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| Title: Structural Analysis of PXIE Cryostat | |
| Calculation No.: NE-EO-2013-003 | Revision Number: 0 |

CALCULATION COVER SHEET

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|--------------------------------------------------|------------------------------|------|
| Supersedes Calculation No.: | Total Number of Attachments: | |
| Analyzed System: PXIE HWR162 | | |
| Purpose of Revision: Initial Issue | | |
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1. Objectives

The objective of this analysis was to determine compliance of the PXIE Cryomodule vacuum vessel with both the Argonne Pressure Systems Safety Manual (APSSM) and the Fermi National Accelerator Laboratory Environmental Safety and Health Manual (FESHM) when subjected to normal service loads.

2. Scope

The scope of this analysis was limited to the PXIE Cryomodule vacuum vessel. The cavities, strongback and any appended equipment or componentry are not included in this analysis.

3. Background

Project-X is a high intensity proton accelerator project intended to support a world-leading high-energy physics program at FermiLab. The Project-X Injector Experiment (PXIE) will be an integrated systems test for the front-end systems of the Project-X accelerator and will demonstrate the technology required for successful operation. A major subsystem of PXIE is a low-beta superconducting cryomodule that contains eight 162.5 MHz half wave resonators optimized for beta = 0.11 and eight magnet packages each integrating a 6 T solenoid with x-y dipole steering magnets. The cryostat vacuum vessel is the object of this analysis.

4. Methodology

This vacuum vessel is designed to comply with both the Argonne Pressure Systems Safety Manual (APSSM; Ref. 1) and the Fermilab Environmental Safety and Health Manual (FESHM; Ref. 2). Both the APSSM and FESHM require vessels with static pressure gradients of less than 15 psi to have their allowable working pressures established by accepted engineering practice. The ASME Boiler and Pressure Vessel Code (Ref. 3) is not mandatory but it recommended and is used here for this purpose. Here, Design by Analysis outlined in Section VIII, Division 2, Part 5 (Ref. 2) is used. This method utilizes finite element analysis. A finite element model of the PXIE cryostat vacuum vessel was created with the Ansys finite element program and subjected to high vacuum, gravity and appurtenance loadings, and analyzed to find component stresses. These stresses were then compared to allowables defined per the BPVC.

5. Overview of Analysis

A total of six analyses were conducted and are summarized in Table 1.

| | | | | | |
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| Analysis Case | Failure Mode | Criteria | Load Cases | Analysis Tool | Material Model |
|---------------|------------------------|-----------------------------------------|------------|------------------|----------------------------|
| A | Plastic Collapse | BPVC Sect. VIII, Div. 2, Part 5.2.3 | 1 | FEA | Elastic, Perfectly Plastic |
| B | Local Failure | BPVC Sect. VIII, Div. 2, Part 5.3.2 | 1 | FEA | Linear Elastic |
| C | Collapse from Buckling | BPVC Sect. VIII, Div. 2, Part 5.4.1.2.a | 1 | FEA | Linear Elastic |
| D | Ratcheting | BPVC Sect. VIII, Div. 2, Part 5.5.6.1 | 1 | FEA | Linear Elastic |
| E | Fatigue | BPVC Sect. VIII, Div. 2, Part 5.5.2.3 | - | Spreadsheet | - |
| F | Weld Analysis | AWS D1.6 | 1 | FEA, Spreadsheet | Linear Elastic |

Table 1
Analysis Overview

6. Assumptions

This analysis is based on the following assumptions:

1. Loads are steady state (no fatigue or inertial effects).
2. All components operate at room temperature.
3. Material response is constant with time (no effects of aging, creep, etc).
4. Materials are isotropic and homogeneous.
5. Residual stresses are not included.

7. Geometry

The cryostat model is based on solid CAD geometry found in STEP-file G15836-B(04-30-2013).stp. This file was then read into the Ansys Design Modeler geometry module, where a full symmetry shell model was created. This model is shown in Figure 1. Bonded contact between bolts holes in the cover and the top flange on the tank is used to attach the cover.

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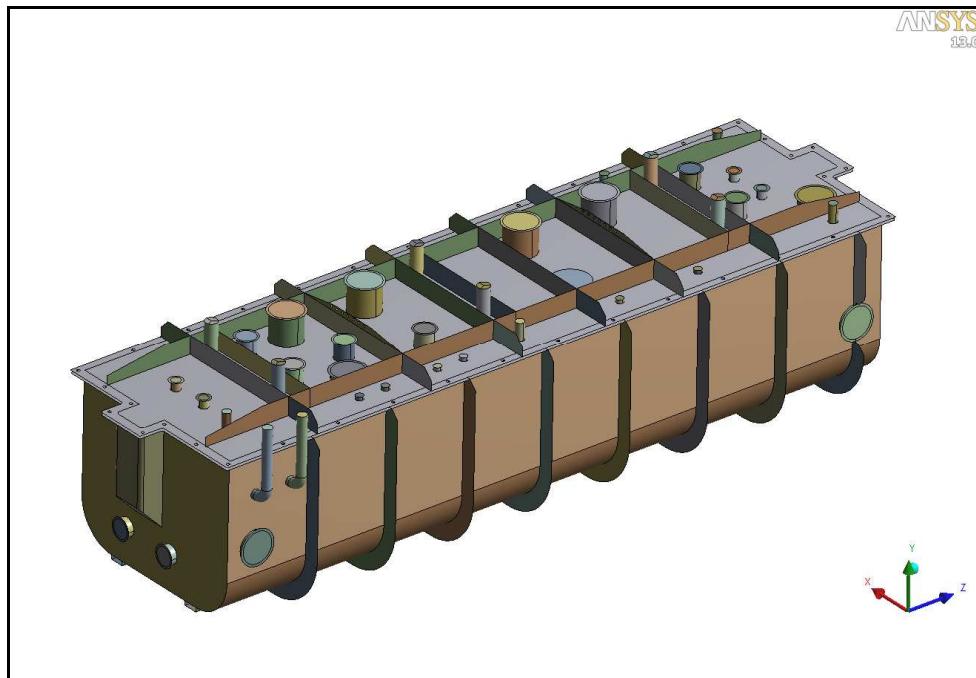


Figure 1
Solid Geometry Model

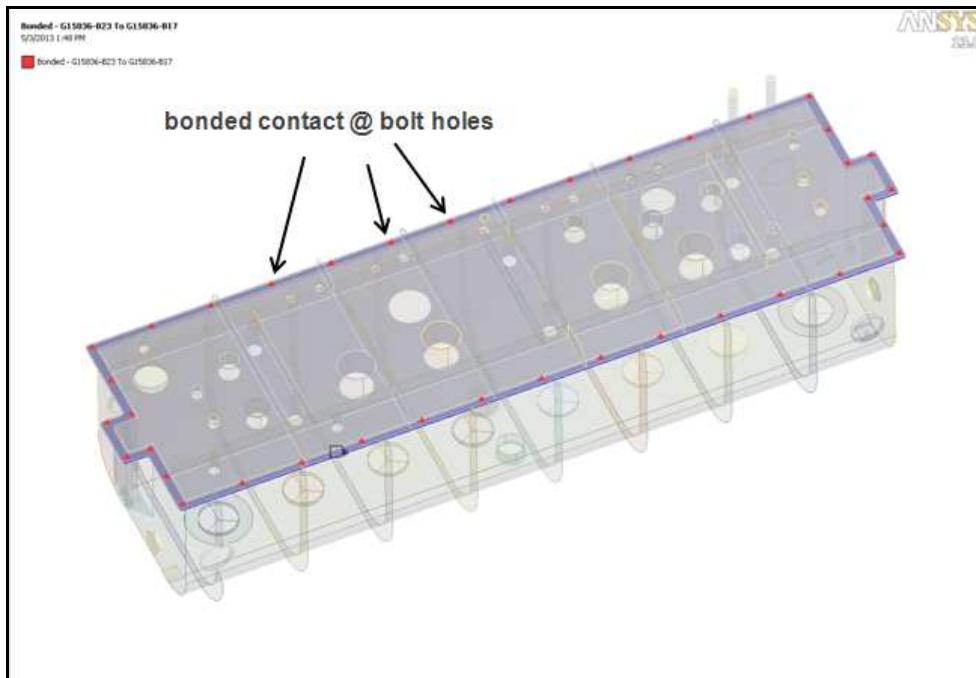


Figure 2
Attachment of Cover to Tank with Bonded Contact

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8. Material Properties

The cryostat is fabricated from 304L stainless steel that is certified to 304 stainless steel mechanical properties. Material properties used in this analysis are given in Table 2.

| Property | Value | Source |
|------------------------------|--------------------|-------------------|
| ρ (lb/in ³) | 0.286 | Ref. 5 |
| E(psi) | 29.0×10^6 | Ref. 5 |
| ν | 0.27 | Ref. 5 |
| S_u (psi) | 70,000 | Ref. 4 |
| S_y (psi) | 30,000 | Ref. 4 |
| S (psi) | 20,000 | Ref. 4 |
| S_{ps} (psi) | 60,000 | Ref. 2, 5.5.6.1.d |

Table 2
Material Properties

Multiples of these values are used throughout this report and are tabulated below.

| S_y (psi) | S_u (psi) | S (psi) | 1.5S (psi) | 2 S_u (psi) | 3S (psi) | 4S (psi) |
|-------------|-------------|-----------|------------|---------------|----------|----------|
| 30,000 | 70,000 | 20,000 | 30,000 | 60,000 | 60,000 | 80,000 |

Table 3
Multiples of Material Properties

9. Boundary Conditions

The cavity is restrained by applying fixed displacements to the edges of the four mounting holes, as shown in Figure 3, so as to provide a kinematic restraint.

Loading comes from multiple sources, as summarized in Table 4. Vacuum is applied to the inner surfaces of the cryostat (Figure 4). Gravity results in self-weight in the metal components. Lastly, the weight of the loaded strongback (8000 lbf.) is applied evenly to the six hanger tubes (Figure 5). Caps were placed on cryostat penetrations so that pressure reactions would be transmitted to the cryostat assembly.

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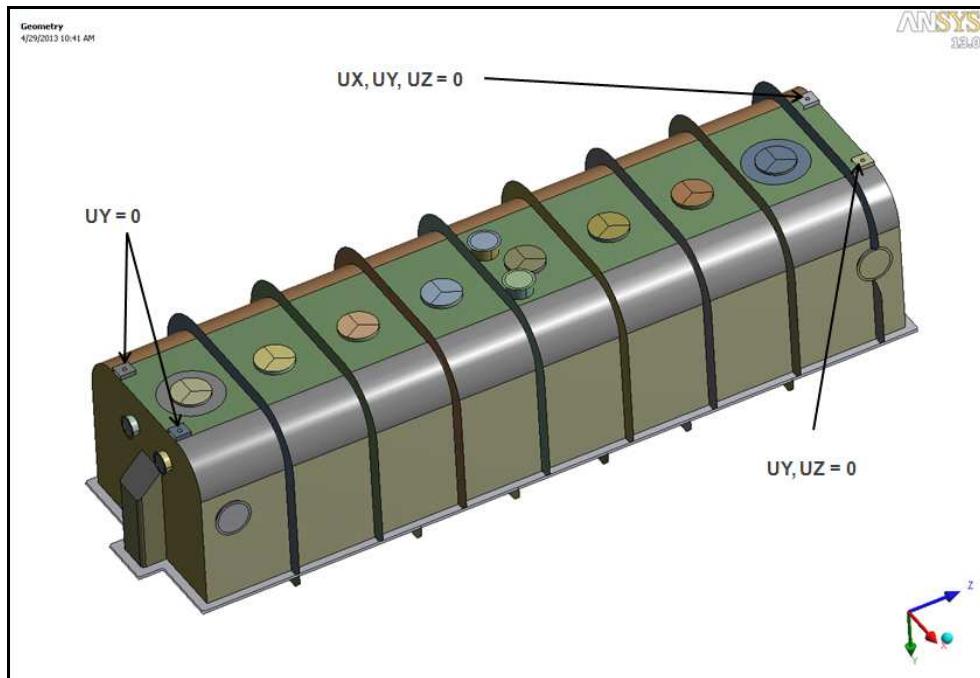


Figure 3
Boundary Conditions

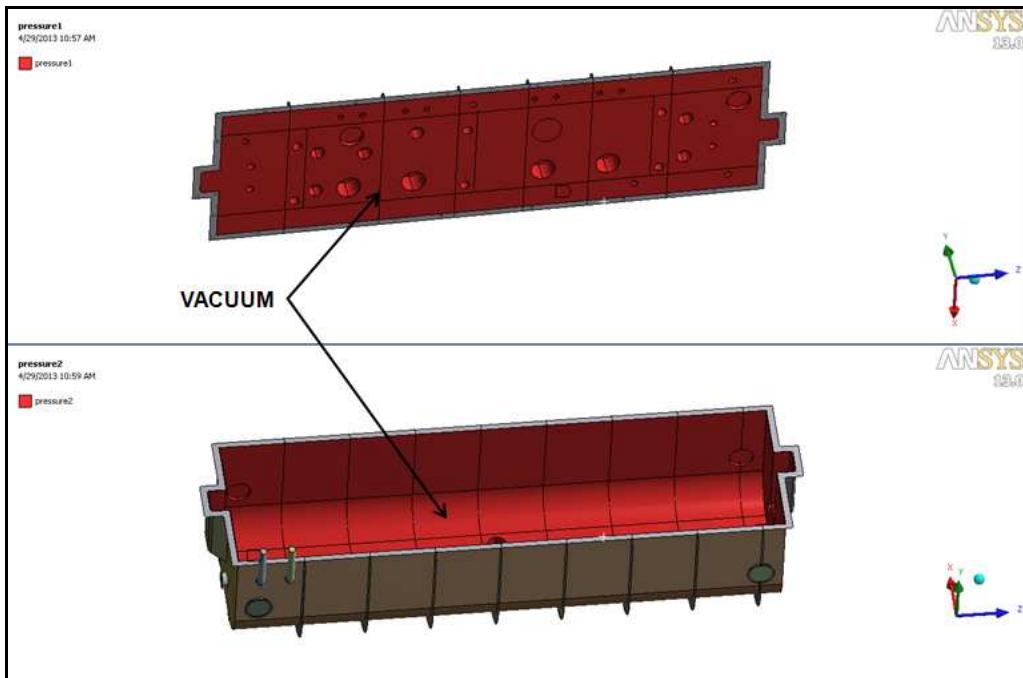


Figure 4
Vacuum Loading

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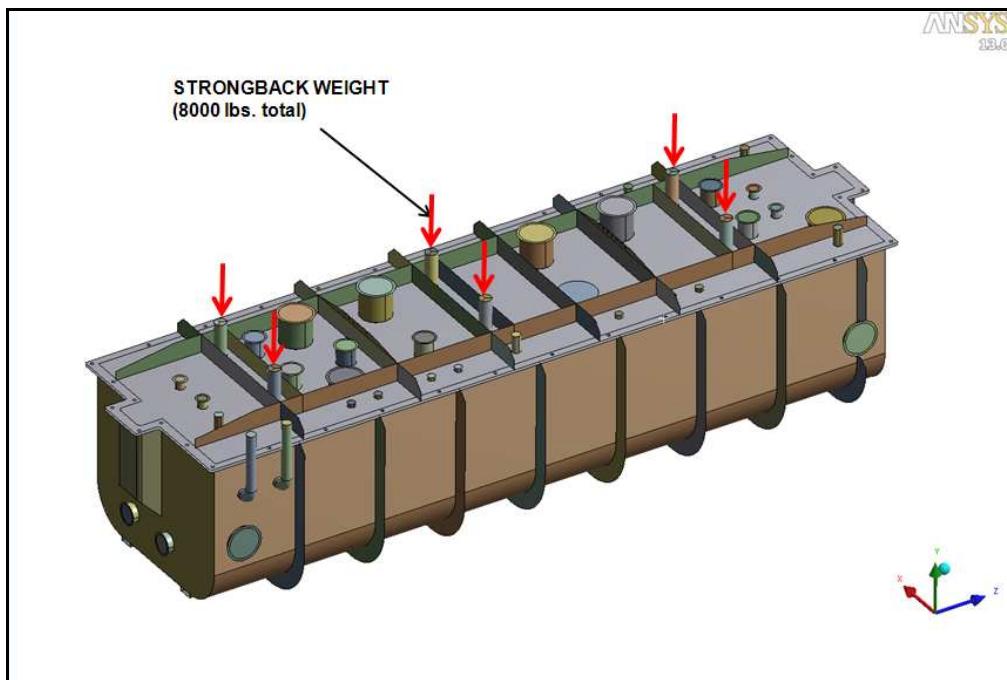


Figure 5
Strongback Loads

10. Solution and Results

Three finite element models were constructed and analyzed, and are summarized in Table 4. All are based on the same solid model and differ in material formulation and load factors.

| Finite Element Model | Analysis Result | | Material Type | Load Factors | Pressure | Gravity | Strongback Weight |
|----------------------|-----------------|---------------------------|----------------------------|--------------|------------|-------------------------|-------------------|
| 1 | A | Plastic Collapse | elastic, perfectly plastic | 1.5 | -22.05 psi | 534.6 in/s ² | 12000 |
| 2 | B,D | Local Failure, Ratcheting | linear elastic | 1 | -14.7 psi | 386.4 in/s ² | 8000 |
| 3 | C | Buckling | linear elastic | 1 | -14.7 psi | 386.4 in/s ² | 8000 |
| - | E | Cyclic Loading | - | - | - | - | - |
| 4 | F | Weld analysis | linear elastic | 1 | -14.7 psi | 386.4 in/s ² | 8000 |

Table 4
Summary of Finite Element Models

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A. Protection Against Plastic Collapse

The limit load method was used to check for plastic collapse. This analysis checks for structural instability due to gross plastic deformation. An elastic perfectly plastic material model is used, a factored load is applied, and structural stability is indicated if the solution converges. This method is outlined at 5.2.3 in Ref. 3.

The finite element model 1 in Table 4 was used for this analysis. The shell model was meshed with 112,759 6-node shell elements. This finite element model is shown in Figure 7. The analysis load case is based on load case combinations given in Table 5.4 in Ref. 3. This table specifies five factored load combinations, but in the absence of temperature, snow, wind, seismic and live loads, the last four load case combinations reduce to the first. The factored loads used for this analysis load case are shown in Table 4 .

Reference 3 specifies that the analysis be run with small displacement theory and an elastic-perfectly plastic (EPP) material model. The yield strength defining the plastic limit is specified as 1.5S. The EPP material model is shown in Figure 6.

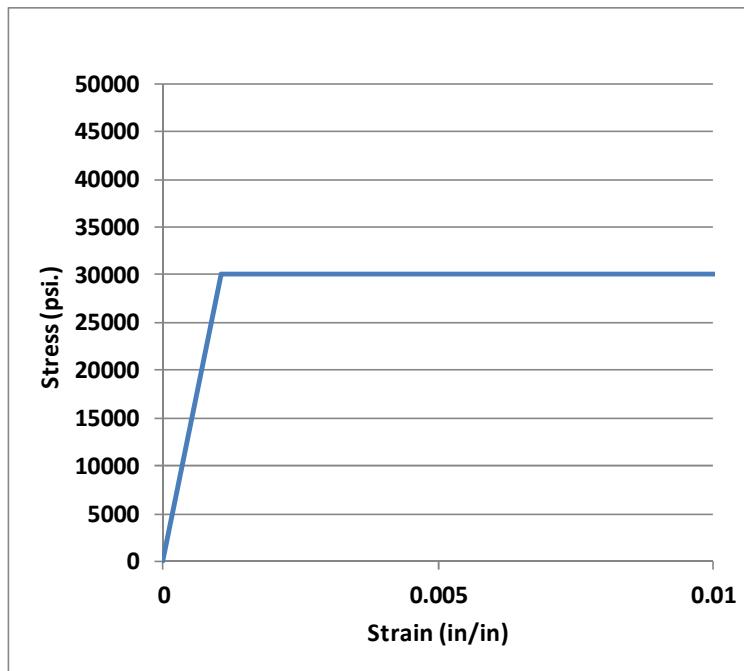


Figure 6
EPP Material Model for 304L Material Certified to 304 Properties

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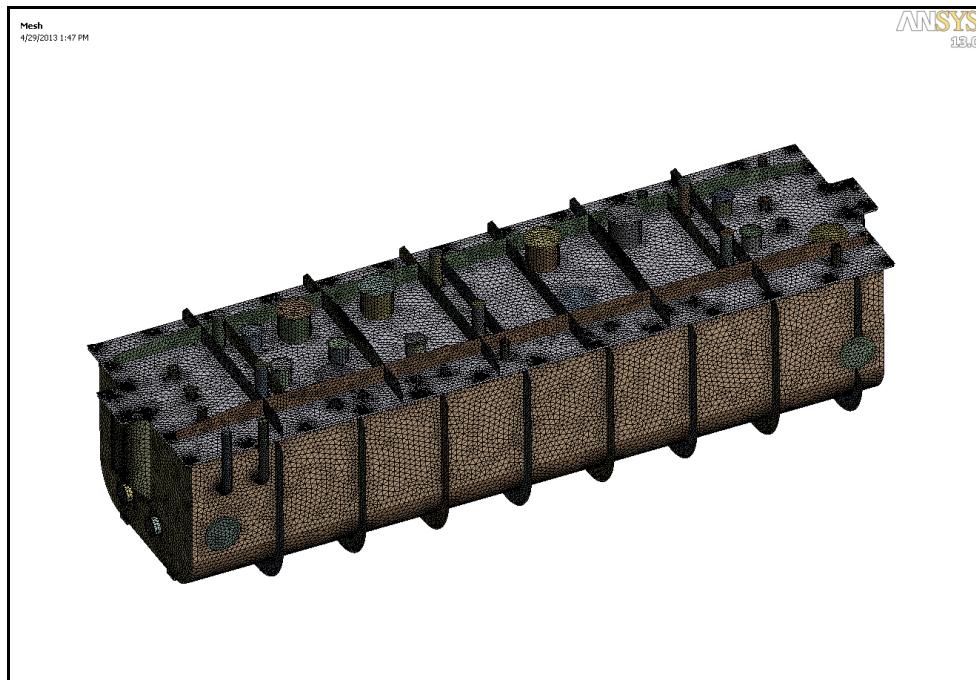


Figure 7
Finite Element Model for Plastic Collapse Analysis

Convergence was achieved, as shown in the sample from the Solution Information shown in Figure 8. This indicates compliance with the code at a pressure differential of 1 atm. The solution was monotonic and direct, without bisection. A plot of summed deflection (Figure 9) show small deflections, no excessive distortion, no indication of snap-through, etc., which demonstrates elastic stability. The requirement for protection against plastic collapse is therefore met. Figure 10 is a plot of von Mises stress, with contours adjusted so that red is greater than S_y (30 ksi).

```
EQUIL ITER 6 COMPLETED. NEW TRIANG MATRIX. MAX DOF INC= 0.1056E-04
LINE SEARCH PARAMETER = 1.000 SCALED MAX DOF INC = 0.1056E-04
FORCE CONVERGENCE VALUE = 0.1557 CRITERION= 47.84 <<< CONVERGED
MOMENT CONVERGENCE VALUE = 0.1514E-01 CRITERION= 0.5760E-04
EQUIL ITER 7 COMPLETED. NEW TRIANG MATRIX. MAX DOF INC= -0.1314E-06
LINE SEARCH PARAMETER = 1.000 SCALED MAX DOF INC = -0.1314E-06
FORCE CONVERGENCE VALUE = 0.1701E-03 CRITERION= 48.82 <<< CONVERGED
MOMENT CONVERGENCE VALUE = 0.4939E-05 CRITERION= 0.5877E-04 <<< CONVERGED
>>> SOLUTION CONVERGED AFTER EQUILIBRIUM ITERATION 7
*** LOAD STEP 1 SUBSTEP 7 COMPLETED. CUM ITER = 39
*** TIME = 1.00000 TIME INC = 0.100000
*** MAX PLASTIC STRAIN STEP = 0.4642E-01 CRITERION = 0.1500

*** ANSYS BINARY FILE STATISTICS
BUFFER SIZE USED= 16384
8.438 MB WRITTEN ON ELEMENT MATRIX FILE: file.emat
1333.688 MB WRITTEN ON ELEMENT SAVED DATA FILE: file.esav
509.062 MB WRITTEN ON ASSEMBLED MATRIX FILE: file.full
3792.562 MB WRITTEN ON RESULTS FILE: file.rst
***** FINISHED SOLVE FOR LS 1 *****
```

Figure 8
Plastic Collapse, Solution Convergence

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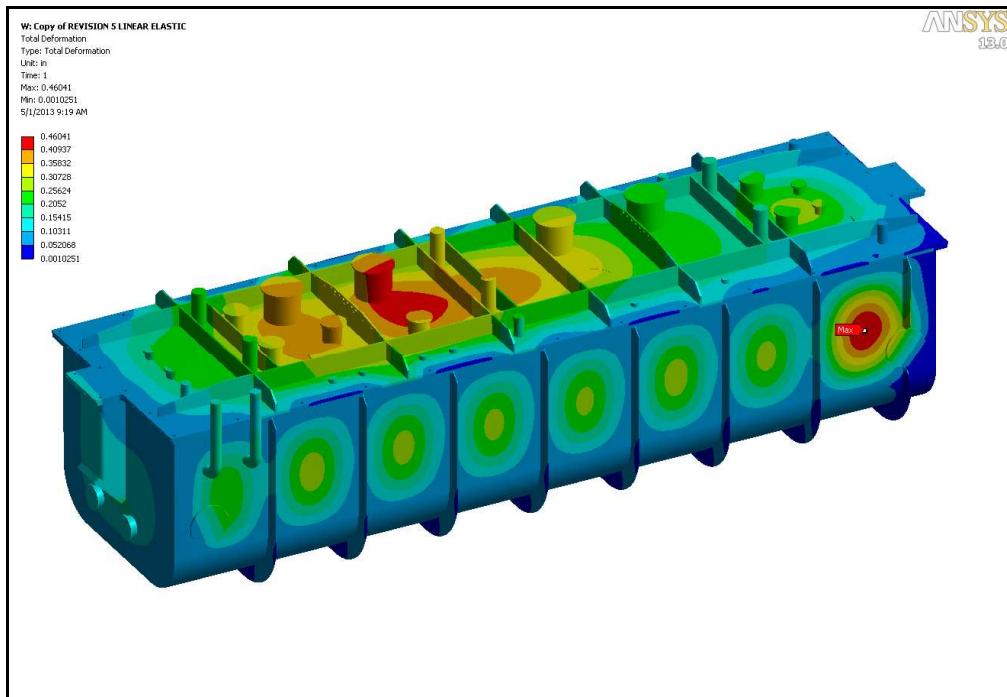


Figure 9
Plastic Collapse, Summed Deflection. Max. = 0.468"

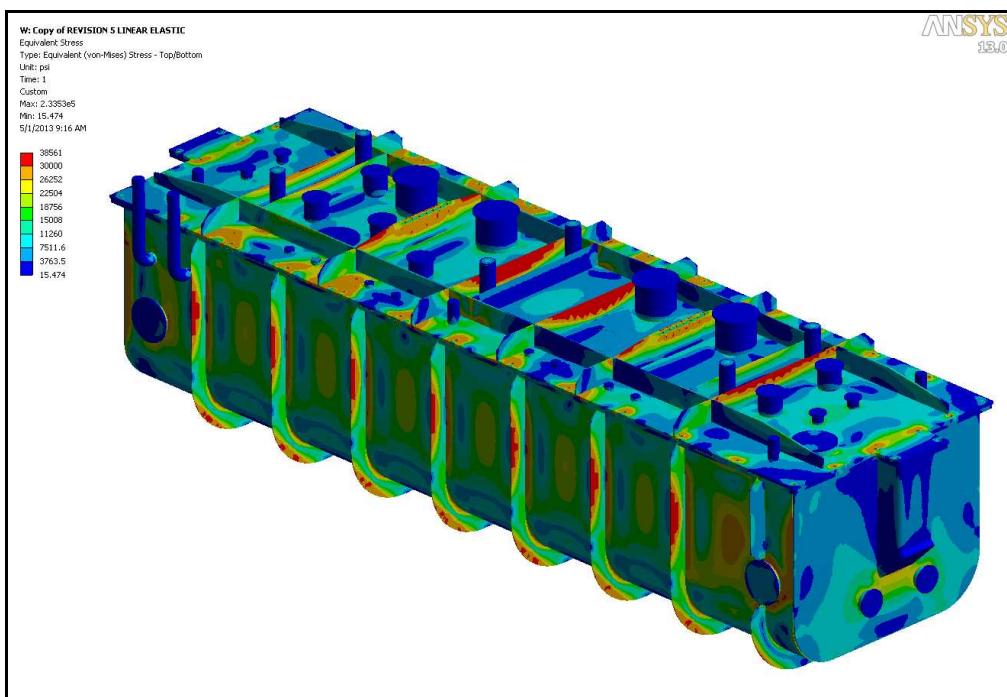


Figure 10
Plastic Collapse, von Mises Stress, Red > 30 ksi.

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B. Protection Against Local Failure

Protection from local failure was demonstrated with the Elastic Analysis method in 5.3.2 for Ref. 3. This method is based on a linear elastic model, and the acceptance criterion is that the sum of the three principal stresses be less than 4S.

The finite element model used for the Plastic Collapse analysis was copied and modified to use only linear elastic materials. This is finite element model 2 in Table 4. The analysis load case used in this analysis is shown in Table 4 and is based on Table 5.3 in Ref. 3. This table specifies eight load case combinations, but in the absence of temperature, snow, wind, seismic and live loads, the last seven load case combinations reduce to the first.

Plots of the sum of the three principle stresses are shown in Figure 11 . Contour levels have been altered so that any value above the 4S allowable given in Table 3 is red. There are some high values visible in Figure 11 at the bolt holes. These are modeling artifacts and can be ignored. The highest value not at a modeling artifact is about 56,500 psi, as shown in Figure 12. This is well below the 4S acceptance criterion of 80 ksi, and the requirement for protection against local failure is therefore met for a pressure differential of 1 atm.

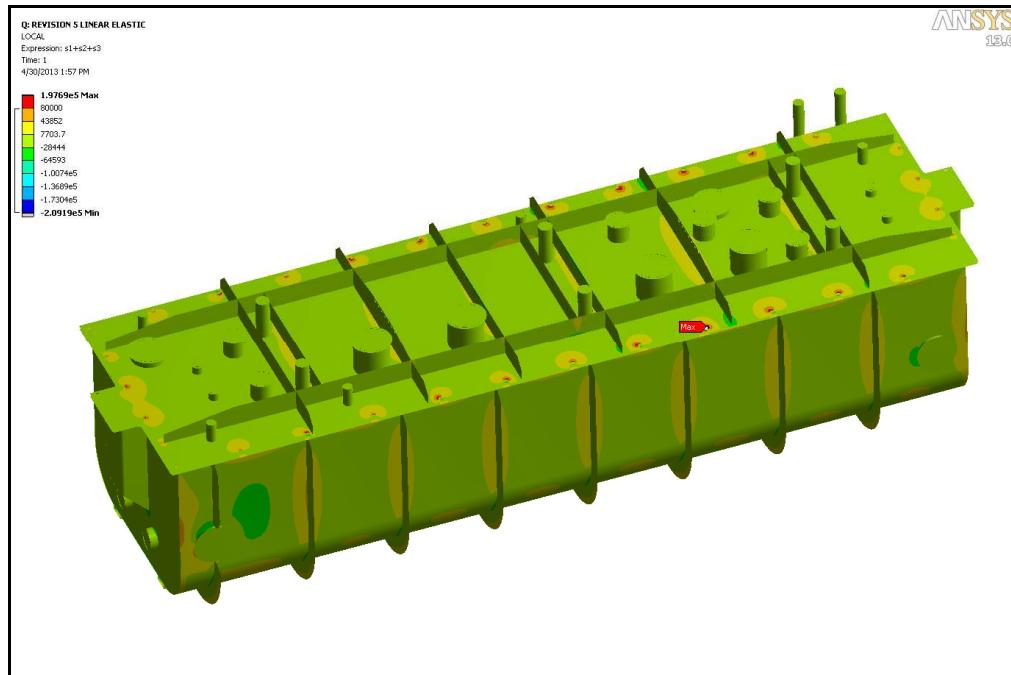


Figure 11
Local Failure, Red > 4S = 80 ksi.

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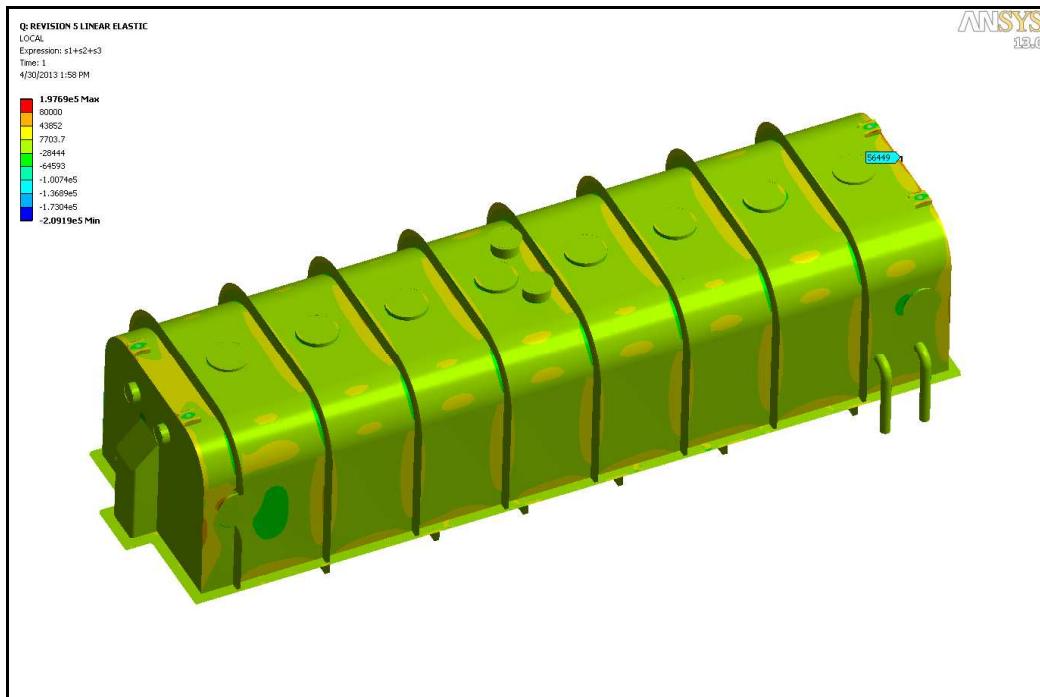


Figure 12
Local Failure, Red > 4S = 80 ksi

C. Protection Against Collapse From Buckling

Protection from collapse from buckling was evaluated using the method given at 5.4.1.2.a in Ref. 3, which specifies a linear elastic pre-stressed eigenvalue buckling analysis. The acceptance criterion is that the buckling load factor Φ_b be greater than $2/\beta_{cr}$, where β_{cr} is the capacity reduction factor. Since the cryostat contains ring-stiffened cylinders under axial compression, $\beta_{cr} = 0.765$ when $D_o/t = 53$, per 5.4.1.3,a in Ref. 3, and Φ_b becomes 2.615.

The finite element model used for the Local Failure analysis was used as the basis for this analysis. The loads used for the prestress run are given in Table 4 for Model 3. The load factor Φ for the first buckling mode was 3.17, which is above $\Phi_b = 2.615$. For this reason it is determined that the requirement of protection against collapse from buckling is met for a pressure differential of 1 atm.

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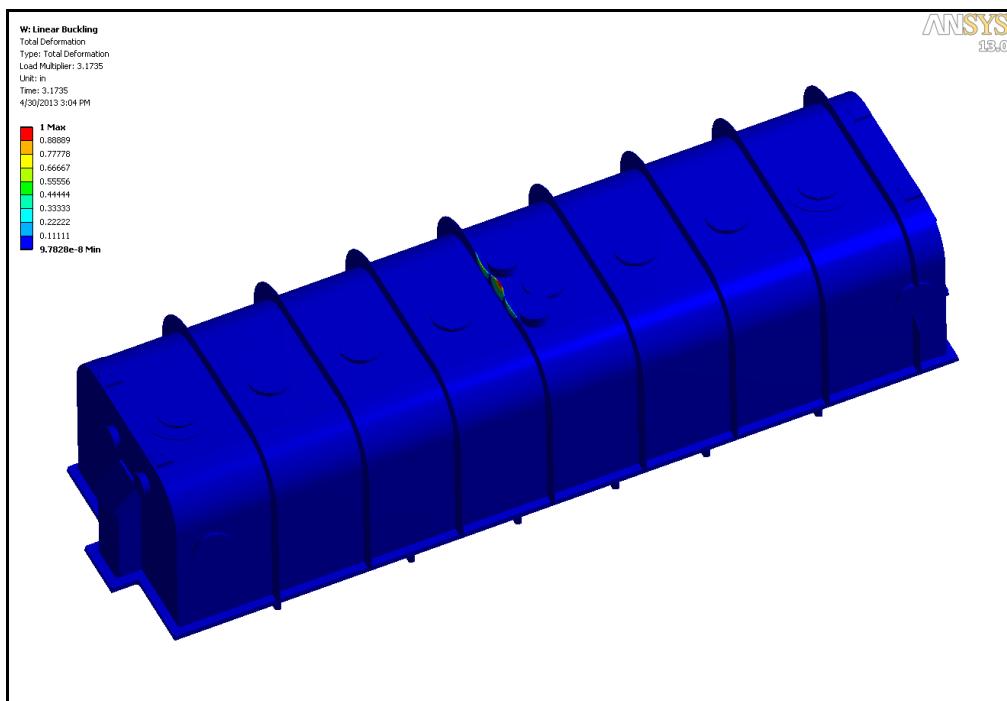


Figure 13
Buckling, First Mode, $\Phi = 3.17$

D. Ratcheting Assessment

Protection from Ratcheting was demonstrated with the Elastic Ratcheting Method in 5.5.6.1 for Ref. 3. This method is based on a linear elastic model, and the acceptance criterion is that the primary plus secondary equivalent stress range $\Delta S_{n,k}$ is less than the allowable primary plus secondary stress range S_{PS} .

Finite element model 2 in Table 4 was used for this assessment. The maximum equivalent stress for each load case was taken as $\Delta S_{n,k}$. The value for S_{PS} in Table 2 was found using the method given at 5.5.6.1.d in Ref. 3, and is essentially the largest of three times S or two times S_y , 60 ksi. A plot of equivalent stress is shown in Figure 14. Contour levels were been altered so that all values above the allowable values for S_{PS} are red. There are some high values visible in Figure 14 at the bolt holes. Again, these are modeling artifacts and can be ignored. The maximum value for $\Delta S_{n,k}$ is about 50,600 psi, which is below S_{PS} . Therefore, the requirement for protection from ratcheting is met.

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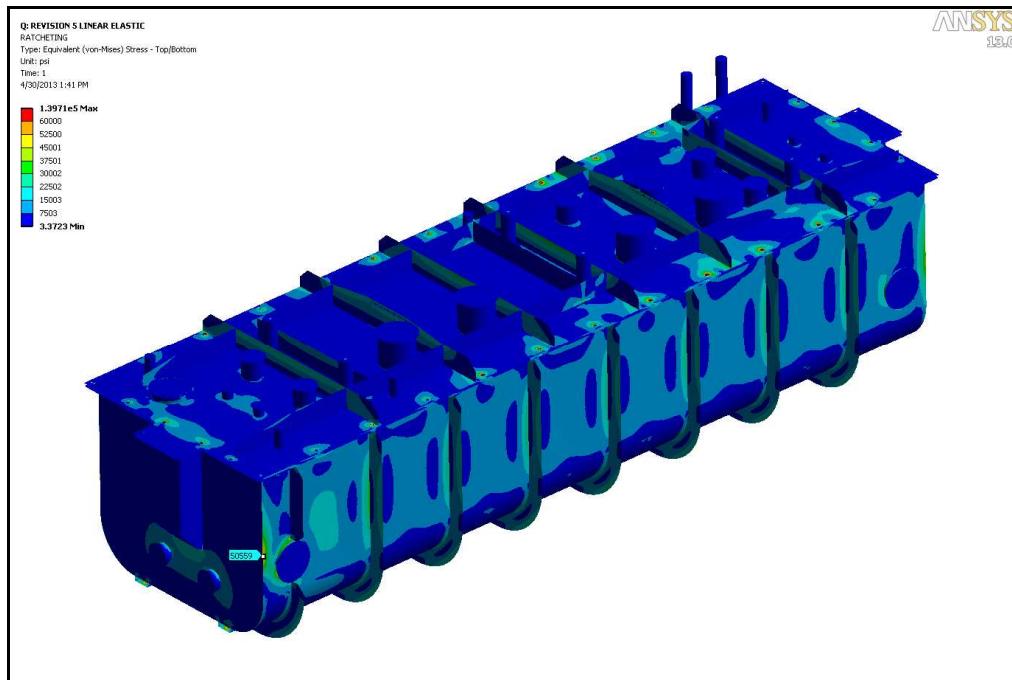


Figure 14
Ratcheting Assessment, Red > S_{ps} =60 ksi.

E. Protection Against Failure from Cyclic Loading

Protection against failure from cyclic loading (fatigue) was not evaluated as the screening method presented in 5.5.2.3 of Ref. 3 was used to determine that a fatigue assessment was not required. The steps employed by the screening method are summarized in Table 5. The total number of expected operating cycles is 80, which is less than 1000, the value given in Table 5.9 of Ref. 3, for integral construction, all other components. Fatigue analysis is therefore not required.

| STEP | | Cycles |
|------|----------------------------------------------------------------|--------|
| 1 | Initial Fabrication Testing | 10 |
| | Initial Cryomodule Cycling | 10 |
| | 30 yrs. @ 2 cycles/yr. | 60 |
| | Total | 80 |
| 2 | $N_{\Delta FP}$ | 80 |
| 3 | $N_{\Delta PO}$ | 0 |
| 4 | $N_{\Delta TE}$ | 0 |
| 5 | $N_{\Delta T\alpha}$ | 0 |
| 6 | $N_{\Delta FP}+N_{\Delta PO}+N_{\Delta TE}+N_{\Delta T\alpha}$ | 80 |

Table 5
Summary of Fatigue Screening Results

| | |
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F. Weld Analysis

A weld schedule was not available at the time of this analysis, so weld configurations were determined by the analyst. Welds were selected for evaluation by inspecting plots of von Mises stress and deflection, and selecting representative welds in high stress and high deflection locations. Symmetry considerations were used to eliminate redundant calculations.

To evaluate these welds, the weld reactions were found by summing the nodal reactions of the nodes at the weld interface and finding their moments about the weld centroid. These reactions were then used to calculate normal and shear stresses, using the methods outlined in Ref. 4. These stresses were then compared to an allowable value determined per Ref. 5. The weld filler to be used for construction has not been determined, so the filler specified in Table 3.3 in Ref. 5 was used for this analysis.

Welds 1 through 86 are double-sided fillet skip welds. All weld sizes started at a nominal $\frac{1}{4}$ " and were increased as needed to get an acceptable safety factor, providing that the weld size did not exceed the thickness of the thinnest plate in the weld. The throat dimension was taken as 0.707 times the weld size. All stresses were treated as shear stresses, per Ref. 7, so the normal and shear components were combined with the square-root-sum-of-squares method to get a single value for comparison to the allowable.

Welds 87 through 92, 106 and 107 are continuous complete joint penetration groove welds. All weld sizes are equal to the thickness of the thinnest plate in the weld, and the throat dimension was taken as the weld size. The first principal stress and maximum shear stress were derived from the calculated weld stress and compared to the allowables in Ref. 7.

Welds 93 through 105 are continuous single-sided fillet welds. Welds 93 and 94 attach one of the mounting channels. The weld size for these welds is $\frac{1}{4}$ ", based on the thickness of the channel flange. The remaining welds are at penetrations made from round tubing with a 0.120" wall, so the weld size was set to $1/8$ ". Again, the throat dimension was taken as 0.707 times the weld size. All stresses were treated as shear stresses, so the normal and shear components were combined by SRSS to get a single value for comparison to the allowable.

Weld locations are identified in Figure 15 through Figure 21. Weld details and weld analysis result summaries are given in Table 6 through Table 19. All weld results show a factor of safety greater than 1 at a pressure differential of 1 atm.

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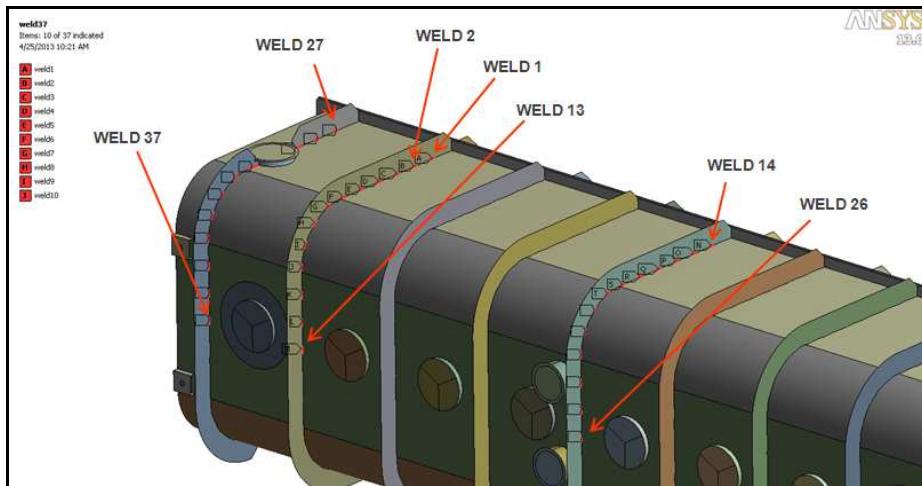


Figure 15
Weld Locations, Weld 1 to Weld 37

| Weld | Type | Plate Thick (in) | Leg Length (in) | Weld Size (in) | Throat Area (in ²) | X _{bar} (in) | Y _{bar} (in) | MOI _x (in ⁴) | MOI _y (in ⁴) | MOI _z (in ⁴) | Sec. Mod. (x) (in ³) | Sec. Mod. (z) (in ³) | Sec. Mod. (xz) (in ³) | Sec. Mod. (yz) (in ³) |
|------|------------|---------------------|--------------------|-------------------|-----------------------------------|--------------------------|--------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|-----------------------------------------|-----------------------------------------|
| 1 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 2 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 3 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 4 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 5 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 6 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 7 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 8 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 9 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 10 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 11 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 12 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 13 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 14 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 15 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 16 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 17 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 18 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 19 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 20 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 21 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 22 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 23 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 24 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 25 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 26 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 27 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 28 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 29 | 2 x 6 skip | 0.25 | 4.42 | 0.25 | 1.56 | 0.21 | 2.21 | 2.544 | 0.071 | 2.615 | 1.151 | 0.333 | 1.183 | 12.255 |
| 30 | 2 x 6 skip | 0.25 | 3.82 | 0.25 | 1.35 | 0.21 | 1.91 | 1.642 | 0.061 | 1.704 | 0.860 | 0.288 | 0.892 | 7.984 |
| 31 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 32 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 33 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 34 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 35 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 36 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 37 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |

Table 6
Weld Details, Weld 1 to Weld 37

Title: Structural Analysis of PXIE Cryostat

Calculation No.: NE-EO-2013-003

Revision Number: 0

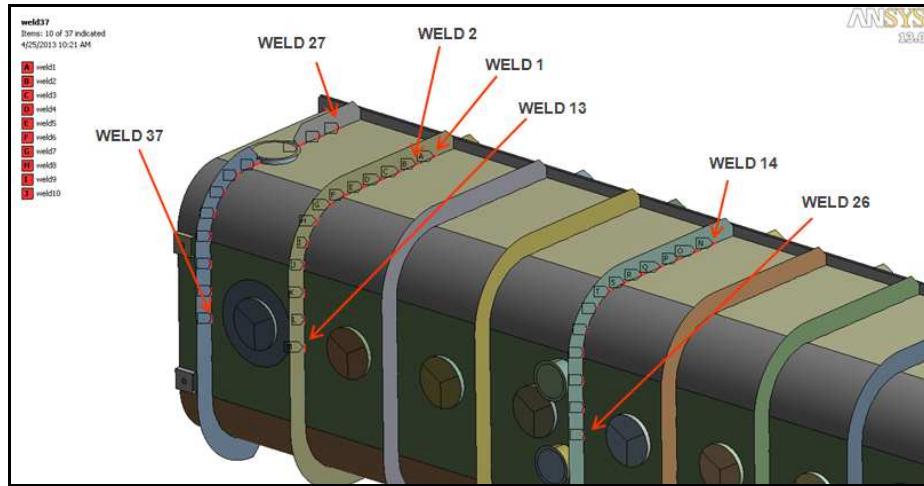


Figure 16
Weld Locations, Weld 1 to Weld 37

| Weld | Shear (FX) (lbf) | Shear (FY) (lbf) | Normal (FZ) (lbf) | Moment (X) (in-lbf) | Moment (Y) (in-lbf) | Torsion (Z) (in-lbf) | F _{bend_mx} (psi) | F _{bend_my} (psi) | F _{normal_fz} (psi) | F _{shear_fx} (psi) | F _{shear_fy} (psi) | F _{shear_xmz} (psi) | F _{shear_ymz} (psi) | F _{normal} (psi) | F _{shear} (psi) | F _{weld} (psi) | Safety Factor |
|------|---------------------|---------------------|----------------------|------------------------|------------------------|-------------------------|-------------------------------|-------------------------------|---------------------------------|--------------------------------|--------------------------------|---------------------------------|---------------------------------|------------------------------|-----------------------------|----------------------------|---------------|
| 1 | 0.4 | -7548 | 1140.3 | 807.6 | 1.8 | -2.1 | 3426.9 | 11.9 | 1612.6 | 0.6 | 10674.6 | 7.8 | -1.7 | 5051 | 10673 | 11808 | 1.78 |
| 2 | -0.5 | -4957.2 | 2149.8 | 334.3 | -18.3 | -2.2 | 1418.5 | -121.3 | 3040.3 | 0.7 | 7010.6 | 8.2 | -1.8 | 4338 | 7009 | 8242 | 2.55 |
| 3 | -1.1 | -1253.5 | 2457.7 | 90 | -32.6 | -1.2 | 381.9 | -216.1 | 3475.7 | 1.6 | 1772.7 | 4.5 | -1.0 | 3642 | 1772 | 4050 | 5.19 |
| 4 | -1.6 | 2866.9 | 2472.1 | -147.7 | -32.4 | 2.1 | 626.7 | -214.8 | 3496.1 | 2.3 | 4054.4 | 7.8 | -1.7 | 3908 | 4056 | 5633 | 3.73 |
| 5 | -0.4 | 6524 | 2201.9 | -356.6 | -15.9 | 3.3 | 1513.2 | -105.4 | 3114.0 | 0.6 | 9226.4 | 12.3 | 2.6 | 4522 | 9229 | 10277 | 2.04 |
| 6 | 2.8 | 7456.5 | 431.6 | -1563.5 | 10.7 | -0.4 | 6634.4 | 70.9 | 610.4 | 4.0 | 10545.2 | 1.5 | -0.3 | 7316 | 10545 | 12834 | 1.64 |
| 7 | 1.2 | 4294.5 | -2687.8 | -1724.1 | 21 | 0.4 | 7315.8 | 139.2 | 3801.2 | 1.7 | 6073.4 | 1.5 | 0.3 | 11256 | 6074 | 12790 | 1.64 |
| 8 | -0.5 | 635.8 | -5281.5 | -355.6 | 14 | -1.6 | 1508.9 | 92.8 | 7469.2 | 0.7 | 899.2 | 6.0 | -1.3 | 9071 | 898 | 9115 | 2.30 |
| 9 | -0.4 | -3252.9 | -4219.4 | 1320 | -0.5 | -0.3 | 5601.1 | -3.3 | 5967.2 | 0.6 | 4600.3 | 1.1 | -0.2 | 11565 | 4600 | 12446 | 1.69 |
| 10 | -1.2 | -7626.7 | -814.6 | 1982 | -16.8 | -1.5 | 8410.2 | -111.4 | 1152.0 | 1.7 | 10785.9 | 5.6 | -1.2 | 9451 | 10785 | 14340 | 1.46 |
| 11 | -1.7 | -8791.6 | 2041.9 | 508.8 | -13.9 | 2.5 | 2159.0 | -92.1 | 2887.7 | 2.4 | 12433.3 | 9.3 | 2.0 | 4955 | 12435 | 13386 | 1.57 |
| 12 | 0.6 | -4928 | 2760.2 | 446.4 | 12.5 | 1.8 | 1894.2 | 82.9 | 3903.5 | 0.8 | 6969.3 | 6.7 | 1.4 | 5881 | 6971 | 9120 | 2.30 |
| 13 | 2.7 | 193.9 | 2947 | -205 | 30 | 0.8 | 869.9 | 198.9 | 4167.7 | 3.8 | 274.2 | 3.0 | 0.6 | 5236 | 275 | 5244 | 4.00 |
| 14 | 7 | -7221.1 | 914.9 | 893.8 | 32.8 | 8.2 | 3792.6 | 217.4 | 1293.9 | 9.9 | 10212.3 | 30.6 | 6.5 | 5304 | 10219 | 11513 | 1.82 |
| 15 | -2.5 | -4604.9 | 2035.4 | 319.9 | -5.6 | -2.7 | 1357.4 | -37.1 | 2878.5 | 3.5 | 6512.4 | 10.1 | -2.2 | 4199 | 6510 | 7747 | 2.71 |
| 16 | -0.2 | -905.3 | 2331.3 | 73.2 | -3.9 | 0.2 | 310.6 | -25.9 | 3297.0 | 0.3 | 1280.3 | 0.7 | 0.2 | 3582 | 1280 | 3804 | 5.52 |
| 17 | 0.3 | 3047.7 | 2346.3 | -137.8 | -0.7 | 0 | 584.7 | -4.6 | 3318.2 | 0.4 | 4310.1 | 0.0 | 0.0 | 3898 | 4310 | 5812 | 3.61 |
| 18 | 0.1 | 6494.9 | 2127.8 | -343.9 | -0.2 | -0.8 | 1459.3 | -1.3 | 3009.2 | 0.1 | 9185.3 | 3.0 | -0.6 | 4467 | 9185 | 10213 | 2.06 |
| 19 | 0.2 | 6975.4 | 111.7 | -1815.3 | -0.5 | -0.9 | 7702.8 | -3.3 | 158.0 | 0.3 | 9864.8 | 3.4 | -0.7 | 7857 | 9864 | 12611 | 1.67 |
| 20 | -0.4 | 3851.4 | -3267.2 | -1550.8 | -1.8 | -0.8 | 6580.5 | -11.9 | 4620.6 | 0.6 | 5446.8 | 3.0 | -0.6 | 11189 | 5446 | 12444 | 1.69 |
| 21 | 0.4 | 242.9 | -5323.9 | -156.5 | 1.1 | -1.5 | 664.1 | 7.3 | 7529.2 | 0.6 | 343.5 | 5.6 | -1.2 | 8201 | 342 | 8208 | 2.56 |
| 22 | 0.3 | -3624 | -3952.2 | 1410.1 | -1.8 | 2.5 | 5983.5 | -11.9 | 5589.3 | 0.4 | 5125.2 | 9.3 | 2.0 | 11561 | 5127 | 12647 | 1.66 |
| 23 | -6.3 | -7894.3 | -671 | 1806.4 | -4.1 | 0.1 | 7665.1 | -27.2 | 948.9 | 8.9 | 11164.3 | 0.4 | 0.1 | 8587 | 11164 | 14085 | 1.49 |
| 24 | 10.7 | -9235.8 | 1811.5 | 1266.3 | 45.9 | 23.7 | 5373.3 | 304.3 | 2561.9 | 15.1 | 13061.5 | 88.5 | 18.9 | 8239 | 13081 | 15459 | 1.36 |
| 25 | -6.5 | -4954.7 | 2966.3 | 43.3 | -40.7 | -15.1 | 183.7 | -269.8 | 4195.0 | 9.2 | 7007.1 | 56.4 | -12.0 | 4109 | 6995 | 8113 | 2.59 |
| 26 | 0.8 | 92.7 | 3011.6 | 2.9 | -14 | 7.2 | 12.3 | -92.8 | 4259.1 | 1.1 | 131.1 | 26.9 | 5.7 | 4179 | 140 | 4181 | 5.02 |
| 27 | 1.6 | -3150.3 | 728.3 | 442.6 | 14 | 24.4 | 1878.1 | 92.8 | 1030.0 | 2.3 | 4455.2 | 91.1 | 19.4 | 3001 | 4476 | 5389 | 3.90 |
| 28 | 12.9 | -1882.3 | 1282.9 | 175.5 | 174.4 | 9.9 | 744.7 | 1156.1 | 1814.3 | 18.2 | 2662.0 | 37.0 | 7.9 | 3715 | 2670 | 4575 | 4.59 |
| 29 | 217.2 | -4317.3 | -1749.2 | -7454.2 | 257.9 | -404.7 | 6476.2 | 773.6 | 1119.4 | 139.0 | 2762.7 | 342.0 | -33.0 | 8369 | 2772 | 8816 | 2.38 |
| 30 | -275.5 | 2330.9 | 816.7 | -4591.5 | -84.2 | -328.7 | 5340.6 | -292.2 | 604.7 | 204.0 | 1725.9 | 368.5 | -41.2 | 5653 | 1779 | 5926 | 3.54 |
| 31 | -18 | 1032.2 | -3640.5 | -631.7 | -164.4 | -21.7 | 2680.5 | -1089.8 | 5148.5 | 25.5 | 1459.8 | 81.0 | -17.3 | 6739 | 1446 | 6893 | 3.05 |
| 32 | 17.5 | -559.6 | -4180.7 | 231.3 | -54.6 | 2 | 981.5 | -361.9 | 5912.5 | 24.7 | 791.4 | 7.5 | 1.6 | 6532 | 794 | 6580 | 3.19 |
| 33 | 7.9 | -2727.1 | -2773.7 | 1081.8 | -54.6 | 5.3 | 4590.4 | -361.9 | 3922.6 | 11.2 | 3856.7 | 19.8 | 4.2 | 8151 | 3861 | 9019 | 2.33 |
| 34 | -19.7 | -4962.1 | -62.7 | 1388.9 | -104.3 | 8 | 5893.5 | -691.4 | 88.7 | 27.9 | 7017.5 | 29.9 | 6.4 | 5291 | 7024 | 8794 | 2.39 |
| 35 | 3.2 | -5014.3 | 1459.8 | 135.6 | 36.3 | 16.3 | 575.4 | 240.6 | 2064.5 | 4.5 | 7091.4 | 60.9 | 13.0 | 2881 | 7105 | 7666 | 2.74 |
| 36 | 6.4 | -2595.3 | 1461.5 | 169.7 | 124.6 | 8.2 | 720.1 | 826.0 | 2066.9 | 9.1 | 3670.3 | 30.6 | 6.5 | 3613 | 3677 | 5155 | 4.07 |
| 37 | 1.7 | 104.1 | 1489.6 | -110.7 | 121.4 | -1.1 | 469.7 | 804.7 | 2106.6 | 2.4 | 147.2 | 4.1 | -0.9 | 3381 | 146 | 3384 | 6.21 |

Table 7
Summary of Weld Analysis, Weld 1 to Weld 37

Title: Structural Analysis of PXIE Cryostat

Calculation No.: NE-EO-2013-003

Revision Number: 0

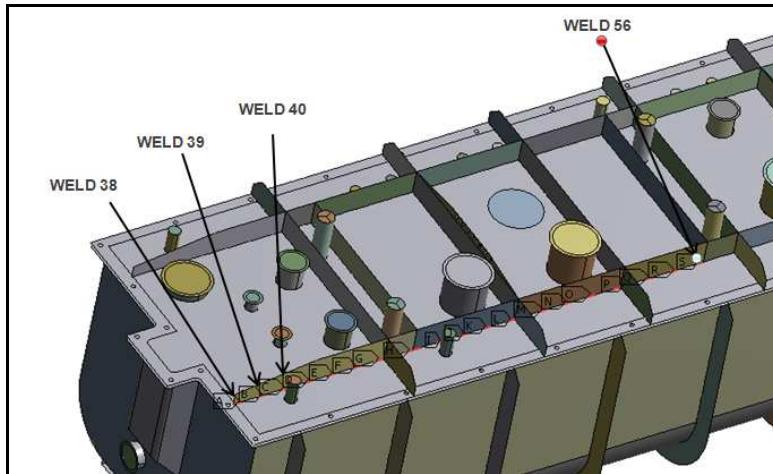


Figure 17
Weld Locations, Weld 38 to Weld 56

| Weld | Type | Plate Thick (in) | Leg Length (in) | Weld Size (in) | Throat Area (in ²) | X _{bar} (in) | Y _{bar} (in) | MOI _x (in ⁴) | MOI _y (in ⁴) | MOI _z (in ⁴) | Sec. Mod. (x) (in ³) | Sec. Mod. (z) (in ³) | Sec. Mod. (xz) (in ³) | Sec. Mod. (yz) (in ³) |
|------|------------|---------------------|--------------------|-------------------|-----------------------------------|--------------------------|--------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|-----------------------------------------|-----------------------------------------|
| 38 | 2 x 6 skip | 0.50 | 2 | 0.25 | 0.71 | 0.34 | 1.00 | 0.236 | 0.081 | 0.317 | 0.236 | 0.239 | 0.317 | 0.936 |
| 39 | 2 x 6 skip | 0.50 | 2 | 0.25 | 0.71 | 0.34 | 1.00 | 0.236 | 0.081 | 0.317 | 0.236 | 0.239 | 0.317 | 0.936 |
| 40 | 2 x 6 skip | 0.50 | 2 | 0.25 | 0.71 | 0.34 | 1.00 | 0.236 | 0.081 | 0.317 | 0.236 | 0.239 | 0.317 | 0.936 |
| 41 | 2 x 6 skip | 0.50 | 2 | 0.25 | 0.71 | 0.34 | 1.00 | 0.236 | 0.081 | 0.317 | 0.236 | 0.239 | 0.317 | 0.936 |
| 42 | 2 x 6 skip | 0.50 | 2 | 0.25 | 0.71 | 0.34 | 1.00 | 0.236 | 0.081 | 0.317 | 0.236 | 0.239 | 0.317 | 0.936 |
| 43 | 2 x 6 skip | 0.50 | 2 | 0.25 | 0.71 | 0.34 | 1.00 | 0.236 | 0.081 | 0.317 | 0.236 | 0.239 | 0.317 | 0.936 |
| 44 | 2 x 6 skip | 0.50 | 4 | 0.25 | 1.41 | 0.34 | 2.00 | 1.885 | 0.162 | 2.047 | 0.943 | 0.478 | 1.024 | 6.050 |
| 45 | 2 x 6 skip | 0.50 | 4 | 0.25 | 1.41 | 0.34 | 2.00 | 1.885 | 0.162 | 2.047 | 0.943 | 0.478 | 1.024 | 6.050 |
| 46 | 2 x 6 skip | 0.50 | 2 | 0.25 | 0.71 | 0.34 | 1.00 | 0.236 | 0.081 | 0.317 | 0.236 | 0.239 | 0.317 | 0.936 |
| 47 | 2 x 6 skip | 0.50 | 2 | 0.25 | 0.71 | 0.34 | 1.00 | 0.236 | 0.081 | 0.317 | 0.236 | 0.239 | 0.317 | 0.936 |
| 48 | 2 x 6 skip | 0.50 | 2 | 0.25 | 0.71 | 0.34 | 1.00 | 0.236 | 0.081 | 0.317 | 0.236 | 0.239 | 0.317 | 0.936 |
| 49 | 2 x 6 skip | 0.50 | 4 | 0.25 | 1.41 | 0.34 | 2.00 | 1.885 | 0.162 | 2.047 | 0.943 | 0.478 | 1.024 | 6.050 |
| 50 | 2 x 6 skip | 0.50 | 2 | 0.25 | 0.71 | 0.34 | 1.00 | 0.236 | 0.081 | 0.317 | 0.236 | 0.239 | 0.317 | 0.936 |
| 51 | 2 x 6 skip | 0.50 | 2 | 0.25 | 0.71 | 0.34 | 1.00 | 0.236 | 0.081 | 0.317 | 0.236 | 0.239 | 0.317 | 0.936 |
| 52 | 2 x 6 skip | 0.50 | 2 | 0.25 | 0.71 | 0.34 | 1.00 | 0.236 | 0.081 | 0.317 | 0.236 | 0.239 | 0.317 | 0.936 |
| 53 | 2 x 6 skip | 0.50 | 4 | 0.25 | 1.41 | 0.34 | 2.00 | 1.885 | 0.162 | 2.047 | 0.943 | 0.478 | 1.024 | 6.050 |
| 54 | 2 x 6 skip | 0.50 | 2 | 0.25 | 0.71 | 0.34 | 1.00 | 0.236 | 0.081 | 0.317 | 0.236 | 0.239 | 0.317 | 0.936 |
| 55 | 2 x 6 skip | 0.50 | 2 | 0.25 | 0.71 | 0.34 | 1.00 | 0.236 | 0.081 | 0.317 | 0.236 | 0.239 | 0.317 | 0.936 |
| 56 | 2 x 6 skip | 0.50 | 2 | 0.25 | 0.71 | 0.34 | 1.00 | 0.236 | 0.081 | 0.317 | 0.236 | 0.239 | 0.317 | 0.936 |

Table 8
Weld Details, Weld 38 to Weld 56

| Weld | Shear (FX) (lbf) | Shear (FY) (lbf) | Normal (FZ) (lbf) | Moment (X) (in-lbf) | Moment (Y) (in-lbf) | Torsion (Z) (in-lbf) | F _{bend_mx} (psi) | F _{bend_my} (psi) | F _{normal_fz} (psi) | F _{shear_fx} (psi) | F _{shear_fy} (psi) | F _{shear_xmz} (psi) | F _{shear_ymz} (psi) | F _{normal} (psi) | F _{shear} (psi) | F _{weld} (psi) | Safety Factor |
|------|------------------------|------------------------|-------------------------|---------------------------|---------------------------|----------------------------|-------------------------------|-------------------------------|---------------------------------|--------------------------------|--------------------------------|---------------------------------|---------------------------------|------------------------------|-----------------------------|----------------------------|---------------|
| 38 | -71.2 | -3236.6 | -2675.5 | -952.4 | -325.2 | 18 | 4041.3 | -1359.4 | 3783.8 | 100.7 | 4577.3 | 56.9 | 19.2 | 6466 | 4599 | 7935 | 2.65 |
| 39 | -25.6 | -4362.7 | 236.1 | 810.3 | -236.5 | 57.9 | 3438.3 | -988.6 | 333.9 | 36.2 | 6169.8 | 182.9 | 61.9 | 2784 | 6236 | 6829 | 3.08 |
| 40 | 8.1 | -1941.8 | 1113.7 | 226.5 | 130.2 | 55 | 961.1 | 544.2 | 1575.0 | 11.5 | 2746.1 | 173.7 | 58.8 | 3080 | 2811 | 4170 | 5.04 |
| 41 | 23.2 | -261.5 | 1407.7 | 176.7 | 370.9 | 27.8 | 749.8 | 1550.4 | 1990.8 | 32.8 | 369.8 | 87.8 | 29.7 | 4291 | 417 | 4311 | 4.87 |
| 42 | 6.7 | 1157.6 | 1858.3 | 27.2 | 372.7 | -5.4 | 115.4 | 1557.9 | 2628.1 | 9.5 | 1637.1 | 17.1 | -5.8 | 4301 | 1632 | 4600 | 4.56 |
| 43 | 66.7 | 2780.8 | 1221.3 | -620.5 | 451.2 | -70.1 | 2633.0 | 1886.0 | 1727.2 | 94.3 | 3932.7 | 221.4 | -74.9 | 6246 | 3871 | 7348 | 2.86 |
| 44 | 1122.2 | -660 | -1295.7 | 409 | 1055.6 | 437.6 | 433.9 | 2206.2 | 916.2 | 793.5 | 466.7 | 427.5 | 72.3 | 3556 | 1335 | 3799 | 5.53 |
| 45 | 2321.3 | -1751.1 | -2011.9 | -577.2 | 2145.9 | -147 | 612.3 | 4485.0 | 1422.6 | 1641.4 | 1238.2 | 143.6 | -24.3 | 6520 | 2159 | 6868 | 3.06 |
| 46 | 121.6 | 1563.6 | -229.1 | -225.2 | 766.3 | 88 | 955.6 | 3203.2 | 324.0 | 172.0 | 2211.3 | 277.9 | 94.0 | 4483 | 2349 | 5061 | 4.15 |
| 47 | 72.7 | 1831.9 | 351.9 | 445.4 | 746.9 | -36.8 | 1890.0 | 3122.1 | 497.7 | 102.8 | 2590.7 | 116.2 | -39.3 | 5510 | 2561 | 6076 | 3.46 |
| 48 | -18.7 | 2710.2 | 1473 | -269.4 | 141.7 | -56 | 1143.1 | 592.3 | 2083.2 | 26.4 | 3832.8 | 176.9 | -59.8 | 3819 | 3778 | 5372 | 3.91 |
| 49 | 1361 | 2335.3 | -522.9 | -1478.3 | 979 | -503.9 | 1568.2 | 2046.1 | 369.7 | 962.4 | 1651.3 | 492.3 | -83.3 | 3984 | 2139 | 4522 | 4.64 |
| 50 | 130.7 | -302.4 | -256.3 | 412.4 | 702.3 | 136.2 | 1749.9 | 2935.7 | 362.5 | 184.8 | 427.7 | 430.2 | 145.6 | 5048 | 841 | 5118 | 4.10 |
| 51 | 14.5 | 218.3 | 1287.3 | 305.3 | 629.2 | 2.8 | 1295.5 | 2630.1 | 1820.5 | 20.5 | 308.7 | 8.8 | 3.0 | 5746 | 313 | 5755 | 3.65 |
| 52 | 124.3 | 1157.4 | 417.6 | -835.8 | 789.5 | -104.4 | 3546.5 | 3300.2 | 590.6 | 175.8 | 1636.8 | 329.7 | -111.6 | 7437 | 1607 | 7609 | 2.76 |
| 53 | 1366.6 | -1045.8 | -40.4 | 1892.1 | 1013.6 | 403.3 | 2007.2 | 2118.5 | 28.6 | 966.3 | 739.5 | 394.0 | 66.7 | 4154 | 1581 | 4445 | 4.72 |
| 54 | -23.8 | -1548.4 | 1018.4 | -359.3 | 249.2 | 54.5 | 1524.6 | 1041.7 | 1440.2 | 33.7 | 2189.8 | 172.1 | 58.2 | 4007 | 2257 | 4599 | 4.57 |
| 55 | 189.2 | -1812.8 | -1363.7 | -642 | 1133.7 | -99.3 | 2724.2 | 4738.9 | 1928.6 | 267.6 | 2563.7 | 313.6 | -106.1 | 9392 | 2525 | 9725 | 2.16 |
| 56 | 1852 | -1745.5 | -2646.2 | 264.8 | 1680.6 | -867.2 | 1123.6 | 7025.0 | 3742.3 | 2619.1 | 2468.5 | 2739.0 | -926.8 | 11891 | 5576 | 13133 | 1.60 |

Table 9
Summary of Weld Analysis, Weld 38 to Weld 56

Title: Structural Analysis of PXIE Cryostat

Calculation No.: NE-EO-2013-003

Revision Number: 0

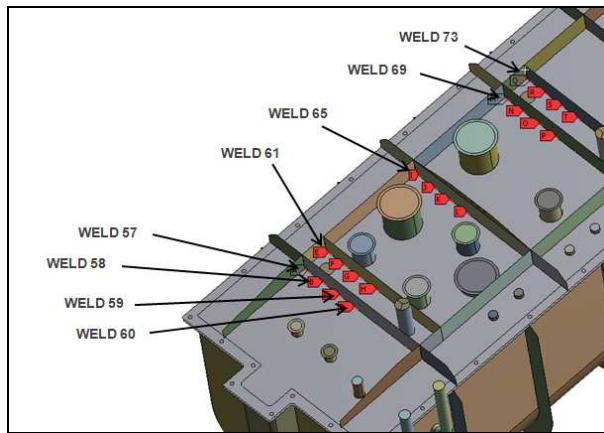


Figure 18
Weld Locations, Weld 57 to Weld 76

| Weld | Type | Plate Thick (in) | Leg Length (in) | Weld Size (in) | Throat Area (in ²) | X _{bar} (in) | Y _{bar} (in) | MOI _x (in ⁴) | MOI _y (in ⁴) | MOI _z (in ⁴) | Sec. Mod. (x) (in ³) | Sec. Mod. (z) (in ³) | Sec. Mod. (xz) (in ³) | Sec. Mod. (yz) (in ³) |
|------|------------|---------------------|--------------------|-------------------|-----------------------------------|--------------------------|--------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|-----------------------------------------|-----------------------------------------|
| 57 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 58 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 59 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 60 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 61 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 62 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 63 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 64 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 65 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 66 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 67 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 68 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 69 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 70 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 71 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 72 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 73 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 74 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 75 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |
| 76 | 2 x 6 skip | 0.50 | 2 | 0.31 | 0.88 | 0.36 | 1.00 | 0.292 | 0.113 | 0.406 | 0.292 | 0.315 | 0.406 | 1.128 |

Table 10
Weld Details, Weld 57 to Weld 76

| Weld | Shear (FX) (lbf) | Shear (FY) (lbf) | Normal (FZ) (lbf) | Moment (X) (in-lbf) | Moment (Y) (in-lbf) | Torsion (Z) (in-lbf) | F _{bend_m} (psi) | F _{bend_m} (psi) | F _{normal_fz} (psi) | F _{shear_fx} (psi) | F _{shear_fy} (psi) | F _{shear_xmz} (psi) | F _{shear_ymz} (psi) | F _{normal} (psi) | F _{shear} (psi) | F _{weld} (psi) | Safety Factor |
|------|------------------------|------------------------|-------------------------|---------------------------|---------------------------|----------------------------|------------------------------|------------------------------|---------------------------------|--------------------------------|--------------------------------|---------------------------------|---------------------------------|------------------------------|-----------------------------|----------------------------|---------------|
| 57 | 45.8 | -3548.6 | 1127 | 738 | 76.9 | 91.6 | 2525.4 | 243.9 | 1285.3 | 52.2 | 4047.2 | 225.8 | 81.2 | 4055 | 4138 | 5793 | 3.62 |
| 58 | -53.4 | -3488.5 | 1260.5 | -243.5 | -188.7 | -30.1 | 833.3 | -598.6 | 1437.8 | 60.9 | 3978.7 | 74.2 | -26.7 | 1673 | 3954 | 4293 | 4.89 |
| 59 | -13 | -2020.8 | 810.1 | 169.7 | -201.8 | -16.6 | 580.7 | -640.1 | 923.9 | 14.8 | 2304.7 | 40.9 | -14.7 | 864 | 2291 | 2448 | 8.58 |
| 60 | 2.3 | -746.1 | 901.7 | 51.6 | -138.3 | -1.1 | 176.6 | -438.7 | 1028.4 | 2.6 | 850.9 | 2.7 | -1.0 | 766 | 850 | 1144 | 18.35 |
| 61 | 438.3 | -5374.5 | 3709.2 | 3254.6 | 352.3 | 44.5 | 11137.2 | 11176.6 | 4230.4 | 499.9 | 6129.6 | 109.7 | 39.5 | 16485 | 6199 | 17612 | 1.19 |
| 62 | 74.3 | -6852.5 | 2801.3 | -751.8 | 365.9 | 88.5 | 2572.7 | 1160.7 | 3194.9 | 84.7 | 7815.3 | 218.2 | 78.5 | 6928 | 7900 | 10507 | 2.00 |
| 63 | 32.9 | -4461.8 | 2366.6 | 148.9 | 326.2 | 47.3 | 509.5 | 1034.8 | 2699.1 | 37.5 | 5088.7 | 116.6 | 41.9 | 4243 | 5133 | 6660 | 3.15 |
| 64 | -16.3 | -1447.6 | 1960 | 64.6 | 141.2 | -4.5 | 221.1 | 447.9 | 2235.4 | 18.6 | 1651.0 | 11.1 | -4.0 | 2904 | 1647 | 3339 | 6.29 |
| 65 | -121.9 | -6773 | 802.3 | 851.7 | -73.7 | -70.1 | 2914.5 | -233.8 | 915.0 | 139.0 | 7724.6 | 172.8 | -62.1 | 3596 | 7669 | 8470 | 2.48 |
| 66 | -8.8 | -6369.6 | 2906.3 | 752.4 | -5.6 | -1.8 | 2574.7 | -17.8 | 3314.7 | 10.0 | 7264.6 | 4.4 | -1.6 | 5872 | 7263 | 9340 | 2.25 |
| 67 | -0.9 | -3567.9 | 3505.9 | 157.4 | 9.5 | -1.1 | 538.6 | 30.1 | 3998.5 | 1.0 | 4069.2 | 2.7 | -1.0 | 4567 | 4068 | 6116 | 3.43 |
| 68 | 4.5 | -1027.4 | 3215.2 | -84.9 | 19.1 | -3.5 | 290.5 | 60.6 | 3667.0 | 5.1 | 1171.8 | 8.6 | -3.1 | 4018 | 1169 | 4185 | 5.02 |
| 69 | -280.4 | -5035.1 | 1138.2 | 721.7 | -212.7 | -29.5 | 2469.7 | -674.7 | 1298.1 | 319.8 | 5742.6 | 72.7 | -26.2 | 3093 | 5730 | 6511 | 3.23 |
| 70 | -97 | -4883.8 | 1659.4 | -11.1 | -458.4 | -80.9 | 38.0 | -1454.1 | 1892.6 | 110.6 | 5570.0 | 199.5 | -71.7 | 476 | 5507 | 5528 | 3.80 |
| 71 | -16 | -2814.4 | 1263.4 | 175 | -371.3 | -26.6 | 598.9 | -1177.8 | 1440.9 | 18.2 | 3209.8 | 65.6 | -23.6 | 862 | 3187 | 3302 | 6.36 |
| 72 | 3.9 | -890.6 | 1262.6 | 22 | -275.9 | -1.9 | 75.3 | -875.2 | 1440.0 | 4.4 | 1015.7 | 4.7 | -1.7 | 640 | 1014 | 1199 | 17.51 |
| 73 | 104.5 | -4078.9 | 2319.7 | 2460.5 | 70.8 | 3.5 | 8419.8 | 224.6 | 2645.6 | 119.2 | 4652.0 | 8.6 | 3.1 | 11290 | 4657 | 12213 | 1.72 |
| 74 | 13.8 | -5352.2 | 2442.9 | -358.1 | 77 | -6.9 | 1225.4 | 244.3 | 2786.1 | 15.7 | 6104.2 | 17.0 | -6.1 | 4256 | 6098 | 7436 | 2.82 |
| 75 | -0.2 | -3346.3 | 1546.5 | 181.5 | 25.5 | -1.9 | 621.1 | 80.9 | 1763.8 | 0.2 | 3816.5 | 4.7 | -1.7 | 2466 | 3815 | 4542 | 4.62 |
| 76 | -4.3 | -1150 | 1546.8 | 50.1 | -19.3 | -2.3 | 171.4 | -61.2 | 1764.1 | 4.9 | 1311.6 | 5.7 | -2.0 | 1874 | 1310 | 2287 | 9.18 |

Table 11
Summary of Weld Analysis, Weld 57 to Weld 76

Title: Structural Analysis of PXIE Cryostat

Calculation No.: NE-EO-2013-003

Revision Number: 0

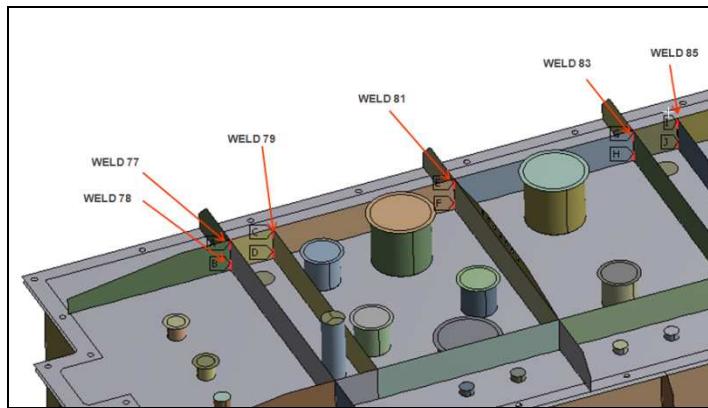


Figure 19
Weld Locations, Weld 77 to Weld 86

| Weld | Type | Plate Thick (in) | Leg Length (in) | Weld Size (in) | Throat Area (in ²) | X _{bar} (in) | Y _{bar} (in) | MOI _x (in ⁴) | MOI _y (in ⁴) | MOI _z (in ⁴) | Sec. Mod. (x) (in ³) | Sec. Mod. (z) (in ³) | Sec. Mod. (xz) (in ³) | Sec. Mod. (yz) (in ³) |
|------|------------|---------------------|--------------------|-------------------|-----------------------------------|--------------------------|--------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|-----------------------------------------|-----------------------------------------|
| 77 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 78 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 79 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 80 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 81 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 82 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 83 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 84 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 85 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |
| 86 | 2 x 6 skip | 0.25 | 2 | 0.25 | 0.71 | 0.21 | 1.00 | 0.236 | 0.032 | 0.268 | 0.236 | 0.151 | 0.268 | 1.255 |

Table 12
Weld Details, Weld 77 to Weld 86

| Weld | Shear (FX) (lbf) | Shear (FY) (lbf) | Normal (FZ) (lbf) | Moment (X) (in-lbf) | Moment (Y) (in-lbf) | Torsion (Z) (in-lbf) | F _{bend_mx} (psi) | F _{bend_my} (psi) | F _{normal_fz} (psi) | F _{shear_fx} (psi) | F _{shear_fy} (psi) | F _{shear_xmz} (psi) | F _{shear_ymz} (psi) | F _{normal} (psi) | F _{shear} (psi) | F _{weld} (psi) | Safety Factor |
|------|---------------------|---------------------|----------------------|------------------------|------------------------|-------------------------|-------------------------------|-------------------------------|---------------------------------|--------------------------------|--------------------------------|---------------------------------|---------------------------------|------------------------------|-----------------------------|----------------------------|---------------|
| 77 | 243.9 | -1002.6 | -792.4 | -1066.6 | 184 | 20.6 | 4525.9 | 1219.7 | 1120.6 | 344.9 | 1417.9 | 76.9 | 16.4 | 6866 | 1495 | 7027 | 2.99 |
| 78 | -194.5 | 236.1 | -1824.9 | 101.7 | 26.4 | 62.5 | 431.5 | 175.0 | 2580.8 | 275.1 | 333.9 | 233.3 | 49.8 | 3187 | 637 | 3250 | 6.46 |
| 79 | -181.1 | 4068.3 | -837.2 | -736.8 | -596.1 | 62.5 | 3126.4 | -3951.4 | 1184.0 | 256.1 | 5753.5 | 233.3 | 49.8 | 359 | 5824 | 5835 | 3.60 |
| 80 | -375.2 | 7924.1 | -4517.1 | -873 | -369.3 | 32.3 | 3704.4 | -2448.0 | 6388.2 | 530.6 | 11206.5 | 120.6 | 25.7 | 7645 | 11251 | 13602 | 1.54 |
| 81 | 173.8 | -876.2 | -1611.6 | -1370.9 | -264.3 | -51.2 | 5817.1 | -1752.0 | 2279.2 | 245.8 | 1239.1 | 191.1 | -40.8 | 6344 | 1276 | 6471 | 3.25 |
| 82 | 253.2 | 1635.8 | -3017.6 | -41 | -154.5 | -29.7 | 174.0 | -1024.2 | 4267.6 | 358.1 | 2313.4 | 110.9 | -23.7 | 3417 | 2337 | 4140 | 5.07 |
| 83 | -11 | -2592.5 | -1035.4 | -1334.1 | 1306.4 | 20.3 | 5661.0 | 8659.9 | 1464.3 | 15.6 | 3666.4 | 75.8 | 16.2 | 15785 | 3684 | 16209 | 1.30 |
| 84 | -128 | 570 | -2451.1 | 89.3 | 555.6 | 35 | 378.9 | 3683.0 | 3466.4 | 181.0 | 806.1 | 130.7 | 27.9 | 7528 | 890 | 7581 | 2.77 |
| 85 | -8.8 | 2871.5 | -721.3 | -509.4 | -24.9 | -3.8 | 2161.5 | -165.1 | 1020.1 | 12.4 | 4061.0 | 14.2 | -3.0 | 3017 | 4058 | 5056 | 4.15 |
| 86 | -143.3 | 5697.6 | -2795.5 | -509.5 | -130.5 | 26.8 | 2162.0 | -865.1 | 3953.5 | 202.7 | 8057.7 | 100.1 | 21.3 | 5250 | 8085 | 9640 | 2.18 |

Table 13
Summary of Weld Analysis, Weld 66 to Weld 86

Title: Structural Analysis of PXIE Cryostat

Calculation No.: NE-EO-2013-003

Revision Number: 0

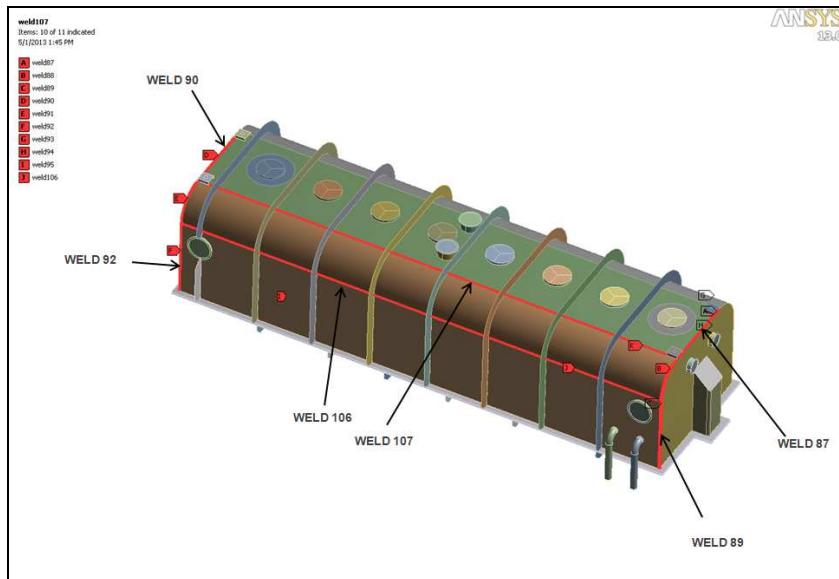


Figure 20
Weld Locations, Welds 87, 89, 90, 92, 106, 107

| Weld | Description | Leg Length (in) | Min. Plate Thick (in) | Throat Area (in ²) | Y _{bar} (in) | MOI _x (in ⁴) | Polar MOI _z (in ⁴) | Sec. Mod. (x) (in ³) | Sec. Mod. (z) (in ³) |
|------|-------------|-----------------|-----------------------|--------------------------------|-----------------------|-------------------------------------|-------------------------------------------|----------------------------------|----------------------------------|
| 87 | CJP | 36.50 | 0.38 | 13.69 | 18.25 | 1074 | 1074 | 59 | 59 |
| 89 | CJP | 37.00 | 0.38 | 13.88 | 18.50 | 1119 | 1119 | 60 | 60 |
| 90 | CJP | 36.50 | 0.38 | 13.69 | 18.25 | 1074 | 1074 | 59 | 59 |
| 92 | CJP | 37.00 | 0.38 | 13.88 | 18.50 | 1119 | 1119 | 60 | 60 |
| 106 | CJP | 225.72 | 0.25 | 56.43 | 112.86 | 169390 | 169390 | 1501 | 1501 |
| 107 | CJP | 225.72 | 0.25 | 56.43 | 112.86 | 169390 | 169390 | 1501 | 1501 |

Table 14
Weld Details, Welds 87, 89, 90, 92, 106, 107

| Weld | Shear (FX) (lbf) | Shear (FY) (lbf) | Normal (FZ) (lbf) | Moment (X) (in-lbf) | Moment (Y) (in-lbf) | Torsion (Z) (in-lbf) | F _{bend_mx} (psi) | F _{normal_fz} (psi) | F _{shear_fx} (psi) | F _{shear_fy} (psi) | F _{shear_xmz} (psi) | F _{normal} (psi) | F _{shear} (psi) | Safety Factor |
|------|------------------|------------------|-------------------|---------------------|---------------------|----------------------|----------------------------|------------------------------|-----------------------------|-----------------------------|------------------------------|---------------------------|--------------------------|---------------|
| 87 | -10795.7 | 227.3 | -11144.3 | 3994.9 | -35126.7 | -5516.5 | 67.86 | 814.20 | 788.73 | 16.61 | 93.71 | 882.06 | 882.59 | 12.16 |
| 89 | -8004.3 | 1805.3 | -6750.6 | 11512.6 | -26256.1 | -40157.4 | 190.31 | 486.53 | 576.89 | 130.11 | 663.84 | 676.84 | 1247.53 | 9.28 |
| 90 | -14215.6 | 59 | -9771 | -6057.6 | -32304.3 | 8604.6 | 102.90 | 713.86 | 1038.58 | 4.31 | 146.17 | 816.76 | 1184.76 | 9.58 |
| 92 | 7871.4 | 365 | -5334.3 | -20424.1 | 19737.1 | 33859.2 | 337.63 | 384.45 | 567.31 | 26.31 | 559.72 | 722.08 | 1127.34 | 10.14 |
| 106 | 5683.2 | 29.8 | -92411.3 | 603750.4 | -3836.5 | -34978.2 | 402.26 | 1637.63 | 100.71 | 0.53 | 23.31 | 2039.89 | 124.02 | 11.68 |
| 107 | -9996.7 | -466.2 | -49729.1 | -176315 | 3632 | -11077.8 | 117.47 | 881.25 | 177.15 | 8.26 | 7.38 | 998.73 | 184.72 | 22.54 |

Table 15
Summary of Weld Analysis, Welds 87, 89, 90, 92, 106, 107

Title: Structural Analysis of PXIE Cryostat

Calculation No.: NE-EO-2013-003

Revision Number: 0

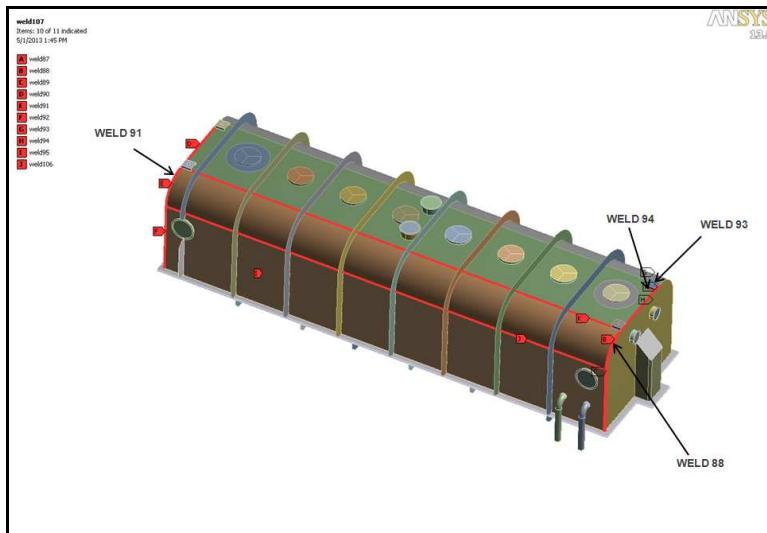


Figure 21
Weld Locations, Welds 88, 92, 93, 94

Curved Continuous CJP

| Weld | Description | Radius (in) | Min. Plate Thick (in) | Throat Area (in ²) | Y _{bar} (in) | MOI _x (in ⁴) | Polar MOI _z (in ⁴) | Sec. Mod. (x) (in ³) | Sec. Mod. (z) (in ³) |
|------|-------------|----------------|--------------------------------|--------------------------------------|--------------------------|----------------------------------------|-------------------------------------------------|-------------------------------------------|-------------------------------------------|
| 88 | CJP | 13.12 | 0.25 | 3.64 | 9.28 | 113.87 | 33.29 | 12.27 | 3.59 |
| 91 | CJP | 13.12 | 0.25 | 3.64 | 9.28 | 113.87 | 33.29 | 12.27 | 3.59 |

Single-sided Fillet

| Weld | Description | Leg Length (in) | Weld Size (in) | Throat Area (in ²) | Y _{bar} (in) | MOI _x (in ⁴) | Polar MOI _z (in ⁴) | Sec. Mod. (x) (in ³) | Sec. Mod. (z) (in ³) |
|------|-------------|-----------------------|----------------------|--------------------------------------|--------------------------|----------------------------------------|-------------------------------------------------|-------------------------------------------|-------------------------------------------|
| 93 | cont. | 5.00 | 0.25 | 0.88 | 2.50 | 1.84 | 1.84 | 0.74 | 0.74 |
| 94 | cont. | 5.00 | 0.25 | 0.88 | 2.50 | 1.84 | 1.84 | 0.74 | 0.74 |

Table 16
Weld Details, Welds 88, 92, 93, 94

Curved Continuous CJP

| Weld | Shear (FX) (lbf) | Shear (FY) (lbf) | Normal (FZ) (lbf) | Moment (X) (in-lbf) | Moment (Y) (in-lbf) | Torsion (Z) (in-lbf) | F _{bend_mx} (psi) | F _{normal_tx} (psi) | F _{shear_fx} (psi) | F _{shear_ty} (psi) | F _{shear_xmz} (psi) | F _{normal} (psi) | F _{shear} (psi) | Safety Factor |
|------|------------------------|------------------------|-------------------------|---------------------------|---------------------------|----------------------------|-------------------------------|---------------------------------|--------------------------------|--------------------------------|---------------------------------|------------------------------|-----------------------------|------------------|
| 88 | -167.9 | -1214 | -984.6 | -4541.7 | -1109.4 | 749.1 | 370.08 | 270.22 | 46.08 | 333.18 | 208.76 | 640.30 | 419.46 | 22.74 |
| 91 | 215.2 | -249.3 | -3263 | -1359.9 | 2722.5 | -4242.3 | 110.81 | 895.51 | 59.06 | 68.42 | 1182.25 | 1006.33 | 1243.20 | 8.95 |

Single-sided Fillet

| Weld | Shear (FX) (lbf) | Shear (FY) (lbf) | Normal (FZ) (lbf) | Moment (X) (in-lbf) | Moment (Y) (in-lbf) | Torsion (Z) (in-lbf) | F _{bend_mx} (psi) | F _{normal_tx} (psi) | F _{shear_fx} (psi) | F _{shear_ty} (psi) | F _{shear_xmz} (psi) | F _{normal} (psi) | F _{shear} (psi) | F _{weld} (psi) | Safety Factor |
|------|------------------------|------------------------|-------------------------|---------------------------|---------------------------|----------------------------|-------------------------------|---------------------------------|--------------------------------|--------------------------------|---------------------------------|------------------------------|-----------------------------|----------------------------|------------------|
| 93 | 2899 | 243.5 | -2840.5 | -32.9 | 999.3 | -286.2 | 44.67 | 3214.14 | 3280.34 | 275.53 | 388.62 | 3258.82 | 3679.29 | 4915 | 4.27 |
| 94 | -2899 | -243.5 | -2773.5 | 948.6 | -1079.6 | -846.2 | 1288.06 | 3138.33 | 3280.34 | 275.53 | 1149.01 | 4426.39 | 4437.91 | 6268 | 3.35 |

Table 17
Summary of Weld Analysis, Welds 88, 92, 93, 94

Title: Structural Analysis of PXIE Cryostat

Calculation No.: NE-EO-2013-003

Revision Number: 0

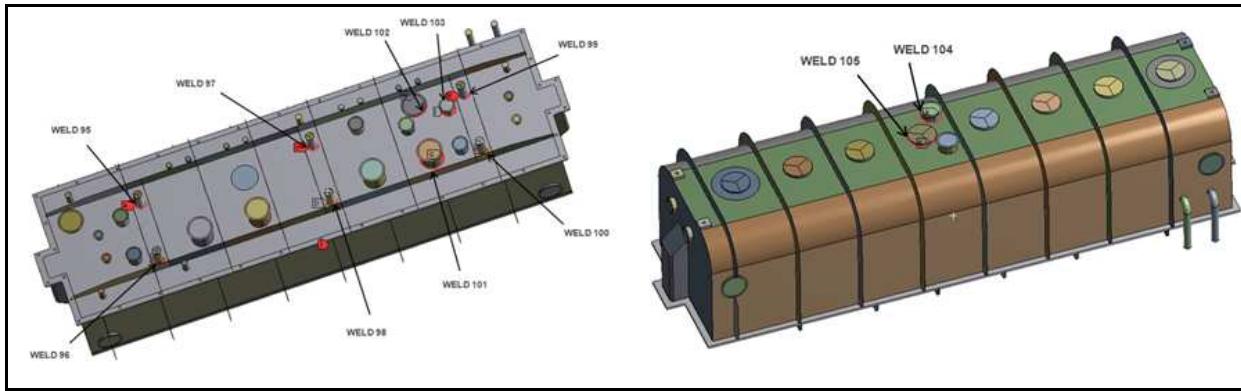


Figure 22
Weld Locations, Weld 95 to Weld 105

| Weld | Type | Dia. (in) | Weld Size (in) | Throat Area (in ²) | X _{bar} (in) | Y _{bar} (in) | MOI _x (in ⁴) | MOI _y (in ⁴) | MOI _z (in ⁴) | Sec. Mod. (x) (in ³) | Sec. Mod. (z) (in ³) | Sec. Mod. (xz) (in ³) | Sec. Mod. (yz) (in ³) |
|------|---------------|--------------|----------------------|--------------------------------------|--------------------------|--------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|-----------------------------------------|-----------------------------------------|
| 95 | circular tube | 3.875 | 0.125 | 1.08 | 1.94 | 1.94 | 2.0193 | 2.0193 | 4.0386 | 1.0422 | 1.0422 | 2.0845 | 2.0845 |
| 96 | circular tube | 3.875 | 0.125 | 1.08 | 1.94 | 1.94 | 2.0193 | 2.0193 | 4.0386 | 1.0422 | 1.0422 | 2.0845 | 2.0845 |
| 97 | circular tube | 3.875 | 0.125 | 1.08 | 1.94 | 1.94 | 2.0193 | 2.0193 | 4.0386 | 1.0422 | 1.0422 | 2.0845 | 2.0845 |
| 98 | circular tube | 3.875 | 0.125 | 1.08 | 1.94 | 1.94 | 2.0193 | 2.0193 | 4.0386 | 1.0422 | 1.0422 | 2.0845 | 2.0845 |
| 99 | circular tube | 3.875 | 0.125 | 1.08 | 1.94 | 1.94 | 2.0193 | 2.0193 | 4.0386 | 1.0422 | 1.0422 | 2.0845 | 2.0845 |
| 100 | circular tube | 3.875 | 0.125 | 1.08 | 1.94 | 1.94 | 2.0193 | 2.0193 | 4.0386 | 1.0422 | 1.0422 | 2.0845 | 2.0845 |
| 101 | circular tube | 9.875 | 0.125 | 2.74 | 4.94 | 4.94 | 33.4196 | 33.4196 | 66.8391 | 6.7685 | 6.7685 | 13.5370 | 13.5370 |
| 102 | circular tube | 9.875 | 0.125 | 2.74 | 4.94 | 4.94 | 33.4196 | 33.4196 | 66.8391 | 6.7685 | 6.7685 | 13.5370 | 13.5370 |
| 103 | circular tube | 5.875 | 0.125 | 1.63 | 2.94 | 2.94 | 7.0374 | 7.0374 | 14.0748 | 2.3957 | 2.3957 | 4.7914 | 4.7914 |
| 104 | circular tube | 7.875 | 0.125 | 2.19 | 3.94 | 3.94 | 16.9489 | 16.9489 | 33.8978 | 4.3045 | 4.3045 | 8.6090 | 8.6090 |
| 105 | circular tube | 11.875 | 0.125 | 3.30 | 5.94 | 5.94 | 58.1153 | 58.1153 | 116.2305 | 9.7878 | 9.7878 | 19.5757 | 19.5757 |

Table 18
Weld Details, Weld 95 to Weld 105

| Weld | Shear (FX) (lbf) | Shear (FY) (lbf) | Normal (FZ) (lbf) | Moment (X) (in-lbf) | Moment (Y) (in-lbf) | Torsion (Z) (in-lbf) | F _{bend_mx} (psi) | F _{bend_my} (psi) | F _{normal_fz} (psi) | F _{shear_fx} (psi) | F _{shear_ty} (psi) | F _{shear_xmz} (psi) | F _{shear_ymz} (psi) | F _{normal} (psi) | F _{shear} (psi) | F _{weld} (psi) | Safety Factor |
|------|------------------------|------------------------|-------------------------|---------------------------|---------------------------|----------------------------|-------------------------------|-------------------------------|---------------------------------|--------------------------------|--------------------------------|---------------------------------|---------------------------------|------------------------------|-----------------------------|----------------------------|------------------|
| 95 | 0.00 | -0.50 | -1513.40 | -0.10 | -0.20 | 0.00 | 0.1 | -0.2 | 1406.7 | 0.0 | 0.5 | 0.0 | 0.0 | 1406.6 | 0.5 | 1406.6 | 14.93 |
| 96 | 0.00 | -0.60 | -1513.40 | 0.00 | 0.10 | 0.00 | 0.0 | 0.1 | 1406.7 | 0.0 | 0.6 | 0.0 | 0.0 | 1406.8 | 0.6 | 1406.8 | 14.93 |
| 97 | 0.10 | -0.20 | -1513.30 | 0.10 | -0.20 | 0.00 | 0.1 | -0.2 | 1406.6 | 0.1 | 0.2 | 0.0 | 0.0 | 1406.5 | 0.2 | 1406.5 | 14.93 |
| 98 | 0.00 | -0.90 | -1513.40 | 0.10 | 0.10 | 0.00 | 0.1 | 0.1 | 1406.7 | 0.0 | 0.8 | 0.0 | 0.0 | 1406.9 | 0.8 | 1406.9 | 14.93 |
| 99 | -0.10 | -0.40 | -1513.30 | -0.10 | -0.20 | 0.00 | 0.1 | -0.2 | 1406.6 | 0.1 | 0.4 | 0.0 | 0.0 | 1406.5 | 0.4 | 1406.5 | 14.93 |
| 100 | 0.00 | -0.90 | -1513.40 | -0.10 | 0.10 | 0.00 | 0.1 | 0.1 | 1406.7 | 0.0 | 0.8 | 0.0 | 0.0 | 1406.9 | 0.8 | 1406.9 | 14.93 |
| 101 | -0.10 | 2.10 | -1529.30 | 0.10 | 0.10 | 0.00 | 0.0 | 0.0 | 557.8 | 0.0 | 0.8 | 0.0 | 0.0 | 557.8 | 0.8 | 557.8 | 37.65 |
| 102 | -0.20 | 0.70 | -1521.80 | 0.00 | -0.10 | 0.00 | 0.0 | 0.0 | 555.1 | 0.1 | 0.3 | 0.0 | 0.0 | 555.0 | 0.3 | 555.0 | 37.83 |
| 103 | -0.30 | -0.30 | -589.10 | -0.40 | 0.10 | 0.00 | 0.2 | 0.0 | 361.2 | 0.2 | 0.2 | 0.0 | 0.0 | 361.4 | 0.3 | 361.4 | 58.11 |
| 104 | 0.00 | 0.00 | -1018.10 | 0.20 | 0.10 | 0.00 | 0.0 | 0.0 | 465.7 | 0.0 | 0.0 | 0.0 | 0.0 | 465.7 | 0.0 | 465.7 | 45.09 |
| 105 | 0.00 | 0.00 | -1612.90 | 0.00 | 0.00 | 0.00 | 0.0 | 0.0 | 489.2 | 0.0 | 0.0 | 0.0 | 0.0 | 489.2 | 0.0 | 489.2 | 42.93 |

Table 19
Summary of Weld Analysis, Weld 95 to Weld 105

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11. Discussion

The goal of this analysis was to confirm compliance with the APSSM and the FESHM, which categorize vacuum systems based on the maximum static differential operating pressure that the system might experience. It was determined that this system qualifies as Category II vessel per the APSSM Mandatory Appendix M, which includes vacuum vessels “that can be protected from pressurization exceeding 15 psi through such engineering controls as pressure relief devices.” This vacuum system is so protected. CGA 341 (Ref. 8) states in section 6.4.2 that vacuum vessels must be relieved with devices of discharge area “at least 0.00024 in² per pound of water capacity of the liquid container.” The LHe volume of the eight HWRs, eight magnet packages, LHe manifold, and LHe manifold lines is < 20 ft³ amounting to < 1250 lb of water equivalent. This results in a required relief area of 0.3 in². The vacuum vessel is relieved via two spring-loaded ISO-80 flanges each with 3.5” bore and 1” of travel, each provides a relief area of 11 in², well in excess of this requirement ensuring that the interior pressure of the vacuum vessel will never exceed atmospheric pressure (14.7 psia).

Per Ref. 1, Category II vacuum systems are not required to comply with the ASME pressure vessel code, but states that “vacuum vessels may be designed in accordance with the applicable sections of the ASME Code.” The intent was to utilize finite element analysis to check this design, so the provisions of Section VIII, Division 2, covering Design by Analysis, were used to guide this analysis.

The assumption of steady loads seems justified by Ref.3. Using Method A for Fatigue Analysis Screening(5.5.2.3, Ref 2), the total number of full or partial pressure cycles, and the total number of temperature cycles with full or partial pressure was estimated to be no more than 80. This is less than any of the limiting criteria given in Ref. 3 Table 5-9. If this estimate is valid, then fatigue is not an issue. The last assumptions must be judged on their own merits. The assumption of room temperature operation is based on the fact that the cryostat contains a vacuum that insulates the equipment inside, and that thermal leak paths are limited. The assumption of no material degradation over time seems reasonable considering the room temperature operation and the laboratory environment. The assumptions of isotropic and homogeneous response and no residual stress are common engineering assumptions.

12. Conclusions

The results of this analysis presented above show that the requirements for Protection Against Plastic Collapse, Protection Against Local Failure, Protection Against Collapse From Buckling, Protection From Ratcheting, Protection Against Failure from Cyclic Loading, per the ASME BPVC, have been met for the loading conditions. Also, all welds meet the requirements of AWS D1.6. Based on this, the following conclusions are drawn:

1. The PXIE Cryostat is in compliance with the Fermi National Accelerator Laboratory Environmental Safety and Health Manual when subjected to an internal vacuum load not to exceed 15 psi as described in this analysis.

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13. References

1. *Argonne Pressure Systems Safety Manual*, Argonne National Laboratory, Lemont, IL, 2012.
2. *Fermilab Environment, Safety and Health Manual*, Fermi National Accelerator Laboratory, Batavia, IL, 2013
3. *ASME Boiler and Pressure Vessel Code, Section VIII, Division 2, Part 5*, American Society of Mechanical Engineers, New York, NY 2010.
4. *ASME Electronic Stress Tables*, Table 1A, page 18, Line 874,
www.est.asme.org/knovel2/asme.
5. *Metallic Materials Properties Development and Standardization*, DOT/FAA/AR-MMPDS-01, Office of Aviation Research, Washington DC, 2003.
6. Shigley, J. E. and Mitchell, L. D. *Mechanical Engineering Design, Fourth Edition*, McGraw Hill, New York, 1983, Chapter 7.
7. *Structural Welding Code - Stainless Steel, AWS D1.6:1999*, American Welding Society, Doral, FL, 1999.
8. *Standard for Insulated Cargo Tank Specification for Nonflammable Cryogenic Liquids*, CGA-341, Compressed Gas Association, 1995.

14. Software

- Ansys Mechanical, Version 13, Build date 11/2/2009, Ansys Inc, Pittsburg, PA.
- Microsoft Windows XP Professional x64, Version 2003, Service Pack 2, Microsoft Corporation, Redmond WA.
- Microsoft Office Excel 2007, (12.0.6654.5003) SP3 MSO (12.0.6607.1000), Microsoft Corporation, Redmond WA.

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**APPENDIX 1
GENERAL CHECKING CRITERIA SHEET**

| ANALYSIS CHECKLIST | Yes | No | N/A | Comments |
|----------------------------------------------------|--------------------------|--------------------------|--------------------------|----------|
| Are analytical methods appropriate? | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | |
| Are assumptions appropriate? | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | |
| Is the analysis complete? | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | |
| Is the source of the input geometry documented? | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | |
| Is the source of material properties documented? | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | |
| Are the boundary conditions clearly explained? | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | |
| Was an applicable and valid computer program used? | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | |
| Are the conclusions supported by the results? | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | |
| Do the results seem reasonable? | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | |
| | | | | |
| | | | | |

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