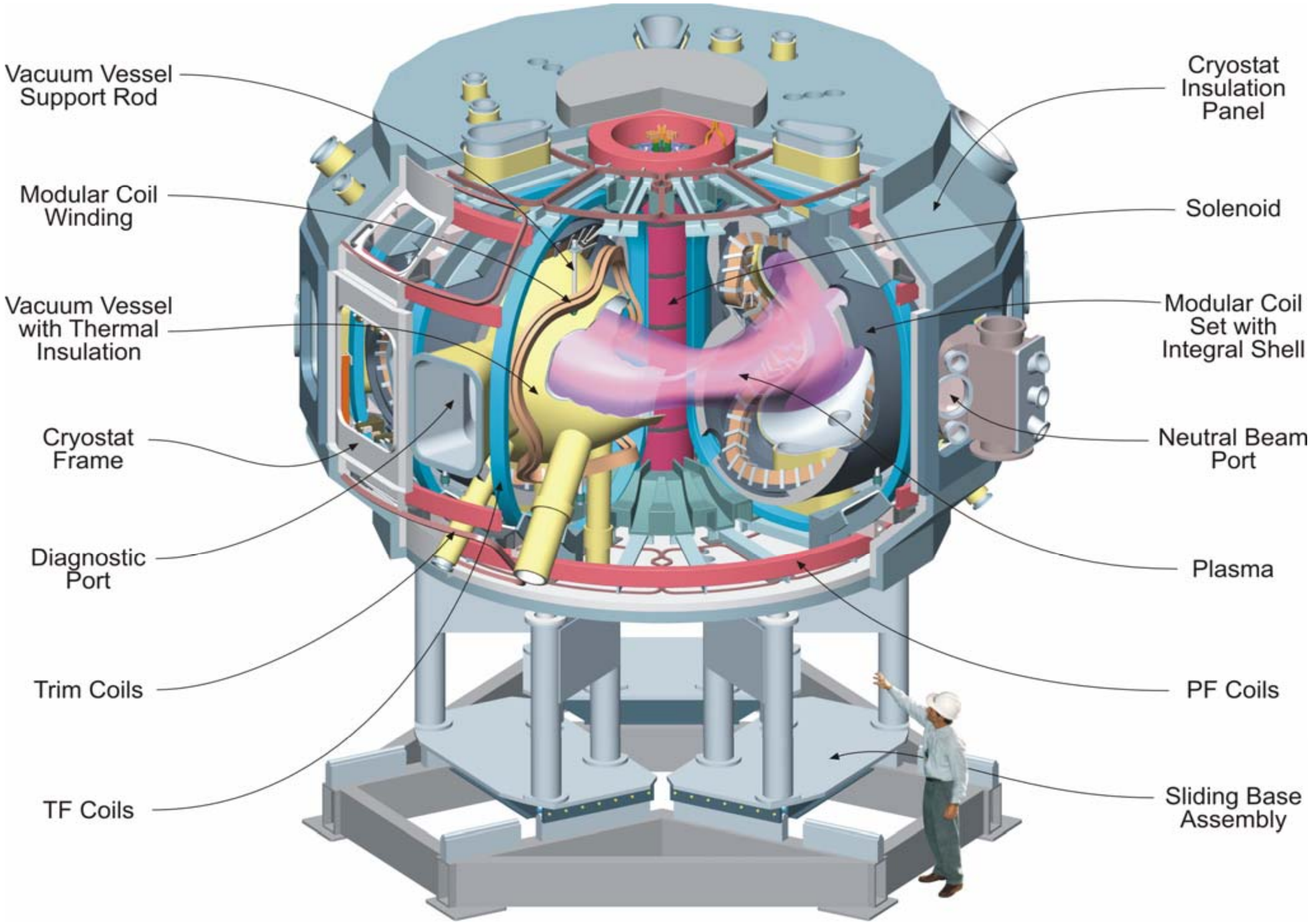
NCSX Modular Coil Welded Interfaces

Presented by the NCSX Engineering Team to the Edison Welding Institute

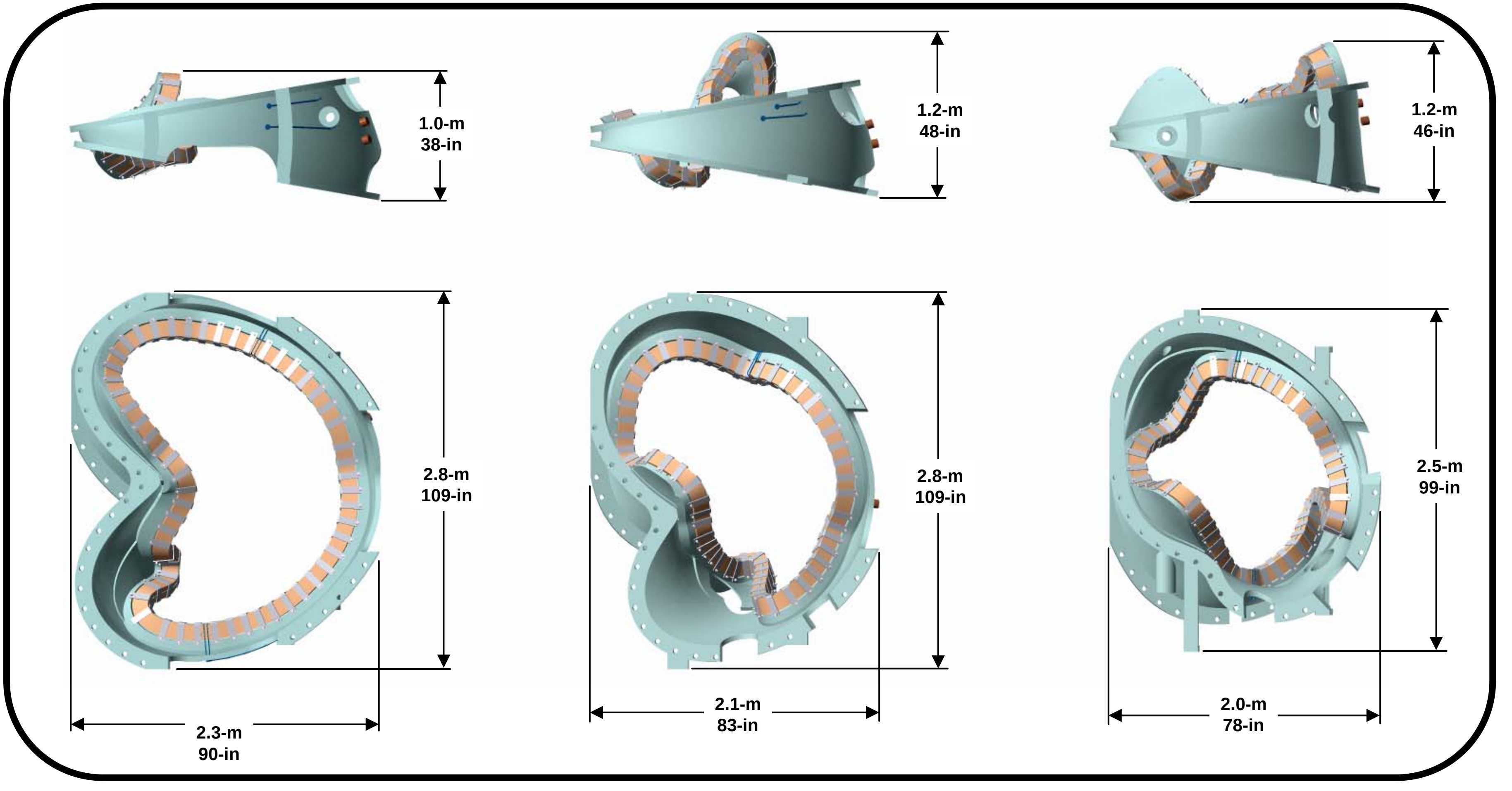
May 30, 2007

NCSX

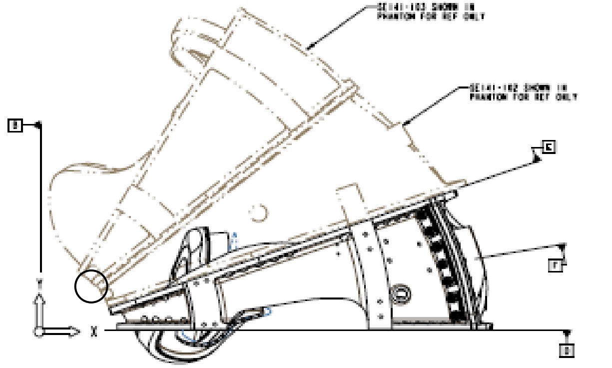

Vacuum Vessel Support Rod
Modular Coil Winding
Vacuum Vessel with Thermal Insulation
Cryostat Frame
Diagnostic Port
Trim Coils
TF Coils
Cryostat Insulation Panel
Solenoid
Modular Coil Set with Integral Shell
Neutral Beam Port
Plasma
PF Coils
Sliding Base Assembly

A NCSX Modular Coil

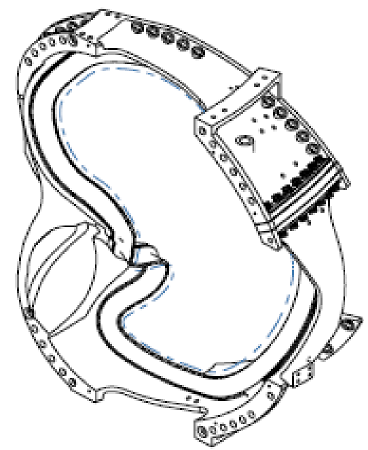
The 3 Types of Modular Coil Castings



Each casting weighs ~6000 lbs.



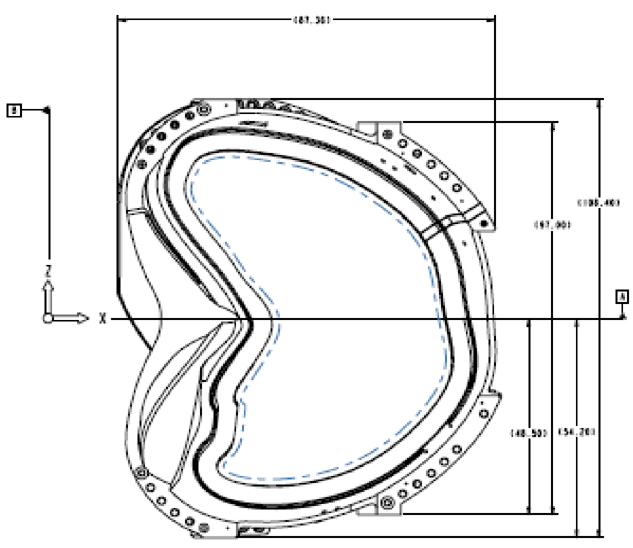
A

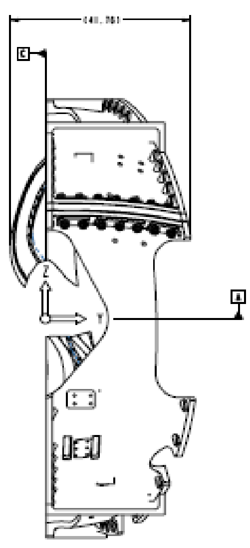


ISOMETRIC VIEW
SCALE 0.10

NOTES:

1. DRAWING PREPARED IN ACCORDANCE WITH ASME Y14.5M-1996.
2. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y14.5M-1994.
3. DIMENSIONS ARE IN INCHES.
4. DRAWING DEPICTS FINAL MACHINED STATE OF ASSEMBLY DEFINED BY PRO/ENGINEER FILE SE141-101.PRT.
5. UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE RELATED TO
   DATUM A- (PRIMARY X-Y PLANE, TOP)
   DATUM B- (SECONDARY Y-Z PLANE, SIDE)
   DATUM C- (TERTIARY X-Z PLANE, FRONT)
6. DIMENSIONS APPLY AT TEMPERATURE OF 20-30°C (68-86°F).
7. DIMENSIONS AND TOLERANCES EXCLUDE PROCESS MATERIAL ALLOWANCES WHICH MAY ADD MASS.
8. APPROXIMATE WEIGHT = 4965 LBS
9. MATCH DRILL OR REAM AS REQUIRED TO ACHIEVE RUNNING FIT BETWEEN PARTS AT ASSEMBLY.
10. (3) LUBRICATE THREADED SURFACES WITH THRED-GARD ANTI-SEIZE COMPOUND FROM FEDERAL PROCESS CORP, CLEVELAND, OH
11. SEE LATEST REVISION OF SPECIFICATION NCSX-CSPEC-141-03 FOR ADDITIONAL REQUIREMENTS.
12. BOND INSULATING SLEEVE (F/N 5) TO WINDING FORM (F/N 2) USING LOCTITE 411, PER MANUFACTURER'S INSTRUCTIONS.
13. (2) ITEM NO. 4 HOLE DIAMETERS TO MATCH OD OF ITEM NO. 6 PLUS .001 TO .002 FOR CLEARANCE FIT.
14. ITEM NO. 7 MAY BE DIVIDED INTO TWO PARTS IF NECESSARY. HOLE DIAMETERS TO MATCH OUTER DIA OF ITEM NO. 5 PLUS .001 TO .002 FOR CLEARANCE FIT.
15. (3) TORQUE ITEM NO. 8 TO 1500 +/- 30 FT LBS.

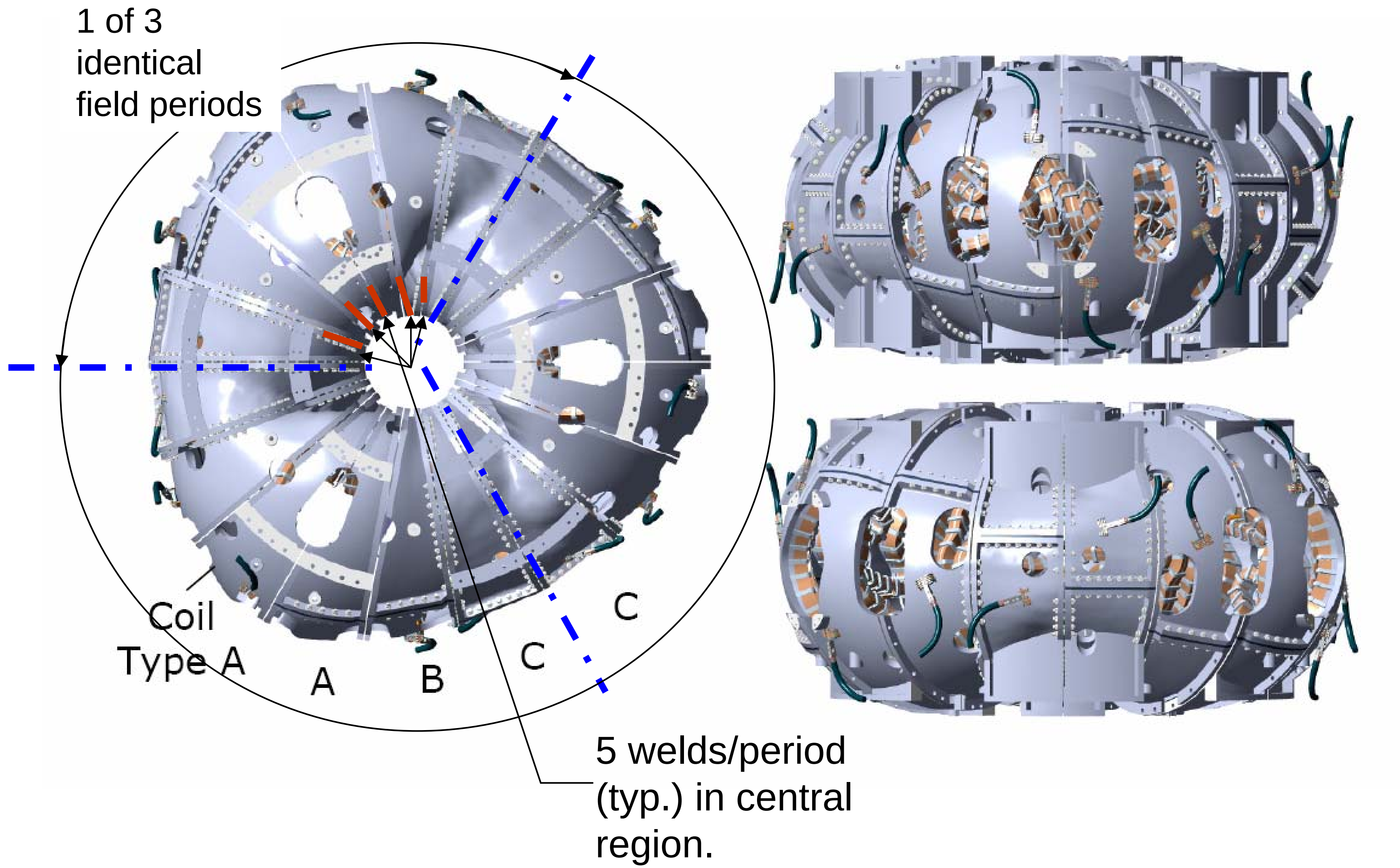




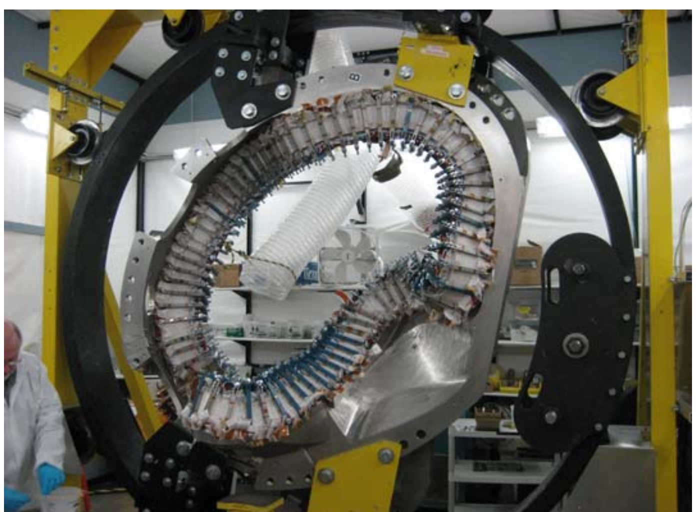
RELEASED FOR FABRICATION / INSTALLATION
PPPL Drafting: Jerry Siegel

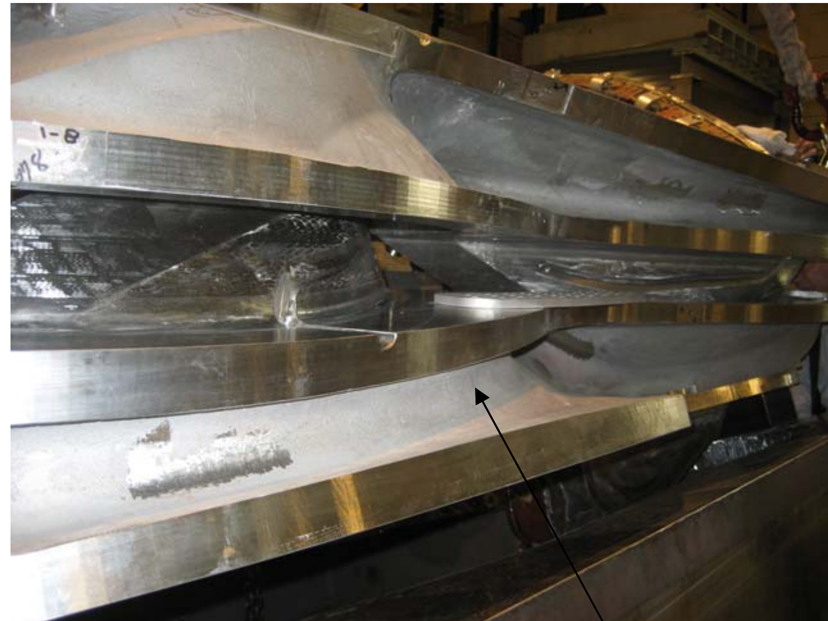
	2		SE141-142	BEARING PLATE - LONG		10
	4		SE141-141	BEARING PLATE - SHORT		9
	14		DS141-060	NUT, 12PT HEX 1.375-6UNC-2B		8
	2		-7	INS SHEET, 26 X 3 X .063 THK	NEMA GRADE G-11CR	7
	7		DS141-036	STUD, 1.375-6UNC-2A X 9.5 LG		6
	14		-5	INS BUSHING, 1.63 OD X 1.38 ID X 1.7 LG	NEMA GRADE G-11CR	5
	1		-4	INS SHEET, 15 X 32 X .063 THK	NEMA GRADE G-11CR	4
	1		SE141-048	POL BREAK SHIM ASSEMBLY TYPE-A		3
	1		SE141-114	PRODUCTION WINDING FORM TYPE-A		2
AR	X		-1	MOD COIL WINDING FORM ASSEMBLY TYPE-A		1
QTY REQD	-1	CAGE CODE	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL / SPECIFICATION	FIND NO
		NEXT ASSEMBLY		PARTS LIST		

The Inner "Legs" of the Central Coils in a Field Period are Welded – Outer 2/3 of Perimeters are bolted.



Photos of A Winding Form





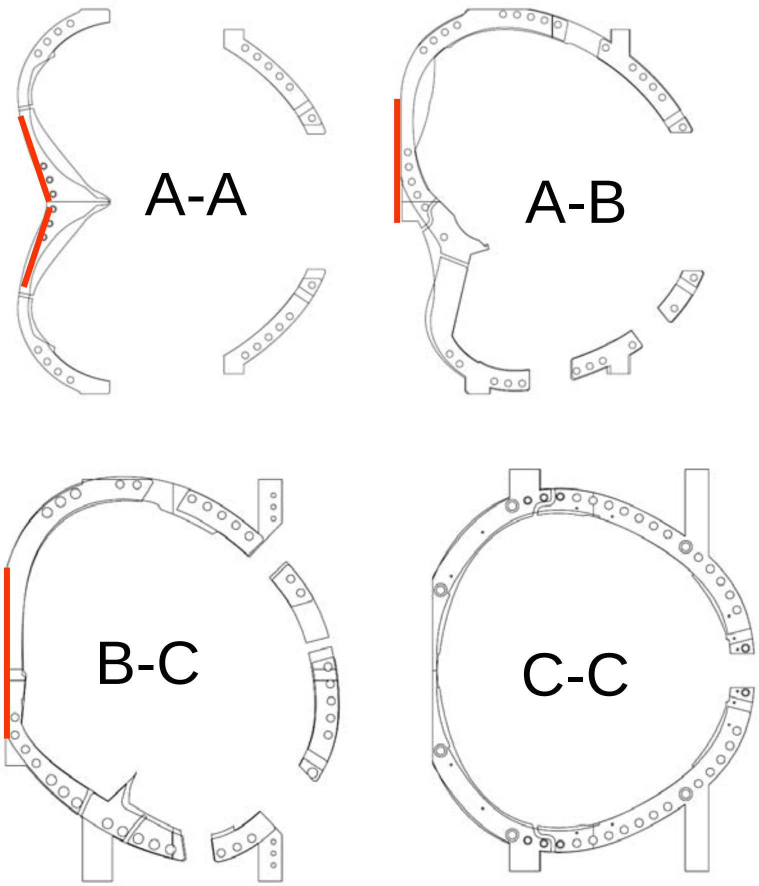
½" shim plate

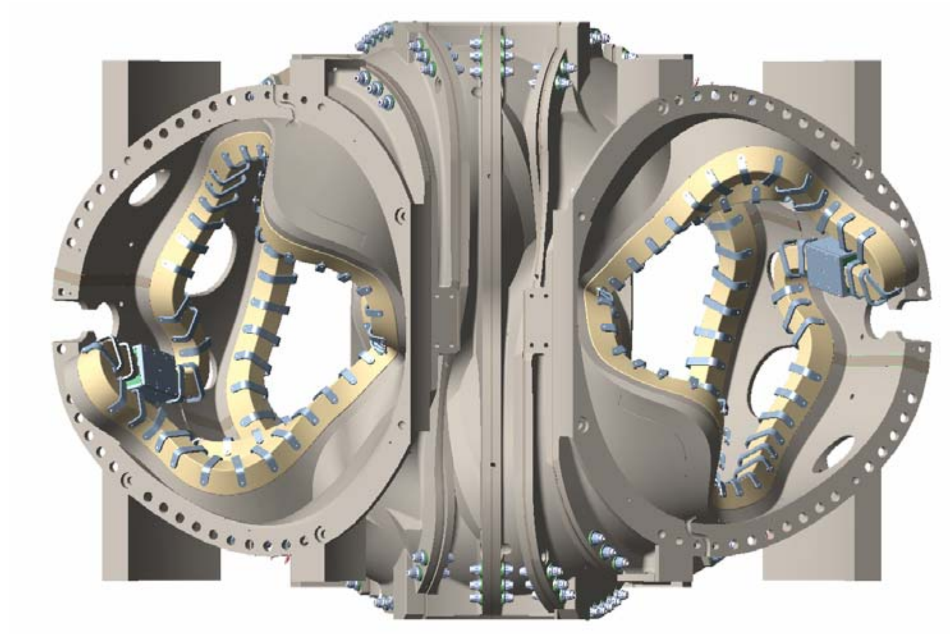
The photo above shows the A-A weld region as the upper casting is being lowered onto the mating casting.

Inner Leg Weld Regions

Major weld load:

Up to ~ 4.5 kips/inch of running load.



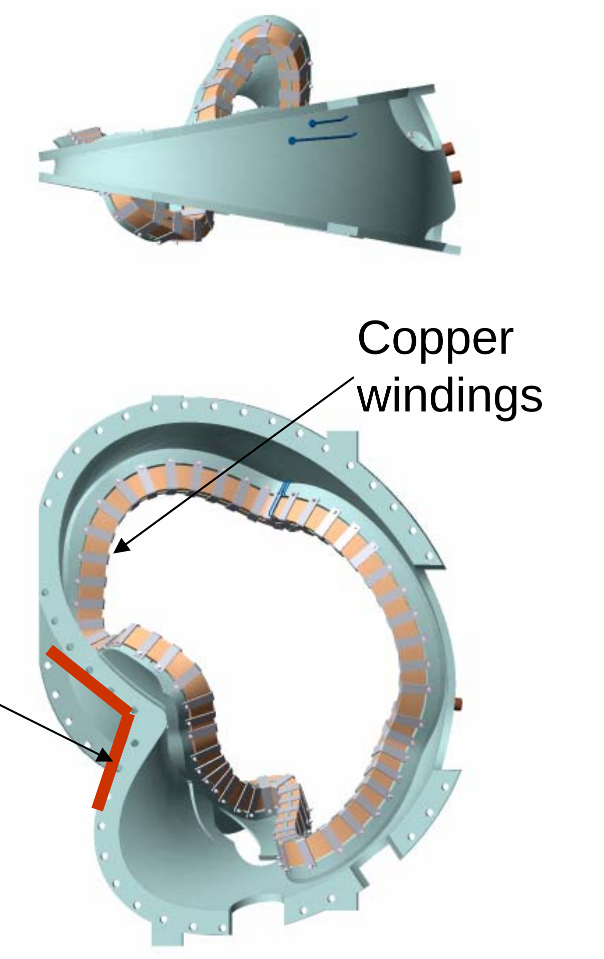


Red indicates weld; note that C-C is not welded.

Issues

- <u>Weld distortion</u>. (See figure on right.)
  - *Preliminary analysis suggests a weld of 0.5 inch is sufficient*
- Permeability of welds must be <1.02.
- Fatigue life of welds. (4 X 130,000 pulses req’d.)

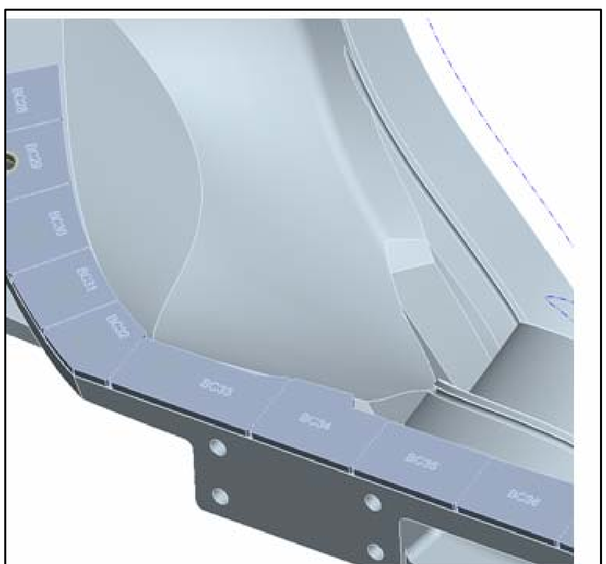
Primary Issue: Will welds here result in distortion >0.010” at the copper windings??

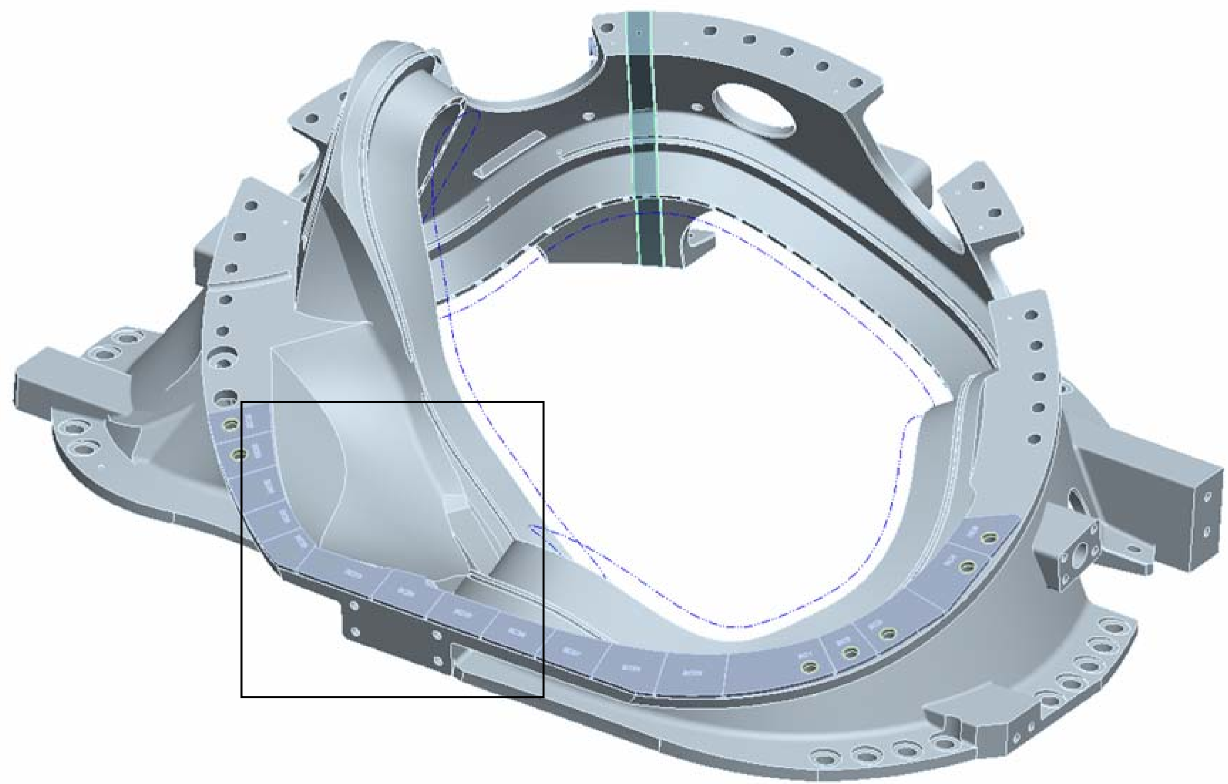


Preliminary analysis suggests a weld of 0.5 inch is sufficient

Inboard shims are cut to shape and thickness

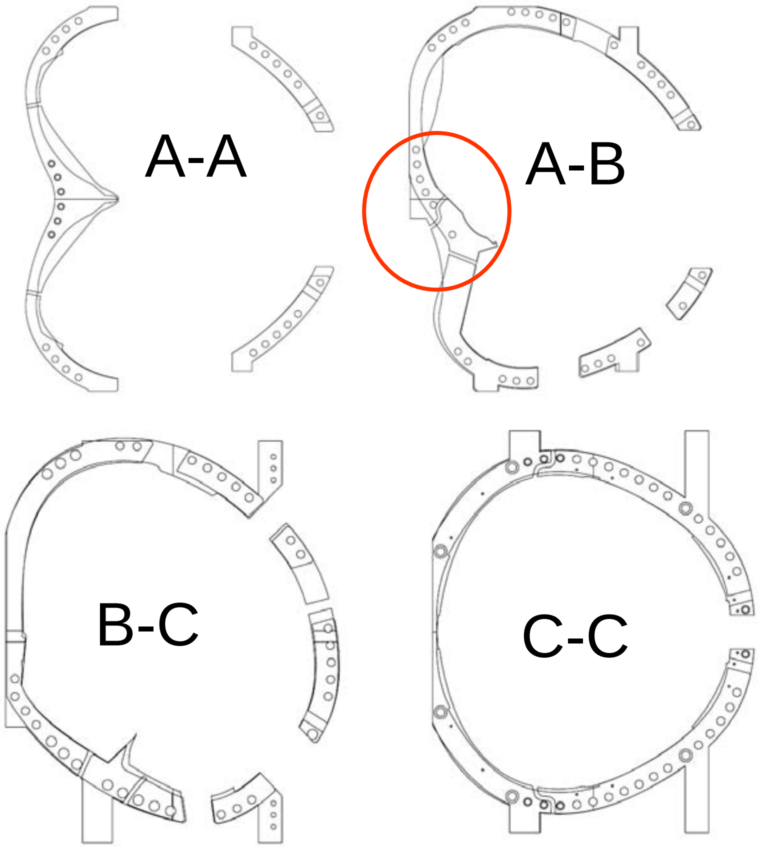
- Shim profile cut on water-jet and one side milled or ground flat
- Other side milled to thickness at assembly
- Shims made from stellalloy
- Shims welded with Metaltek casting repair wire for low permeability

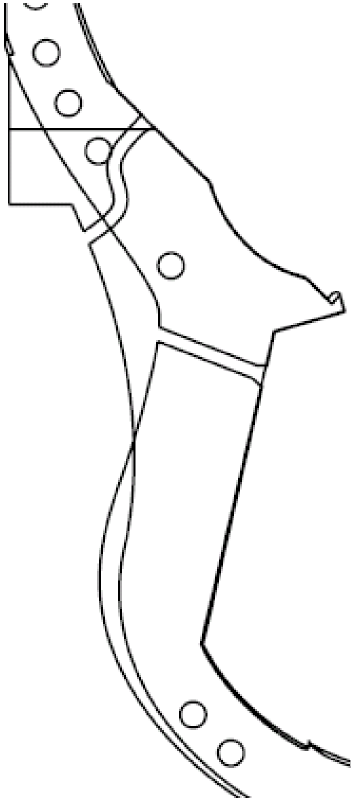


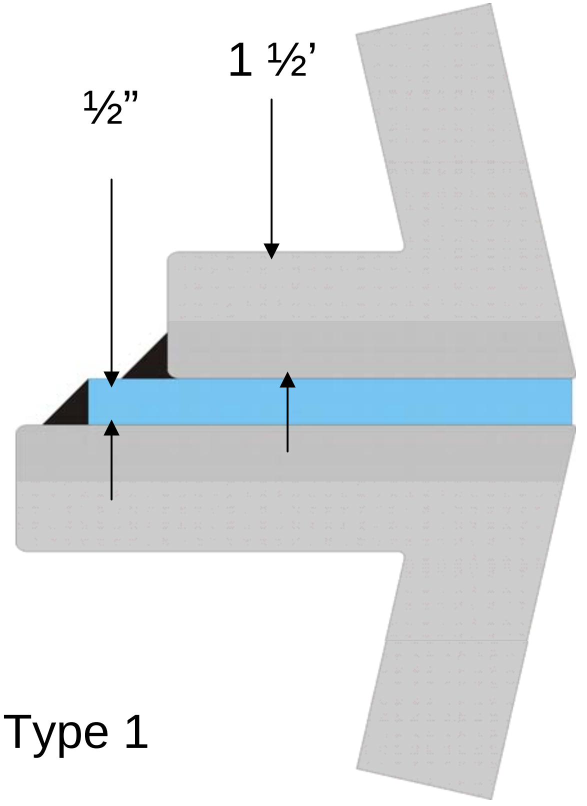


Weld design options depend on location

- Flanges do not match up in some locations



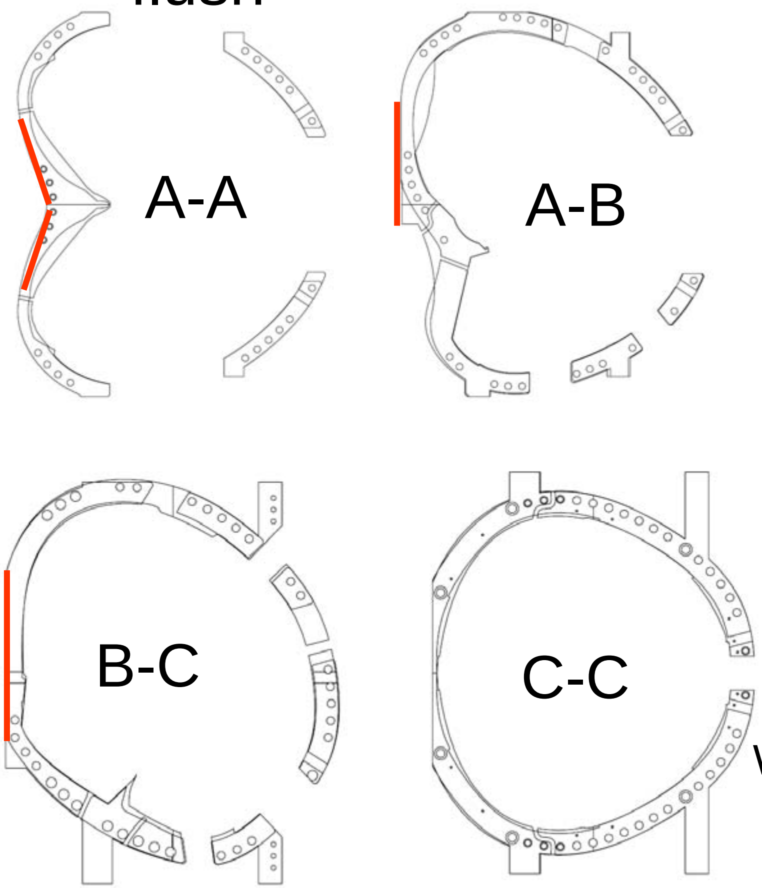


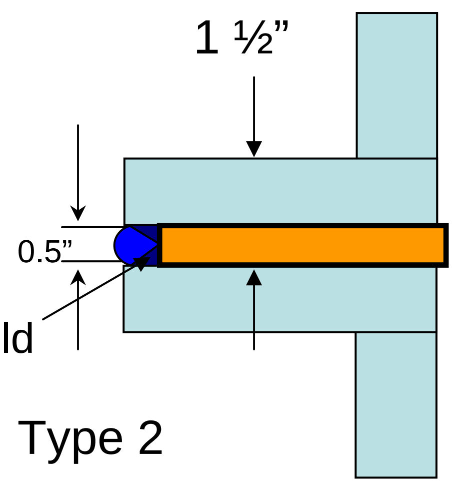


Type 1

Weld design options depend on location

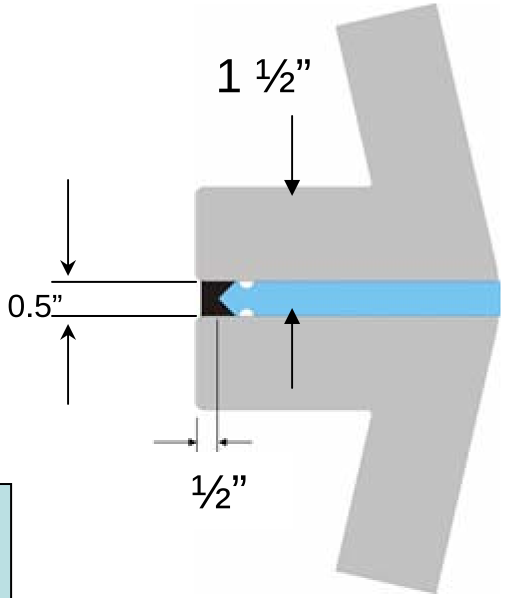
- Flange edges abut solenoid in some areas, shim must be flush





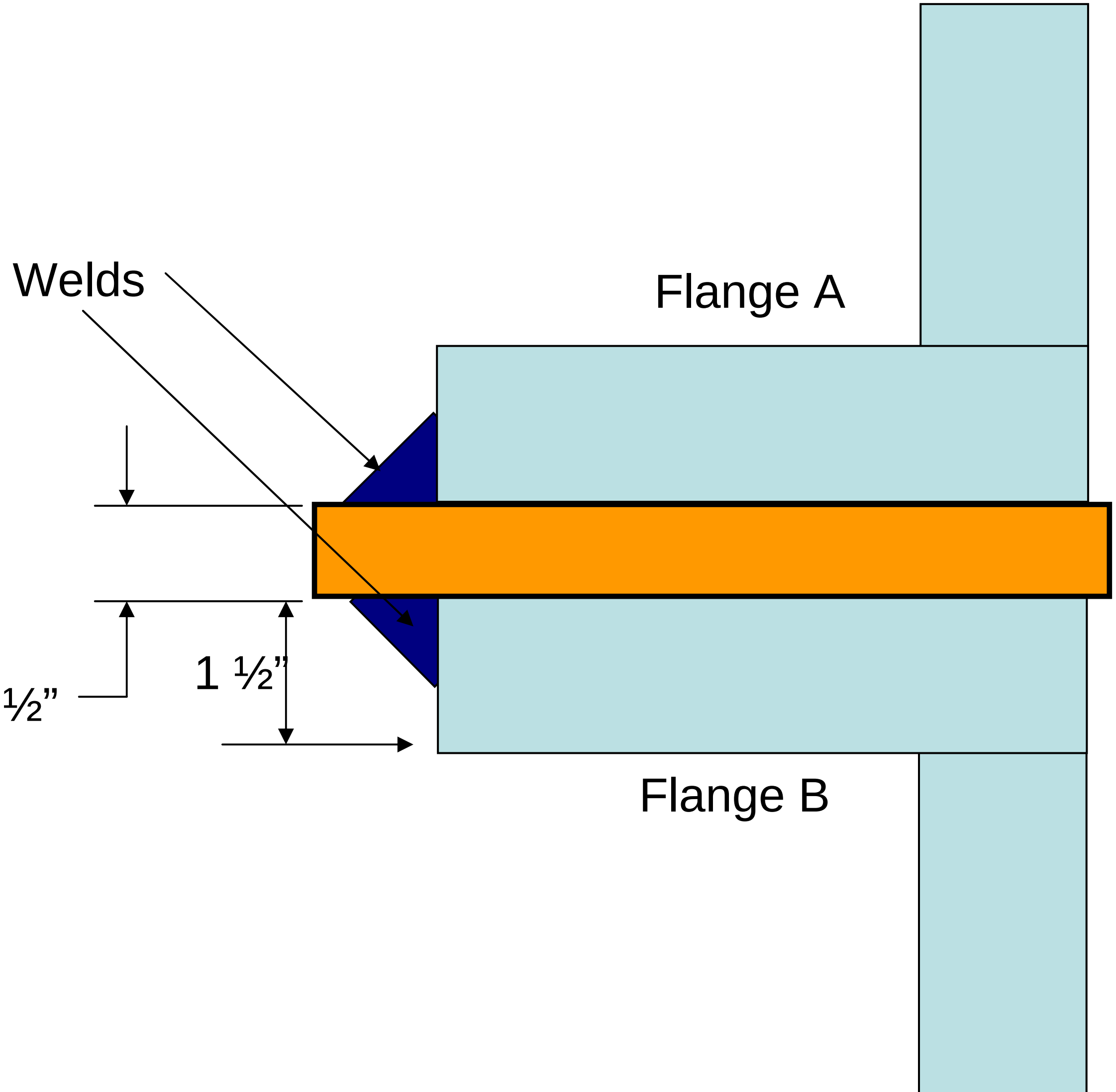
Type 2

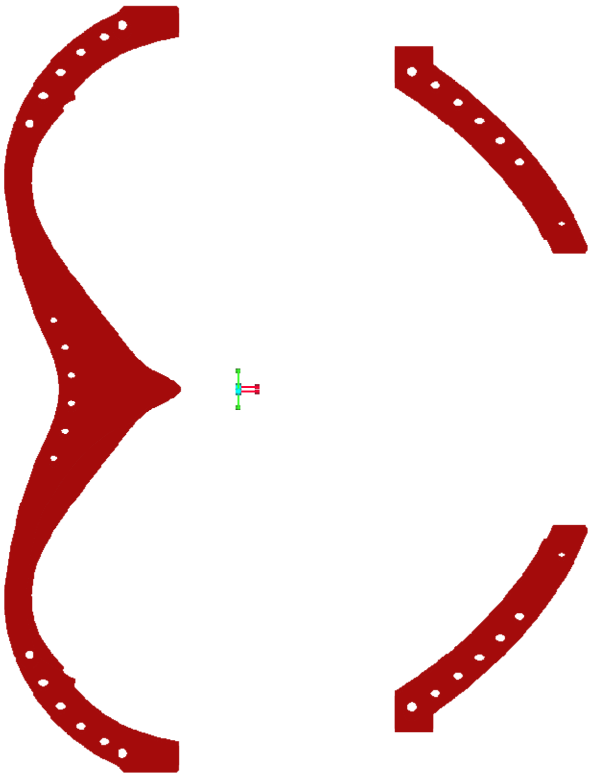
(not analyzed yet)



Type 2A

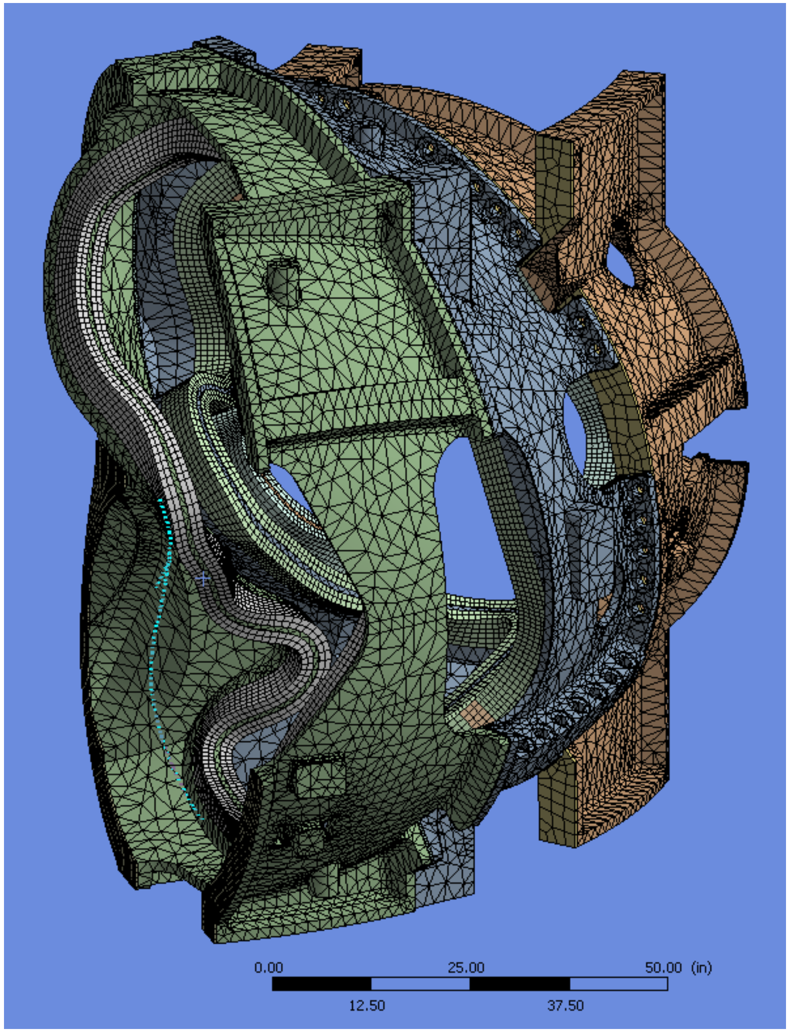
Type 3

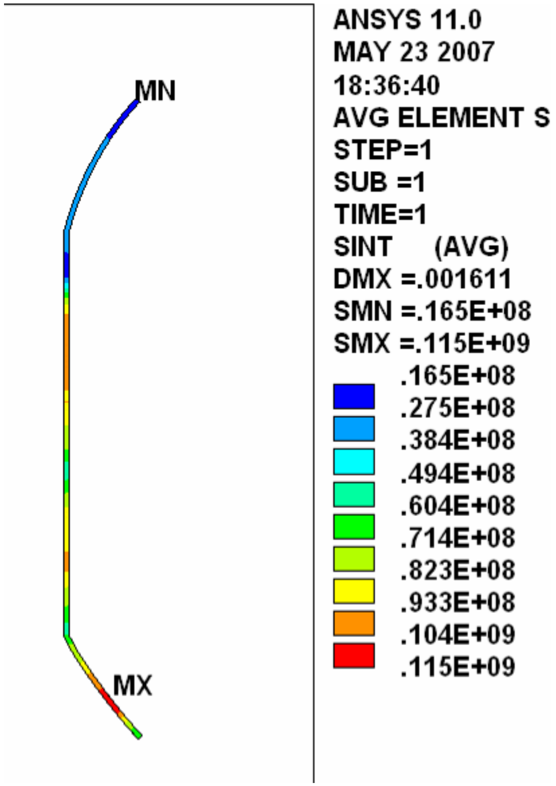




This can be used on non straight sections AA

Weld Stresses Calculated with ANSYS Global Model





Peak Stress of 19,246 psi

Chemical Composition of Casting Alloy and Weld Wire

	C	Mn	Si	Cr	Ni	Mo	P	S	N
Min. %	.040	2.3	--	18.0	13.0	2.1	--	--	.24
Max. %	.070	2.8	0.7	18.5	13.5	2.5	0.035	0.025	.28

Table 3-1 Weight % of Chemical Constituents in Casting Alloy

	C	Mn	Si	Cr	Ni	Mo	P	S	Cu	N
Min. %	--	5.0	--	19.0	15.0	2.5	--	--	--	--
Max. %	0.03	9.0	1.0	22.0	18.0	4.5	0.03	0.02	0.3	0.3

Table 3-2 Weight % of Chemical Constituents of Bare Weld Wire

Casting Alloy Mechanical Properties

Temperature	77K	293K
Elastic Modulus	21 Msi (144.8 Gpa)	20 Msi (137.9 Gpa)
0.2% Yield Strength	72 ksi (496.4 Mpa)	30 ksi (206.8 Mpa)
Tensile Strength	95 ksi (655 Mpa)	78 ksi (537.8 Mpa)
Elongation (Casting)	32%	36%
Elongation (Weld Material)	25%	28%
Charpy V – notch Energy	35 ft. lbs. (47.4 J)	50 ft-lbs (67.8 J)

Table 3-4 Minimum Mechanical Properties

Measured Properties of Actual Castings and Weld Wire

updated 2/15/07

AVERAGES

Type C

Casting Compariso	77K (-320F)							293K (RT)						
Property	**Required**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**Required**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Elastic Modulus	21 Msi (144.8 Gpa)	23.3	25.5	24.9	26.5	30.2	28.8	20 Msi (137.9 Gpa)	23.1	22.7	21.6	23.1	27.3	24.1
0.2% Yield Strength	72 ksi (496.4 Mpa)	98.4	93.2	97.1	97.8	102.5	99.5	34 ksi (234.4 Mpa)	35.1	36.6	38.3	37.4	38.8	44.5
Tensile Strength	95 ksi (655 Mpa)	170.3	163.8	163.1	164.8	170.9	159.9	78 ksi (537.8 Mpa)	83.7	82.4	82.7	83.1	87.0	83.7
Elongation	32.0%	55.7%	54.3%	55.7%	54.0%	42.4%	42.3%	36.0%	52.0%	53.5%	52.5%	55.7%	58.0%	40.3%
Charpy V – notch Energy	35 ft. lbs. (47.4 J)	77.7	84.3	99.7	86.7	80.3	85.3	50 ft-lbs (67.8 J)	142.0	150.7	157.3	175.7	139.0	152.3

Type A

Casting Compariso	77K (-320F)							293K (RT)						
Property	**Required**	**A-1**	**A-2**	**A-3**	**A-4**	**A-5**	**A-6**	**Required**	**A-1**	**A-2**	**A-3**	**A-4**	**A-5**	**A-6**
Elastic Modulus	21 Msi (144.8 Gpa)	25.5	25.3	26.7	28.9	26.4	27.9	20 Msi (137.9 Gpa)	21.7	22.2	21.9	22.9	23.1	22.6
0.2% Yield Strength	72 ksi (496.4 Mpa)	97.3	99.9	98.9	100.0	101.0	103.2	34 ksi (234.4 Mpa)	36.6	43.3	43.2	43.8	42.4	44.5
Tensile Strength	95 ksi (655 Mpa)	166.3	165.3	166.0	165.9	165.2	163.0	78 ksi (537.8 Mpa)	82.4	83.7	82.6	84.6	82.2	89.2
Elongation	32.0%	56.0%	56.3%	51.0%	46.0%	48.7%	38.3%	36.0%	53.2%	56.0%	53.3%	50.3%	50.0%	49.0%
Charpy V – notch Energy	35 ft. lbs. (47.4 J)	78.7	79.0	87.3	76.7	70.3	73.0	50 ft-lbs (67.8 J)	163.7	164.0	158.0	150.3	146.3	126.7

Type B

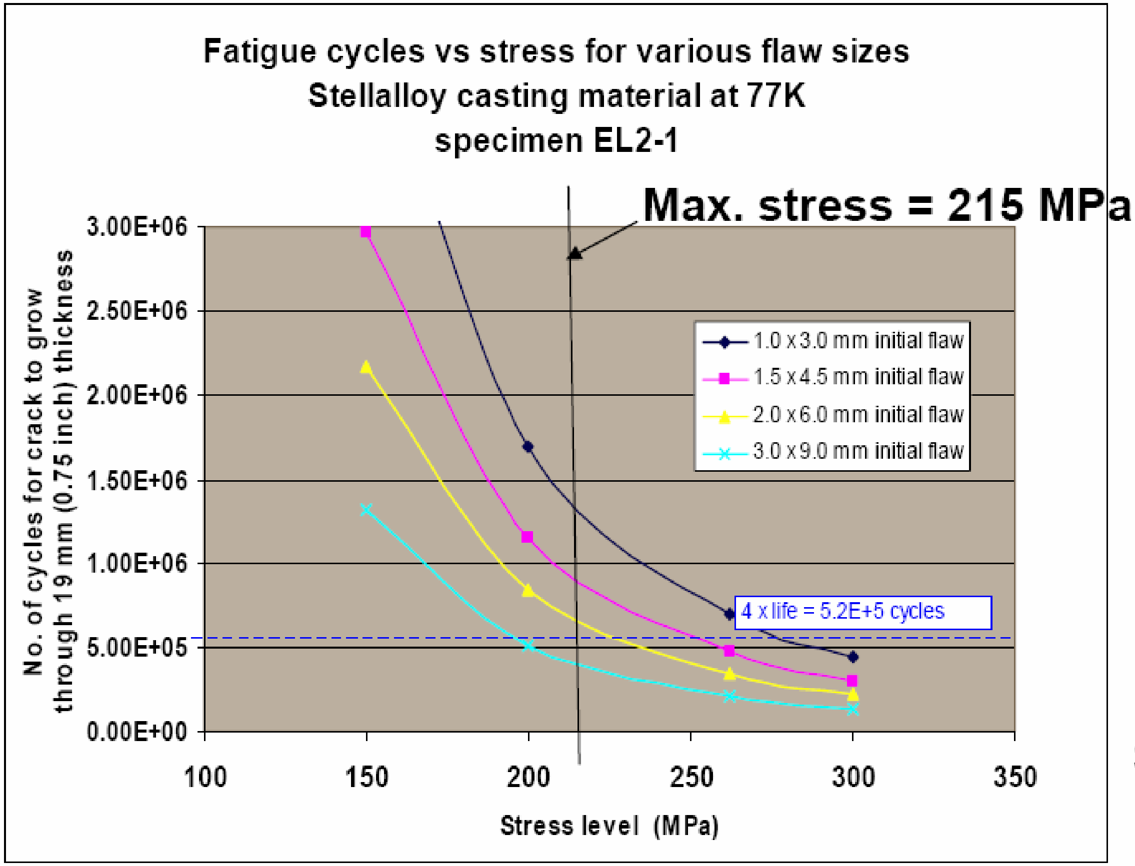
Casting Compariso	77K (-320F)							293K (RT)						
Property	**Required**	**B-1**	**B-2**	**B-3**	**B-4**	**B-5**	**B-6**	**Required**	**B-1**	**B-2**	**B-3**	**B-4**	**B-5**	**B-6**
Elastic Modulus	21 Msi (144.8 Gpa)	25.9	27.4	29.3	25.3	29.3		20 Msi (137.9 Gpa)	22.7	22.5	22.6	22.8	22.6	
0.2% Yield Strength	72 ksi (496.4 Mpa)	98.7	103.9	107.4	100.2	107.4		34 ksi (234.4 Mpa)	43.3	58.9	42.7	42.6	42.7	
Tensile Strength	95 ksi (655 Mpa)	164.9	177.5	172.5	166.1	177.5		78 ksi (537.8 Mpa)	86.0	86.6	84.1	85.6	84.1	
Elongation	32.0%	46.3%	50.3%	56.3%	53.3%	56.3%		36.0%	47.3%	49.5%	44.7%	43.5%	44.7%	
Charpy V – notch Energy	35 ft. lbs. (47.4 J)	88.0	63.7	74.7	65.7	74.7		50 ft-lbs (67.8 J)	146.7	135.7	115.0	119.7	115.0	

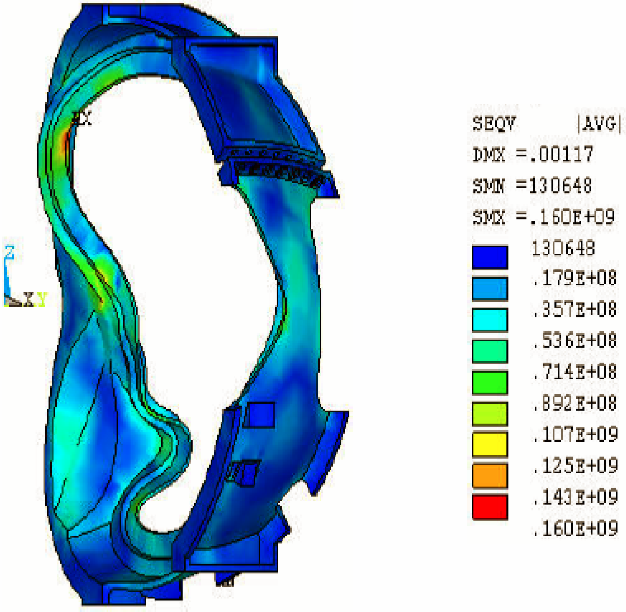
Weld Material	77K (-320F)							293K (RT)							
Property	**Required**	**Lincoln 3018926/7 8309**	**Lincoln Lot # 3012668/8 2743**	**Lincoln 3018513/7 8308**	**Lincoln Lot # 3017006/7 2262**	**Metrode Lot # WO21735**	**Metrode Lot # WO19711**	**Required**	**Lincoln 3018926/7 8309 Doc #10**	**Lincoln Lot # 3012668/8 2743** see previous info ->	**Lincoln 3018513/7 8308**	**Lincoln Lot # 3017006/7 2262**	**Metrode Lot # WO21735**	**Metrode Lot # WO19711**	**Previously Reported Heat/Lot # 3012668/8 2743**
Elastic Modulus	21 Msi (144.8 Gpa)	23.3	27.1 Doc#9	27	23.2	24.3	26.4 Doc#9	20 Msi (137.9 Gpa)	24.5 Doc 10	22.6	23.4	24.9	23	23.1 Doc#10	25.5 Doc#10
0.2% Yield Strength	72 ksi (496.4 Mpa)	114.3	126.3 Doc#9	128.2	112.4	102.1	109.5 Doc#9	34 ksi (234.4 Mpa)	56.9 Doc #10	57.4	65.2	54.9	54.8	63.9 Doc#10	56.5 Doc#10
Tensile Strength	95 ksi (655 Mpa)	157.5	187.7 Doc#9	182.1	176.4	166.6	166.9 Doc#9	78 ksi (537.8 Mpa)	93.9 Doc #10	93.7	95.2	92.1	88.2	98.1 Doc#10	85 Doc#10
Elongation	32%	16.0%	33% Doc#9	34.0%	48.0%	38.0%	34% Doc#9	36.0%	42% Doc #10	41.5%	38.0%	42.5%	37.5%	54% Doc#10	55% Doc#10
Charpy V – notch Energy	35 ft. lbs. (47.4 J)	36.33	51 Doc#11	54	53	48	48 Doc#11	50 ft-lbs (67.8 J)	100 Doc #10	98	103	117	93	111 Doc#12	102 Doc#12

Derivation of S_m

- Per the NCSX Structural Design Criteria, Sm shall be the lesser of 1/3 of the ultimate strength or 2/3 of the yield strength at temperature.
- Since the weld region includes the Stelalloy casting, weld metal, HAZ, and shims made of 316-LN, the strength values shall be the lesser of these.
- At this time, 316-LN for the shim material has not been finalized, so for the present we shall use the lowest values between the Stellalloy and the weld material at 77K. For the yield, this is 93.2 ksi for the C2 casting; 2/3 of yield =61.5 ksi. **The lowest ultimate strength is 157.5 for the weld wire; 1/3 of this =52.5, so this is what we shall use.**
- A <u>weld efficiency factor factor</u> of 0.55 shall be applied to this, since it is a *butt joint*. ***Therefore, the Sm=0.6*52.5=28.9ksi.***
- ***Issue: What is required for fatigue?*** What stress concentration factor should be used for this type of weld?

Stellalloy has Good Fatigue Properties





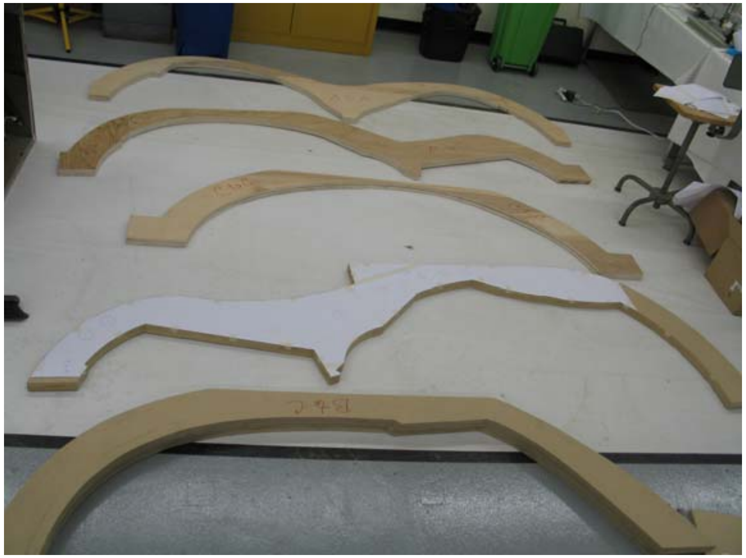
Stress in the Type A Castings

Plans for Qualifying the Weld Material for Fatigue

- Will require test specimens in conformance with standard ASTM-E647.
- For the Stellalloy material, we tested compact tension specimens at the Florida Magnet Lab. These tests were in conformance with E647.
- To test the weld material (and HAZ, if necessary, in separate tests), we need to weld A Stellalloy plate to a 316 plate with the weld wire then cut specimens from this welded plate.
- A center cracked tension specimen will be used - this is nothing more than a rectangular specimen with a pre-notched crack in its center. The plate needs to conform to certain geometric requirements, all are detailed in E647 with diagrams.
- Can probably do as few as three tests, if the scatter of the results is minimal.
  - With appreciable scatter, we would probably need to do a minimum of six specimens. All tests will be performed for appropriate load ranges, temperatures and environmental conditions.
  - Crack growth rates can be very sensitive to variations in these test conditions, so it is important to perform the tests under conditions that approximate design conditions as close as possible.

Suggestions from the EWI Conference Call

- Recommend ultrasonically testing the welds.
  - Action: Frank Malinowski is checking on local labs. Need to check if there are issues with cast material.
- Butt welds are better in fatigue than fillet welds.
  - **Action: consider changing to butt welds everywhere if TIG access is adequate.**
- Suggest UT tests followed by longitudinal and lateral sections of the test welds.
  - EWI will include in proposal.
- Suggest making full scale inner leg weld tests.
  - **Will do.**
  - **Test pieces will be like these wooden models.**
  - **316SS plate is in;**
  - **Action: Larry Dudek will get models from Mike Cole and fabricate pieces.**



Suggestions from the EWI Conference Call (cont'd.)

- Considering PPPL's expertise in TIG along with other technical factors, TIG is the way to go.
  - Conclusion: TIG will be used.
- Analytical distortion predictions on a reasonably short timescale may be possible at EWI, depending on the modeling effort required.
  - EWI will examine at our CAD models to see if they can be used.
  - EWI will investigate if "hot" properties of 316 can be used as a reasonable stand-in for Stelalloy hot properties which are needed for modeling.

Test plate results – magnetic permeability

VVSA-3 Port 12A Rejected Flange Cover Magnetic Permeability Before and After Annealing - 6/1/07

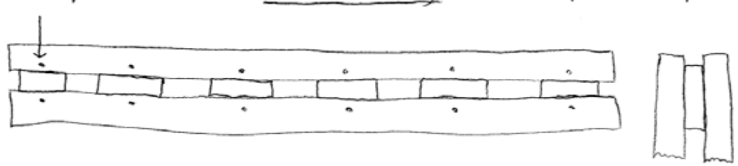
Front Face - Before Annealing (Mu)	Front Face - After Annealing (Mu)
>1.1 <1.2	<1.02
>1.1 <1.2	<1.02
>1.1 <1.2	<1.02
>1.1 <1.2	<1.02
>1.1 <1.2	<1.02
>1.1 <1.2	<1.02

1150 C anneal followed by rapid cooling does reduce permeability of 316LN to acceptable levels.

Coil to Coil Weld Trial Magnetic Permeability (1)

5/31/07

12 points measured before welding = >1.1 μ <1.2 μ

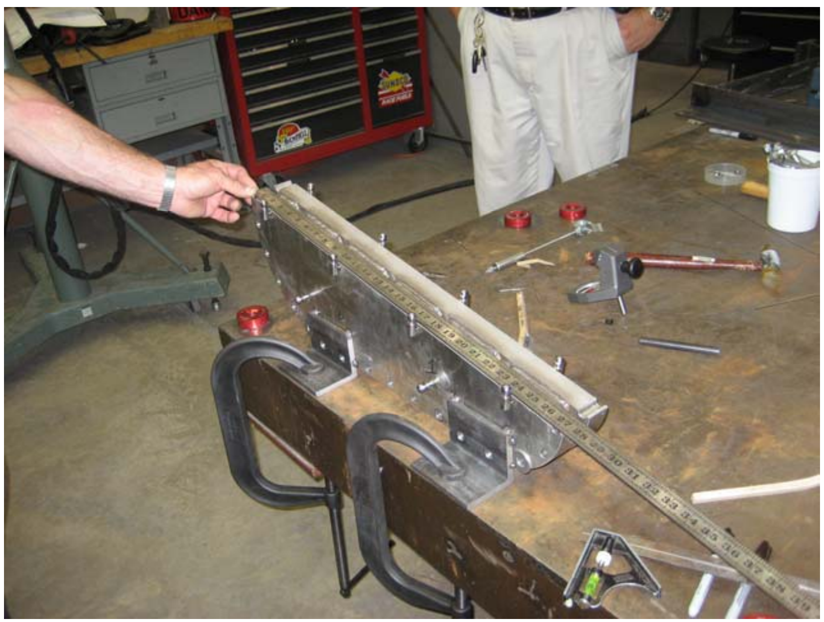


6/1/07 After welding same 12 points measured the same,
>1.1 μ <1.2 μ

Need to investigate of cutting caused permeability increase along edges.

1st Weld Test Piece

- 316 LN plate, ~1.5” thick; 304 shim plates, 0.5” thick.
- Max. temperature in plates was 305F.
- 8-9 weld passes.



1st Weld Test Piece

Close up view of a TiG weld

1st Weld Test Piece

End view showing shim position prior to weld