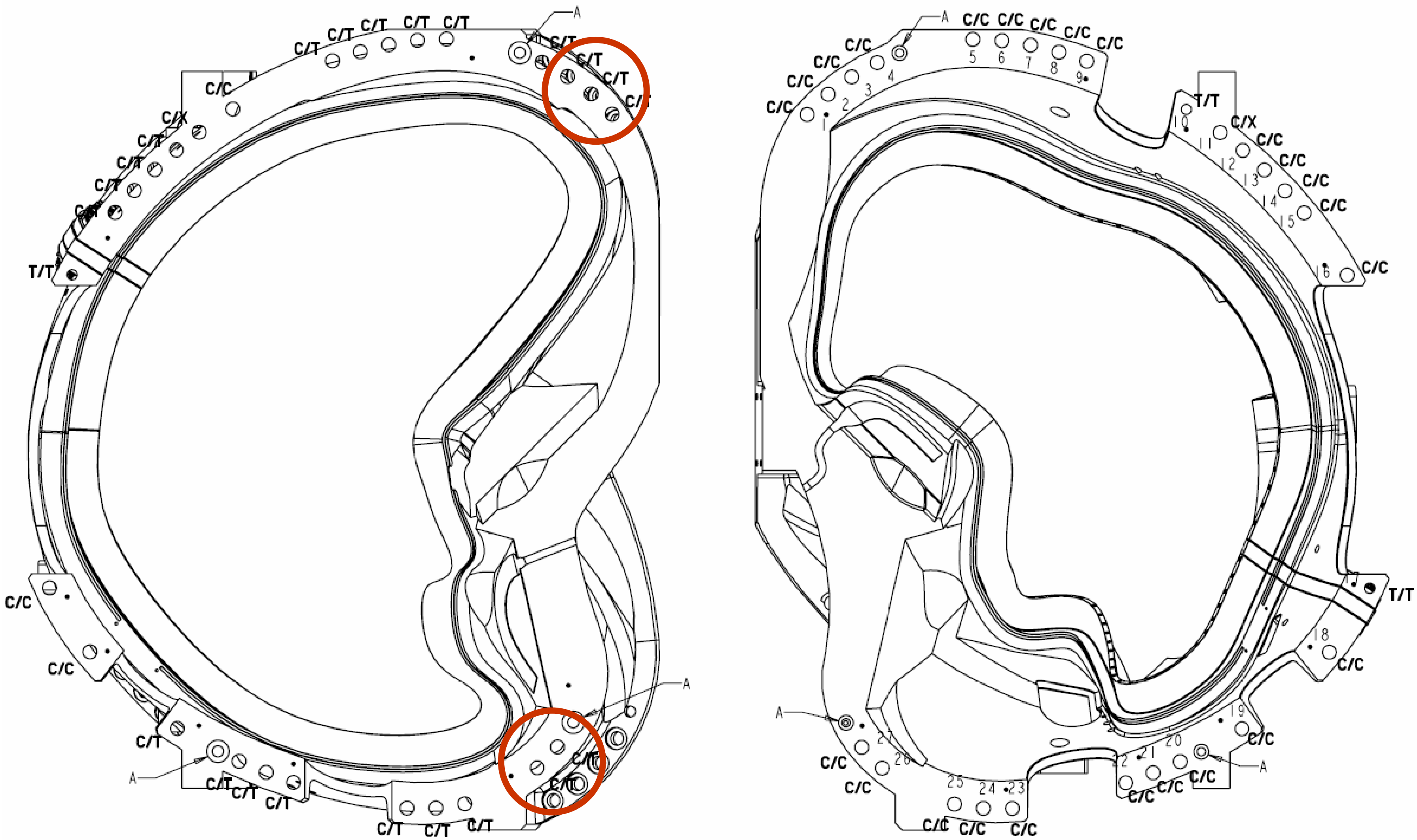


Type-C

Type-C

A1 is special

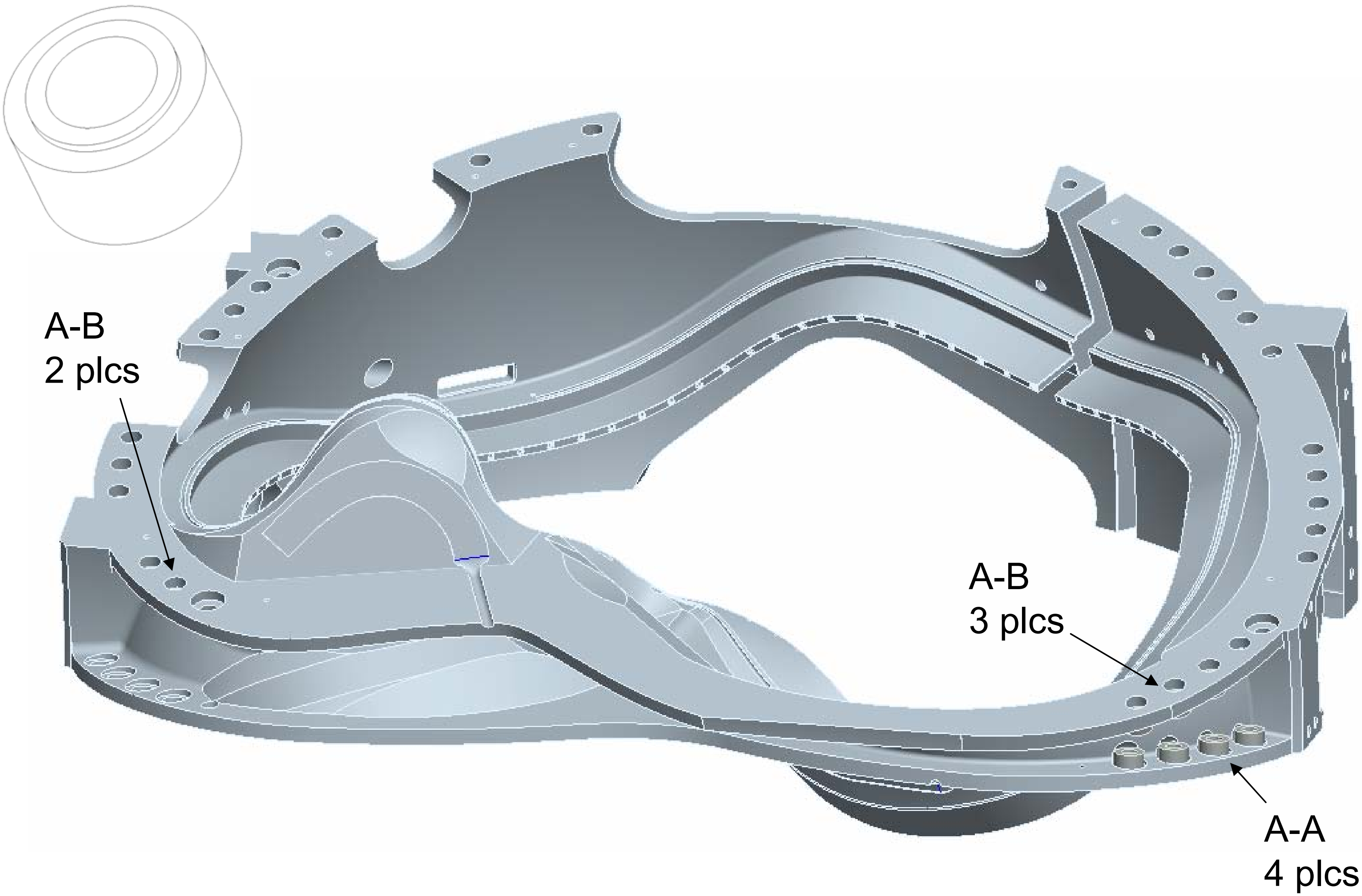
NOTES:
A/A = BASELINE/PROPOSED
A = ALIGNMENT FEATURE
C = CLEARANCE HOLE, 1.885 ±.003 THRU
⌴Ø3.0 X MIN DEPTH BACKSIDE
T = THREADED HOLE, 1.375-6 UNC-2B THRU
X = HOLE TO BE ELIMINATED



TYPE-A DATUM-E
(WINDING SIDE-B)

TYPE-B DATUM-D
(WINDING SIDE-A)

A1 Welded Adaptor w/ Tapped Hole



A1 Photograph

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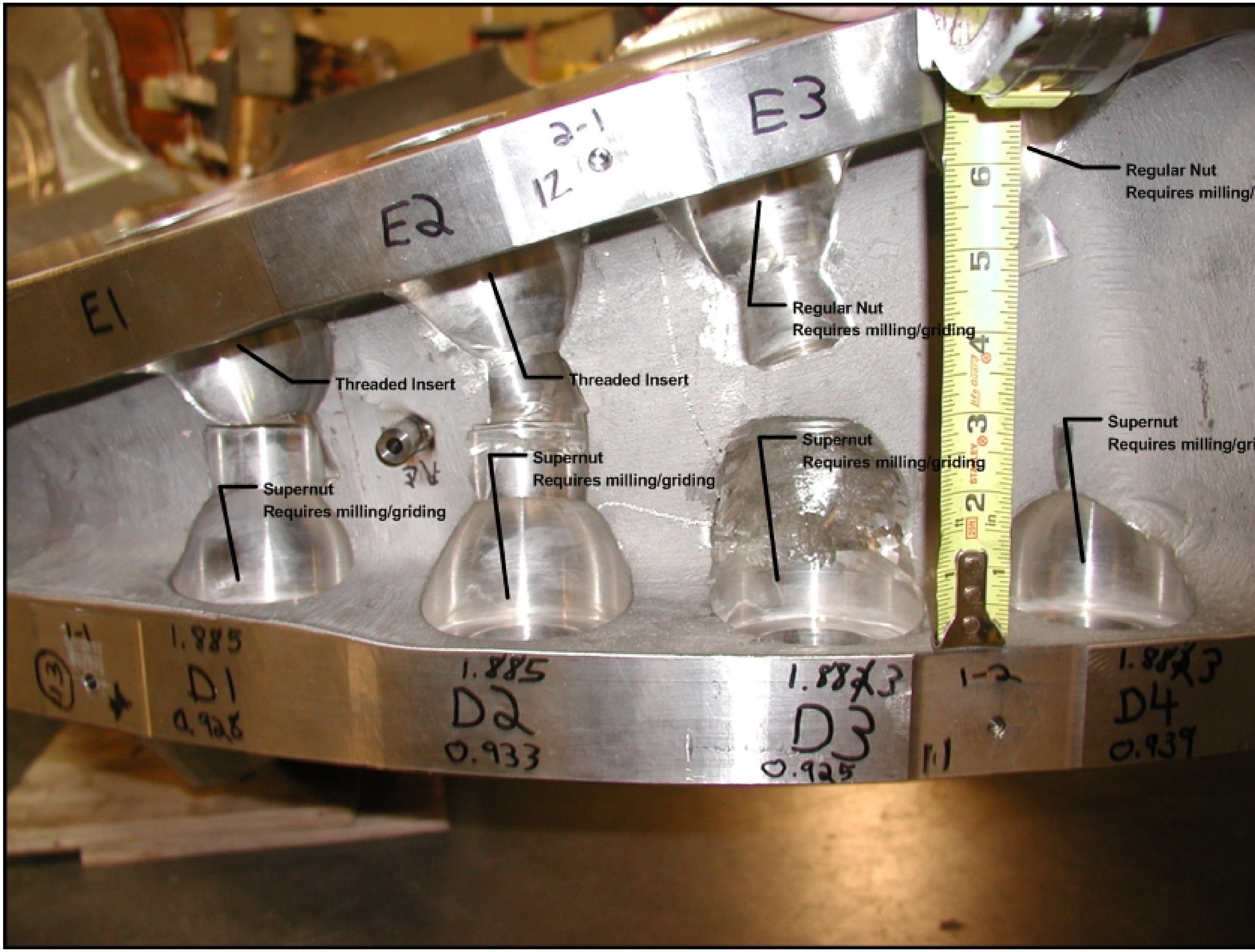
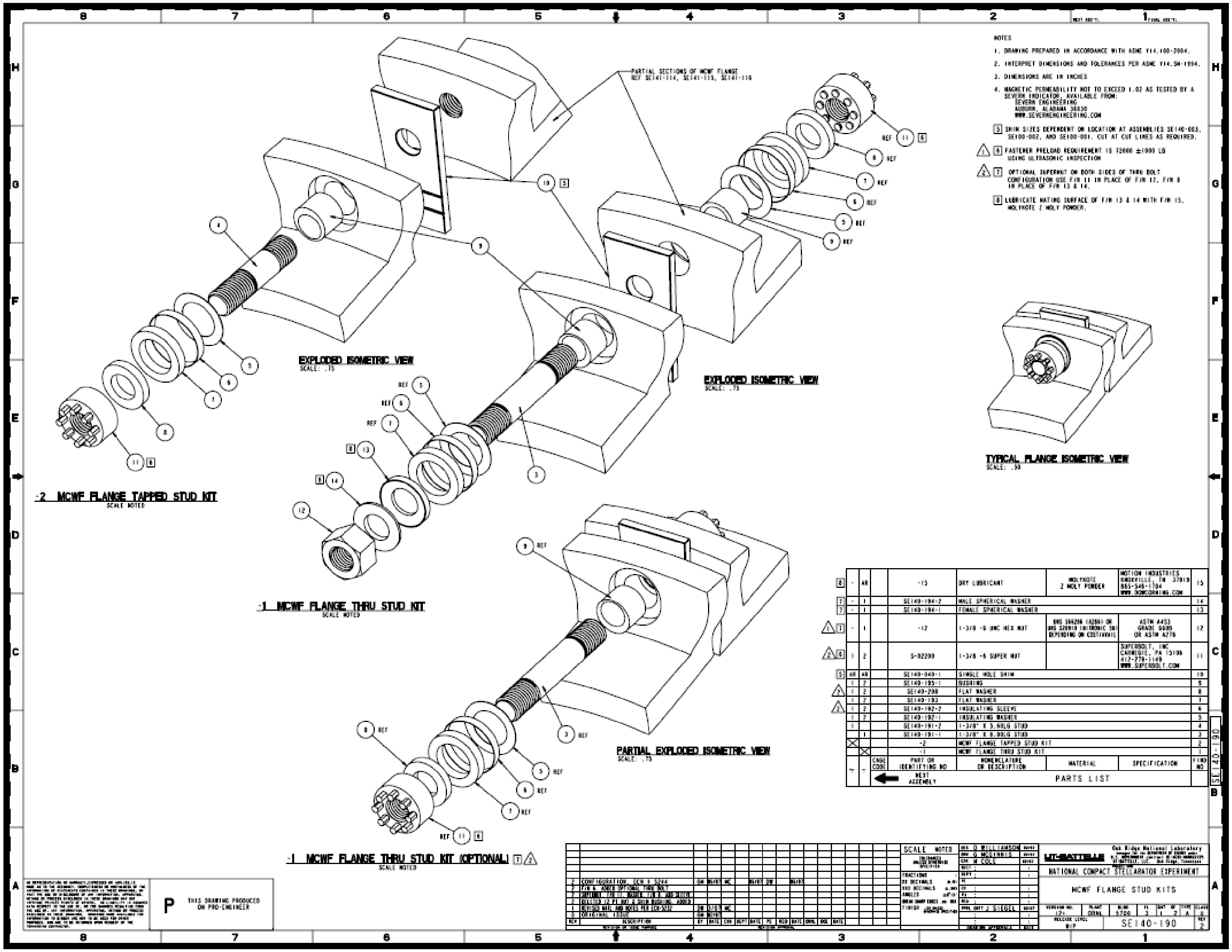


Inventory of Tapped/Through Holes

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

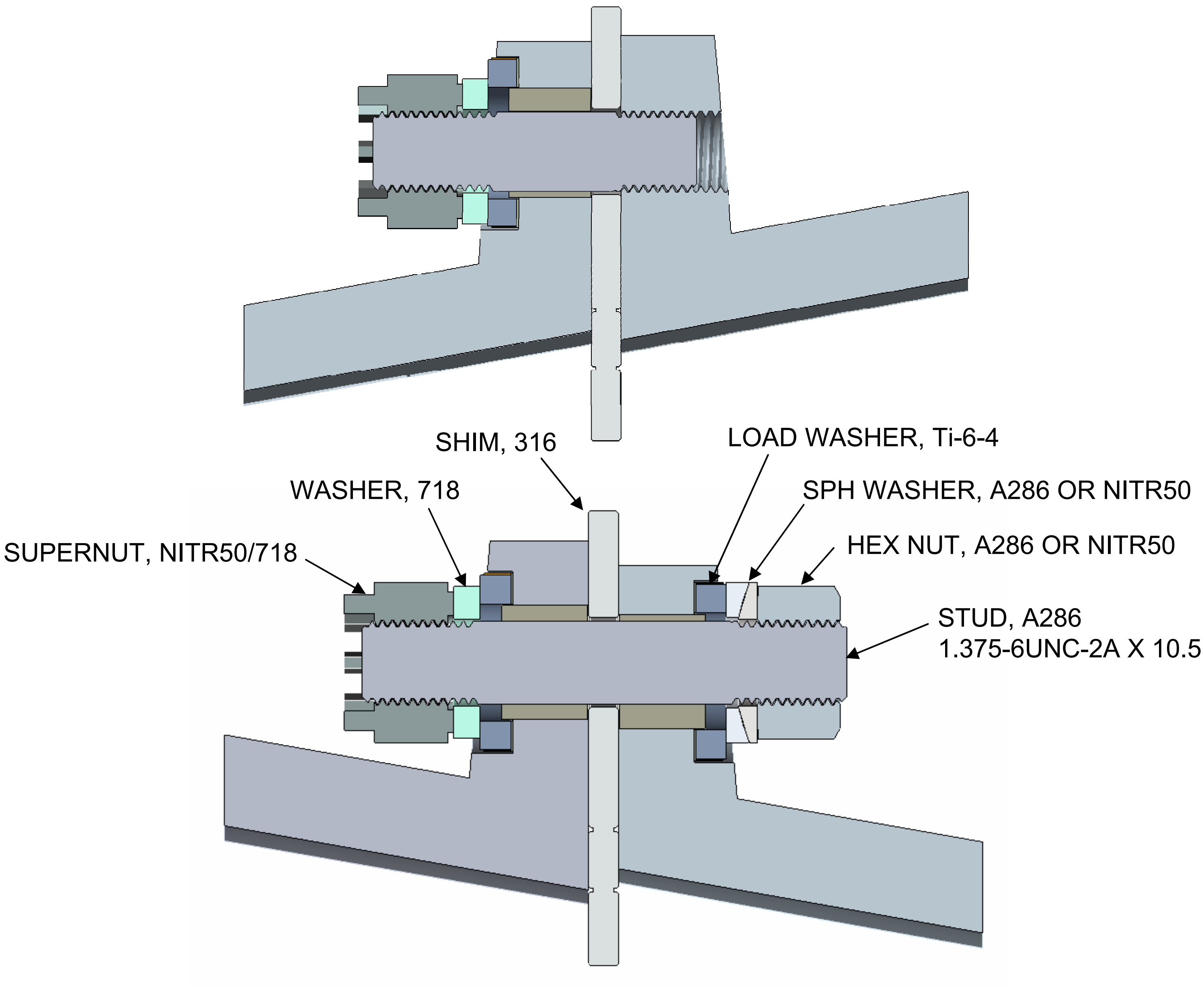
Design of Outboard Bolted Joint

Bolt Configuration

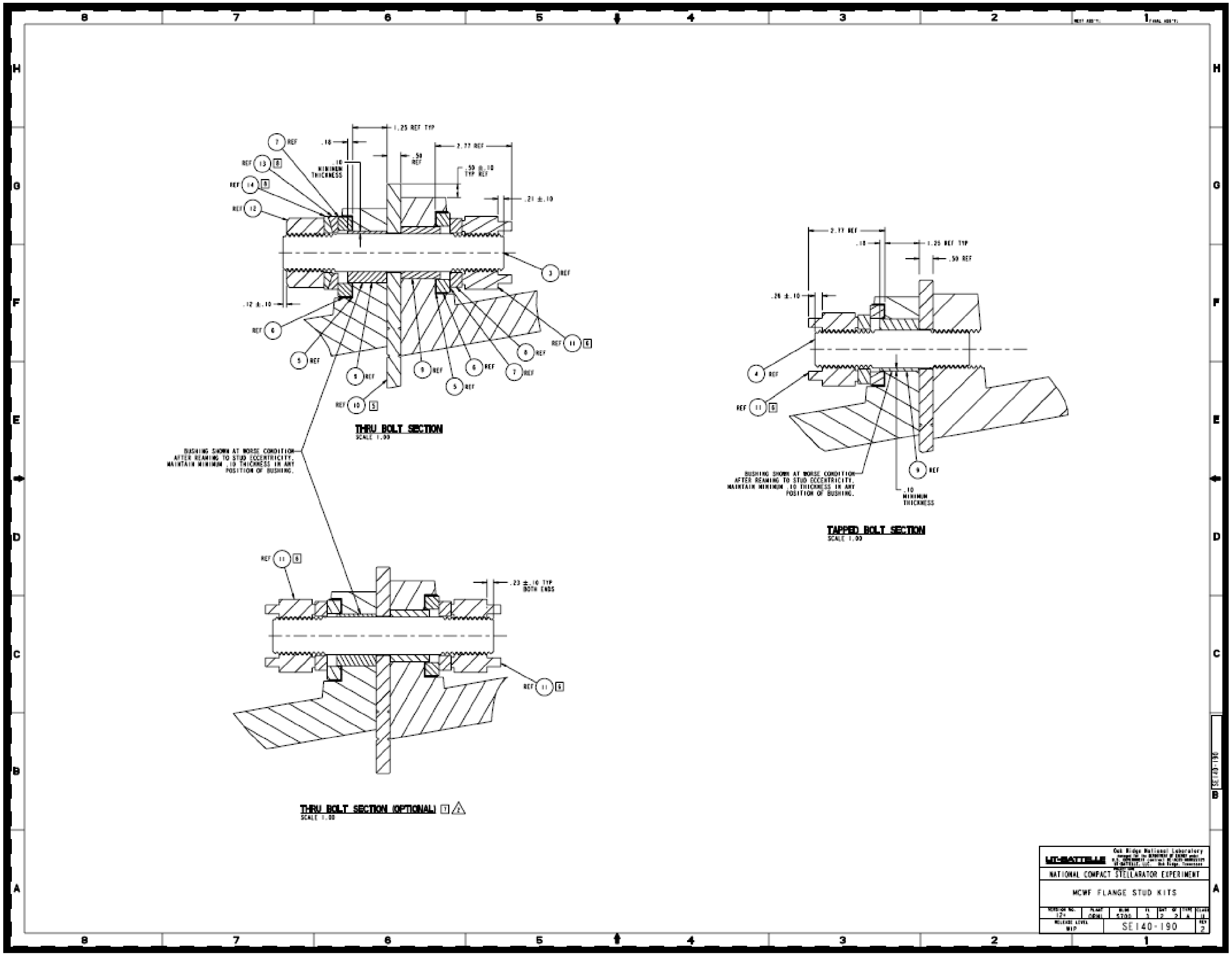


Bolt Configuration

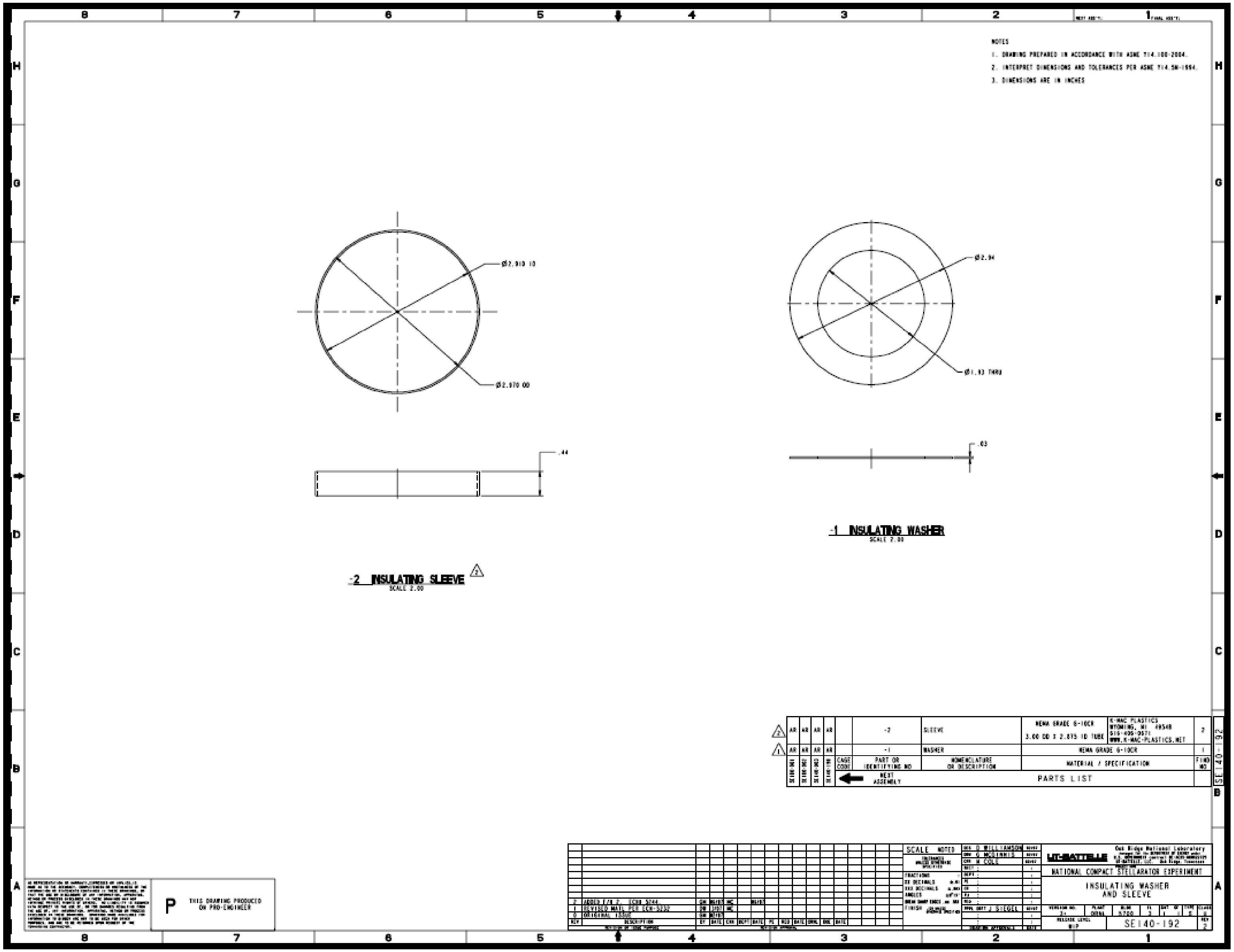
NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT



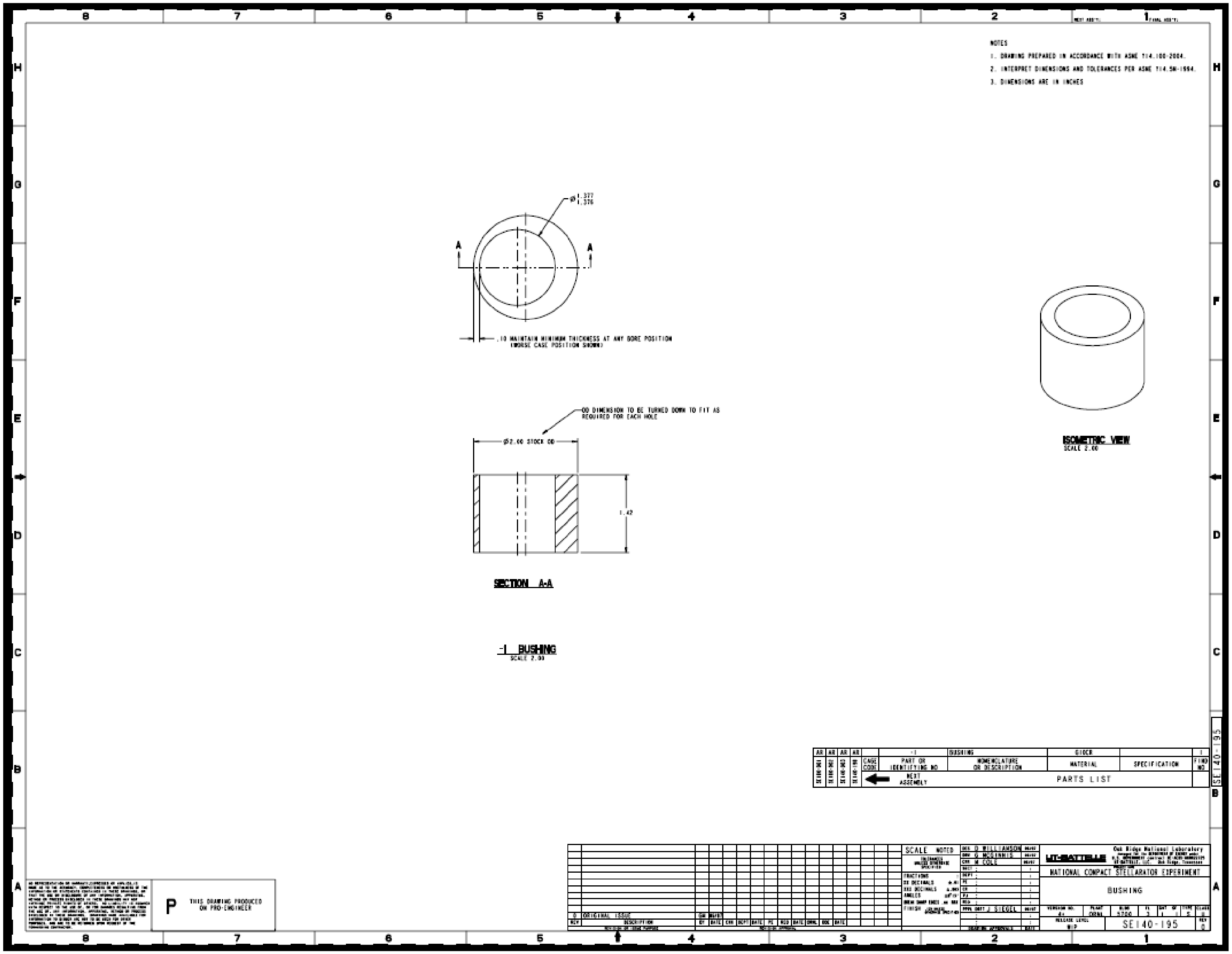
Bolt Configuration



Insulating Washer



Bushing

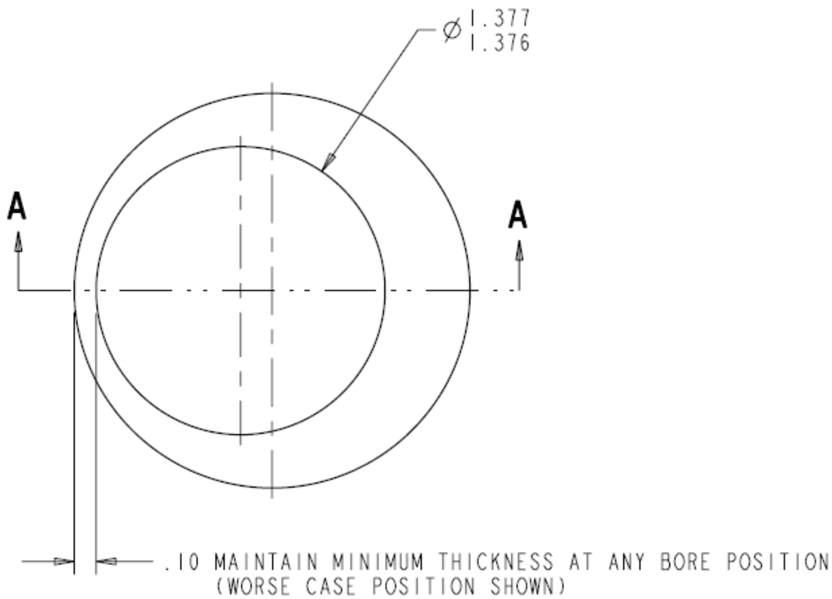


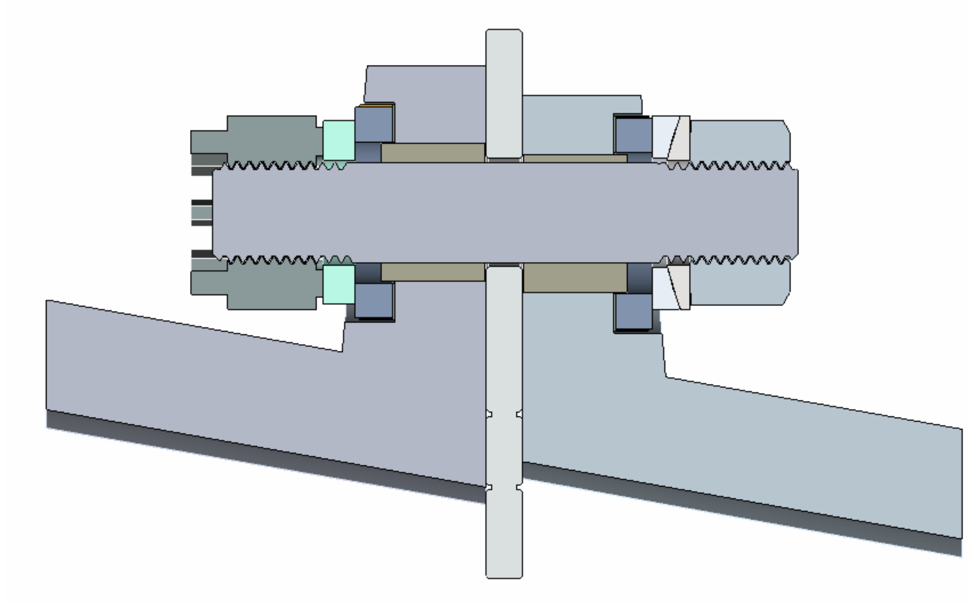
NOTES
SECTION A-A
-1 BUSHING
ISOMETRIC VIEW
PARTS LIST
NATIONAL COMPACT STELLARATOR EXPERIMENT
BUSHING

Flange Bushing

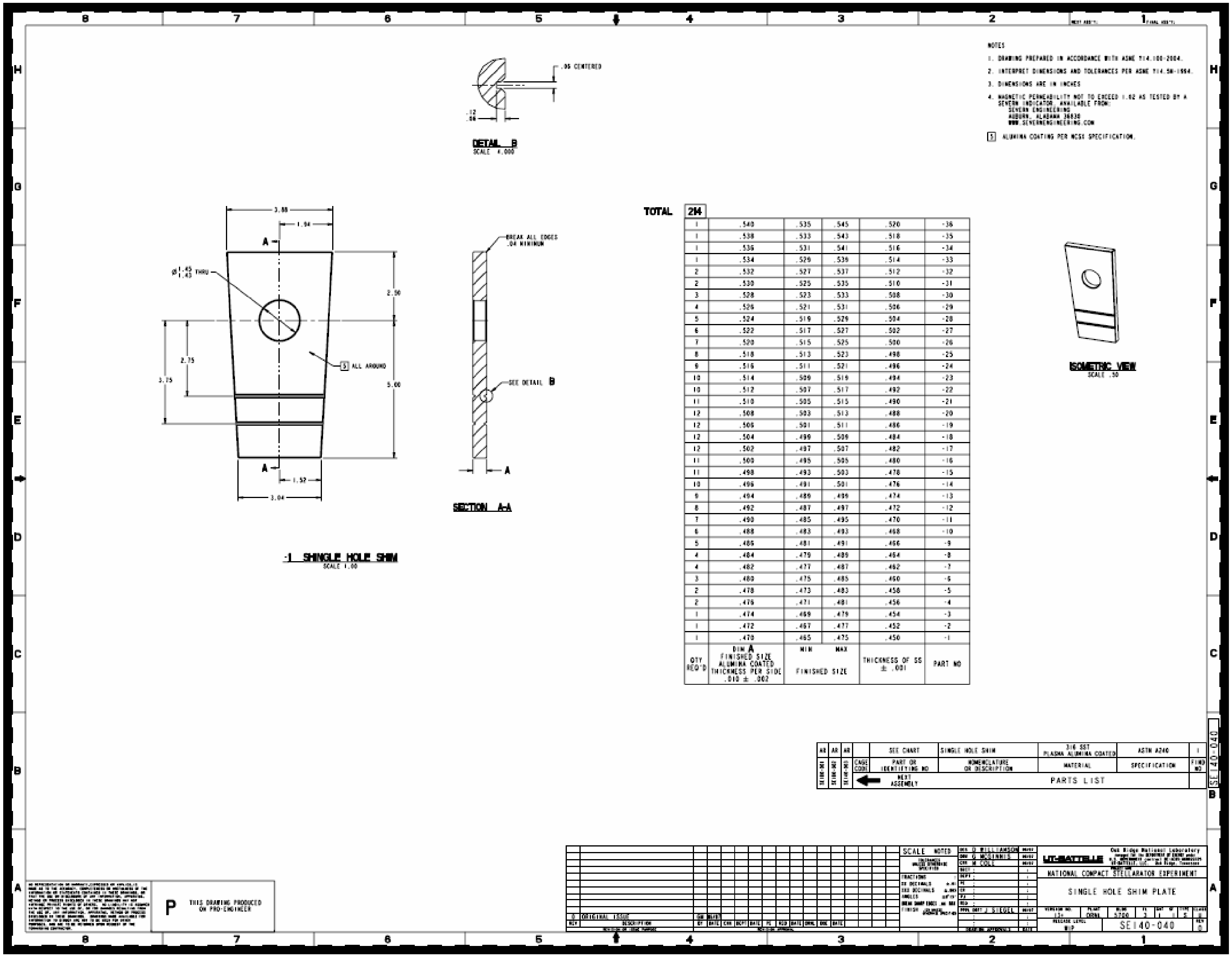
Function:
- Maintains Relative Position of Coils
- Electrical isolation
- Structural support

Qty Required:
- 110 concentric
- 486 eccentric





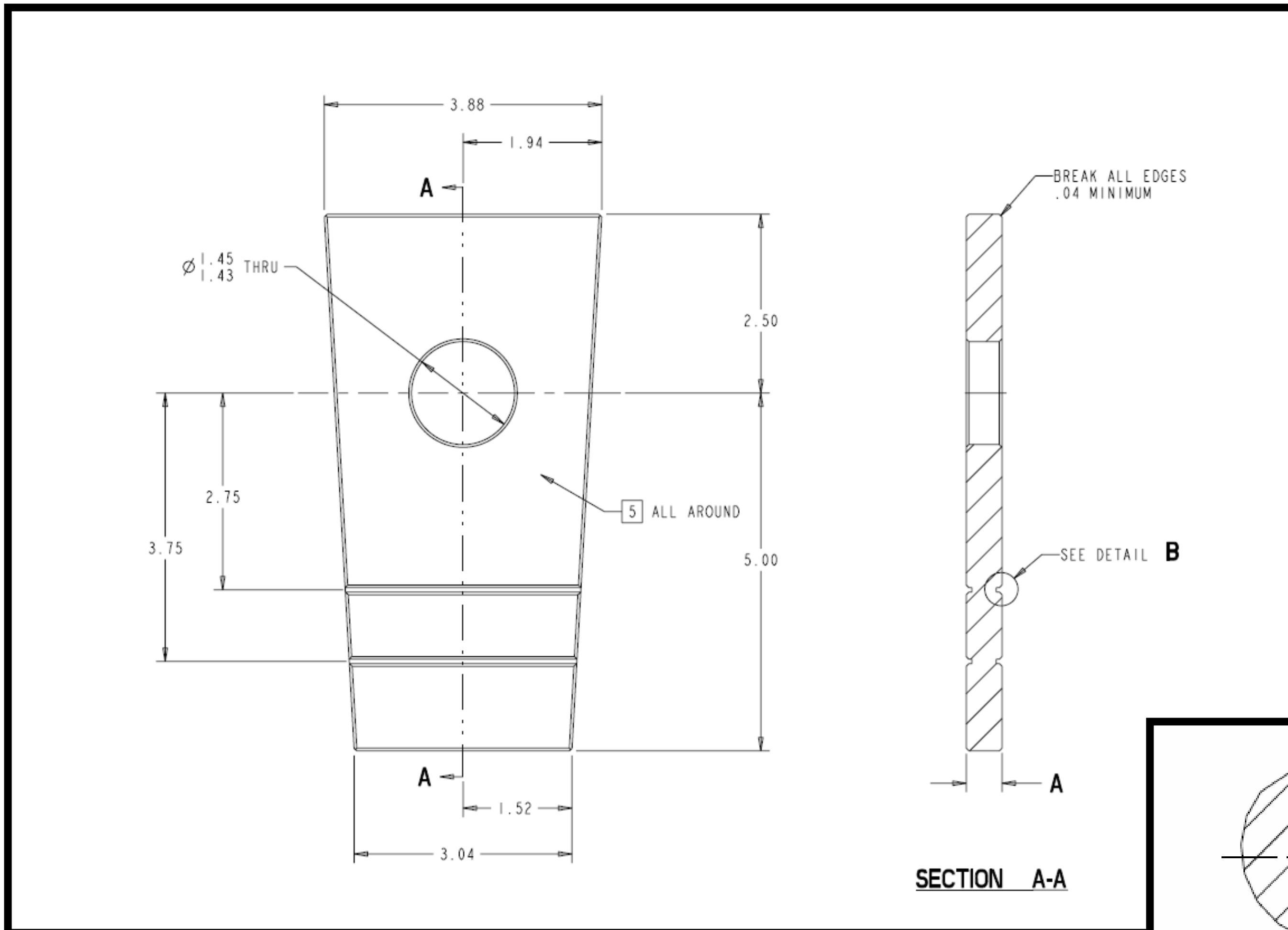
Shim Design

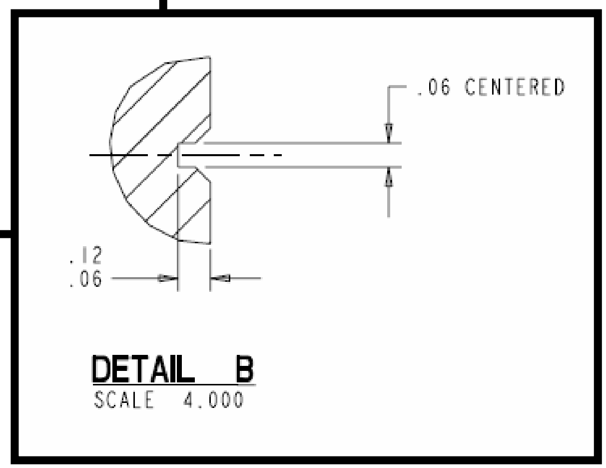


TOTAL 214

QTY REQ'D	DIM A FINISHED SIZE ALUMINA COATED THICKNESS PER SIDE .010 ± .002	MIN FINISHED SIZE	MAX FINISHED SIZE	THICKNESS OF SS ± .001	PART NO
1	.540	.535	.545	.520	-36
1	.538	.533	.543	.518	-35
1	.536	.531	.541	.516	-34
1	.534	.529	.539	.514	-33
2	.532	.527	.537	.512	-32
2	.530	.525	.535	.510	-31
3	.528	.523	.533	.508	-30
4	.526	.521	.531	.506	-29
5	.524	.519	.529	.504	-28
6	.522	.517	.527	.502	-27
7	.520	.515	.525	.500	-26
8	.518	.513	.523	.498	-25
9	.516	.511	.521	.496	-24
10	.514	.509	.519	.494	-23
10	.512	.507	.517	.492	-22
11	.510	.505	.515	.490	-21
12	.508	.503	.513	.488	-20
12	.506	.501	.511	.486	-19
12	.504	.499	.509	.484	-18
12	.502	.497	.507	.482	-17
11	.500	.495	.505	.480	-16
11	.498	.493	.503	.478	-15
10	.496	.491	.501	.476	-14
9	.494	.489	.499	.474	-13
8	.492	.487	.497	.472	-12
7	.490	.485	.495	.470	-11
6	.488	.483	.493	.468	-10
5	.486	.481	.491	.466	-9
4	.484	.479	.489	.464	-8
4	.482	.477	.487	.462	-7
3	.480	.475	.485	.460	-6
2	.478	.473	.483	.458	-5
2	.476	.471	.481	.456	-4
1	.474	.469	.479	.454	-3
1	.472	.467	.477	.452	-2
1	.470	.465	.475	.450	-1

Universal Shim (details)





Universal Shim (initial qty)

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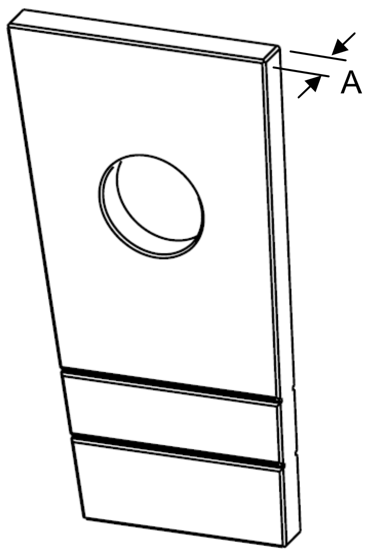

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3	.528	.523	.533	.508	-30
4	.526	.521	.531	.506	-29
5	.524	.519	.529	.504	-28
6	.522	.517	.527	.502	-27
7	.520	.515	.525	.500	-26
8	.518	.513	.523	.498	-25
9	.516	.511	.521	.496	-24
10	.514	.509	.519	.494	-23
10	.512	.507	.517	.492	-22
11	.510	.505	.515	.490	-21
12	.508	.503	.513	.488	-20
12	.506	.501	.511	.486	-19
12	.504	.499	.509	.484	-18
12	.502	.497	.507	.482	-17
11	.500	.495	.505	.480	-16
11	.498	.493	.503	.478	-15
10	.496	.491	.501	.476	-14
9	.494	.489	.499	.474	-13
8	.492	.487	.497	.472	-12
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6	.488	.483	.493	.468	-10
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4	.482	.477	.487	.462	-7
3	.480	.475	.485	.460	-6
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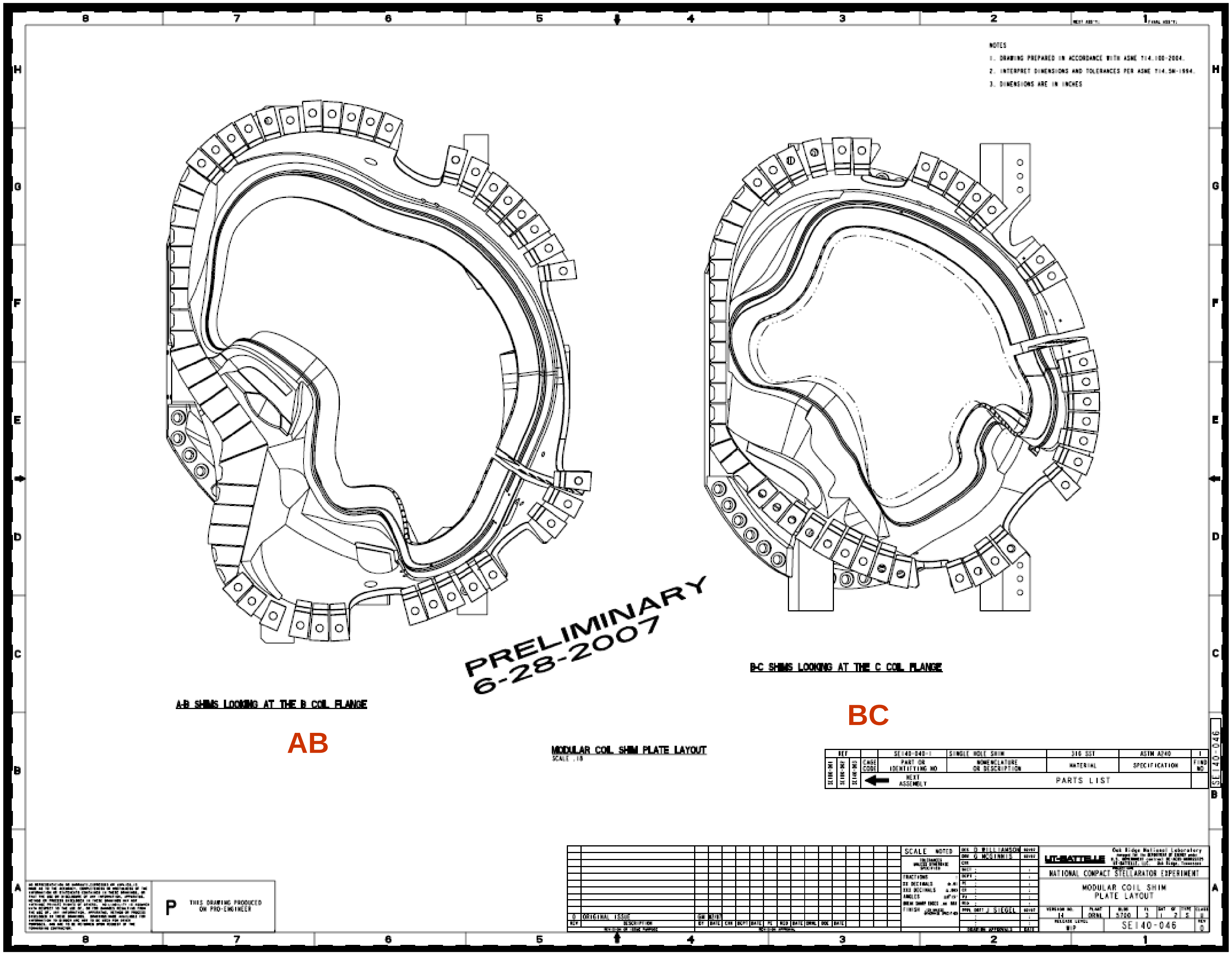
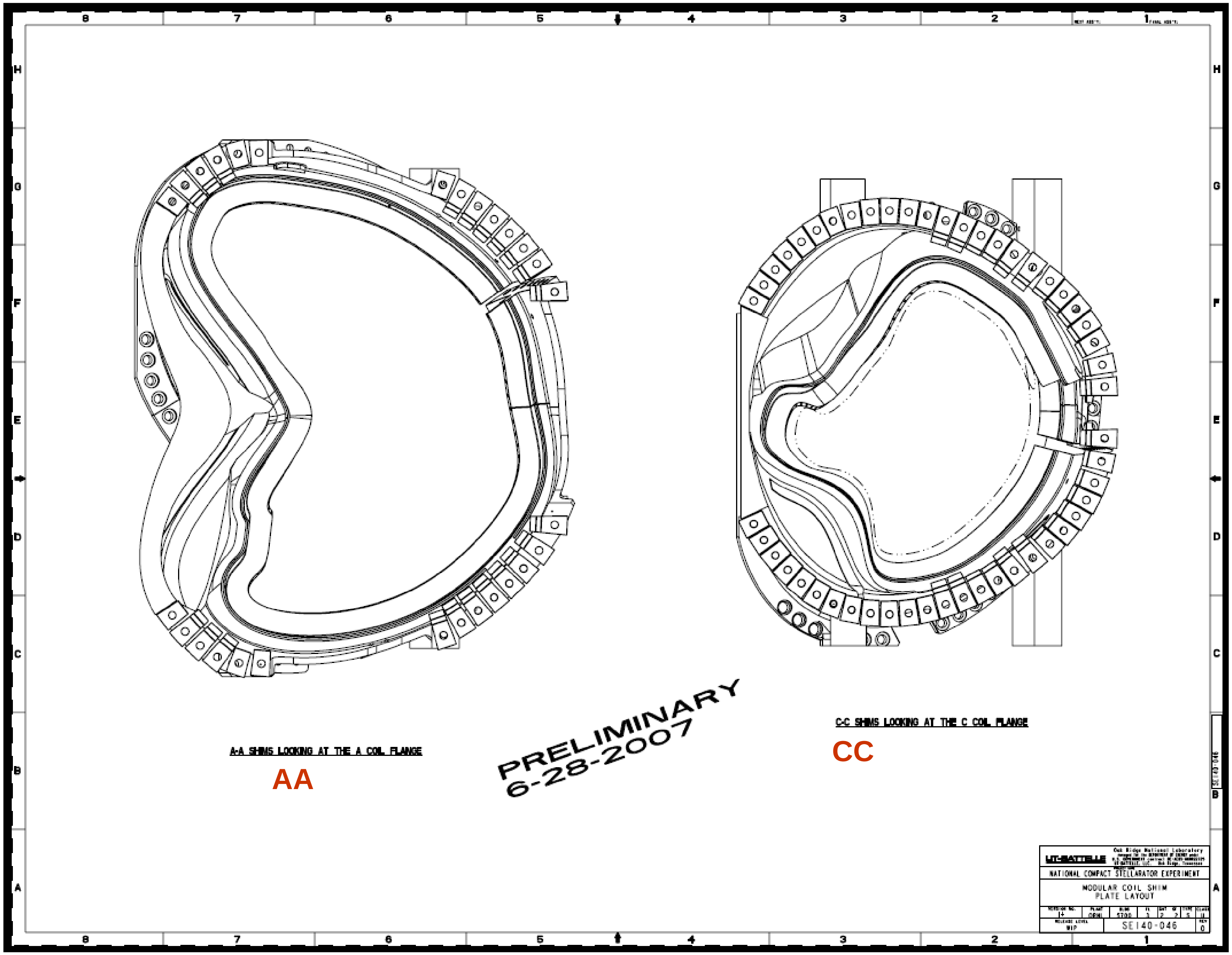
2	.476	.471	.481	.456	-4
1	.474	.469	.479	.454	-3
1	.472	.467	.477	.452	-2
1	.470	.465	.475	.450	-1

Shim Configuration

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

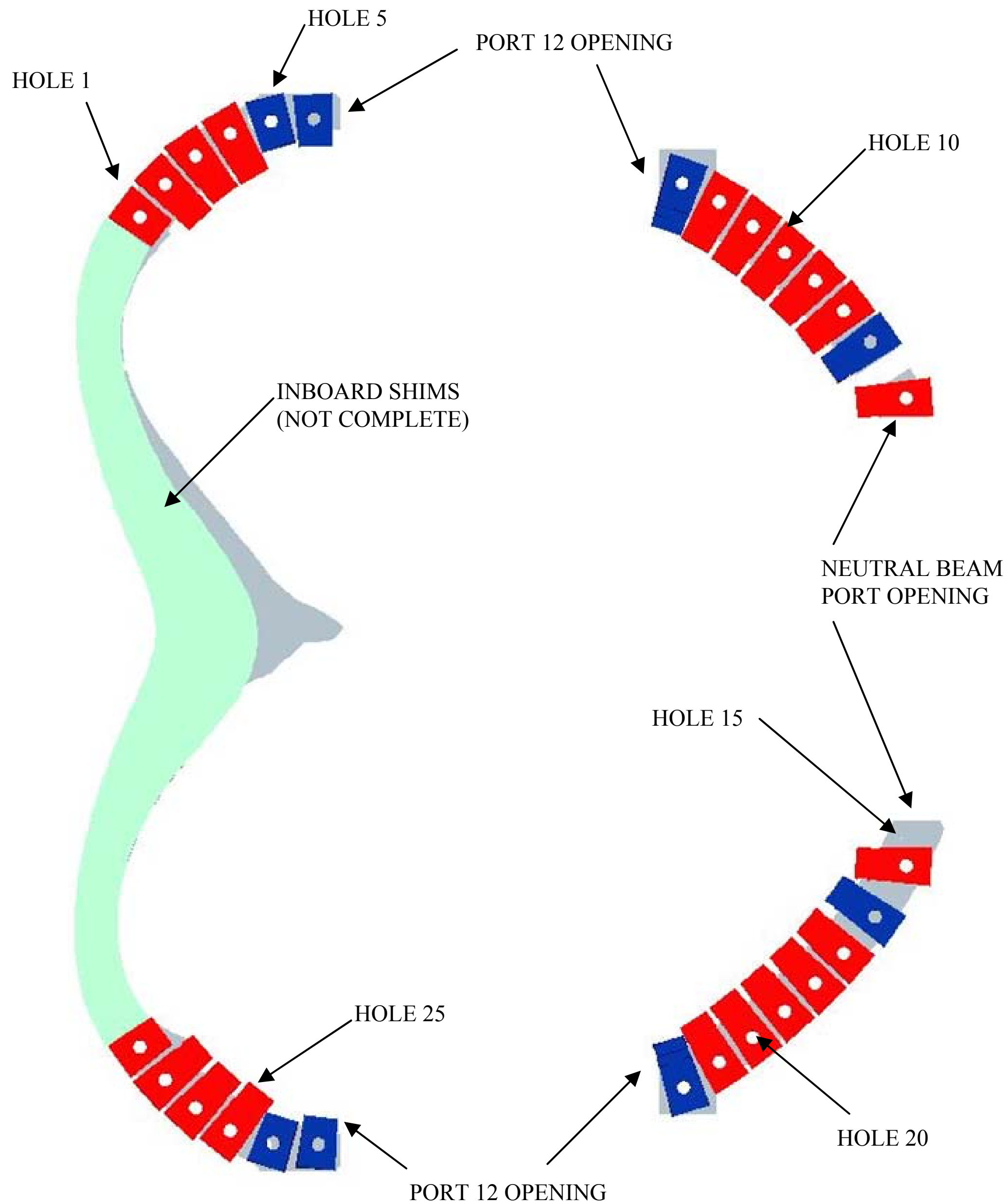


Shim Configuration



Shim Layout AA

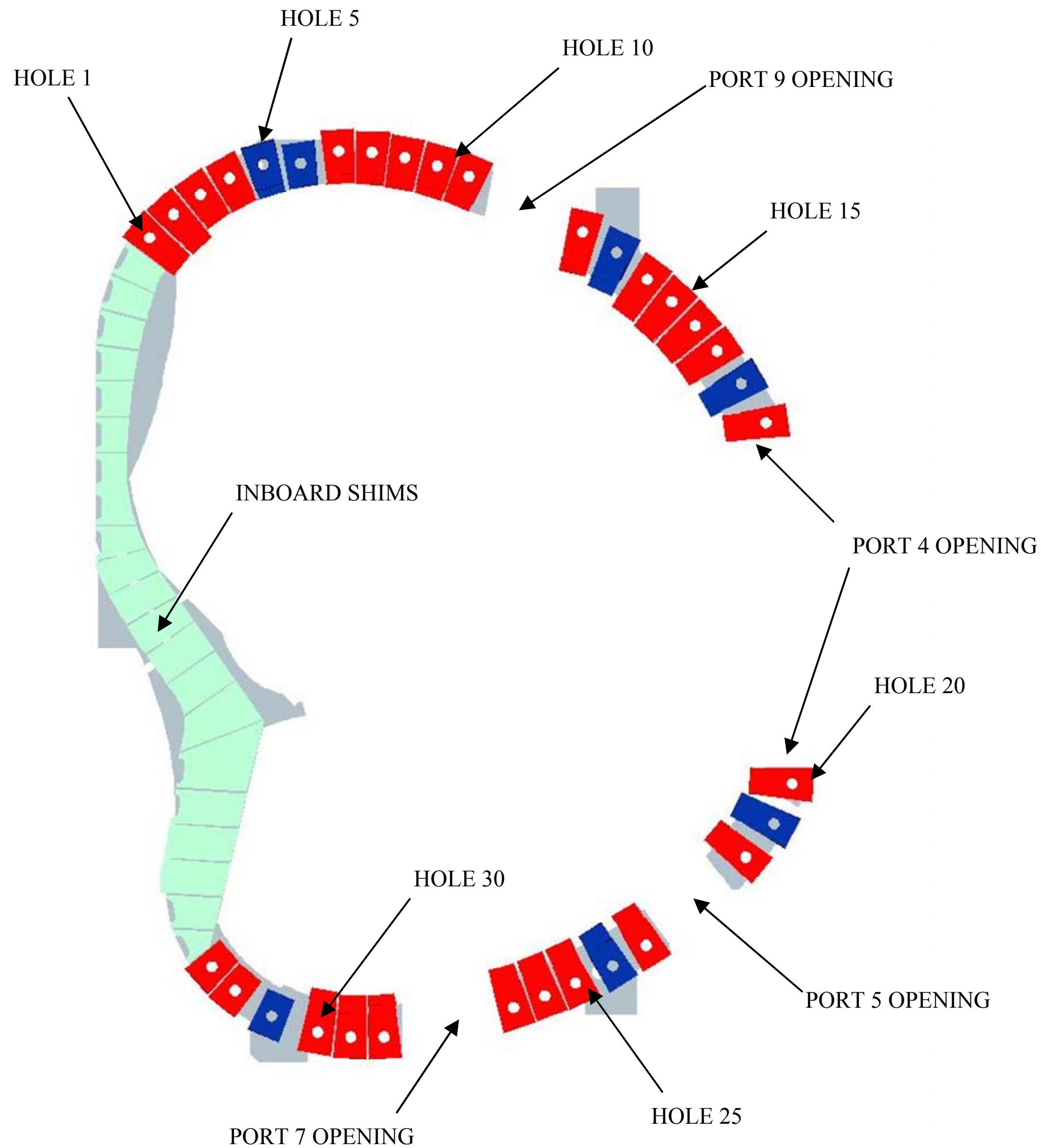
AA Hole #	Shim Length Hole to Bottom	No Bolt Shim
1	2.75	
2	5.00	
3	5.00	
4	5.00	
5		2.75
6		2.75
7		5.00
8	5.00	
9	5.00	
10	5.00	
11	5.00	
12	5.00	
13		5.00
14	5.00	
15	5.00	
16		5.00
17	5.00	
18	5.00	
19	5.00	
20	5.00	
21	5.00	
22		5.00
23		2.75
24		2.75
25	5.00	
26	5.00	
27	5.00	
28	2.75	



Shim Layout AB

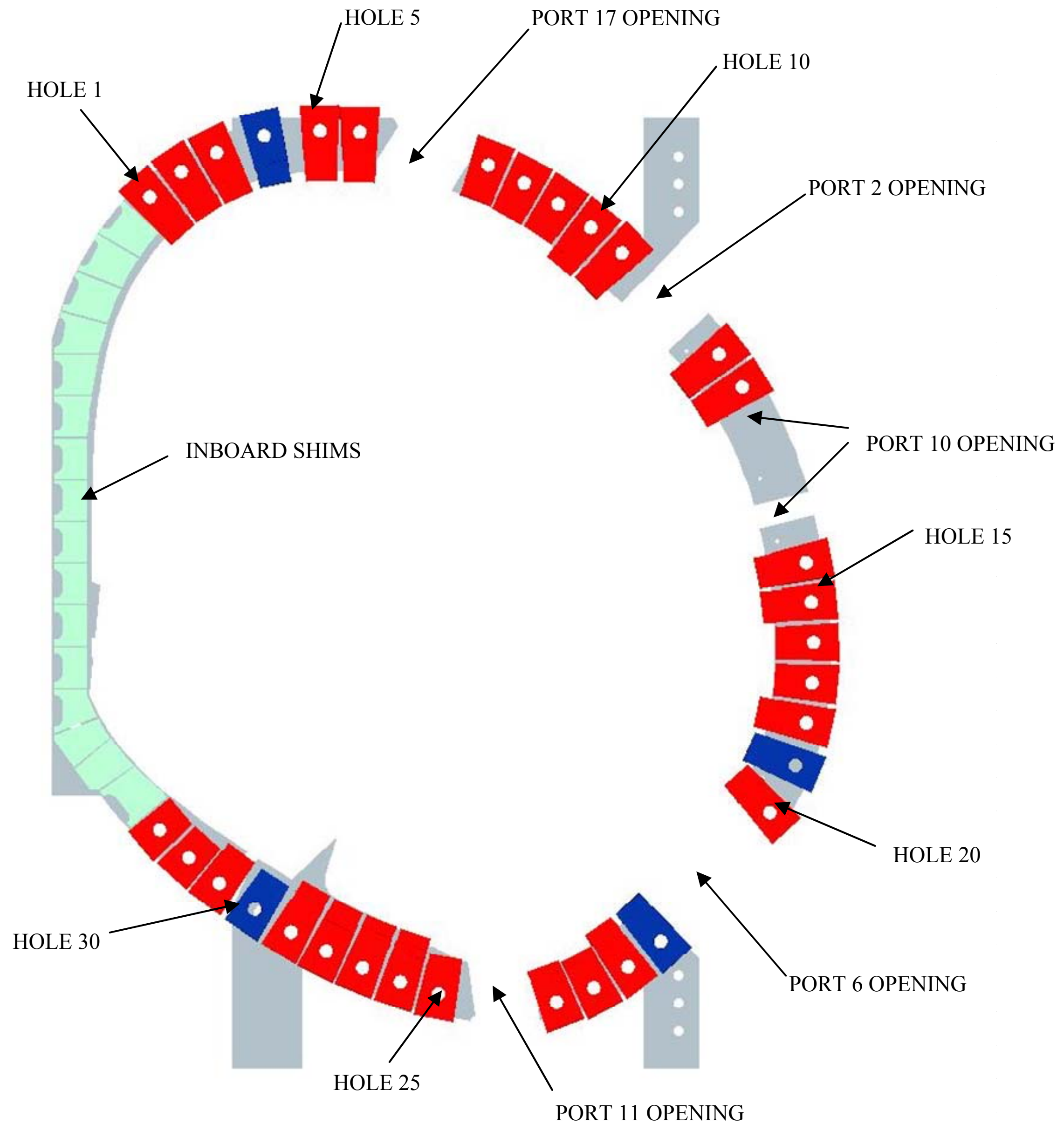
NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

AB Hole #	Shim Length Hole to Bottom	No Bolt Shim
1	5.00	
2	5.00	
3	3.75	
4	3.75	
5		3.75
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	



Shim layout BC

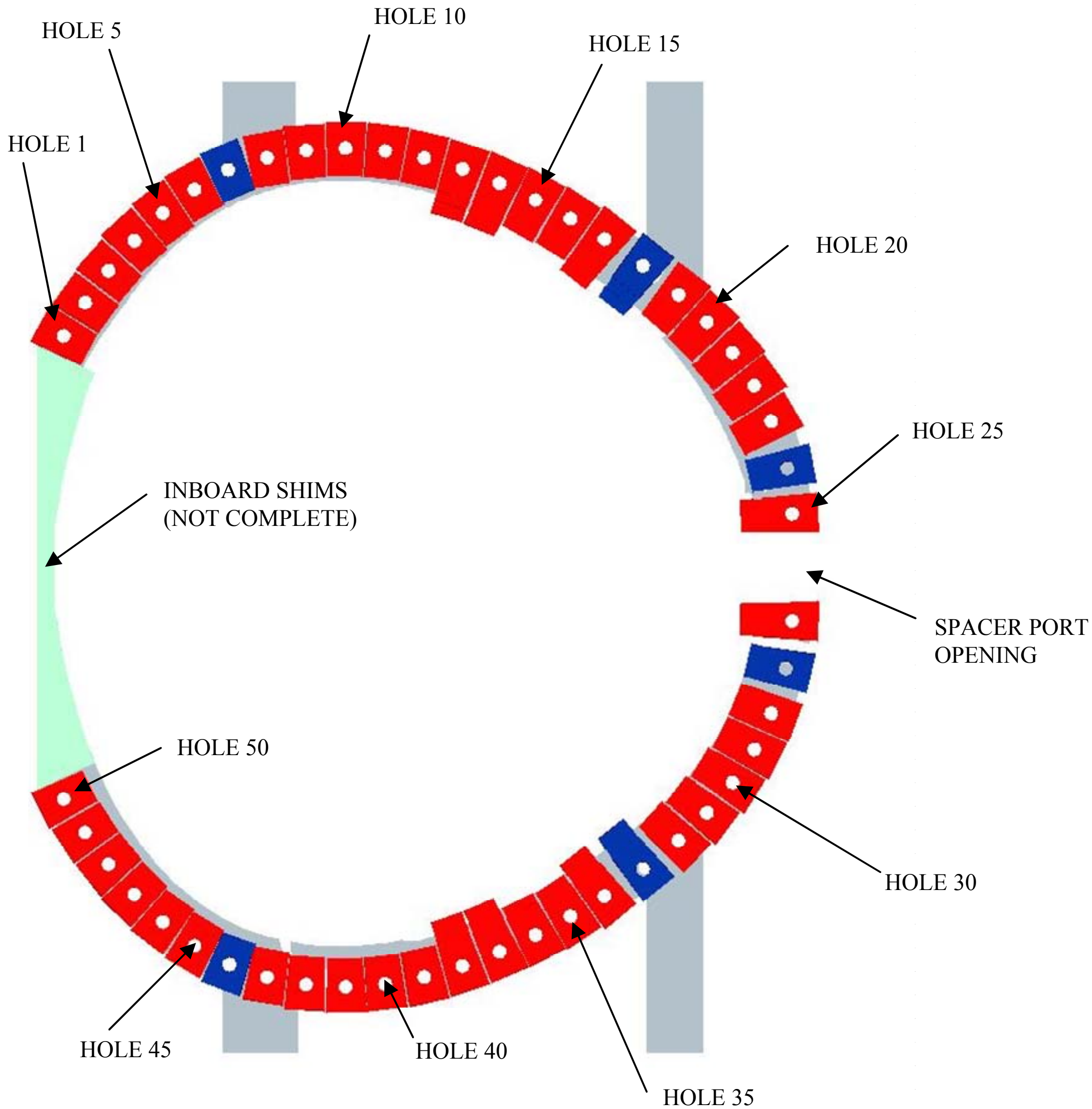
BC Hole #	Shim Length Hole to Bottom	No Bolt Shim
1	5.00	
2	5.00	
3	5.00	
4		5.00
5	5.00	
6	5.00	
7	3.75	
8	3.75	
9	3.75	
10	5.00	
11	5.00	
12	5.00	
13	5.00	
14	5.00	
15	5.00	
16	3.75	
17	3.75	
18	5.00	
19		5.00
20	5.00	
21		5.00
22	5.00	
23	3.75	
24	3.75	
25	3.75	
26	5.00	
27	5.00	
28	5.00	
29	5.00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



Shim Layout CC

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

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	



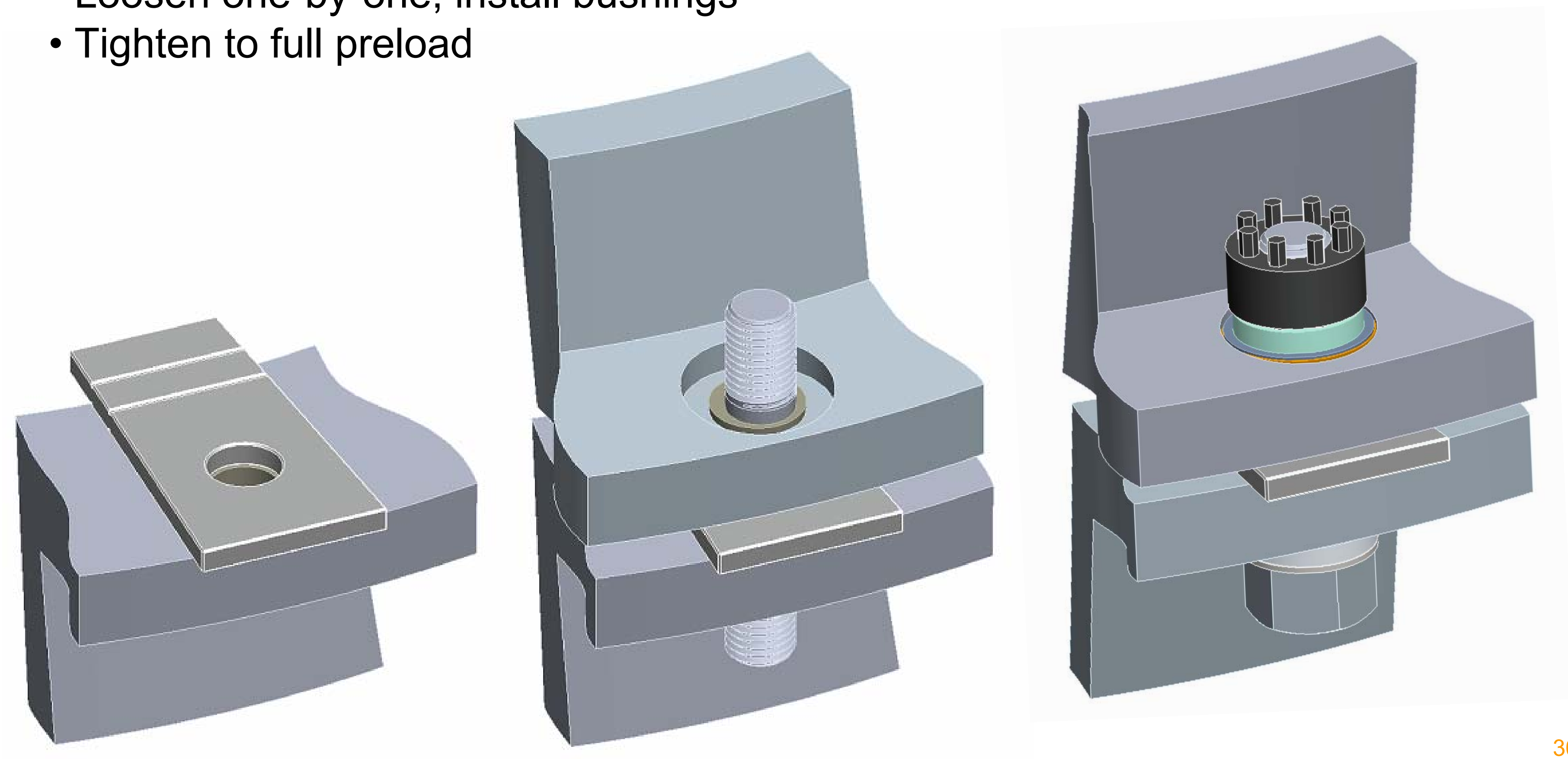
Shim Table – All Flanges

SHIM LENGTH-HOLE TO BOTTOM	AA FLANGE	AB FLANGE	BC FLANGE	CC FLANGE	TOTAL
2.75	6	4	2	24	36
3.75		8	10	16	34
5.00 (UN-CUT)	22	21	21	10	74
TOTAL PER FLANGE	28	33	33	50	
TOTAL PER FIELD PERIOD	28	66	66		**160**
TOTAL PER MACHINE	84	198	198	150	**630**

Assembly Sequence

Proposed modification to Machine Asm Seq Plan R7:

- Place initial set of metal shims on lower coil
- Position upper coil w/o bolting, measure and install bushings
- Install fasteners, torque to 50% preload, measure
- Loosen studs, install final shims, tighten, measure
- ~~Loosen one-by-one, install bushings~~
- Tighten to full preload

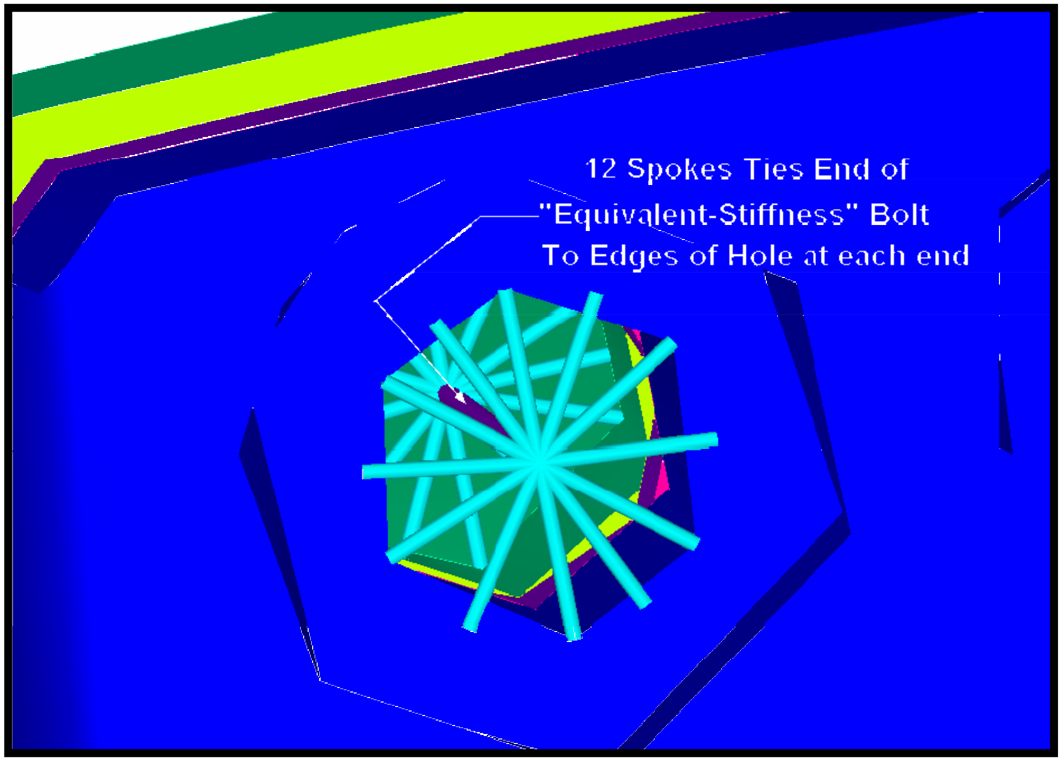


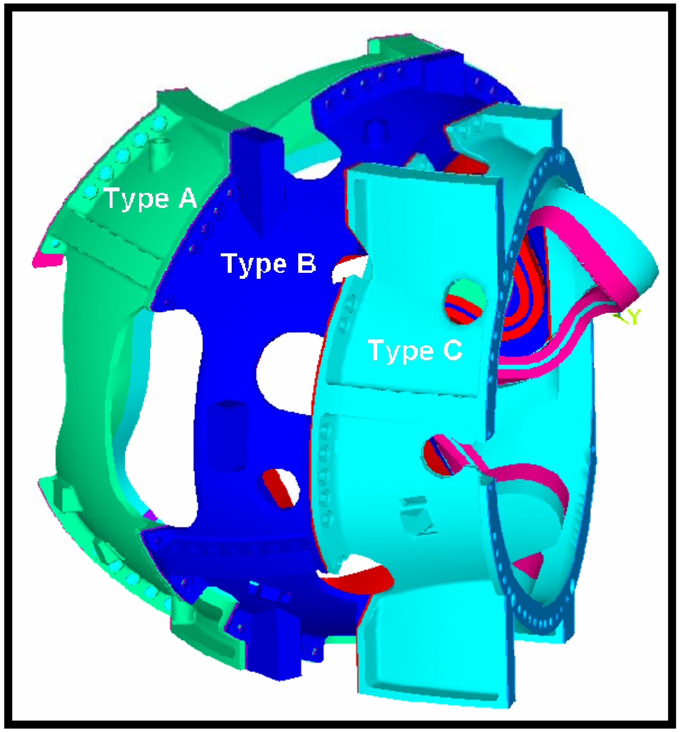
Finite Element Analysis

Analysis Assumptions

- 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



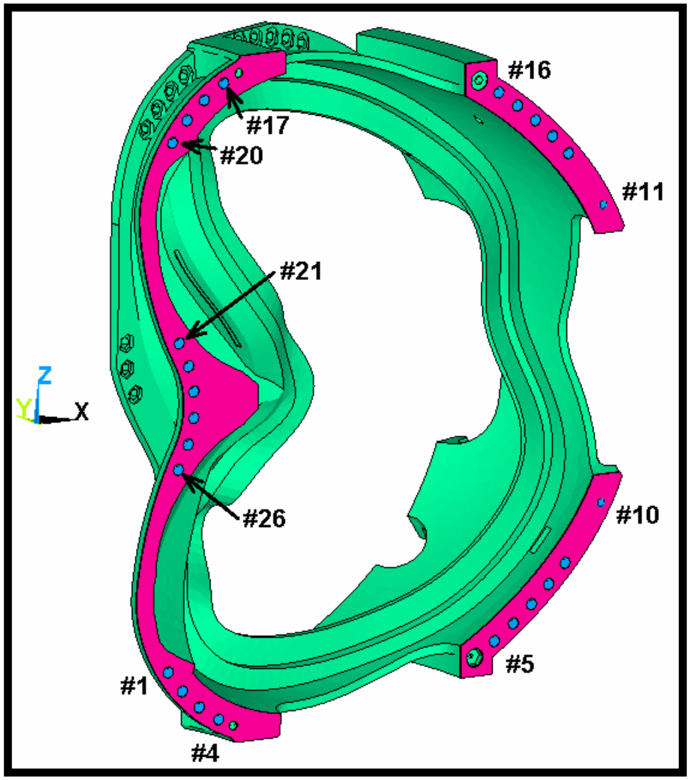


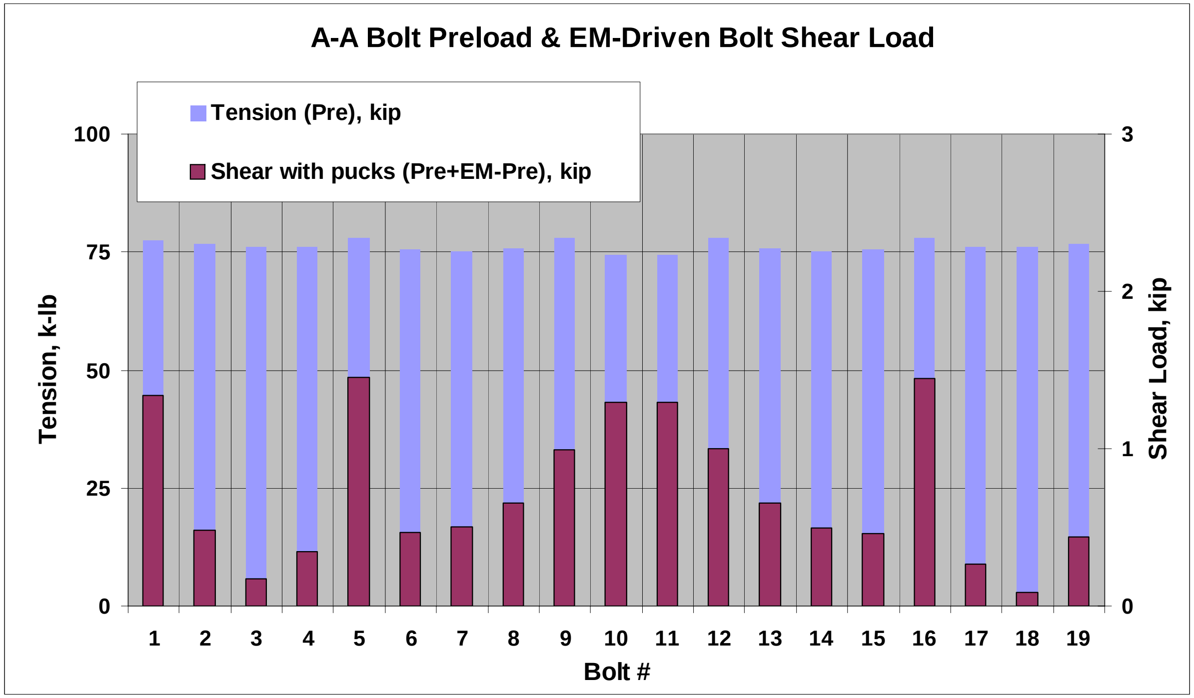
At one particular interface, pipe elements with appropriate section properties are used to represent the characteristics of a bolted interface. Contact elements at this interface are allowed sliding contact (no separation).

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.

AA Bolt loadings (outboard)





This model has inner leg bolts and friction of 0.4 over the entire surface. The inner leg is now welded and thus, the conditions on the outboard can be no worse than the condition presented. This is Conservative.

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

AA Joint

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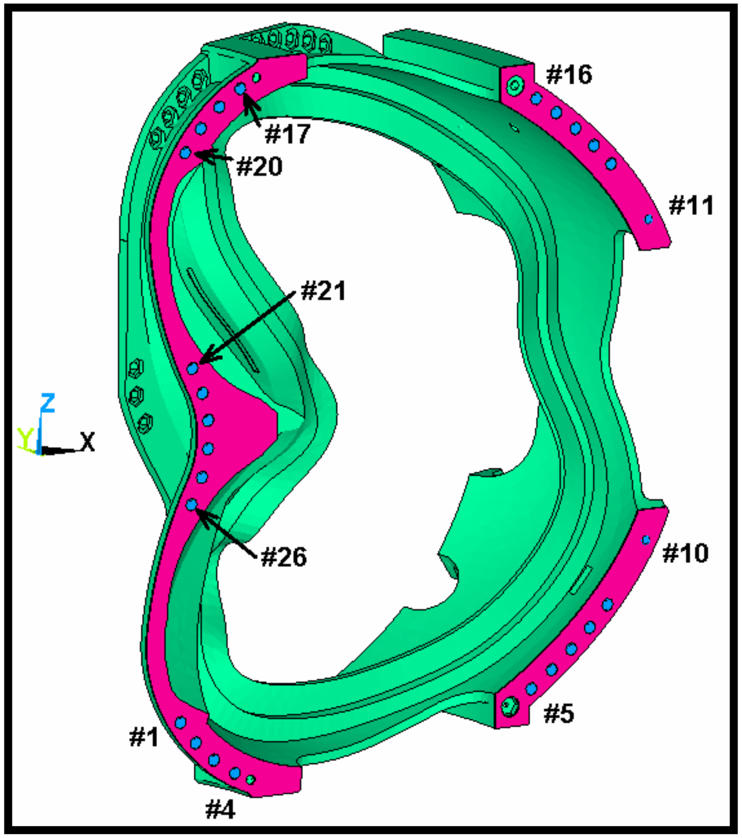
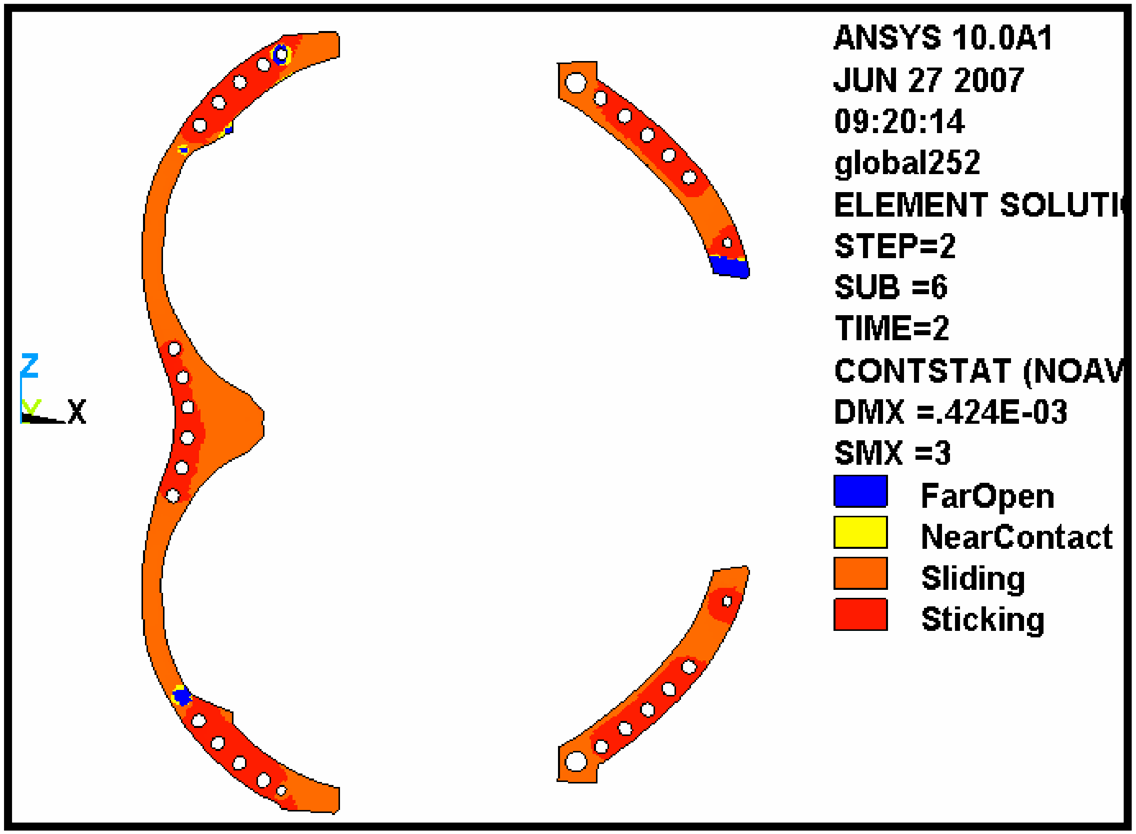
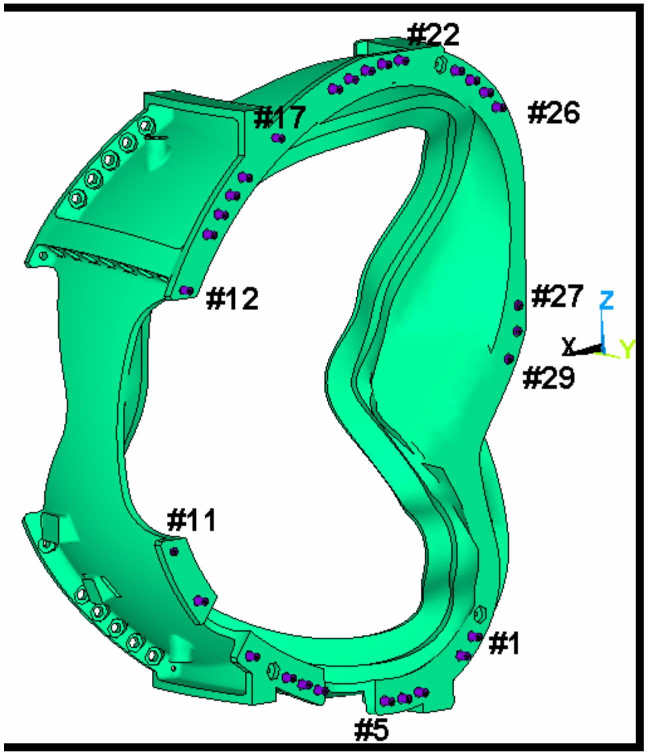
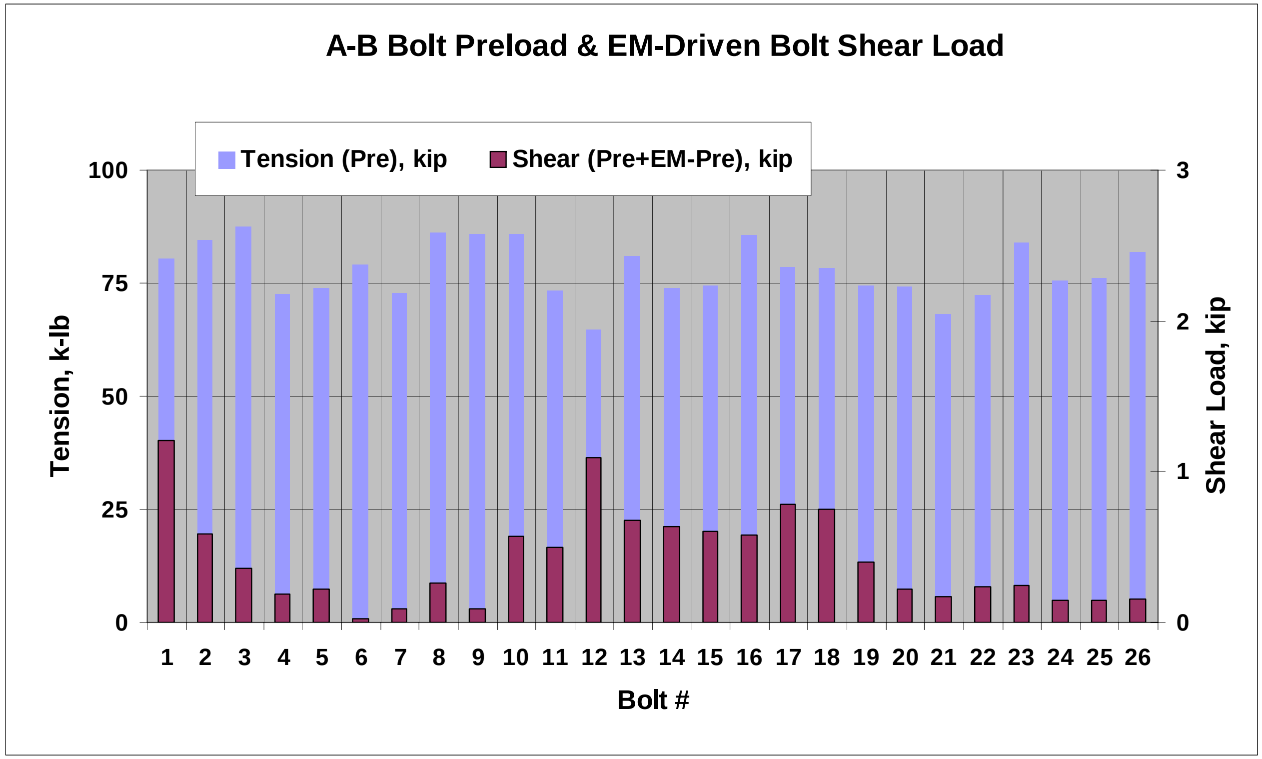




The Joint is stuck (red) under every outboard bolt.

AB joint



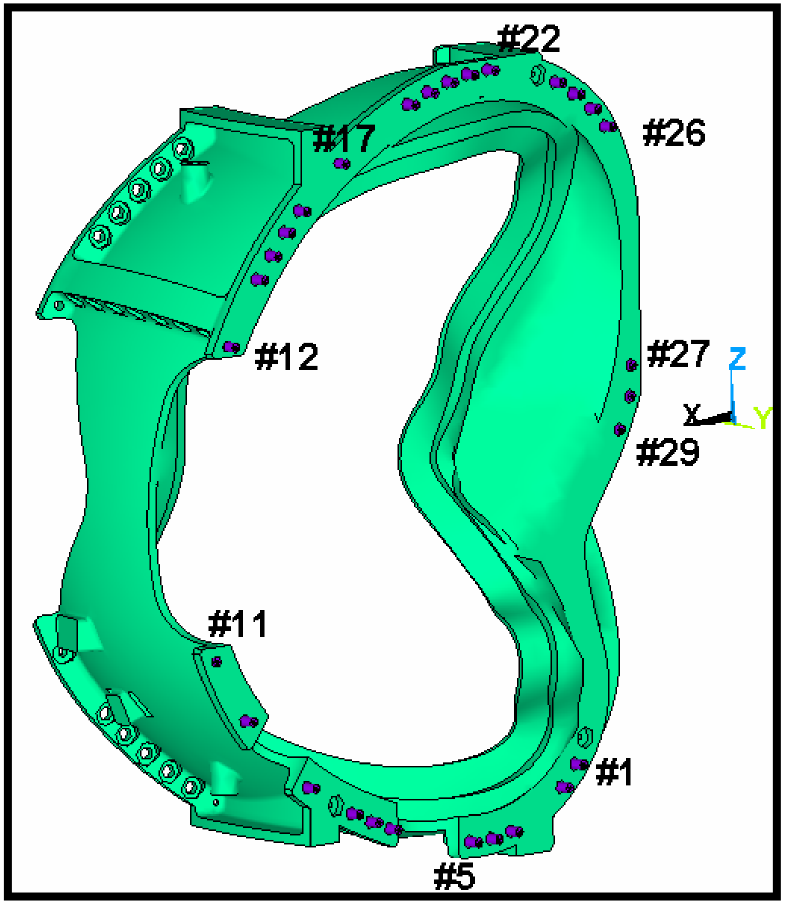


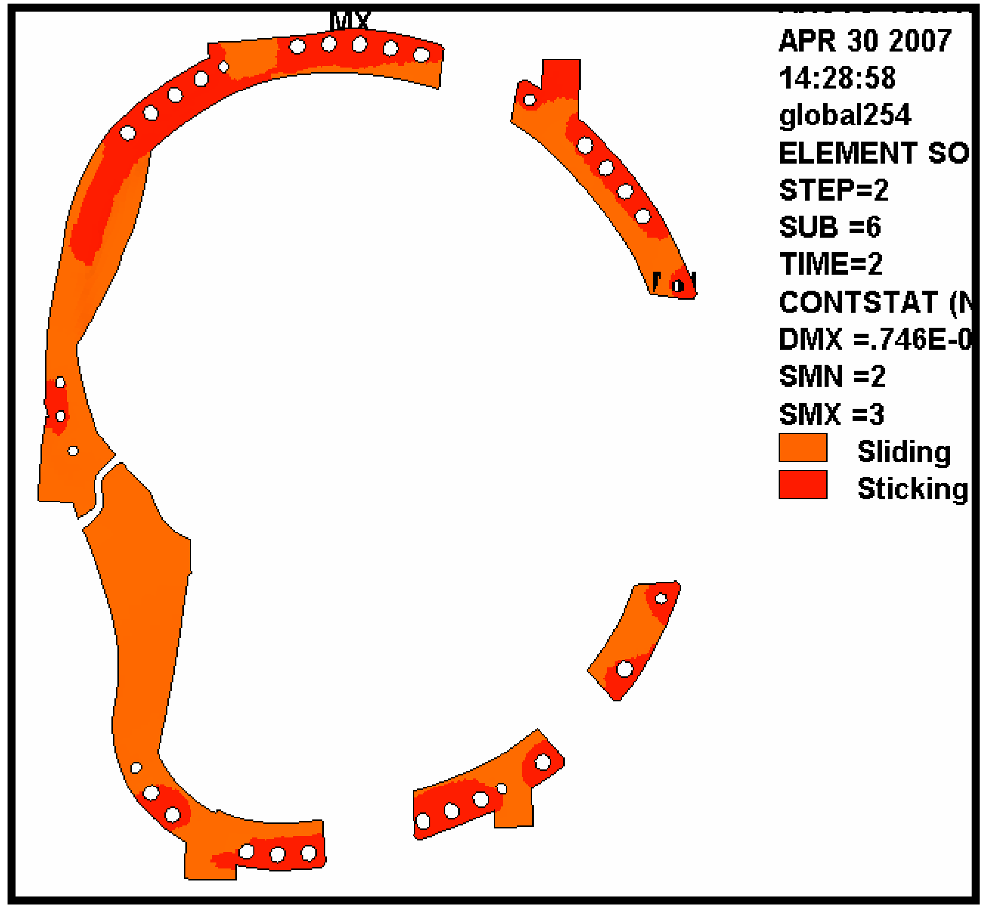
This model has inner leg bolts and friction of 0.4 over the entire surface. The inner leg is now welded and thus, the conditions on the outboard can be no worse than the condition presented. This is Conservative.

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

AB Joint

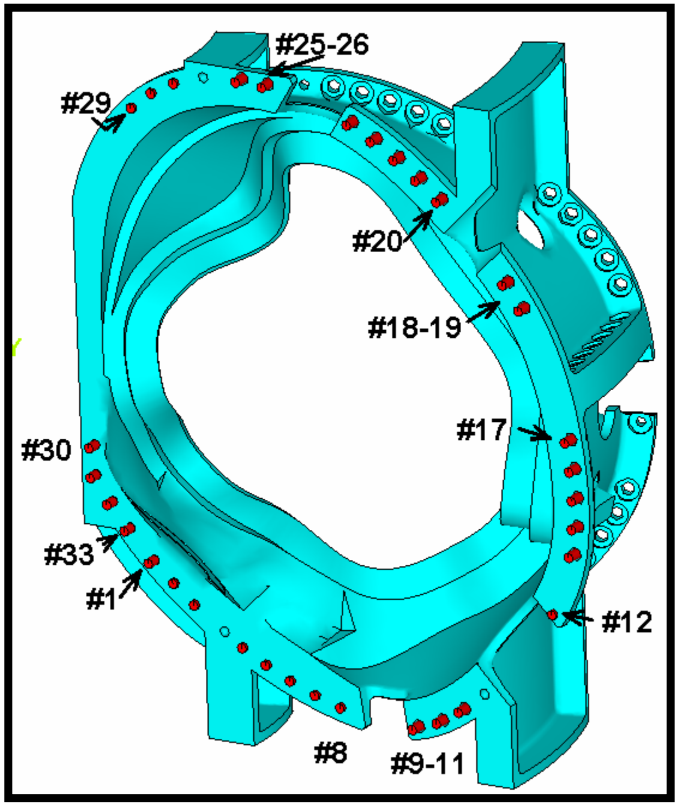
NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

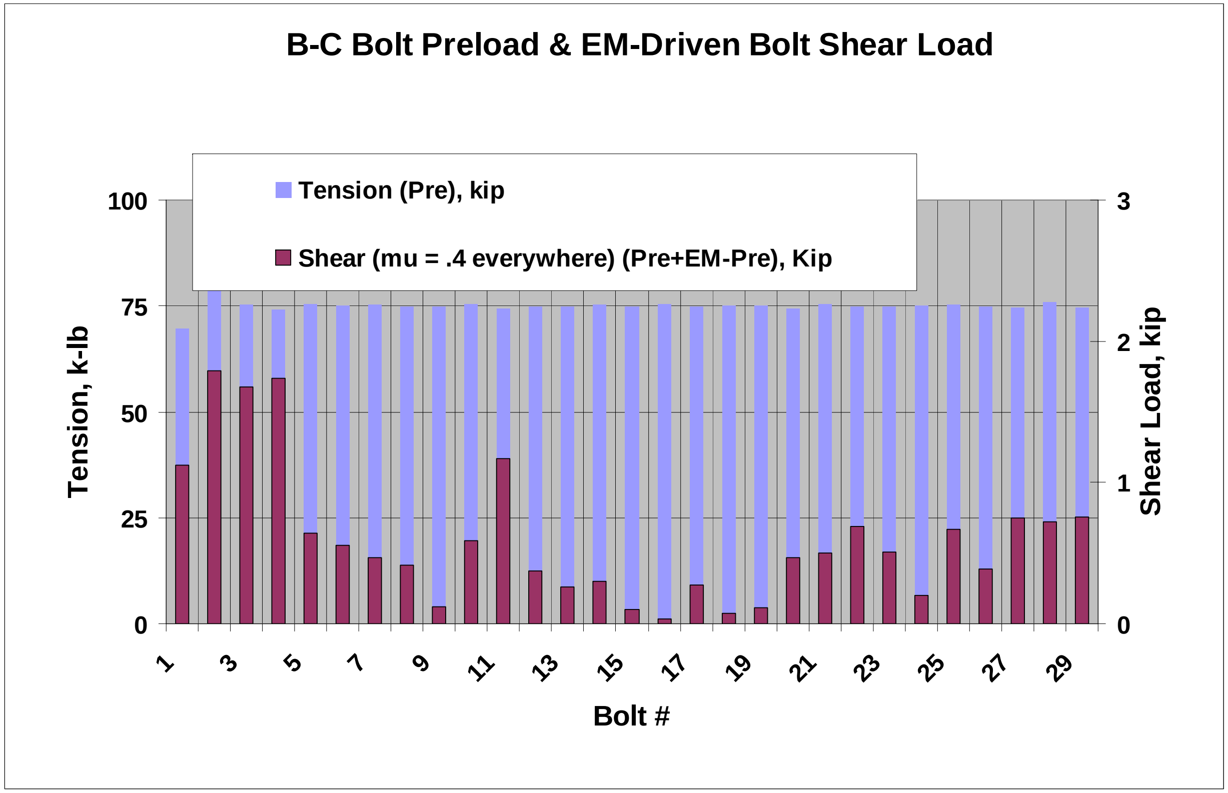




The Joint is stuck (red) under every outboard bolt.

BC Joint

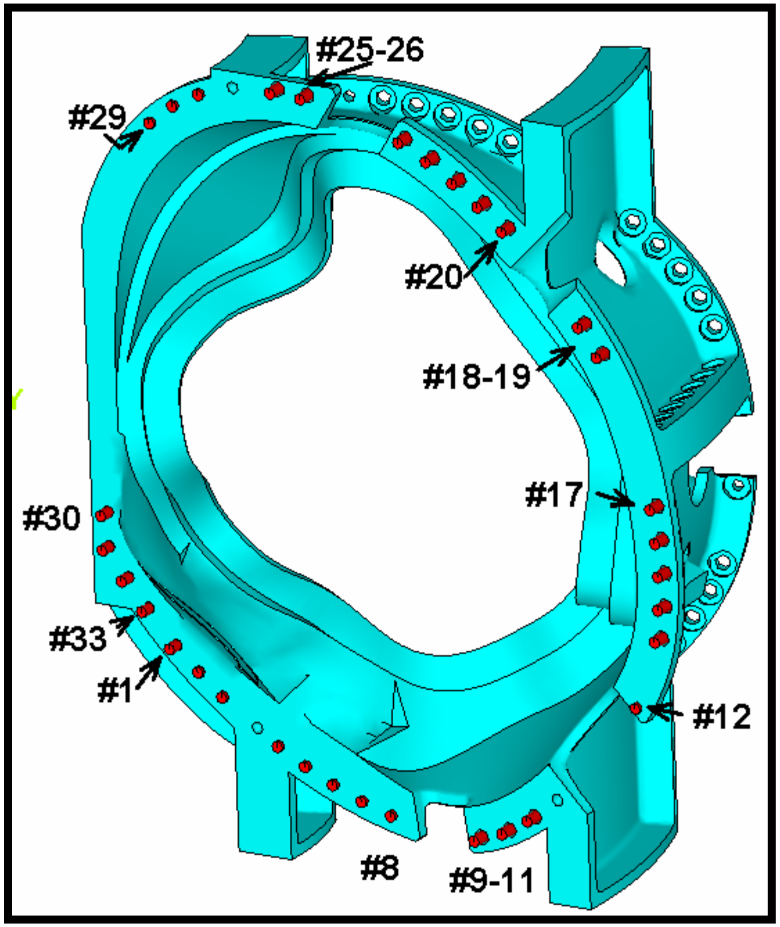


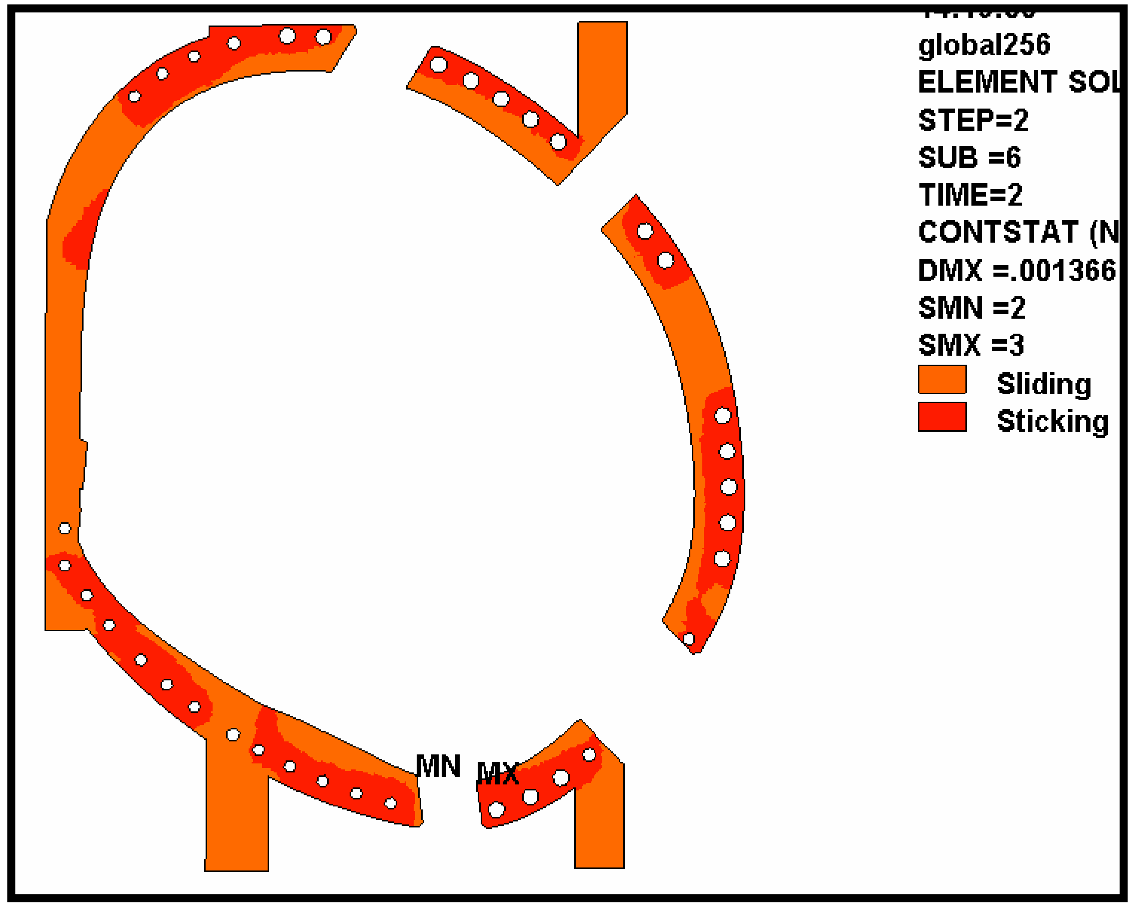


This model has inner leg bolts and friction of 0.4 over the entire surface. The inner leg is now welded and thus, the conditions on the outboard can be no worse than the condition presented. This is Conservative.

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

BC Joint

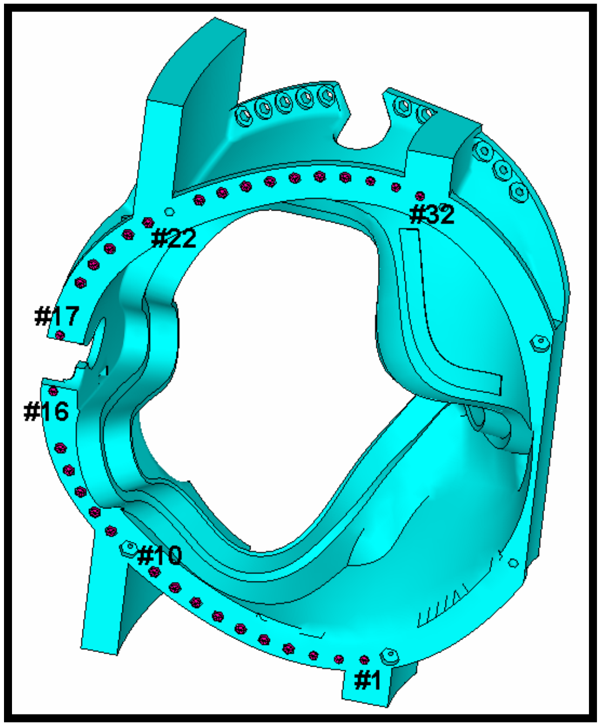


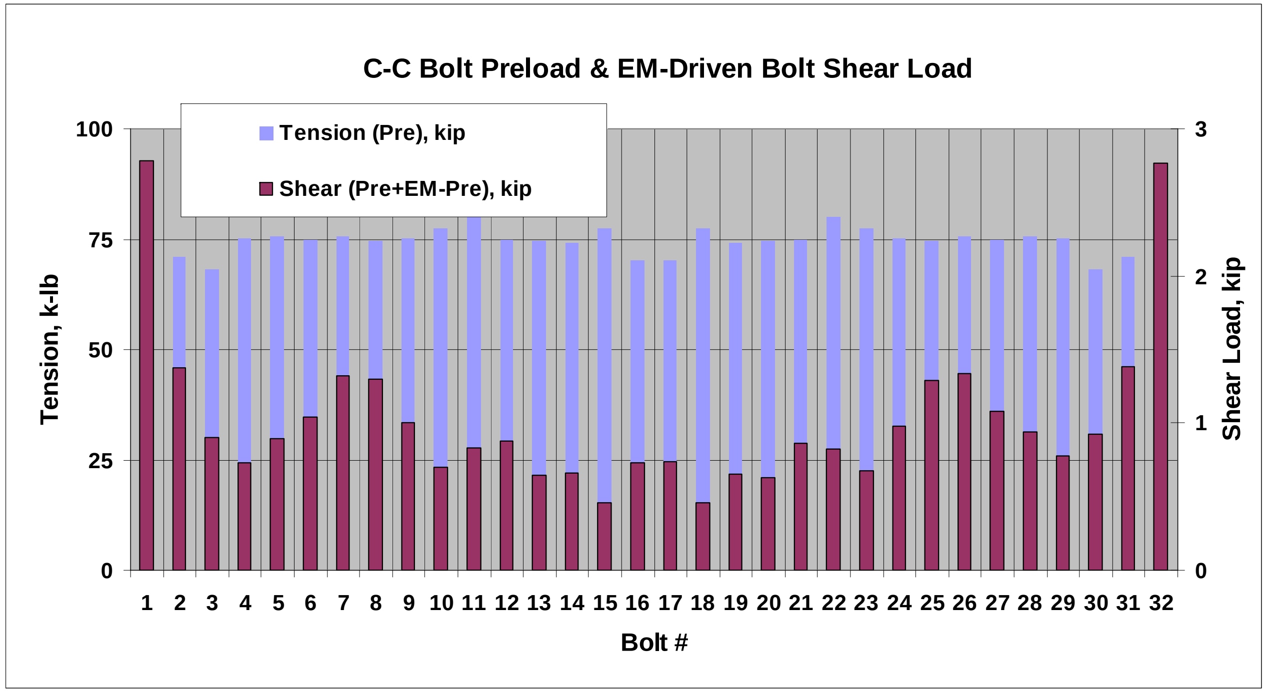


The Joint is stuck under every outboard bolt.

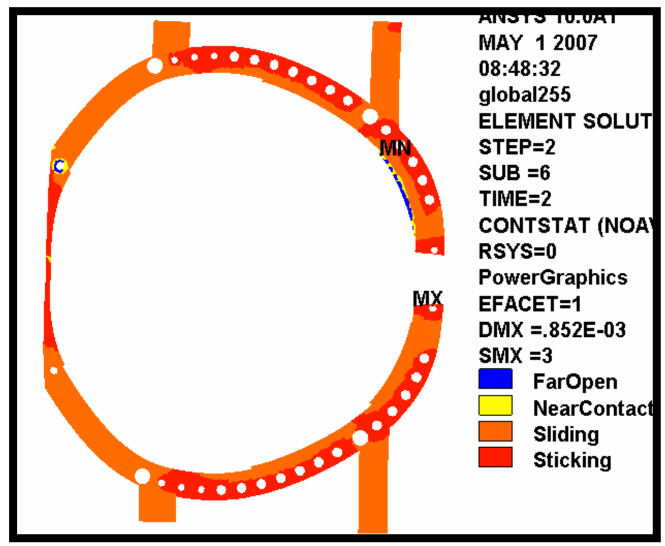
CC-Joint

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT





- 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 shear)



Options to restrain movement of inboard leg.

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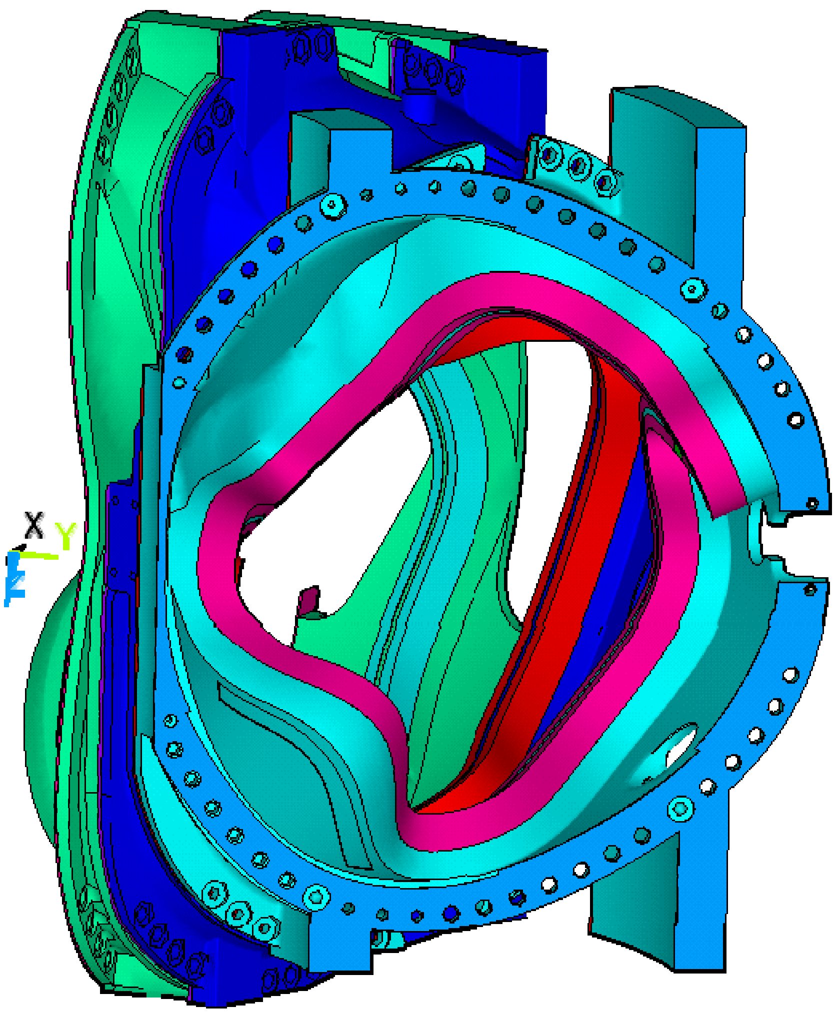
Options include adding 6 to 12 bolts on the inner leg (model on right has 12 bolts added north and south of the midplane.)



Option 1 for inner leg: Add 6 Inner bolts (3 top and 3 bottom)

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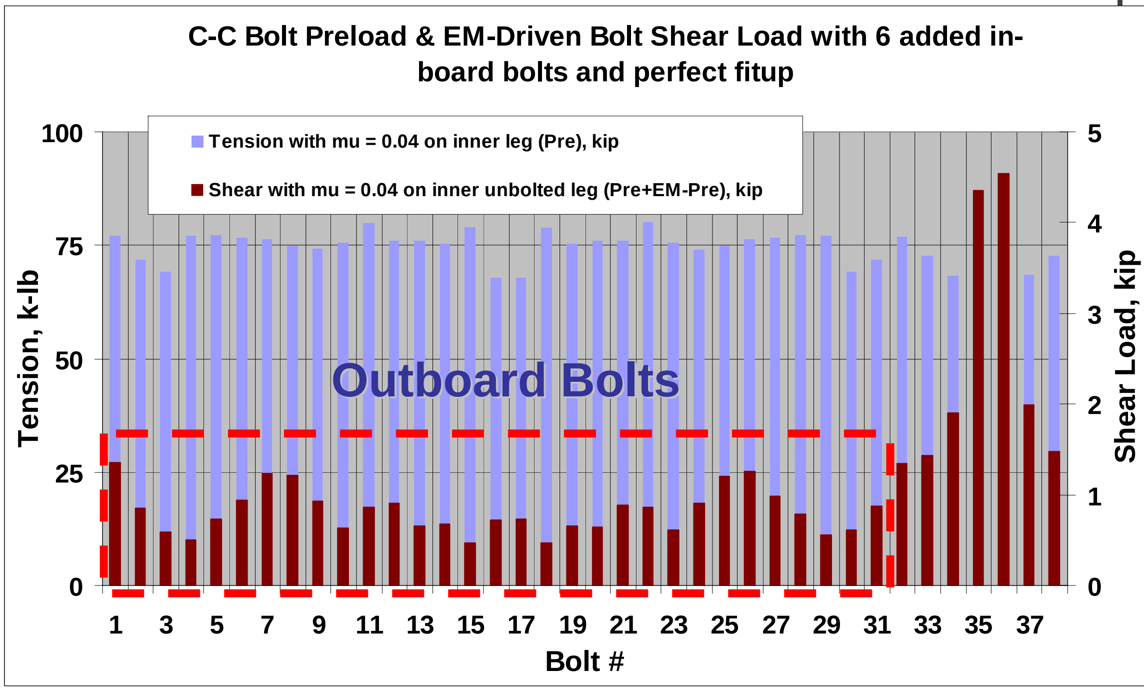

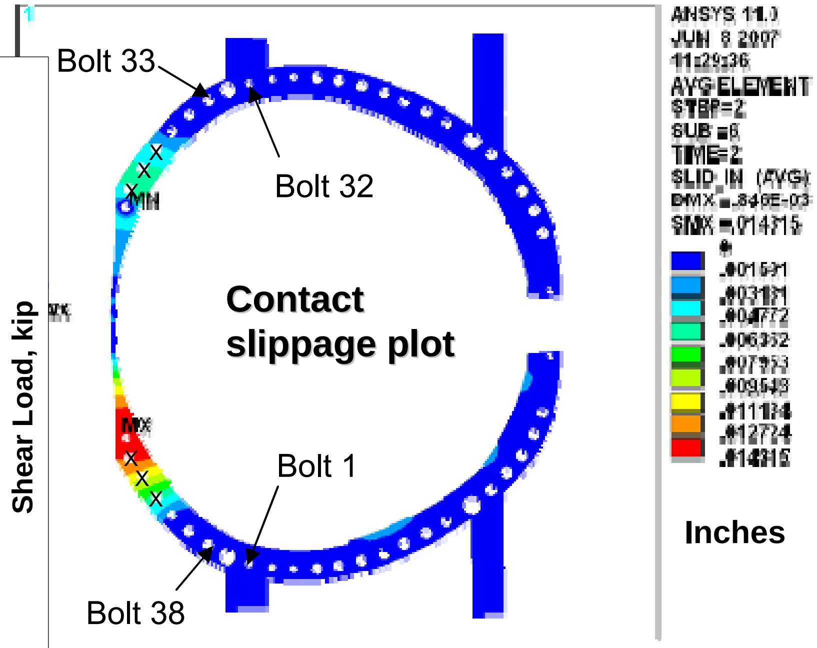

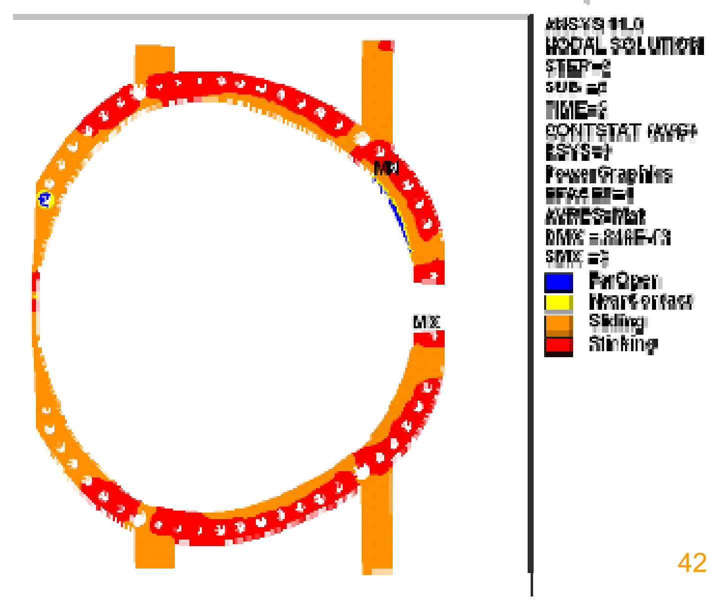

Friction = <u>0.04</u> on Inner-leg region, mu = 0.4 everywhere else

Outer Bolts #1 and #32 are now completely stuck

Inner most added bolts (#35 and #36) still slip and may need to be enlarged to 1.5" for increased preload. <u>These are not considered as "outboard bolts" and are outside the scope.</u>

Option 2 for inner leg: Add 12 Inner bolts (6 top and 6 bottom)

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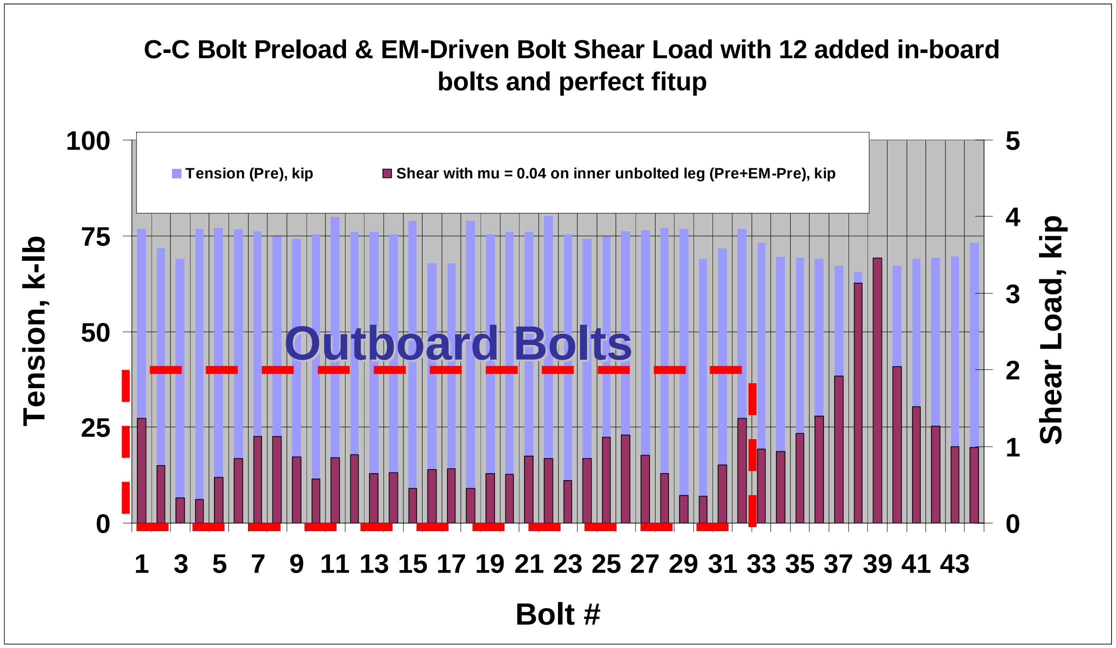
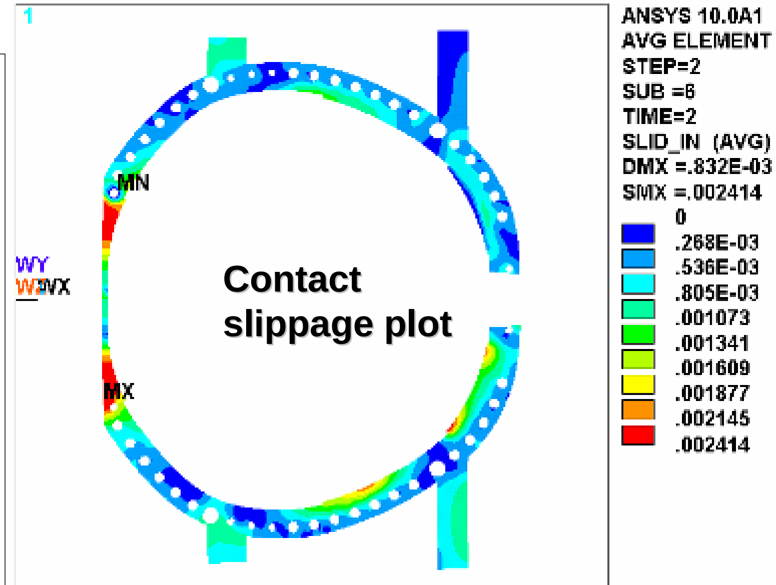
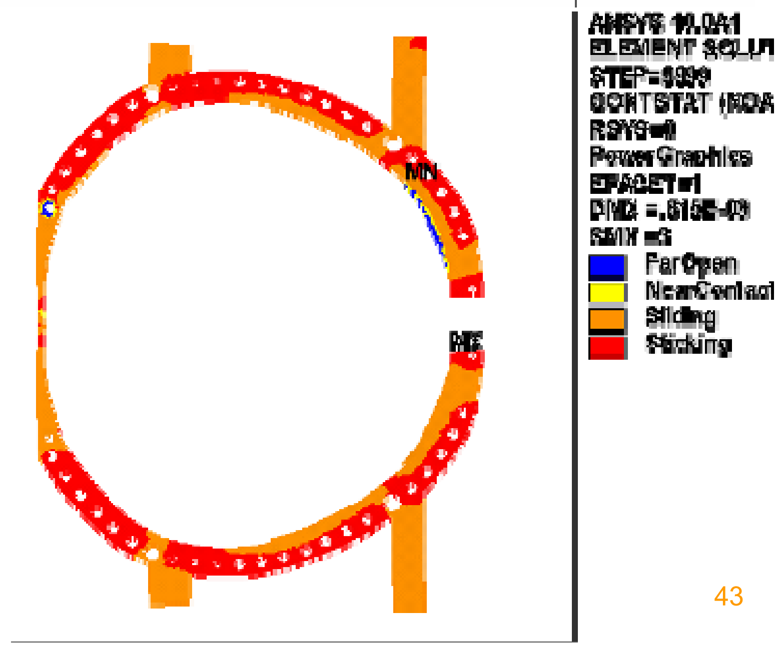






Friction = <u>0.04</u> on Inner-leg region, mu = 0.4 everywhere else

Outer Bolts #1 and #32 are now completely stuck. Inner leg slippage has been essentially eliminated.

Innermost inboard bolts (#38 - #39) are stuck.

CC Summary

- In either option for restraining the inboard leg, the outboard bolts (#1- #32) of CC do not slip.
- The innermost added inboard bolt and perhaps all of the added inboard bolts should be increased from 1.375” to 1.5” to provide additional preload to the joint on the inner leg.

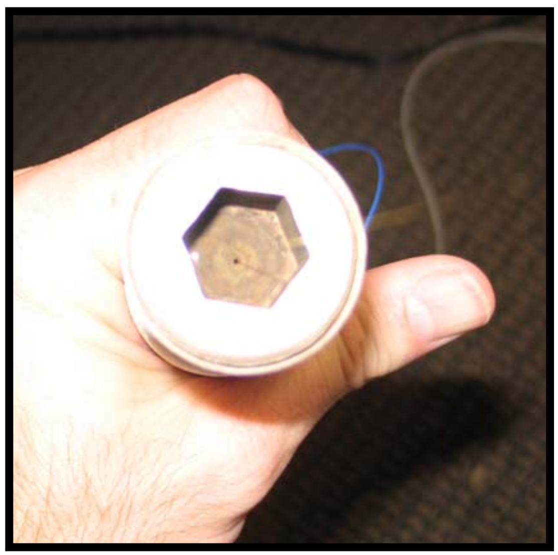
AA, AB, BC Summary

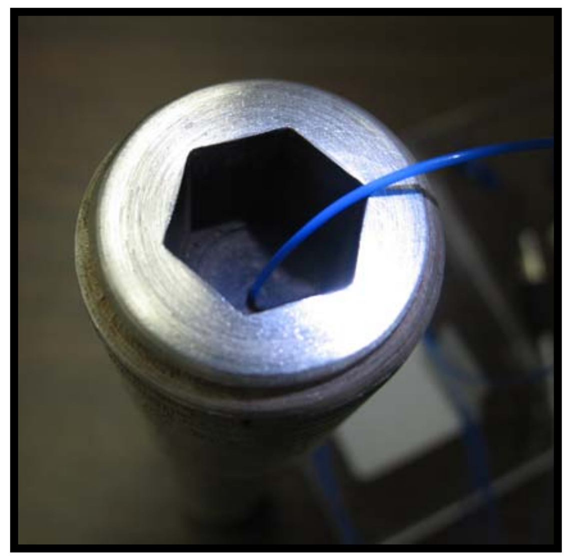
- The analysis performed shows that the outboard bolts do not slip when 0.4 friction is applied everywhere with the previously added inboard bolts. This is consistent with the linear analysis which tabulated Average COF's (Fan and Brooks appendix slide).
- By welding the inboard region, the conditions studied are conservative as the welds will be stiffer and react more load than the previously added inboard bolts. The end bolts will not see increased load.

Confirmatory Experimental Testing

Measurement of preload

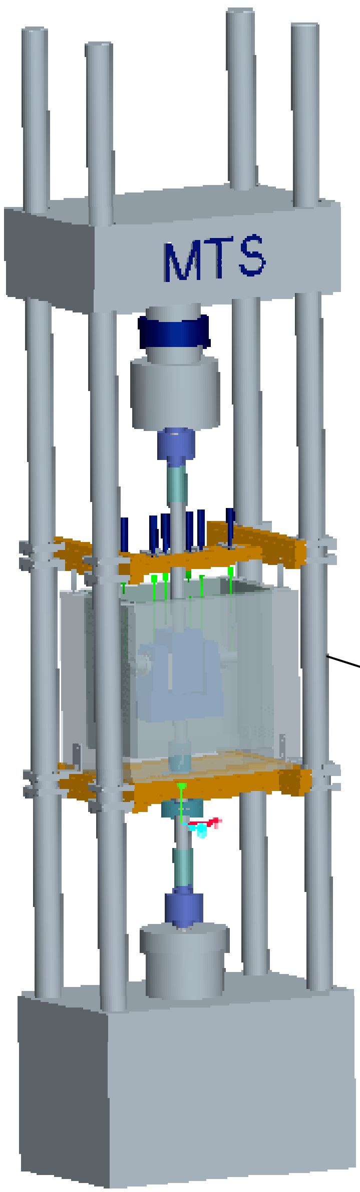
- Fiber optic gages (which can be calibrated before installation!!) can be installed in a number of bolts to monitor preload during life.
- The gages would indicate when to re-torque when and if the preload lessons.
- Largest obstacle (drilling a 0.02” hole through a 9” long stud has been achieved.)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

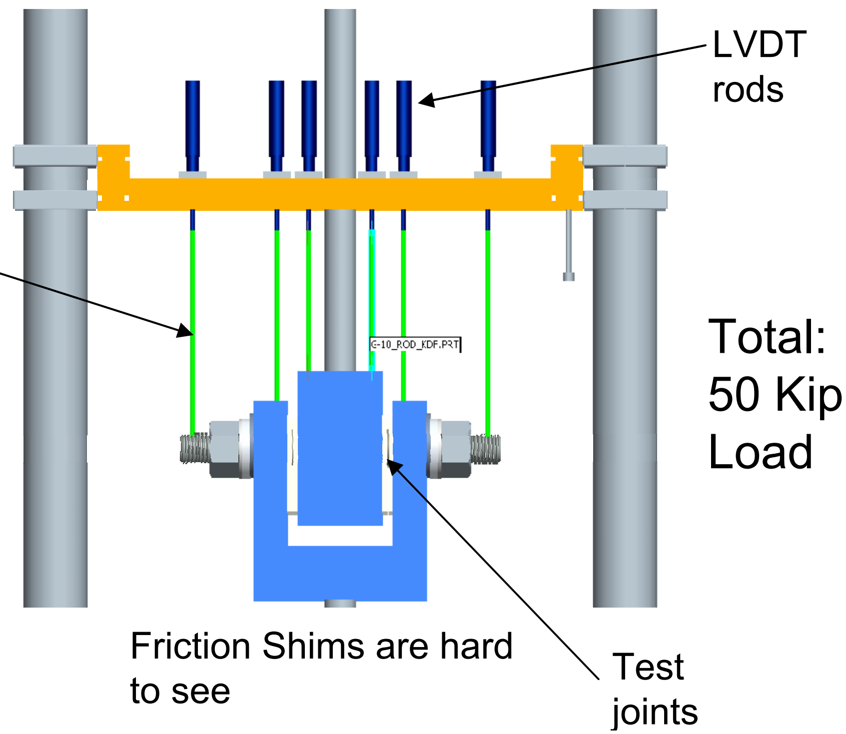




Shear Testing at ORNL

- 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)





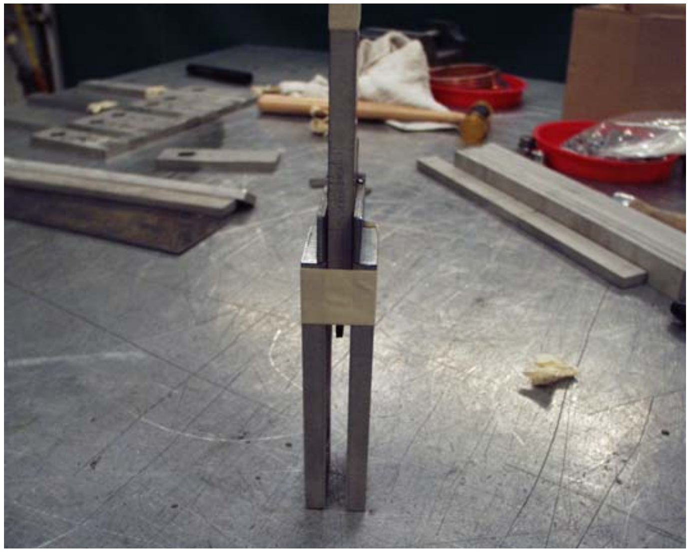
Alumina Friction Testing

- μ ≈ 0.4 observed *without binder* in a few cases.
- μ > 0.6 observed with binder (design adaptation)
- Mu is also dependent on surface roughness of the alumina. A minimum surface roughness will be added to the already-signed Rev. 0 spec
- Previous analysis based on shear averages has shown that the outboard shims can live with μ < 0.4 down to 0.2. A μ of .4 was chosen due to the end bolt effects when the inner leg was not welded.

Friction Testing Setup

- A traditional tension/compression testing machine has been configure to pull “double shear” combinations.
- Side rams allow the application of normal (transverse) loads

Typical Test Combination



- A 0.38” thick x 1.00” wide center element receives the application of friction-encouraging medium (alumina, in these cases)
- Wider (1.50”) side plates are added to each side of the center element with an axial overlap of 1.0”
- The normal/transverse load (10 kip max) is added at the center of the overlap areas (2 in**2 total area)

2nd Design Test Combination

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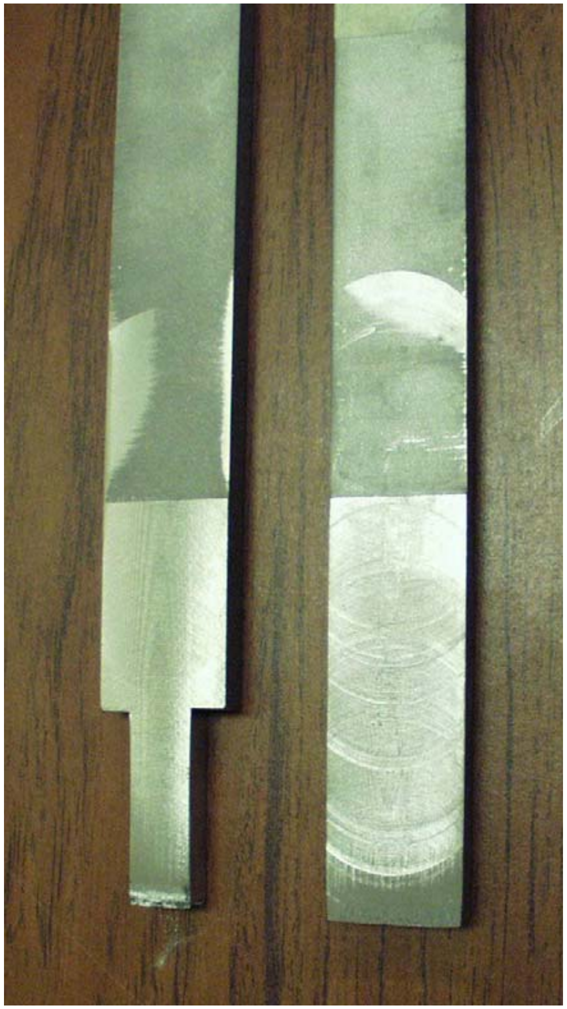


- **The original design called for a maximum loading of 10 kip over the available area**
- **A choice was made to reduce the test area rather than upgrade the test rig after analysts began predicting 17 ksi loading needs.**
- **The lessened area results in 10 kip max applied on two series ½ in**2 areas (1 in**2 total)**

Observations

- Ellis and Gettelfinger procured two families of alumina on side-plates
  - With and without bondcoat
    - The 3 least desirable friction results were in the “no bondcoat” population admidst desirable results
    - Is the “no bondcoat” correlation a red herring?

Alumina, 2 Constant Pressures, Variable SS Finish

Contact Pressure	Finish	Apparent Mu
9.5 ksi	32 microinch	.64B
9.5	60	.41N*
9.5	125	.74B**
9.5	250	.70B
19	32	.59B
19	60	.72N
19	125	.81N
19	250	.82N

*Pre-test cleaning in question

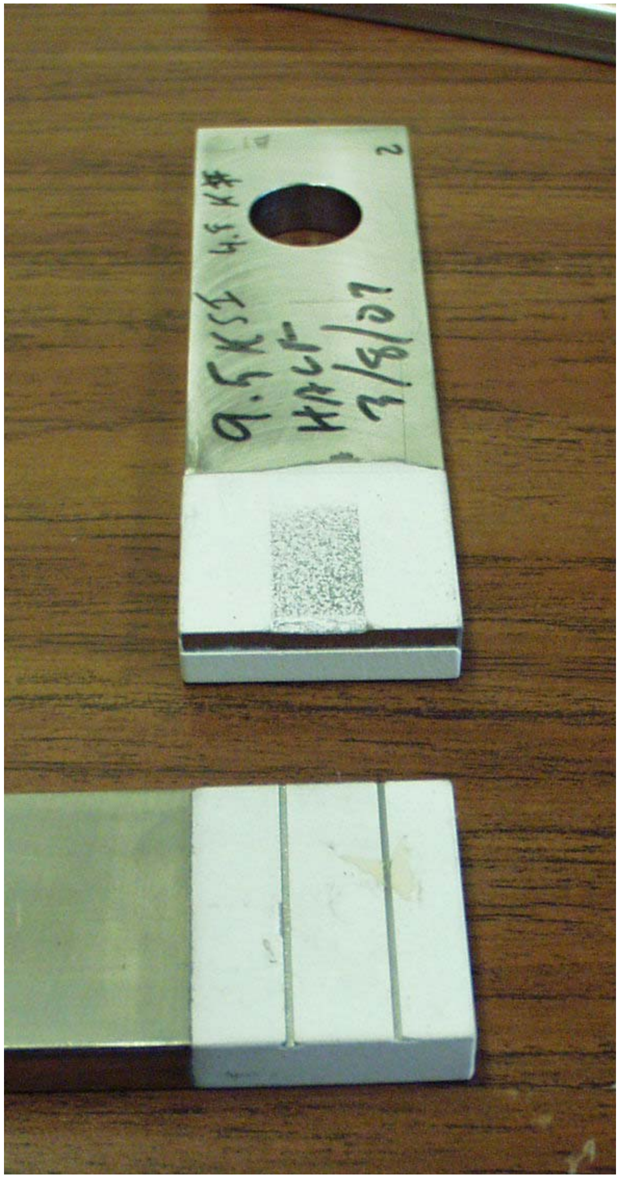
**Machine shutdown on software trip

Alumina, Constant SS Finish, Variable Pressure

Pressure	Finish	Apparent Mu
6.0 ksi (Full Width)	125 microinch	.62B
8.0 (Full Width)	125	.83N
9.5 (Full Width)	125	.73B
10. (Half Width)	125	.45N
12 (Half Width)	125	.59B
14 (Half Width)	125	.45N
16 (Half Width)	125	.82B
19 (Half Width)	125	.65N

Trimmable Shim Feasibility

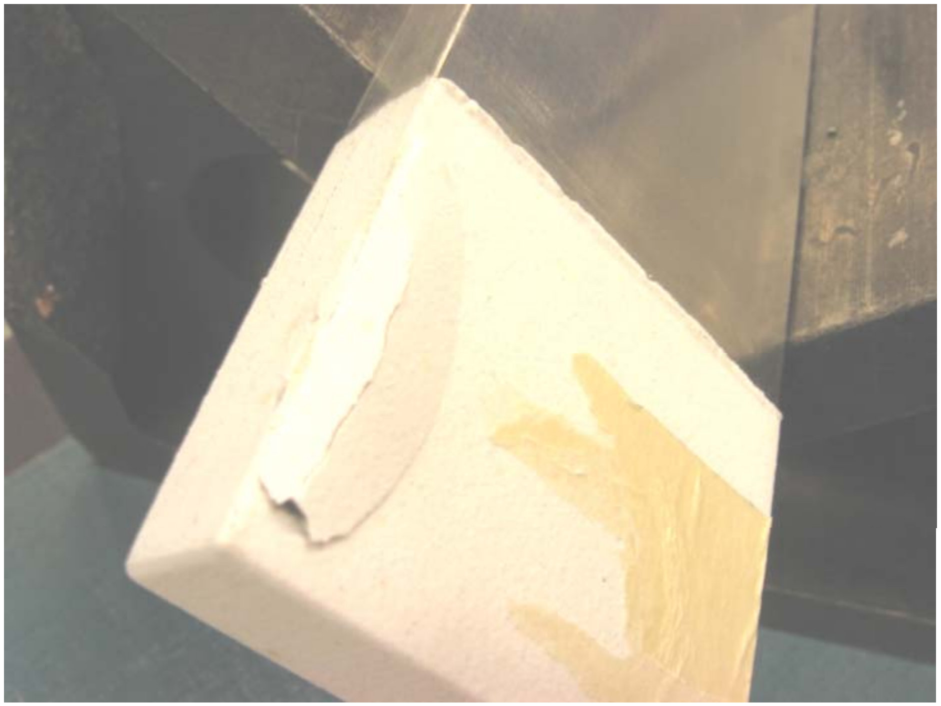
- Machining checks show that slowly turning carbide tools may be used without chipping the alumina
- The slitting saw (used on lower specimen) may be appropriate for trimmable shims



Shall We Radius?

- The Rev. X shim pictured was provided with a 1/16 radius on all edges to possibly avoid alumina fracture at line contact areas.
- A cost-saving proposal has only hand chamfering to about 0.040”.

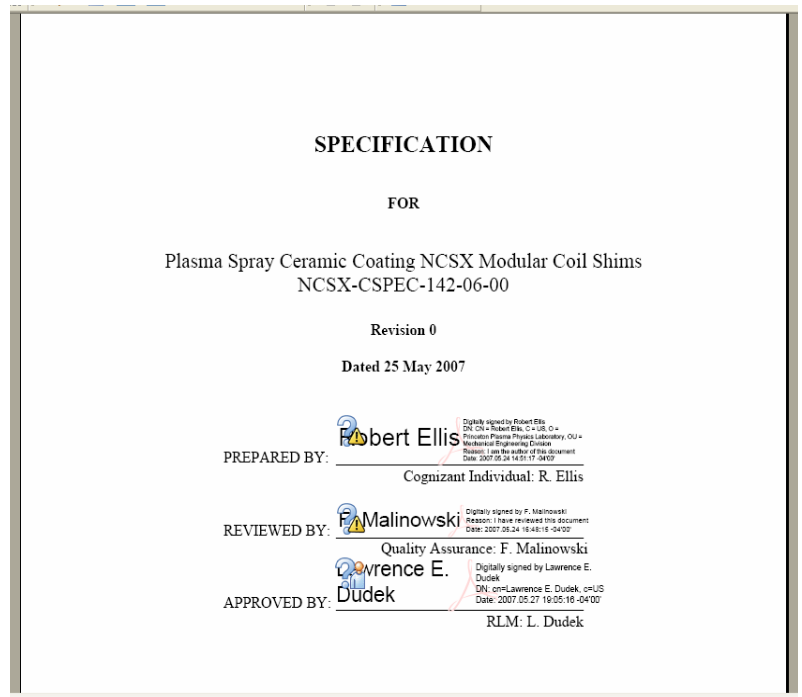
First Rough Inquiry



- This alumina-with-bondcoat sideplate was supported in a cast iron welder's vee block (45 degree style) and had a 1" dia platen loaded onto its 1" uppermost edge. The sideplate had edges broken to some arbitrary and probably inconsistent value.
- The edge survived a 1 kip load without obvious damage. A 2.3 kip (caught by the "instantaneous peak" meter) load resulted in the fracture pictured.
- Next up – Investigation at small angles: ~0.2 degrees rather than 45.

Alumina Spec, Rev.0

- Thickness 0.012” +0.003/-0.002
- Roughness >100 microinch RMS
- Vacuum Bake to 300 C (by PPPL)
- Dunk check in LN2 (by PPPL)
- Initial Test Population required by spec



SPECIFICATION

FOR

Plasma Spray Ceramic Coating NCSX Modular Coil Shims
NCSX-CSPEC-142-06-00

Revision 0

Dated 25 May 2007

PREPARED BY: Robert Ellis
Digitally signed by Robert Ellis
DN: CN = Robert Ellis, C = US, O = Princeton Plasma Physics Laboratory, OU = Mechanical Engineering Division
Reason: I am the author of this document
Date: 2007.05.24 14:51:17 -04'00'
Cognizant Individual: R. Ellis

REVIEWED BY: F. Malinowski
Digitally signed by F. Malinowski
Reason: I have reviewed this document
Date: 2007.05.24 16:48:15 -04'00'
Quality Assurance: F. Malinowski

APPROVED BY: Lawrence E. Dudek
Digitally signed by Lawrence E. Dudek
DN: cn=Lawrence E. Dudek, c=US
Date: 2007.05.27 19:05:16 -04'00'
RLM: L. Dudek

Conversation with Incumbent Supplier

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- Robert Rigney of A&A asserts that normal alumina coatings have surface shear strength of 2-3 ksi.
- The nickel aluminide bondcoat increases this to 6-7 ksi.
- Roughness is a controllable parameter
  - Rigney suggests that NCSX considers a larger particle size to achieve the desired rougher surface.
  - Also suggests that the larger particle would have better “bite in” capability.

Recap

- Decision Point:
  - Larger alumina particle size

  Or

  - Use current size
- Investigate edge loading at flat angles
- Go to cycle testing

Conclusion

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- Are the requirements well defined?
  Yes. Mod coil B-spec needs revision, Station 2 spec to be issued
- Does the design meet the requirements?
  Yes. Outboard shim details unaffected by remaining inb work.
- Is the design adequately underpinned by analysis and testing
  Yes. Final analysis w/ inb, checking to be done. Tests confirmatory.
- Are the drawings complete and ready to be released for fabrication?
  Yes. Drawing comments have been incorporated and checked
- Have chits from previous MC design reviews been addressed?
  Yes. Chits from Feb-07 PDR follow:

#	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.

#	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.

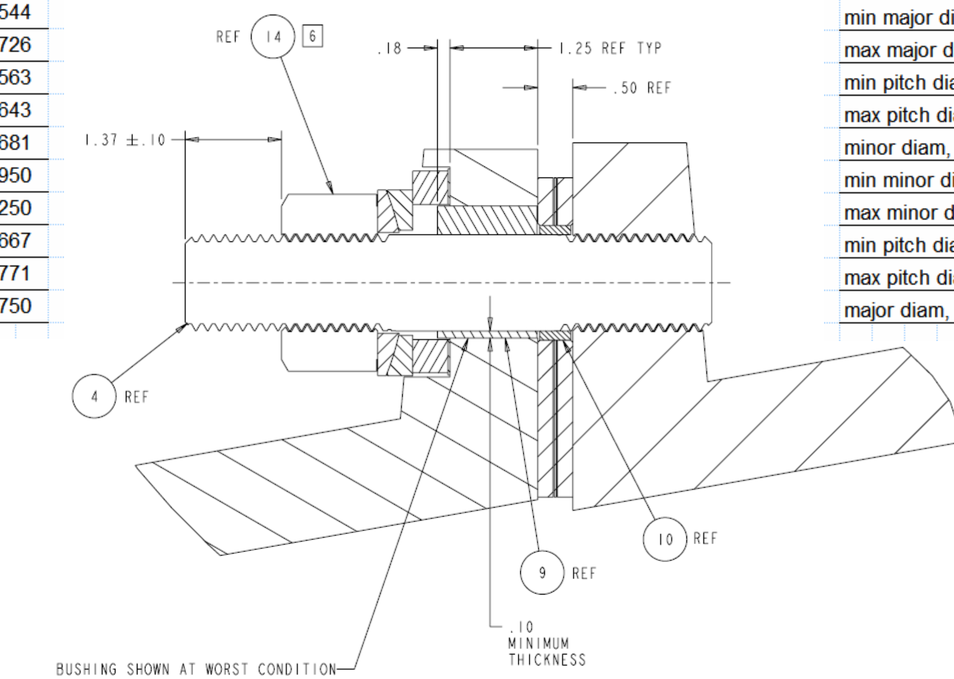
#	Chit/Audit Finding [Originator]	Project Disposition	Status
12	Make as many similar parts as possible i.e. all shims have same shape. [Viola]	Plan is to minimize the number of different parts	Universal shim with cutoff lengths will minimize qtys.
13	In place of planned " welded threaded hole adapters" 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

#	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.

Back-up Slides / APPENDIX

Bolted Joint Parameters (1)

STUD / NUT - 1.375-6UNC-2AB		
nominal diameter	in	1.3750
number of threads / inch	-	6
min major diam, ext	in	1.3544
max major diam, ext	in	1.3726
min pitch diam, ext	in	1.2563
max pitch diam, ext	in	1.2643
minor diam, ext	in	1.1681
min minor diam, int	in	1.1950
max minor diam, int	in	1.2250
min pitch diam, int	in	1.2667
max pitch diam, int	in	1.2771
major diam, int	in	1.3750



TAPPED BOLT SECTION
SCALE 1.00

STUD / FLANGE - 1.375-6UNC-3AB		
nominal diameter	in	1.3750
number of threads / inch	-	6
min major diam, ext	in	1.3568
max major diam, ext	in	1.3750
min pitch diam, ext	in	1.2607
max pitch diam, ext	in	1.2667
minor diam, ext	in	1.1705
min minor diam, int	in	1.1950
max minor diam, int	in	1.2146
min pitch diam, int	in	1.2667
max pitch diam, int	in	1.2745
major diam, int	in	1.3750

MATERIALS-			STELLALLOY		A286		316SS		INCO 718		TITANIUM		G-11CR	
			77K	293K	77K	293K	77K	293K	77K	293K	77K	293K	77K	293K
modulus of elasticity	E	ksi	23300	21600	31100	29100	30100	28200	30800	29600	17100	15800	3500	2700
poisson's ratio	v	-	0.283	0.294	0.298	0.31	0.283	0.294	0.307	0.308	0.327	0.333		
shear modulus	G	ksi	18161	16692	23960	22214	23461	21793	23565	22630	12886	11853		
thermal exp coefficient	a	ppm/K	13.0			13.0		16.0		12.5		9.3		6.5
integrated thermal exp	u	ppm	2834		2638		2760		2150		1600		5500	
tensile strength	Su	ksi	159	82	166	130	183	90	238	190	226	145		
yield strength	Sy	ksi	93	35	97	85	94	40	186	157	218	137	115	66

Bolted Joint Parameters (2)

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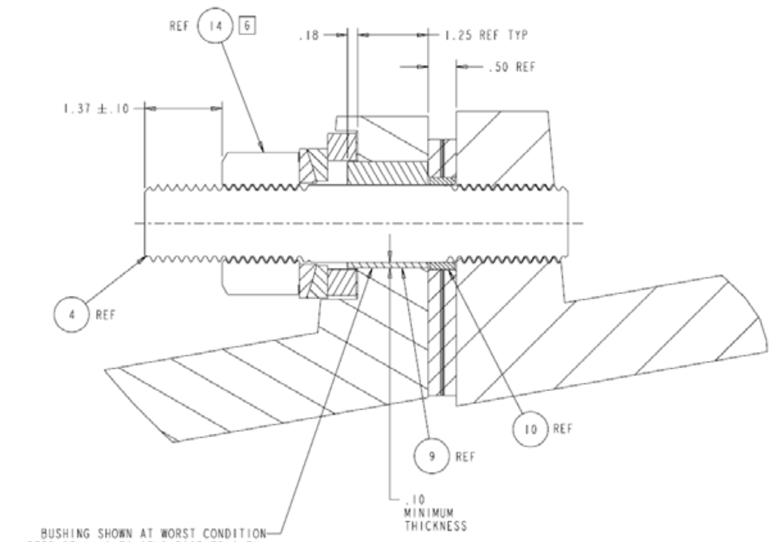
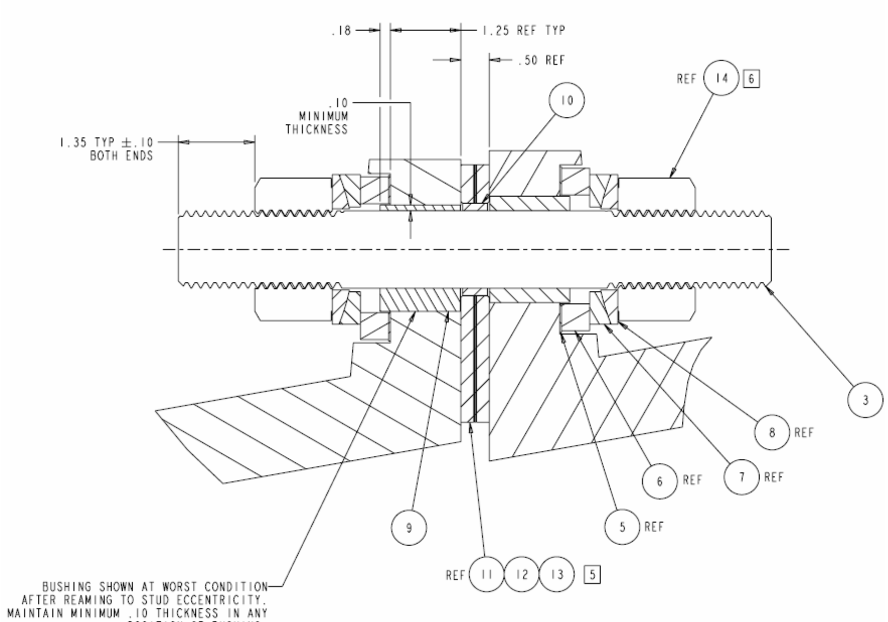


TAPPED BOLT SECTION
SCALE 1.00



THRU BOLT SECTION
SCALE 1.00

Internal thread (hole) parameters - tapped hole

			Assumes thread engagement length is determined by the internal thread.
Ref	6		*Assumes ext/int threads have the same class, e.g, 1, 2, or 3.*
Le	1.375	in	Fastener engagement length - set equal to nominal flange thickness for tapped hole - may be 1.5in with overcast
Le/D	1		1-1.5 is normal
Knmax	1.2146	in	Max minor diameter of internal thread
Enmax	1.2745	in	Max pitch diameter of internal thread
An	4.60140919	in2	Shear area of internal thread (Eq. 4)
Material	Stellalloy		Flange material
Tn	82	ksi	Tensile strength of flange material
Spn	29.75	ksi	Proof strength of flange material
Lemin	0.90844988	in	Min fastener engagement length - if stud and nut are the same material (Eq. 5)
J	1.19252555		Relative strength of external and internal threads (Eq. 6)
Q	1.08334969	in	Required length of engagement (Eq. 7)
Le/Q	1.2692116		If <1, thread engagement inadequate to develop full strength of bolt

External thread (bolt) parameters - A286 stud in tapped hole

			Thread and material properties are entered in the tables. *Thread reference must be an ODD number for an external thread, even for an internal thread.*
Ref	5		Reference column in thread properties table
D	1.375	in	Nominal diameter
n	6	/in	Threads per inch
	A286		Bolt/stud material
Ts	130	ksi	Tensile strength of bolt material @ 293K
Esmin	1.2607	in	Minimum pitch diameter of external thread
At1	1.15488023	in2	For bolt strengths <100ksi (Eq. 1)
At2	1.14339773	in2	For bolt strengths >100ksi (Eq. 2)
At	1.14339773	in2	Tensile area of bolt thread
As	3.46121874	in2	Shear area of external thread (Eq. 3)
Dsmin	1.3568	in	Min major diameter of external thread
F	149	kips	Force required to fail joint
	149	*kips*	*Force to break bolt*
	225	*kips*	*Force to strip bolt threads*
	189	*kips*	*Force to strip threads in tapped hole*

Bold Preload

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

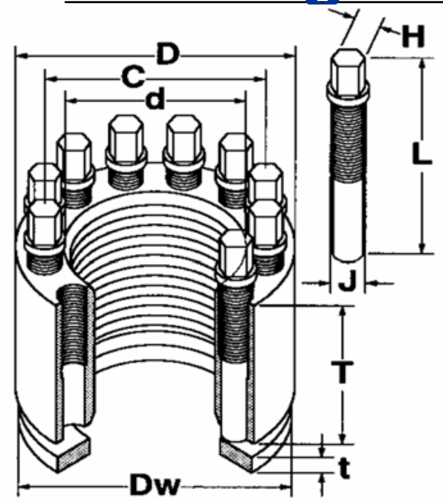
- Nominal preload of 75-kips based on 85% of A286 yield strength
- Cool-down relaxation is -4% with Inconel load washer, +2% with Titanium
- Preload uncertainty for hydraulically tensioned studs w/ ultrasonic inspection

For Su < 180-ksi (Bickford),			
tensile stress area	As	in2	1.1543
proof strength	Sp	lb	72250
nominal preload	Po	lb	75058
initial bolt stress		ksi	65

preload uncertainty (nasa tm-106943)			10%
joint type		thru	tapped
max preload	lb	84256	79523
min preload	lb	68937	65064
applied torque	ft-lb	1755	1732

load washer mat'l		Inconel		Titanium	
joint type		thru	tapped	thru	tapped
grip length	in	5.0900	2.7950	5.0900	2.7950
dL bolt	in	0.0134	0.0074	0.0134	0.0074
dL sph washer	in	0.0014	0.0014	0.0014	0.0014
dL flat washer	in	0.0011	0.0011	0.0008	0.0008
dL ins washer	in	0.0002	0.0002	0.0002	0.0002
dL flange	in	0.0035	0.0035	0.0035	0.0035
subtotal	in	0.0061	0.0061	0.0059	0.0059
subtotal x2	in	0.0123	0.0061	0.0117	0.0059
dL shim	in	0.0015	0.0015	0.0015	0.0015
dL total	in	0.0137	0.0076	0.0132	0.0073
change in strain	in/in	-6E-05	-8E-05	4.6E-05	1.6E-05
change in stress	ksi	-1.8	-2.4	1.3	0.5
final preload	lb	72967	72293	76596	75598

Bolt Tightening (2)



Supernut

Dw=2.5-in
D= 2.46-in
L=1.93-in
T= 1.75-in
A286
(4340 is std)

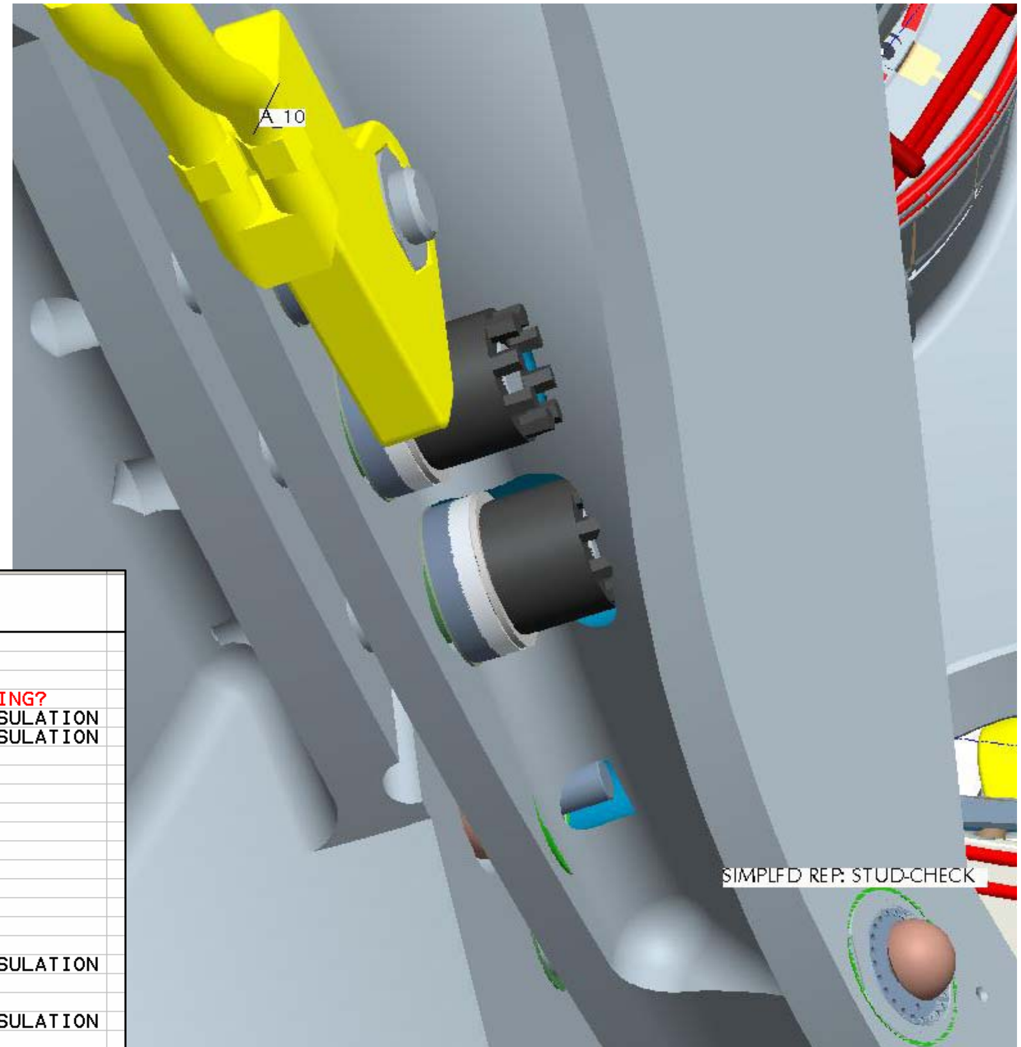


Table B-C based on CAD Layout

BC HOLE #	TAPPED OR THRU STUD	COIL SIDE TO WRENCH FROM	RECOMMENDED TOOL	ISSUES
1	TAPPED	C	LP-TORQUE	NONE
2	TAPPED	C	LP-TORQUE	NONE
3	TAPPED	C	LP-TORQUE	NONE
4	TAPPED	C	LP-TORQUE	GRIND CASTING?
5	TAPPED	C	LP-TORQUE	AROUND PORT INSULATION
6	TAPPED	C	LP-TORQUE	AROUND PORT INSULATION
7	TAPPED	C	LP-TORQUE	NONE
8	TAPPED	C	LP-TORQUE	NONE
9	TAPPED	C	LP-TORQUE	NONE
10	TAPPED	C	SOCKET/SUPER-NUT	NONE
11	TAPPED	C	LP-TORQUE	NONE
12	TAPPED	C	LP-TORQUE	NONE
13	TAPPED	C	LP-TORQUE	NONE
14	TAPPED	C	LP-TORQUE	NONE
15	TAPPED	C	LP-TORQUE	NONE
16	TAPPED	C	LP-TORQUE	NONE
17	TAPPED	C	LP-TORQUE	NONE
18	TAPPED	C	LP-TORQUE	AROUND PORT INSULATION
19	TAPPED	C	SOCKET/SUPER-NUT	NONE
20	TAPPED	C	LP-TORQUE	NONE
21	TAPPED	C	LP-TORQUE	AROUND PORT INSULATION
22	TAPPED	C	LP-TORQUE	NONE
23	TAPPED	C	LP-TORQUE	GRIND CASTING?
24	TAPPED	C	LP-TORQUE	GRIND CASTING?
25	TAPPED	C	LP-TORQUE	GRIND CASTING?
26	TAPPED	C	LP-TORQUE	GRIND CASTING?
27	TAPPED	B	SUPER-NUT	GRIND CASTING?
28	TAPPED	B	SUPER-NUT	GRIND CASTING?
29	TAPPED	B	LP-TORQUE	NONE

Joint Stiffness

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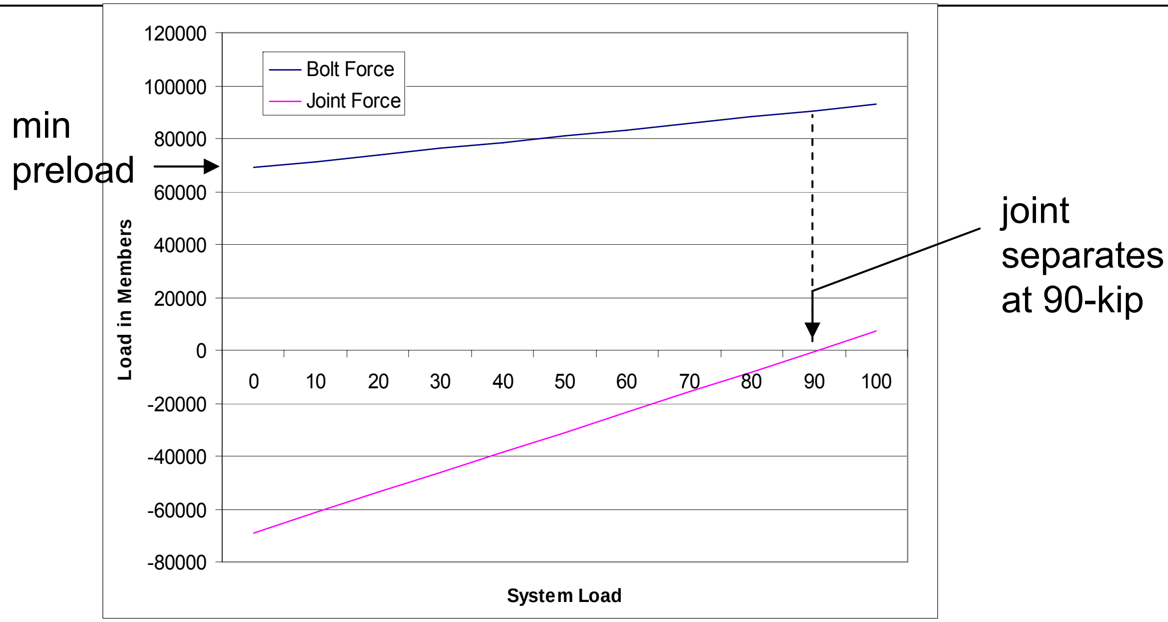
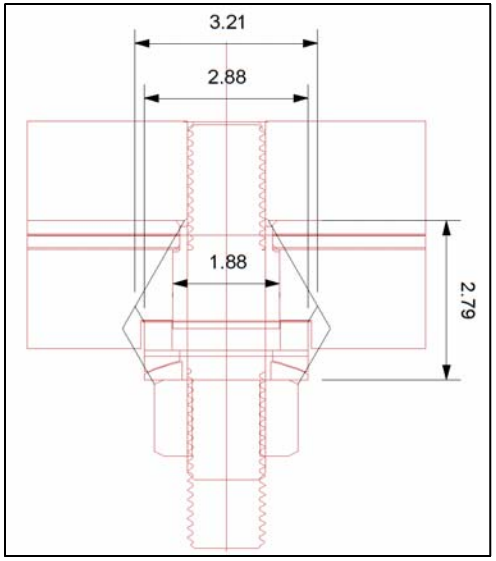
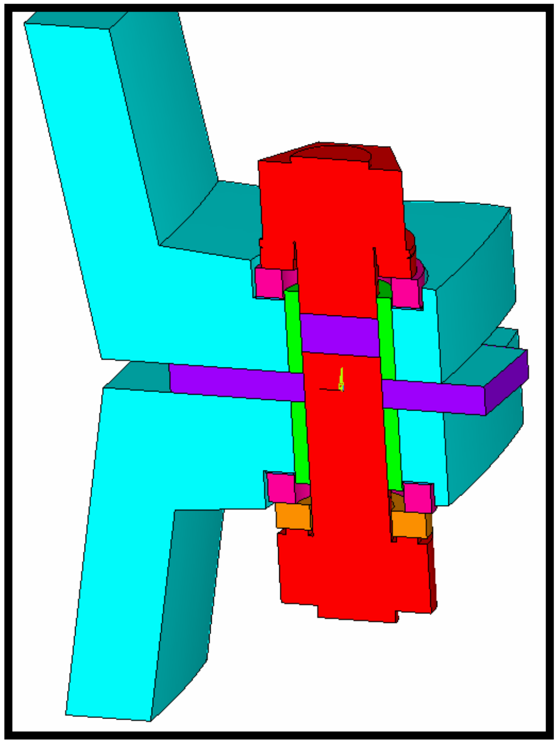


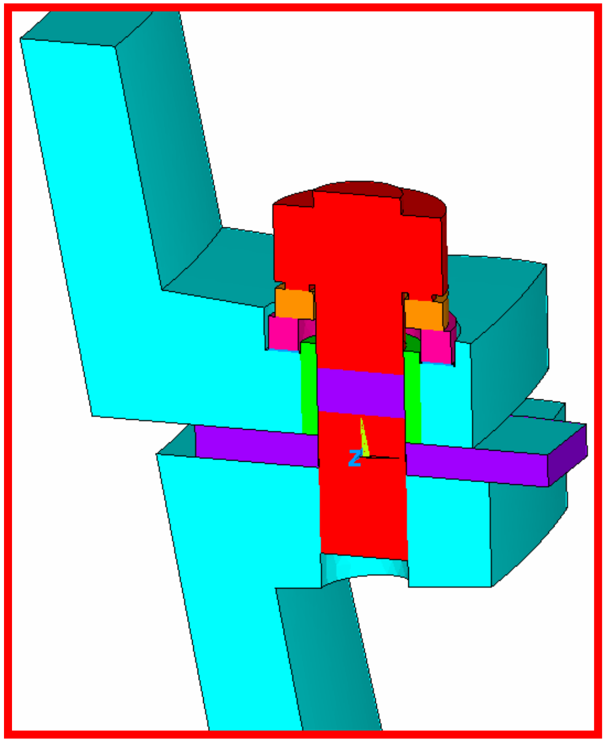
joint type			thru	tapped
effective clamp area	Ac	in2	8.3573	4.5063
washer area		in2	3.7385	3.7385
bolt stiffness	kb	lb/in	6599	12018
sph washer stiffness	k1	lb/in	211243	211243
flat washer stiffness	k2	lb/in	118136	118136
ins washer stiffness	k3	lb/in	336465	336465
flange stiffness	k4	lb/in	144414	144414
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



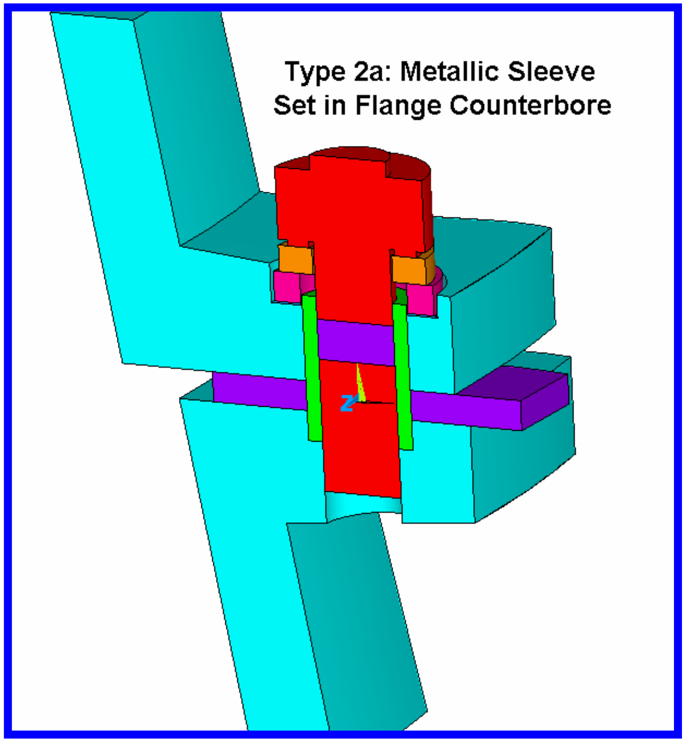
Individual Joint Analysis
– If friction fails.



Type 1 Bolted Connection



Type 2 Bolted Connection

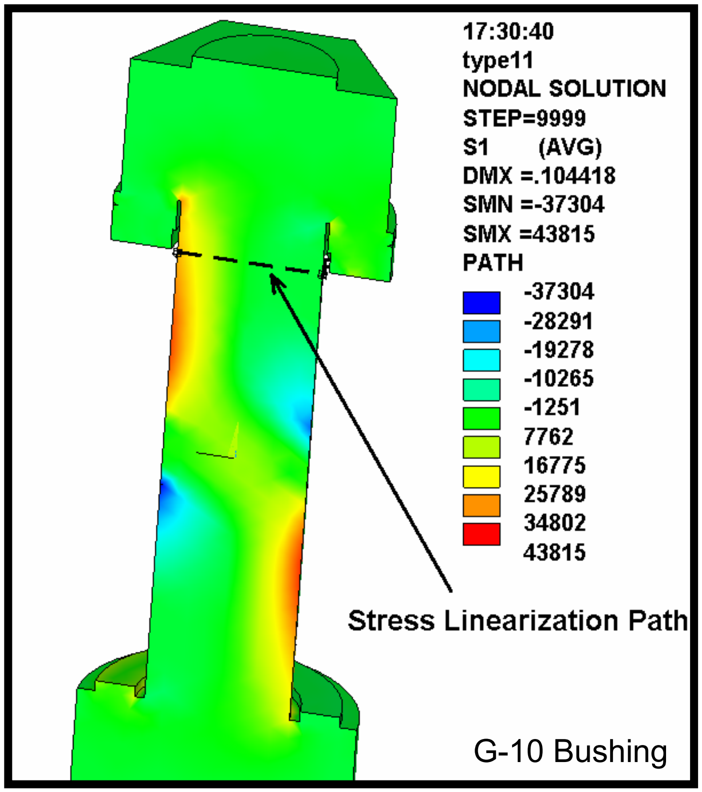


Type 2a Bolted Connection,
Extended Metallic Bushing

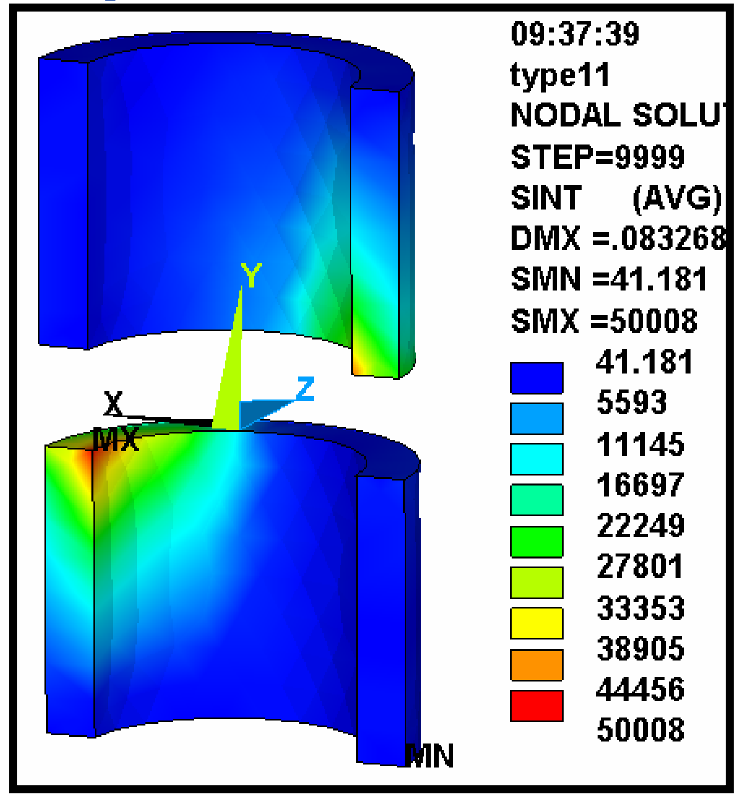
Individual Joint analysis (Type 1)

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT

- 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 1 Bolt
from 20 kip Shear Load



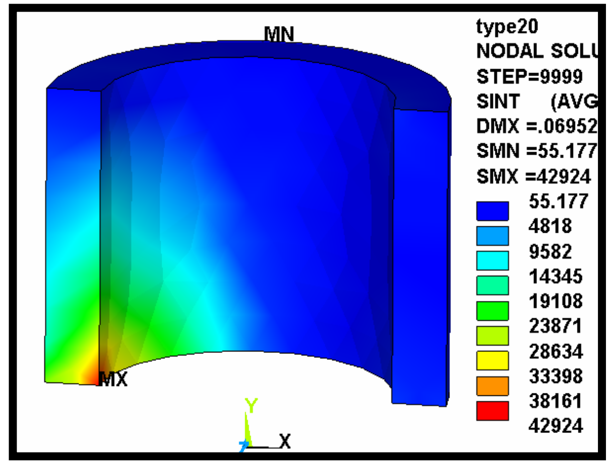
Stress Intensity of bushing

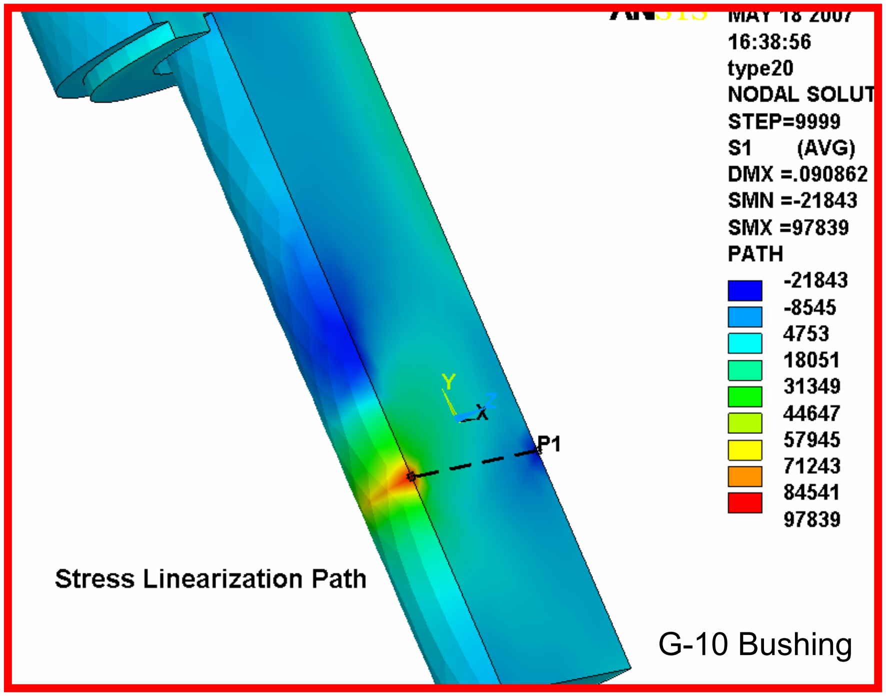
- Max bushing stress is 50-ksi
- Compare to bushing material:
  - Compressive strength = 60-ksi
  - Min bearing strength = 30-ksi
- **Max shear load = ~12-kip Static**

Individual Joint analysis
(Type 2 and 2a)

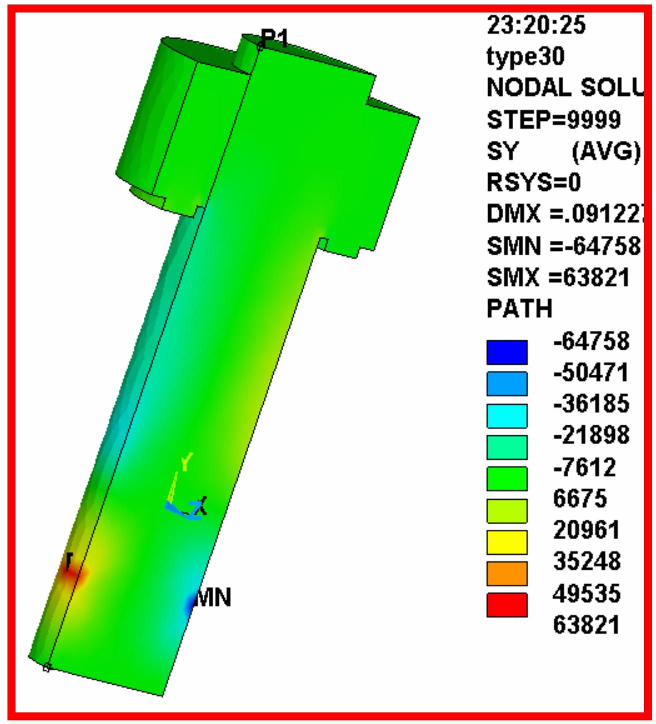
- Load Step 1 (time=1.0): Bolt Preload ~72 kip, 0.0 kip Shear Load
- Load Step 2 (time=2.0): Bolt Preload plus **20 kip** Shear Load

Stress Intensity of bushing (type 2)





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



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

Tabular Results

from Individual bolt Study

Joint Type	Type 1		Type 2		Type 2a
Bushing Material	G-11CR	SS	G-11CR	SS	SS
Un-Intensified Stress Range per 20 kip Shear Load (ΔS1), ksi	30.4	17.9	50.4	42.9	35.4
Thread Stress Intensification Factor	4	4	4	4	4
Peak Stress Range per 20 kip Shear Load, ksi	0.3	0.0	47.4	41.5	26.3
Total Intensified Stress Range per 20 kip Shear Load, ksi	122	72	249	213	168
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

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- 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:

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

- 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.

105

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

Fatigue Curves for outboard bolts: should slippage occur

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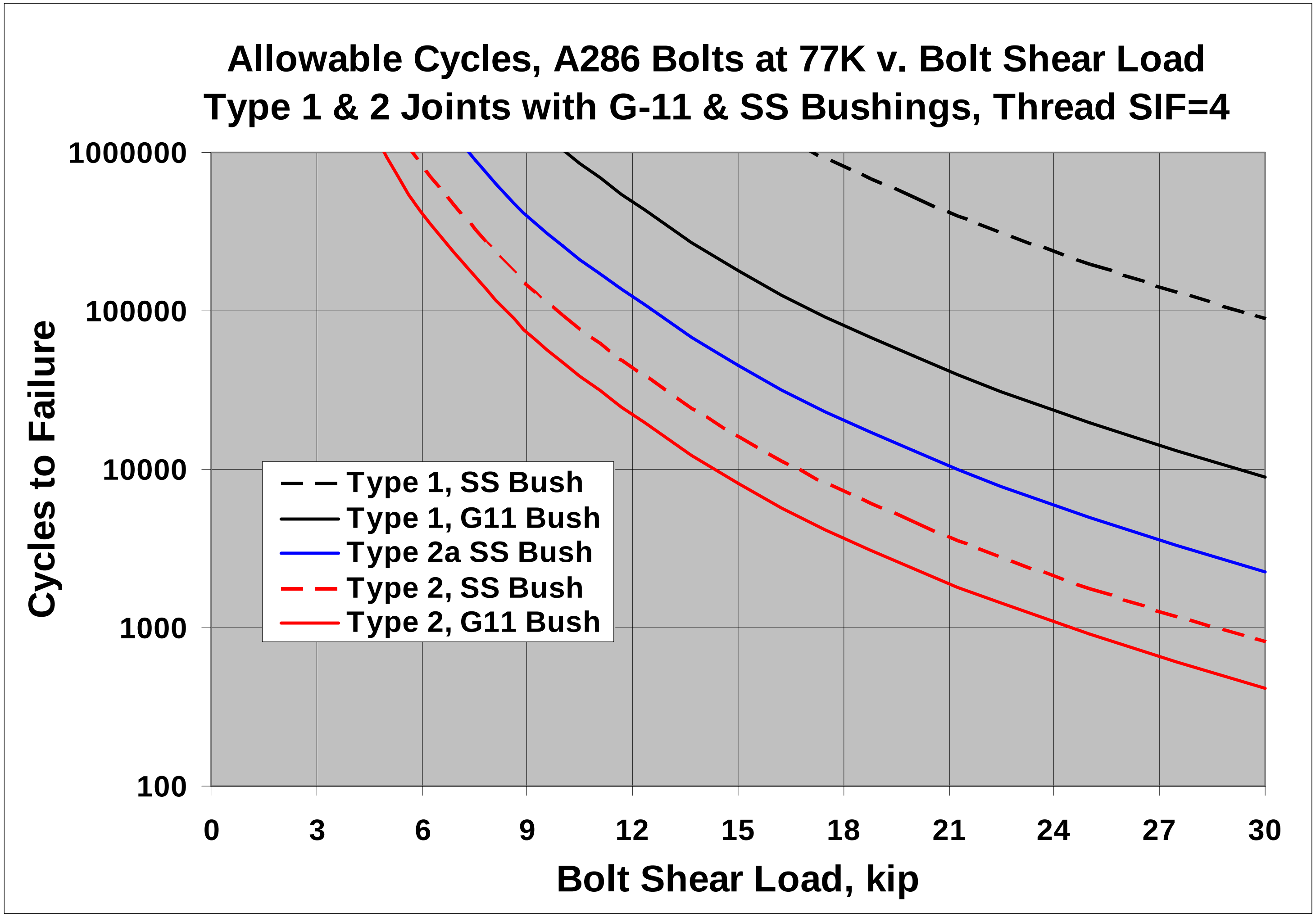
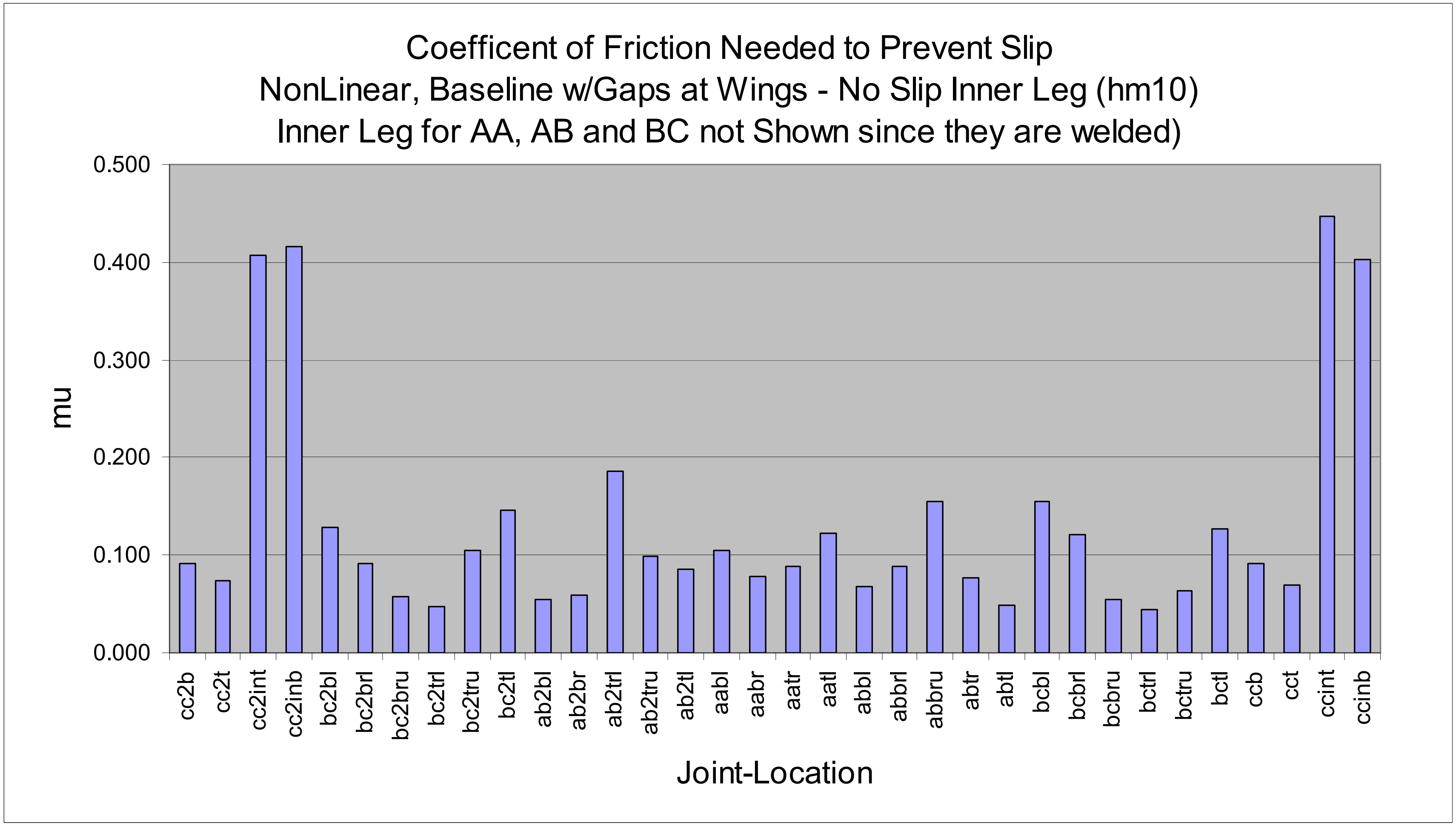


Maximum fatigue loading of type 2 with G11 = 5 kips

Maximum fatigue loading of type 1 with G11 = 10 kips

Linear Analysis for Friction coef.

- AVERAGES



From MCWF Toridal Joint Shear forces2

Inner Legs for AA, AB and BC not shown.

Imperfect Fit-Up Run (CC)

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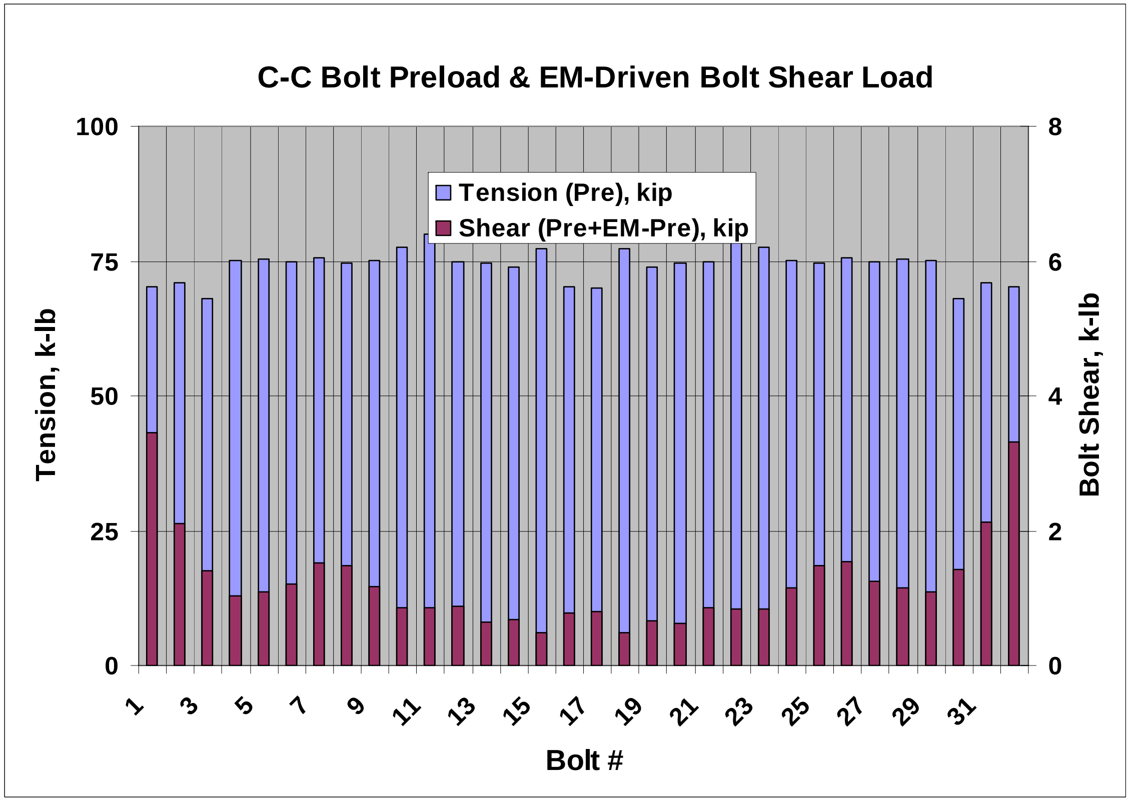
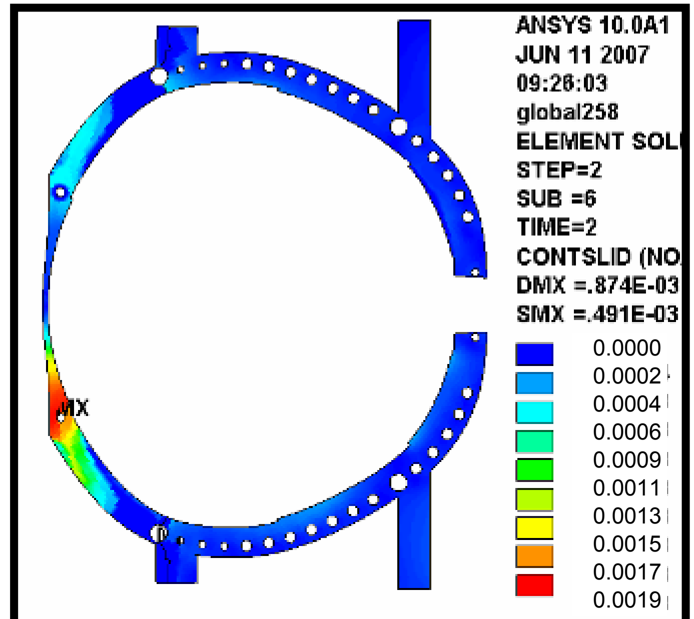
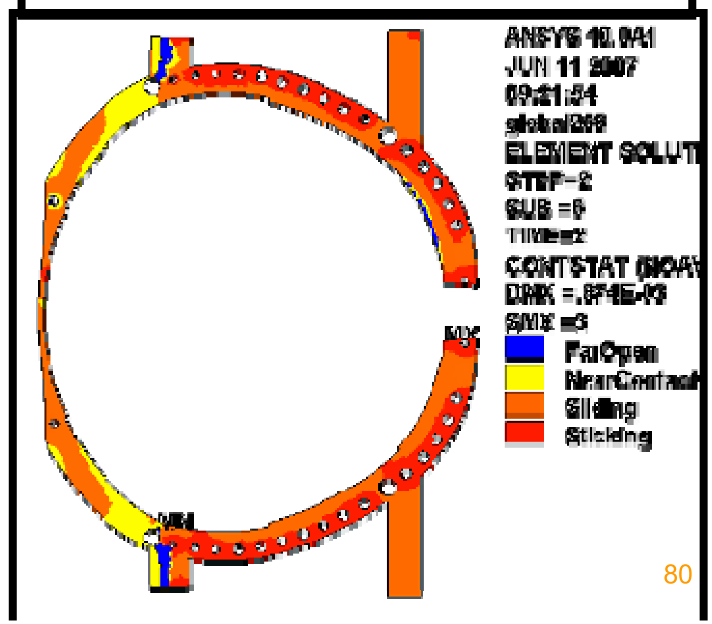
0.005” gap on inboard leg Friction = 0.04 on Inner-leg region, mu = 0.4 everywhere else





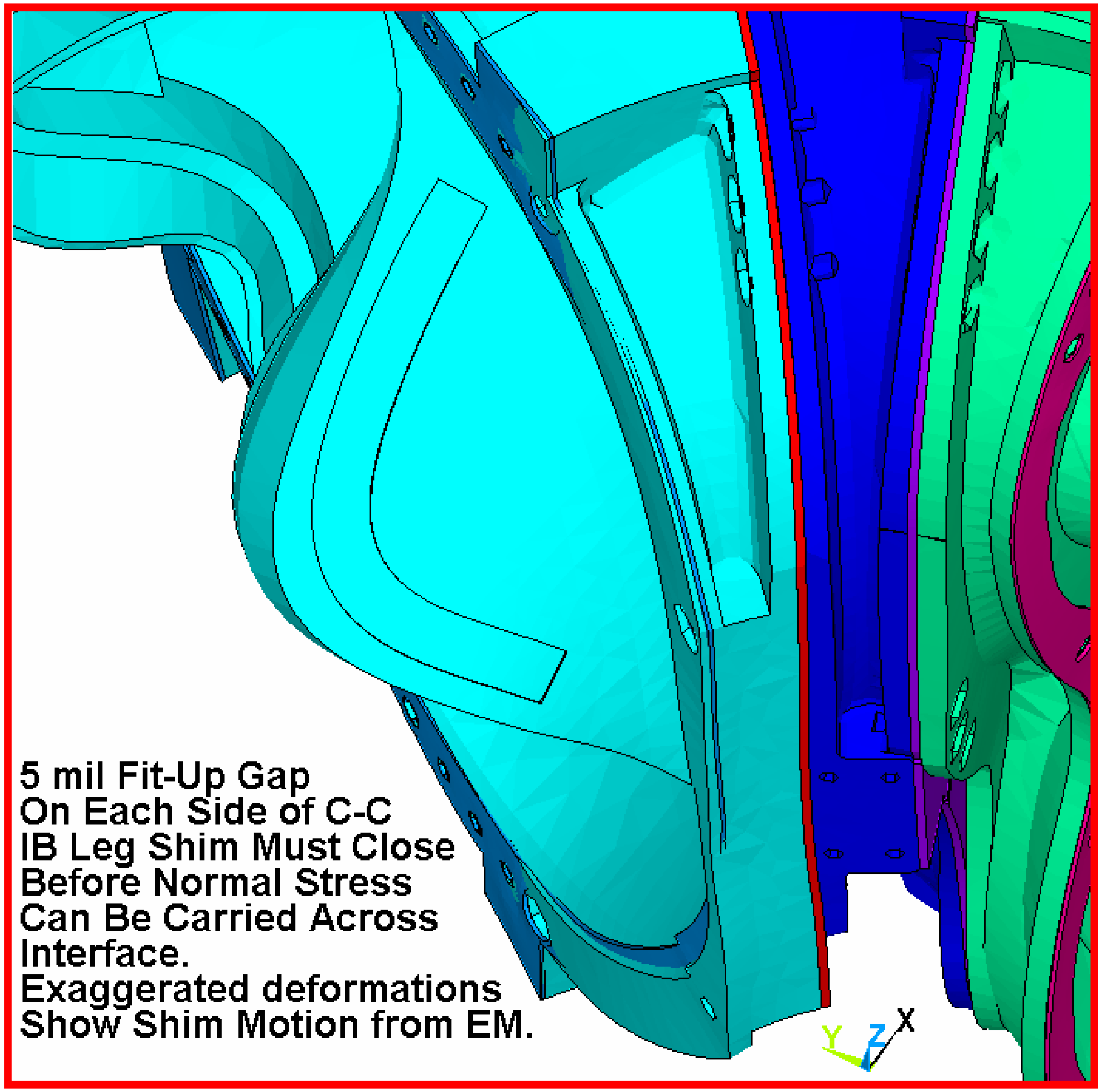


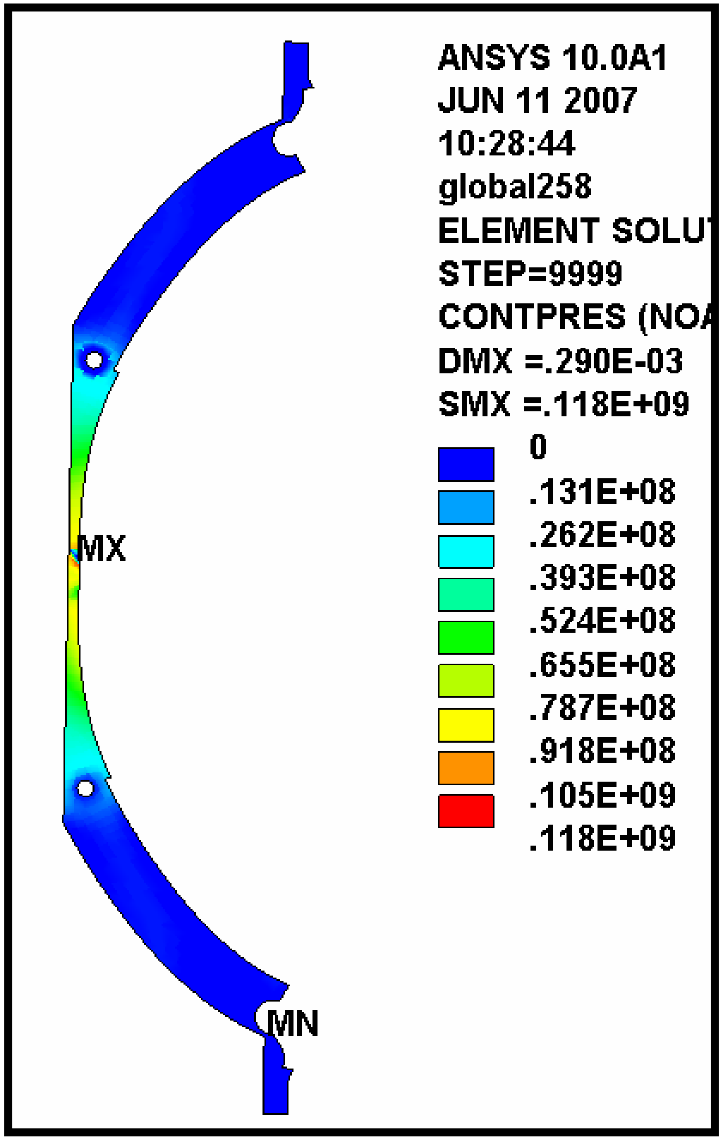
No Added Inboard Bolts

Inner most bolts see 3.3 Kips

Sliding is more than 19 mils

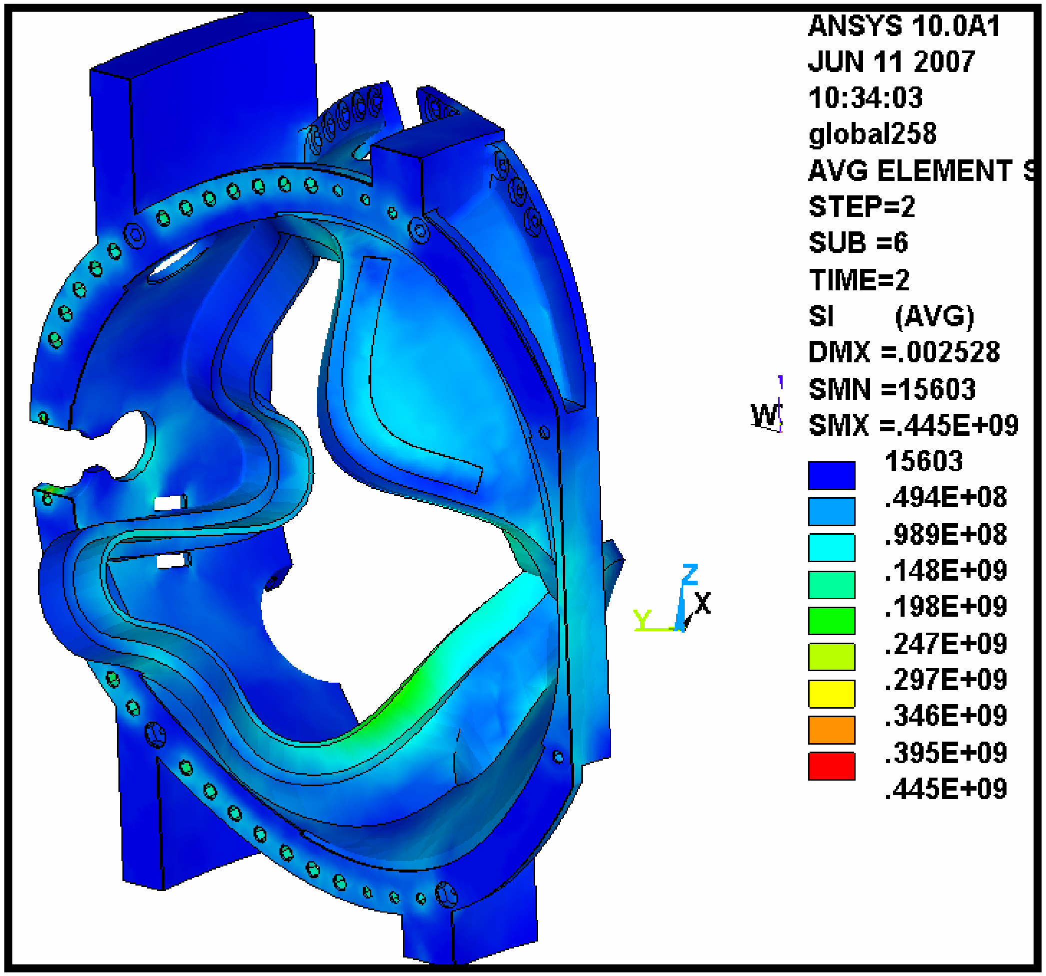
Slides from Imperfect Fit-Up Run



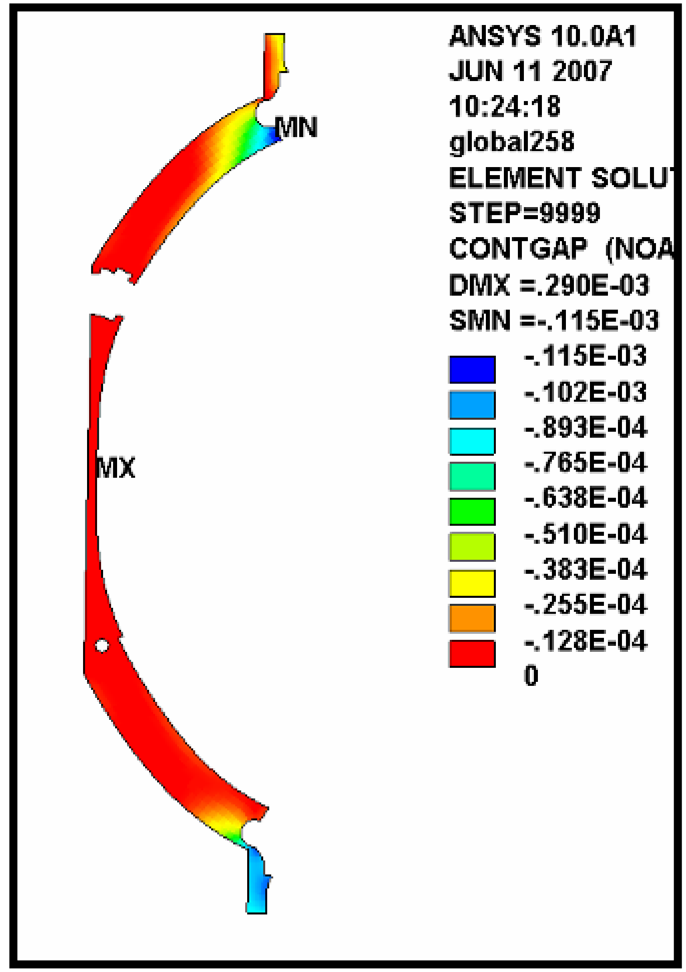


Slides from Imperfect Fit-Up Run

NCSX NATIONAL COMPACT STELLARATOR EXPERIMENT



Stress intensity Plot (Pa)



Gap Plot (Pa)