Enclosure 1 to TN E-37268

Calculation Package Number TN-LC-0204, Revision 2

AREVA TRANSNUCLEAR INC.	**Form 3.2-1** **Calculation Cover Sheet** **TIP 3.2 (Revision 6)**	**Calculation No.:**	TN-LC-0204
		Revision No.:	2
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DCR NO (If applicable) : 65200-021 R2	**PROJECT NAME:** TN-LC Transport Packaging
PROJECT NO: 65200	**CLIENT:** Transnuclear, Inc.

CALCULATION TITLE:

TN-LC TRANSPORT CASK TRUNNION, TRUNNION LOCAL STRESS AND TIE DOWN SYSTEM EVALUATIONS.

SUMMARY DESCRIPTION:

1) Calculation Summary

This calculation analyzes the stresses in the cask trunnions and in the tie down system for lifting loads during transport conditions.

2) Storage Media Description

Secure network server initially, then redundant tape backup

If original issue, is licensing review per TIP 3.5 required?

Yes ☐ **No** ☐ **(explain below)** **Licensing Review No.:** LR__________

N/A

Software Utilized:	**Version:**
None	N/A

Calculation is complete: Originator Name and Signature: Mark Tung	9/26/13 Date:
Calculation has been checked for consistency, completeness and correctness: Checker Name and Signature: Jeff Pieper	9/26/13 Date:
Calculation is approved for use: Project Engineer Name and Signature: Olivier Gandou	9/26/13 Date:

REVISION SUMMARY

REV.	DATE	DESCRIPTION	AFFECTED PAGES	AFFECTED DISKS
0	09/27/10	Initial Issue	All	All
1	04/19/12	Changed material of the trunnion and increased diameter of trunnion shoulder; revised evaluation of trunnion shoulder, trunnion bolts and attachment blocks; corrected allowable for the shear key weld; revised calculation of shear key area bearing area and bearing stress; clarified explanations, modified sketches and added new ones. The changes are prompted by DCR 65200-006.	All (1)	All

Note 1: Due to an extensive amount of changes in Revision 1, including section structure of the document, the detail location of changes is not tracked by means of revision bars.

2	03/26/13	Modified trunnion attachment block welds per DCR 65200-021 R2. Updated and clarified weld analysis methodology. Minor editorial changes, updated references, and number corrections.	1-5, 7-10, 14, 15, 20-25, 28, 32-34	All

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1.0 PURPOSE

This calculation qualifies the TN-LC cask trunnions design, trunnion bolts, trunnion attachment blocks and their welds for lifting the TN-LC package during transport, and calculates pertinent stresses in the cask outer shell in the vicinity of the trunnion attachment blocks due to lifting loads. It also evaluates the stresses in the shear key bearing block, pad plate, and welds during transport conditions.

2.0 REFERENCES

2.1 TN Document 65200.0101, Rev.4 "Design Criteria Document (DCD) for the TN-LC Transport Package."

2.2 "Pressure Vessel Design Handbook", Second Edition, Henry Bednar, 1986.

2.3 TNLC-0401 Rev. 0, "Thermal Analysis of TN-LC Transport Cask for Normal Conditions of Transport."

2.4 TNLC-0200 Rev. 1, "Transport Packaging Weight, CG location and moment of inertia calculation."

2.5 Machinery Handbook, 26th Edition, Industrial Press, 2000.

2.6 10CFR Part 71, "Packaging and Transportation of Radioactive Materials."

2.7 ANSI N14.6, "American National Standard for Radioactive Materials - Special Lifting Devices for Shipping Containers Weighing 10,000 Pounds (4500 kg) or More", 1993.

2.8 Machine Design, August 17, 1967, "Eccentrically Loaded Joints", Richard T. Burger.

2.9 WRC Bulletin 107, March 1979 Revision, "Local Stresses in Spherical and Cylindrical Shells Due to External Loading."

2.10 NUREG/CR 6007, "Stress Analysis of Closure Bolts for Shipping Casks," Lawrence Livermore National Laboratory, 1992.

2.11 ASME Boiler and Pressure Vessel Code, Section III, Subsection NF, 2004 including 2006 addenda.

3.0 METHODOLOGY

3.1 Parameters

The parts materials as given in [2.4] are listed in Table 1, along with those materials mechanical properties (from [2.1]). Nominal dimensions from [2.4] are used in evaluations.

The materials are conservatively assumed to be at an average temperature of 300°F [2.3].

The weld electrode for SA-240 Type 304 base metal is 80 ksi ultimate at room temperature. The ultimate stress of the material is calculated for 300ºF based on SA-240 Type 304 as follows:

Room Temp Ultimate Stress of Base Metal: 75 ksi [2.1]
300ºF Ultimate Stress of Base Metal: 66.2 ksi [2.1]
Room Temp Ultimate Stress of Weld Metal: 80 ksi [2.11]
300ºF Ultimate Stress of Weld Metal: (66.2/75)x80= 70.6 ksi

Table 1: Steel Structural Properties at 300°F (ksi)

Part	Material	S_y [ksi]	S_u [ksi]	E [ksi]
Single shoulder trunnions	SA-182 TYPE FXM19	43.3	94.2	N/A
Trunnions attachment blocks	SA-240 TYPE 304	22.4	66.2	N/A
Outer shell	SA-240 TYPE XM19	43.3	94.2	N/A
Trunnion bolts	SA-540 Gr. B23 Cl. 1	140.3	165.0	26,700
Shear key bearing block	SA-182 TYPE F6NM	84.6	115.0	N/A
Pad plate	SA-240 TYPE 304	22.4	66.2	N/A
Weld Material	Weld Metal for SA-240 Type 304	N/A	70.6*	N/A

*Calculated Value for 300ºF

The weights of the components of the cask are found in [2.4] and the weight of basket contents is taken from [2.1]. The bounding weights for each analysis are:

- Trunnion analysis:
  - Empty cask with trunnions (conservative): 41,000 lb,
  - Basket with its fuel contents (conservative): 8,000 lb.
- Shear key bearing block analysis:
  - Empty cask with trunnions (conservative): 41,000 lb,
  - Impact limiters: 3,200 lb,
  - Basket and its fuel contents (conservative): 8,000 lb.

The trunnion bolts are 1"– 8 UNC [2.4] assuming 2.25" long. The bolt parameters are summarized in the Table 2.

Table 2: Trunnion Bolt Parameters [2.5].

D_b	Bolt nominal diameter (in)	1.00
S_{bolt}	Bolt stress area (in^2)	0.606
n	Number of threads per inch	8
$K_{n\ max}$	Maximum minor diameter of internal threads (in)	0.890
$E_{s\ min}$	Minimum pitch diameter of external threads (in)	0.9067
$D_{s\ min}$	Minimum major diameter of external threads (in)	0.9755
$E_{n\ max}$	Maximum pitch diameter of internal threads (in)	0.9320
Q_{min}	Minimum torque (ft-lb)	400
Q_{max}	Maximum torque (ft-lb)	450

Table 3: Design Parameters

N_{tr}	Number of trunnions	2
a_v	Vertical acceleration (g)	6
a_L	Longitudinal acceleration (g)	10
Th_{os}	Outer shell thickness (in)	1.5
N_b	Number of bolts per trunnion	8
K	Nut factor for trunnion bolts	0.135
D_{bolt}	Bolt circle diameter (in)	6.875
Th_{tool}	Thickness of lifting tool (in)	1.00
D_{ext1}	Diameter of trunnion shoulder (in)	4.25
L_{sh}	Length of trunnion shoulder (in)	2.25
L_{hub}	Length of trunnion hub (in)	2.69
D_{hub}	Diameter of trunnion hub (in)	4.00
D_{hole}	Diameter of trunnion bolt counterbore (in)	1.8
D_{max}	Maximum outer diameter of trunnion (in)	9.50
Th_{flange}	Thickness of flange at closure bolt cylinder (in)	1.75
R_{os}	Outer radius of the outer shell (in)	15
$Th_{w\ ext}$	Thickness of the attachment block external weld (in)	0.75
$Th_{w\ int}$	Thickness of the attachment block internal weld (in)	0.00
$D_{w\ int}$	Diameter of the attachment block internal weld (in)	4.010
$D_{w\ ext}$	Length of the side of the attachment block external weld (in)	10.5
D_{ab}	Outer surface diameter of the attachment block (in)	38.5
H_{ab}	Depth of the counterbore for trunnion in the attachment block (in)	0.77
α_c	Angle of shear key plug assembly chamfer (degrees)	18
Δ_{sk}	Distance between shear key top surface and thermal shield shell (in)	0.37
H_{ss}	Height of shear key bearing block (in)	4.25
b	Width of the base of the shear key bearing block (in)	13.62
d	Longitudinal dimension of the shear key bearing block (in)	9.62
Th_{ss}	Thickness of shear key bearing block wall (in)	2.75
Th_{pp}	Thickness of pad plate (in)	1.0
b_{pp}	Longitudinal dimension of pad plate (in)	28.00
d_{pp}	Lateral dimension of pad plate (in)	21.21
α_t	Coefficient of thermal expansion of trunnions at 300 °F (in/in/°F)	8.7×10^{-6}
α_b	Coefficient of thermal expansion of trunnion bolts at 300 °F (in/in/°F)	6.9×10^{-6}
T	Analysis temperature (°F)	300

3.2 Acceptance Criteria

3.2.1 Trunnions

The TN-LC transport cask is lifted by the upper two removable trunnions. The trunnion attachment blocks are welded to the cask structural shell and as such are considered a structural part of the package. The removable trunnion bodies, although designed per subsection NF of the ASME code, are not structural part of the transportation package and are evaluated per the requirements of 10CFR71.45 [2.6]. The trunnions are designed and fabricated based on ANSI N14.6 [2.7].

In addition, the package must be designed such that "failure of any lifting device under excessive load would not impair the ability of the package to meet the requirements" of [2.6].

<u>Single Shoulder Trunnions:</u>

For 6 g loads, the stresses must remain below S_y. For 10 g loads, the stresses must remain below the ultimate strength S_u. [2.1]

3.2.2 Shear Key Bearing Block

10CFR71.45 (b) (1) requires that a system of tie–down devices that is a structural part of the package must be capable of withstanding, without generating stress in any material of the package in excess of its yield strength, a static force applied to the center of gravity of the package having a horizontal component along the direction in which the vehicle travels of 10 times the weight of the package with its contents.

Therefore, for 10 g loads, the stresses must remain below S_y (or $0.6 \times S_y$ in the case of shear stress). The stresses for the weld between the outer shell and pad must be lower than $0.6 \times S_y$ of the weakest base material.

3.2.3 Margin of Safety

It will be calculated as follows:

$$\text{Margin} = \frac{\text{Allowable stress}}{\text{Calculated stress}} - 1.$$

The margin should always be positive.

3.2.4 Weld Analysis

Per Table NF-3324.5(a)-1 [2.11], tension normal to the axis on the effective throat of a partial penetration groove weld is limited to 0.3*Su, and shear stress on the base metal is limited to 0.4*Sy.

ASME Subsection NF-3322.1 [2.11] limits the maximum tensile stress in structural steel to 0.6*Sy and 0.5*Su, and limits the shear stress to 0.4*Sy. Therefore, per ASME NF, the weld metal allowable tensile stress is a factor of (0.5/0.3)=1.67 less than the base metal stress.

Therefore, the ANSI N14.6 stress criteria for weld evaluations are as follows:

Allowable base metal tension: Lesser of (Sy/6) and (Su/10)
Allowable base metal shear stress: (0.4/0.6)x[Lesser of (Sy/6) and (Su/10)]
Allowable weld metal stress intensity: (0.3/0.5)x(Su/10)

For XM-19 Material: Sy/6 = 7.22 and Su/10 = 9.42. Therefore, yield stress governs and the weld base metal tension will be evaluated based on 6x the lifted load, compared against yield stress. Base metal shear will be checked based on (0.6/0.4)*6 = 9x the lifted load, compared against yield stress of the base metal.

For SA-240 Type 304 material: Sy/6 = 3.73 and Su/10 = 6.62. Therefore, yield stress governs and the base metal tension will be evaluated based on 6x the lifted load, compared against yield stress. Base metal shear will be checked based on (0.6/0.4)*6 = 9x the lifted load, compared against yield stress of the base metal.

Weld metal stress intensity will be evaluated based on (0.5/0.3)*10 = 16.67x the lifted load, compared against the ultimate stress of the weld metal.

3.3 Method

3.3.1 Trunnions Evaluation

First, the stresses in various sections of the trunnions are calculated. Then, the trunnion bolts are evaluated. Stresses in the trunnion flange and in the welds of the trunnion attachment block are also analyzed. Finally, the local stresses in the cask outer shell at the trunnion attachment block are calculated.

3.3.2 Shear Key Bearing Block Evaluation

The shear key bearing block and pad plate are parts of the cask structure designed to resist the 10 g longitudinal transportation load. The shear key

bearing block is a welded structure. The 21.21" × 28" × 1" pad plate is used to spread the longitudinal shear load over a large area of the cask structural shell to which it is welded, thus preventing the cask outer shell to be subjected to any bending moment resulting from the longitudinal load.

First the bearing stress between the shear key and the shear key bearing block is calculated. Bending stresses in the shear key bearing block are evaluated as well. Finally, the welds between the shear key bearing block and the pad plate and between the pad plate and the cask outer shell are analyzed.

4.0 ASSUMPTIONS

A Dynamic Load Factor (DLF) of 1.15 is used for the lifting loads.

The maximum weight of the packaging contents is conservatively taken as 8,000 lb [2.4].

The section of the shear key bearing block perpendicular to the cask axis, which is a circular sector, is conservatively assumed to bend like a straight beam.

The reference temperature is 70°F.

The ultimate stress of weld material at 300ºF is calculated based on the reduction in ultimate strength of A240 Type 304 base metal for 300ºF. Calculations are performed in material property section of analysis.

5.0 CALCULATIONS

5.1 Single Shoulder Trunnions

5.1.1 Lifting load

The TN-LC transport cask is lifted from the fuel pool vertically by its upper two removable trunnions using the fuel building crane. The weights of its components are: [2.4]

- Empty cask with trunnions: maximum 41,000 lb.
- Basket with its fuel contents: maximum 8,000 lb.

The maximum weight of the cask is W_L = 49,000 lb for the vertical lift from the fuel pool, distributed evenly between the two upper trunnions. Using a dynamic load factor of 1.15 and a lifting load of 6 g, the vertical design load (yield) for one trunnion is:

$$F_V = W_L \times DLF \times \frac{a_V}{N_{tr}} = 49{,}000 \times 1.15 \times \frac{6}{2} = 169{,}050 \text{ lb.}$$

Trunnion section is shown on Figure 1.

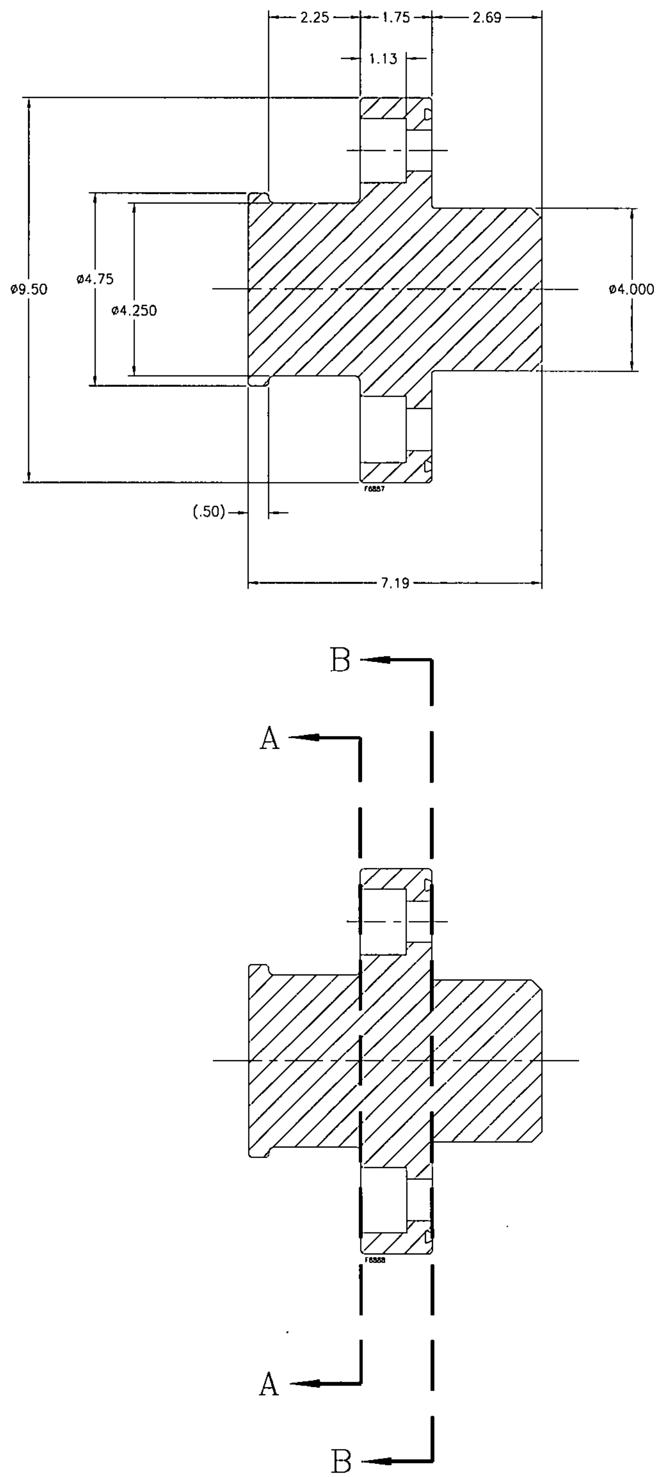

Figure 1: Single Shoulder Trunnion

5.1.2 Trunnion stresses

The stresses in sections A-A and B-B of the trunnion, shown in Figure 1, are calculated in Table 4.

Table 4: Single Shoulder Trunnion Stress Calculation

Section	**A–A**	**B–B**
Stress area (in^2)	$S_{AA} = \frac{\pi}{4}\left(D_{ext1}^2\right) =$ $\frac{\pi}{4}\left(4.25^2\right) = 14.19$	$S_{BB} = \frac{\pi}{4}\left(D_{hub}^2\right) =$ $\frac{\pi}{4}\left(4.0^2\right) = 12.57$
Moment of inertia (in^4)	$I_{AA} = \frac{\pi}{64}\left(D_{ext1}^4\right) =$ $\frac{\pi}{64}\left(4.25^4\right) = 16.01$	
Bending distance (in)	$L_{AA} = L_{sh} - Th_{tool}$ $= 2.25 - 1 = 1.25$	
Bending moment (in.lb)	$M_{AA} = F_V \times L_{AA}$ $= 169{,}050 \times 1.25$ $= 211{,}312.50$	
Shear stress (ksi)	$\frac{F_V}{S_{AA}} = \frac{169{,}050}{14.19}$ $= 11.91$	$\frac{F_V}{S_{BB}} = \frac{169{,}050}{12.57}$ $= 13.45$
Bending stress (ksi)	$\frac{M_{AA}}{I_{AA}} \times \frac{D_{ext1}}{2}$ $= \frac{211{,}312.5}{16.01} \times \frac{4.25}{2}$ $= 28.04$	
Max. stress intensity (ksi)	$\sqrt{28.04^2 + 4 \times 11.91^2}$ $= 36.80$	$2 \times 13.45 = 26.90$

5.1.3 Trunnion Bolt Stress Evaluation

5.1.3.1 Load Due to Trunnion Moment

The trunnions are attached to the cask using eight 1"- 8 UNC bolts. The bolts are in tension because of the moment on the trunnion flange. The shear load is supported by trunnion hub and the hole in the trunnion (welded to the cask body) attachment block. The radial clearance between the screw heads (and shanks) and the trunnion flange holes is large enough so that the shear load is supported by the trunnion hub–to–block hole interface by bearing, and not by the bolts.

The bending length is equal to (section B_B is shown in Figure 1):

$$L_{B\_B} = L_{sh} + Th_{flange} - Th_{tool} = 2.25 + 1.75 - 1.0 = 3.0 \text{ in.}$$

Therefore, the bending moment M_{B_B} is equal to $M_{B\_B} = F_V \times L_{B\_B}$, which is equal to:

$$M_{B\_B} = 169{,}050 \times 3 = 507{,}150 \text{ in.-lb.}$$

According to [2.8], case 4, for bolt patterns symmetrical about the vertical axis and flange rotating about the bottom bolt, the maximum bolt force F_m due to the bending moment M_{B_B} is:

$$\begin{aligned} F_m &= \left[\frac{2}{3\times D_{bolt}/2\times N_b}\left(1+\cos\frac{\pi}{N_b}\right)\right]M_{B\_B} \\ &= \left[\frac{4}{3\times 6.875\times 8}\left(1+\cos\frac{\pi}{8}\right)\right]\times 507{,}150 \\ &= 23{,}653.22 \text{ lb.} \end{aligned}$$

5.1.3.2 Bolt Preload

Per [2.4], the trunnion bolts should be torqued at the torque range from 400 ft-lb to 450 ft-lb.

Bolt preload for minimum torque (Q_{min}) is:

$$P_{\min} = \frac{Q_{\min}}{K \times D_b} = \frac{400\times 12}{0.135\times 1} = 35555.6\,lb.$$

Bolt preload for maximum torque (Q_{max}) is:

$$P_{\min} = \frac{Q_{\max}}{K \times D_b} = \frac{450 \times 12}{0.135 \times 1} = 40000.0\, lb.$$

5.1.3.3 Thermal Load

From Reference [2.10], Table 4.4, the bolt force due to the differential thermal expansion is calculated as follows:

$$F_{th} = 0.25 \times \pi \times D_b^2 \times E_b \times (\alpha_t \times \Delta T_t - \alpha_b \times \Delta T_b).$$

$\Delta T_t = \Delta T_b$ = temperature change = 300 − 70 = 230 °F.

Therefore:

$$F_{th} = 0.25 \times \pi \times 1^2 \times 26.7 \times 10^6 \times (8.7 \times 10^{-6} - 6.9 \times 10^{-6}) \times 230 = 8681.63 \text{ lb.}$$

5.1.3.4 Bolt Stresses

For a lifting load of 6 g, the trunnion bolt maximum stress σ_{bolt} due to the prying force F_m to is equal to:

$$\sigma_{bolt} = \frac{F_m}{S_{bolt}} = \frac{23{,}653.22}{0.606} = 39031.7 \text{ psi.}$$

For a lifting load of 10 g, the trunnion bolt maximum stress σ_{max} due to the prying force $10/6 \times F_m$ is equal to:

$$\sigma_{bolt} = \frac{10}{6}\frac{F_m}{S_{bolt}} = \frac{10}{6} \times \frac{23{,}653.22}{0.606} = 65052.9 \text{ psi.}$$

The trunnion bolt maximum stress σ_{max} due to the combined action preload $P_{\max}$ and thermal load F_{th} is equal to:

$$\sigma_{bolt} = \frac{(P_{\max} + F_{th})}{S_{bolt}} = \frac{(40{,}000.0 + 8681.63)}{0.606} = 80332.7 \text{ psi.}$$

Bolt stresses due to bolt preload and thermal load govern.

5.1.3.5 Minimum Engagement Length

The minimum engagement length L_e for the bolt and flange is (see Ref. [2.5], page 1490):

$$L_e = \frac{2 \times S_{bolt}}{3.1416 \times K_{n\max} \times \left[\frac{1}{2} + .57735 \times n \times \left(E_{s,\min} - K_{n\max}\right)\right]}$$

$$L_e = \frac{2 \times 0.606}{3.1416 \times 0.890 \times \left[\frac{1}{2} + .57735 \times 8 \times (0.9067 - 0.890)\right]}$$

$$L_e = 0.751\,\text{in}$$

According to [2.5], page 1490:

$$J = \frac{A_s \times S_{ue}}{A_n \times S_{ui}}.$$

S_{ue} is the tensile strength of external thread material, equal to 165 ksi, and S_{ui} is the tensile strength of internal thread material, equal to 66.2 ksi.

A_s is the shear area of external threads:

$$A_s = 3.1416 \times n \times L_e \times K_{n\max} \times \left[\frac{1}{2n} + 0.57735 \times \left(E_{s\min} - K_{n\max}\right)\right]$$

A_n is the shear area of internal threads:

$$A_n = 3.1416 \times n \times L_e \times D_{s\min} \times \left[\frac{1}{2n} + 0.57735 \times \left(D_{s\min} - E_{n\max}\right)\right]$$

Therefore:

$$A_s = 3.1416 \times 8 \times 0.751 \times 0.890 \times \left[\frac{1}{2 \times 8} + 0.57735 \times (0.9067 - 0.890)\right]$$

$$A_s = 1.212\,\text{in}^2.$$

$$A_n = 3.1416 \times 8 \times 0.751 \times 0.9755 \times \left[\frac{1}{2 \times 8} + 0.57735 \times (0.9755 - 0.9320)\right].$$

$$A_n = 1.613\,\text{in}^2.$$

So:

$$J = \frac{1.212 \times 165}{1.613 \times 66.2} = 1.872\,.$$

Therefore, the minimum required engagement length $Q = J \times L_e = 1.872 \times 0.751 = 1.41$ in.

According to [2.4], helicoils 1185–16CN–3000 of maximum length 3.0 in. are used with bolts of maximum threaded length 1.63 in = 2.25 in (total bolt shank length) – 1.75 in (trunnion flange thickness) + 1.13 in (counter bore depth). The helicoils are cut to fit with the maximum threaded length of the bolt which is 1.63 in.

5.1.4 Trunnion Flange Stresses

The trunnion flange is shown in Figure 2

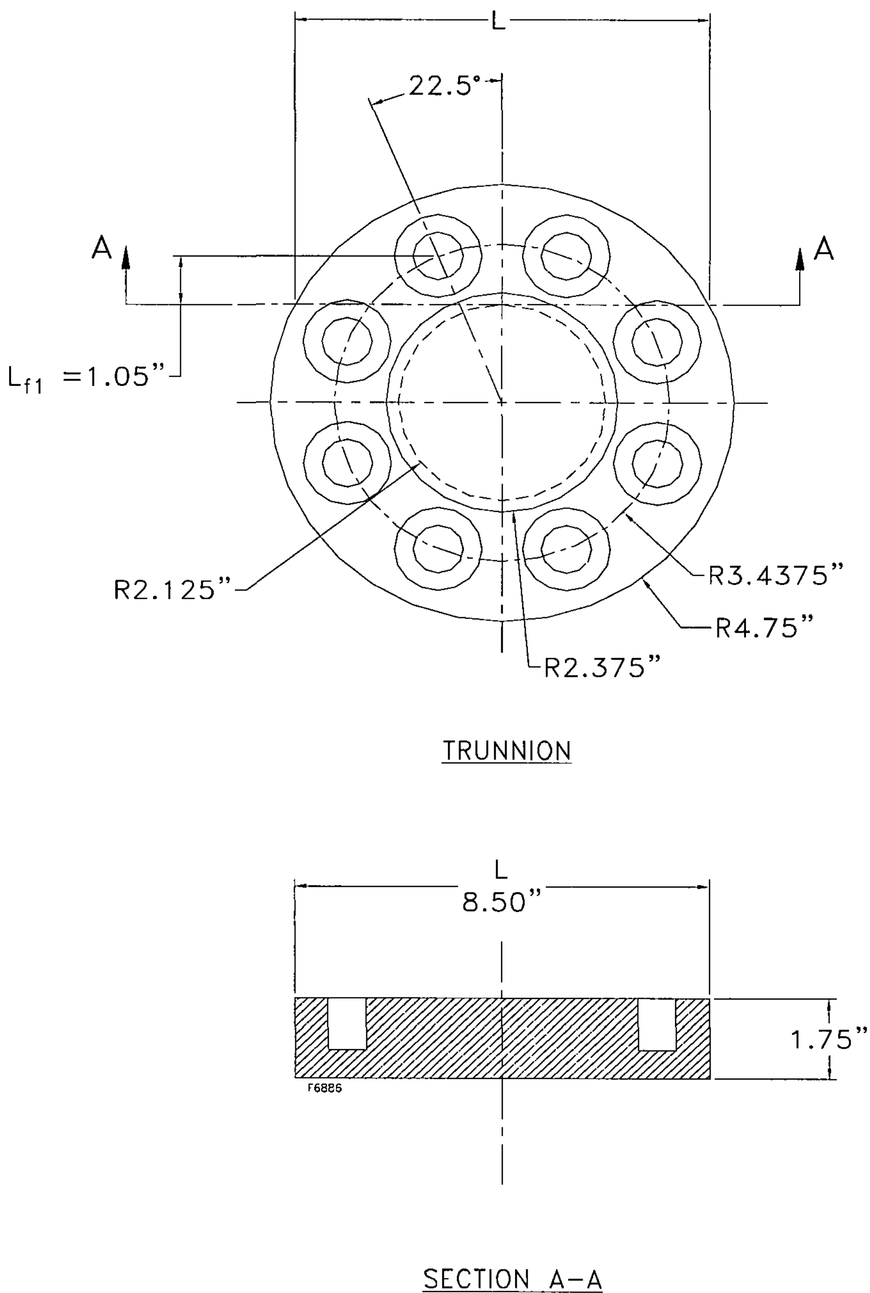

Figure 2: Trunnion Flange

Stresses at Section A-A (Figure 2)

Length L_{f1} = 0.5 × (D_{bolt} × cos (22.5°) – D_{ext1}) =0.5×(6.875 × cos(22.5°) – 4.25) = 1.05 in.

Flange length: $L = 2\sqrt{(D_{\max}/2)^2 - (D_{ext1}/2)^2} = 2\times\sqrt{\left(\left(\frac{9.5}{2}\right)^2 - \left(\frac{4.25}{2}\right)^2\right)} = 8.50\,\text{in}$.

It is assumed conservatively that the effective length, L_{ef}, of the net area of the flange section AA is reduced by $2\times D_{hole}$ due to the close proximity of the bolt holes:

$$L_{ef} = L - 2\times D_{hole} = 8.5 - 2\times 1.8 = 4.9\,in.$$

Flange thickness at AA: Th_{flange} = 1.75 in.

Maximum bolt load due to 6g is F_m.

It is conservatively assumed that the two bolts are exposed to the same load F_m.

Bending moment at A–A:

$$M = 2\times F_m \times L_{f1} = (2\times 1.05\times 23{,}653.22) = 49{,}671.8\ \text{in.lb.}$$

Modulus of section at A-A is estimated by relation:

$$Z = \frac{L_{ef}\times Th_{flange}^2}{6} = \frac{4.9\times 1.75^2}{6} = 2.5\,\text{in}^3$$

The bending stress is equal to:

$$\frac{M}{Z} = \frac{49{,}671.8}{2.5} = 19868.7\ psi.$$

The shear stress is equal to:

$$\frac{2\times F_m}{L_{ef}\times Th_{flange}} = \frac{2\times 23{,}653.22}{4.9\times 1.75} = 5516.8\,psi.$$

The maximum stress intensity is equal to:

$$\sqrt{\sigma_b^{\,2} + 4\times\tau^2} = \sqrt{19{,}868.7^2 + 4\times 5516.8^2} = 22726.8 \text{ psi}.$$

5.1.5 Trunnion Attachment Block and Cask Shell Weld

There is a 3/4" groove weld on the outer perimeter of the attachment block and the cask shell [2.4]. On the inside of the attachment block, there is a seal weld. Strength of the seal weld is ignored. The outer weld is subjected to a bending moment plus direct shear loading.

Tension in base metal is evaluated for 6x lifted load and compared to Sy. Shear in base metal is evaluated for 9x lifted load and compared to Sy. Weld metal is evaluated for 16.67x lifted load and compared to Su of weld metal. Refer to Section 3.2.4 for weld loading details.

6x Load for Base Metal Tensile Stress Check:	169,050 lbs
9x Load for Base Metal Shear Stress Check:	253,575 lbs
16.67x Load for Weld Metal Stress Check:	469,677 lbs

The outer surface diameter of the cask attachment block is 38.5 in. Since the inner radius of the cask shell at attachment block is 15 in, the maximum height of the block at a distance (10.5/2) = 5.25 inch from the block symmetry plane is:

$$H_{\max} = \sqrt{\left(\frac{38.5}{2}\right)^2 - 5.25^2} - \sqrt{15^2 - (5.25)^2} = 4.47 \text{ in}.$$

The minimum height of the block is:

$$H_{\min} = \sqrt{\left(\frac{38.5}{2}\right)^2 - 5.25^2} - \sqrt{15^2 - \left(\frac{4.010}{2}\right)^2} = 3.65 \text{ in}.$$

The average height H_{avg} is therefore 0.5 × (4.47+3.65) = 4.06 in.

The bending length for the weld is conservatively calculated using H_{max}:

$L_{sh} - Th_{tool} + H_{max} + Th_{flange} - H_{ab}$ = 2.25–1.0 + 4.47 + 1.75 – 0.77 = 6.7 in. [2.4]

Cask Shell Base Metal Check

Base metal tensile stress is caused by bending action. The stress is calculated based on a 6x load and compared to Sy. Refer to Section 3.2.4 for weld loading details.

The weld bending moment is equal to F_{V6} × (bending length), which is equal to:

$$M_{w6} = 169{,}050 \times 6.7 = 1{,}132{,}635 \text{ in.lb.}$$

The base metal moment of inertia at the cask shell is calculated based on the standard formula for the area moment of inertia of a rectangle, $bh^3/12$. In this case the cross section is square (b=h). Therefore, the moment of inertia is:

$$I_{weld} = \frac{1}{12}\left[D_{w\_ext}^4 - \left(D_{w\_ext} - 2\times Th_{w\_ext}\right)^4\right]$$

$$I_{weld} = \frac{1}{12}\left[10.5^4 - (10.5 - 2\times 0.75)^4\right]$$

$$I_{weld} = 466.17 \text{ in}^4$$

The base metal tensile stress at cask shell σ_b is:

$$\sigma_b = \frac{M_w \times 0.5 \times D_{w\_ext}}{I_{weld}} = \frac{1{,}132{,}635 \times 0.5 \times 10.5}{466.17}$$

$$\sigma_b = 12{,}755.7 \text{ psi}$$

The base metal shear stress is caused by direct shear loading. The stress is calculated based on a 9x load and compared to Sy. Refer to Section 3.2.4 for weld loading details. The weld shear stress at cask shell is equal to:

$$A_{weld} = D_{w\_ext}^2 - \left(D_{w\_ext} - 2\times Th_{w\_ext}\right)^2 = 10.5^2 - (10.5 - 2\times 0.75)^2 = 29.25 \text{in}^2$$

$$\tau = \frac{F_{v9}}{A_{weld}} = \frac{253{,}575}{29.25} = 8669.2\, psi$$

Weld Metal Stress Intensity

Weld metal stress intensity is caused by a combination of bending and shear stresses. The stress is calculated based on a 16.67x load and compared to Su of the weld metal. Refer to Section 3.2.4 for weld loading details.

Therefore, the weld bending moment is equal to $F_{V16.67}$ × (bending length), which is equal to:

$$M_{w16.67} = 469{,}677 \times 6.7 = 3{,}146{,}836 \text{ in.lb.}$$

The moment of inertia and area of the weld are the same as calculated above for base metal. The weld bending stress at trunnion block σ_b is:

$$\sigma_b = \frac{M_{w16.67} \times 0.5 \times D_{w\_ext}}{I_{weld}} = \frac{3{,}146{,}836 \times 0.5 \times 10.5}{466.17}$$

$$\sigma_b = 35{,}440 \text{ psi}$$

The weld metal shear stress is equal to:

$$\tau = \frac{F_{v16.67}}{A_{weld}} = \frac{469{,}677}{29.25} = 16{,}057\, psi$$

The maximum weld metal stress intensity is equal to:

$$\sqrt{\sigma_b^{\,2} + 4 \times \tau^2} = \sqrt{35440^2 + 4 \times 16057^2} = 47{,}826 \text{ psi}.$$

Attachment Block Base Metal Check

The attachment block base metal is a 45º groove. The moment of inertia is the same as calculated previously, but bending action causes a component of tension and a component of shear on the 45º face. Likewise, the direct shear load causes a component of tension and a component of shear on the 45º face.

The tensile stress component from bending load is calculated based on previous bending stress. The stress is adjusted for the 45º weld surface and is reduced by a factor of 1.414 to account for the increased surface area:

$$\sigma_b = 12{,}755.7 \text{ psi} \quad \text{(calculated previously)}$$
$$\sigma = \sigma_b \cos(45)/1.414 = 6{,}379 \text{ psi}$$

The tensile stress component from direct shear load is calculated as follows:

$$\tau = \frac{F_{v9}}{A_{weld}} = \frac{253{,}575}{29.25} = 8669.2\,psi$$
$$\sigma_\tau = \tau \cos(45)/1.414 = 4335 \text{ psi}$$

Total tensile stress is equal to:

$$\sigma = 6379 + 4335 = 10{,}714 \text{psi}$$

The base metal shear stress is caused by a combination of bending action and direct shear. The shear stress is calculated based on a 9x load and compared to Sy. Refer to Section 3.2.4 for weld loading details.

Shear stress component due to bending is calculated as follows:

$$M_{w9} = 253{,}575 \times 6.7 = 1{,}698{,}953 \text{ in.lb.}$$

$$\sigma_b = \frac{M_{w9} \times 0.5 \times D_{w\_ext}}{I_{weld}} = \frac{1{,}698{,}953 \times 0.5 \times 10.5}{466.17}$$

$$\sigma_b = 19{,}133.6 \text{ psi}$$

$$\tau = \sigma_b \sin(45)/1.414 = 9568 \text{ psi}$$

Shear stress due to direct shear:

$$\tau_\tau = \frac{F_{v9}}{A_{weld} \times 1.414} = \frac{253{,}575}{29.25 \times 1.414} = 6{,}131\,psi$$

Total shear stress:

$$\tau = 9568 + 6131 = 15{,}699\,psi$$

5.1.6 Stress in Trunnion Attachment Block

The shear and bending stress in the attachment block are bounded by the evaluation of the attachment welds.

The bearing stress in the trunnion hub-to-block interface:

$$\frac{F_V}{L_{hub} \times D_{hub}} = \frac{169{,}050}{2.69 \times 4.0} = 15.7\ ksi.$$

5.1.7 Local Stresses in Cask Outer Shell at Trunnion Attachment Block

Local stresses are calculated using the methodology [2.9]. for a square attachment with circumferential side length equal to 2 × c_1 and longitudinal side length equal to 2 × c_2

The trunnion shear loads in the longitudinal and circumferential directions are respectively $V_L = F_V = 169{,}050$ lb and $V_C = 0$ lb.

The bending length is calculated using H_{ave}:

$L_{sh}–Th_{tool} + H_{ave} + Th_{flange} – H_{ab}$= 2.25–1.0 + 4.06 + 1.75 – 0.77 = 6.29 in. [2.4]

The external overturning moments supported by the intersection in the longitudinal and circumferential directions with respect to the shell are respectively:

$$M_L = 169{,}050 \times 6.29 = 1{,}063{,}324.5 \text{ in.lb. and } M_C = 0 \text{ in.lb.}$$

The thickness of the outer shell is Th_{os} = 1.5 in. The cylinder mean radius is:

$$R_m = R_{os} - 0.5 \times Th_{os} = 15\text{-}0.5\text{x}1.5 = 14.25 \text{ in.}$$

The block circumferential side length is equal to 2 × c_1 = 10.50 in. Its equivalent longitudinal length 2 × c_2=10.50 in. since the block shape is square [2.4]

Therefore:

$$c_1 = c_2 = c = 5.25\,\text{in}\,.$$

The geometric parameters are:

$$\gamma = \frac{R_m}{Th_{os}} = \frac{14.25}{1.5} = 9.5\,,\ \beta = \beta_1 = \beta_2 = \frac{c}{R_m} = \frac{5.25}{14.25} = 0.37\,.$$

The above quantities are used as the input data in the supplementary spreadsheet (file TN-LC-0204-Rev-2.xls, documented in the Section 8.0) to calculate the stresses in the outer shell of the cask. The spreadsheet layout is documented as Table 5.

Table 5: Cask Outer Shell Stresses Calculations (Single Shoulder Trunnion)

From fig.:	Read curves for:		Mult.	Abs. stress values		Au	Al	Bu	Bl	Cu	Cl	Du	Dl
3C & 4C			0	0	0	0	0	0	0	0	0	0	0
1C & 2C-1			0	0	0	0	0	0	0	0	0	0	0
3A			0	0						0	0	0	0
1A			0	0						0	0	0	0
3B	1.152	β=0.37	9,475	10,916		-10,916	-10,916	10,916	10,916				
1B or **1B-1**	0.0284		540,101	15,339		-15,339	15,339	15,339	-15,339				
	Σ(phi - circumferential stresses)					**-26,255**	**4,423**	**26,255**	**4,423**	**0**	**0**	**0**	**0**
3C & 4C			0	0	0	0	0	0	0	0	0	0	0
1C-1 & 2C			0	0	0	0	0	0	0	0	0	0	0
4A			0	0						0	0	0	0
2A			0	0						0	0	0	0
4B	0.414	β=0.37	9,475	3,923		-3,923	-3,923	3,923	3,923				
2B or **2B-1**	0.0474		540,101	25,601		-25,601	25,601	25,601	-25,601				
	Σ(X - longitudinal stresses)					**-29,524**	**21,678**	**29,524**	**-21,678**	**0**	**0**	**0**	**0**
	Shear stress due to torsion M_T				0	0	0	0	0	0	0	0	0
	Shear stress due to load V_C				0	0	0	0	0				
	Shear stress due to load V_L				5,367					5,367	5,367	5,367	5,367
			Σ(shear stresses τ)			0	0	0	0	5,367	5,367	5,367	5,367
			Stress intensities			**29,524**	**21,678**	**29,524**	**21,678**	**10,733**	**10,733**	**10,733**	**10,733**

The maximum stress intensity is 29,524 psi.

The trunnion attachment block and the cask shell are at the same temperatures.

5.2 Shear Key Bearing Block

5.2.1 Horizontal Load

The TN-LC transport cask is blocked in translation by its shear key. The weight of its elements during transport is:

- Empty cask trunnions(conservative): maximum 41,000 lb,
- Impact limiters (top and bottom): (conservative) maximum 3,200 lb,
- Basket with its fuel contents (conservative): maximum 8,000 lb.

The maximum weight of the cask is $W_H = 52{,}200$ lb for horizontal loads, concentrated on the shear key plug assembly (10 g).

5.2.2 Bearing Stress between the Shear Key and the Shear Key Bearing Block

Using a dynamic load factor of 1.15, the horizontal design load (yield) is:

$$F_H = W_H \times DLF \times a_L = 52{,}200 \times 1.15 \times 10 = 600{,}300 \text{ lb}.$$

The bearing stress due to the 10g longitudinal transportation load is calculated assuming the load is applied uniformly to one face of the shear key slot. The key dimensions related to shear key bearing block evaluations are presented in Figure 3.

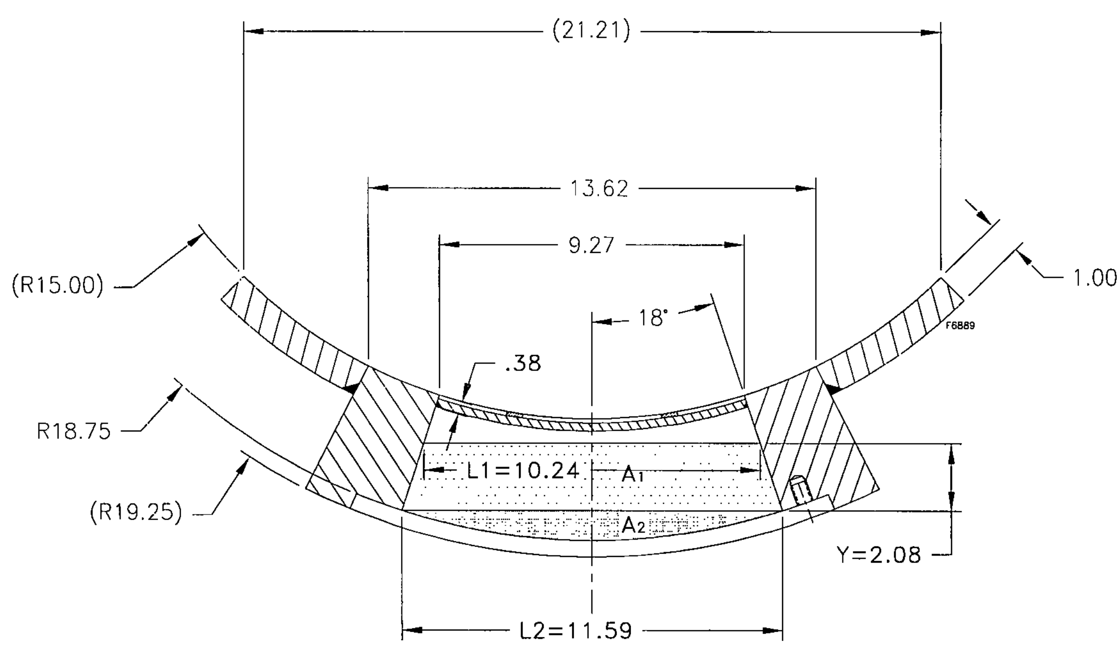

Figure 3: Shear Key Plug Assembly

The bearing area is divided into two areas (see Figure 3): a trapezoidal area A_1, of average width $(L_1+L_2)/2$ and height Y, and an area A_2, which is a segment of solid circle (see Figure 3). The bearing area is the sum of A_1 and A_2. The bearing area A_1 is calculated as:

$$A_1 = \frac{L_1 + L_2}{2} \times Y$$

where:

L_1 is the width of the top surface of the shear key assembly (shear key chamfer top width).

L_2 is the width of the shear key assembly at the lowest lateral point of the contact with the shear key bearing block assembly.

Y is the distance between the planes L_1 and L_2.

The angle of shear key assembly chamfer is α_c=18°.

From geometrical relations (see Figure 3)

$$L_2 = 2\times 18.75\times \sin(18°) = 11.59 \text{ in.}$$

The analysis assumes that the top surface of shear key is separated from the thermal shield shell component by Δ_{sk} = 0.37", so that the distance of the shear key top surface to the TN-LC cask center is 15.0+0.38+0.37 =15.75" (Figure 3).

From the geometric relations of shear key bearing block (see Figure 3):

$$Y = \sqrt{(18.75-15)^2 - \left(\frac{11.59-9.27}{2}\right)^2} - [15.75 - 15.0\times\cos(18°)] = 3.566 - 1.484 = 2.08$$

$$L_1 = L2 - 2\times Y\times \tan(\alpha_c) = 11.59 - 2 \times 2.08 \times tg(18°) = 10.24 \text{ in.}$$

Therefore:

$$A_1 = \frac{L_1 + L_2}{2}\times Y = \frac{10.24 + 11.59}{2}\times 2.08 = 22.70\,\text{in}^2$$

The solid circle area A_2, with the span angle α_c=18° (0.314 radians) can be assessed by the expression:

$$A_2 = \frac{1}{2} \times (18.75)^2 \times [2 \times 0.314 - \sin(2 \times 18°)]$$

$$A_2 = 7.11\,\text{in}^2.$$

Therefore, A = 22.70+7.11 = 29.81 in^2.

The bearing stress is equal to:

$$\frac{F_H}{A} = \frac{600{,}300}{29.81} = 20{,}137.5\text{ psi}$$

5.2.3 Stresses in the Shear Key Bearing Block

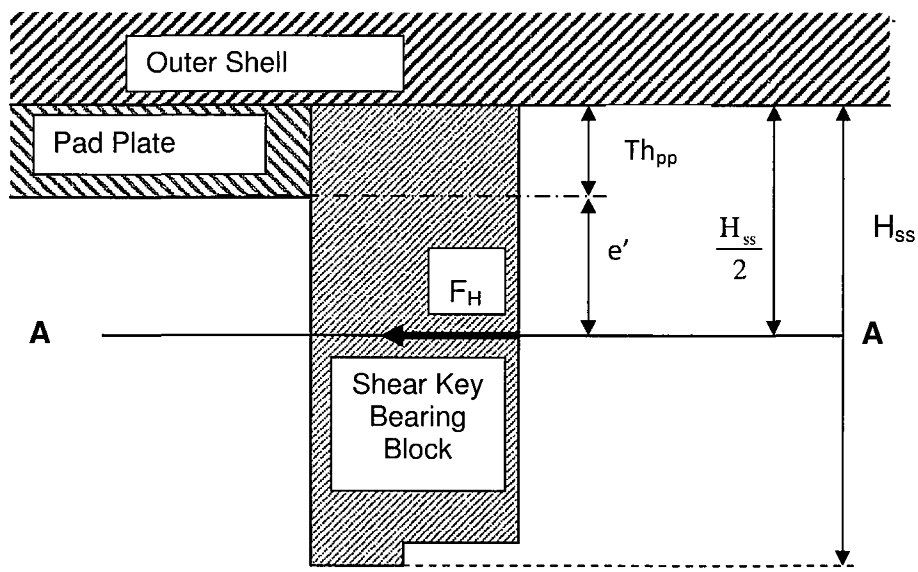

Figure 4: Shear Key Bearing Block Bending Length

The maximum bending length at the horizontal section A–A on the Shear key bearing block for the longitudinal load is (see Figure 4):

$$e' = \frac{H_{ss}}{2} - Th_{pp} = \frac{4.25}{2} - 1 = 1.125\,\text{in}.$$

Therefore, the maximum bending moment at the horizontal section A–A on the shear key bearing block for the longitudinal load is:

$$M_{A\text{-}A} = F_H \times e' = 600{,}300 \times 1.125 = 675{,}337.50 \text{ in.lb}.$$

The moment of inertia is:

$$I_{yy} = \frac{bd^3}{12} - \frac{(b - 2\times Th_{ss})\times(d - 2\times Th_{ss})^3}{12} = \frac{13.62\times 9.62^3}{12} - \frac{8.12\times 4.12^3}{12}$$

$$I_{yy} = 963.1 \text{ in.}^4$$

The bending stress is equal to:

$$\frac{M_{A-A}\times d/2}{I_{yy}} = \frac{675{,}337.50\times {}^{9.62}\!/_{2}}{963.1} = 3{,}372.7 \text{ psi}.$$

The shear stress is equal to:

$$\frac{F_H}{b\times d - (b - 2\times Th_{ss})\times(d - 2\times Th_{ss})} = \frac{600{,}300}{13.62\times 9.62 - 8.12\times 4.12} = 6{,}152.5 \text{ psi}.$$

The maximum stress intensity is equal to:

$$\sqrt{3{,}372.7^2 + 4\times 6{,}152.5^2} = 12{,}758.9 \text{ psi}.$$

5.2.4 Weld Between the Shear Key Bearing Block and the Pad Plate.

The shear key bearing block is welded to the 1"–thick pad plate with a $t_w = 3/8$" partial penetration groove weld (black weld on Figure 5). The weld is loaded in bending, resulting from the offset "e" (see Figure 5) of the 10 g longitudinal point to the pad plate center.

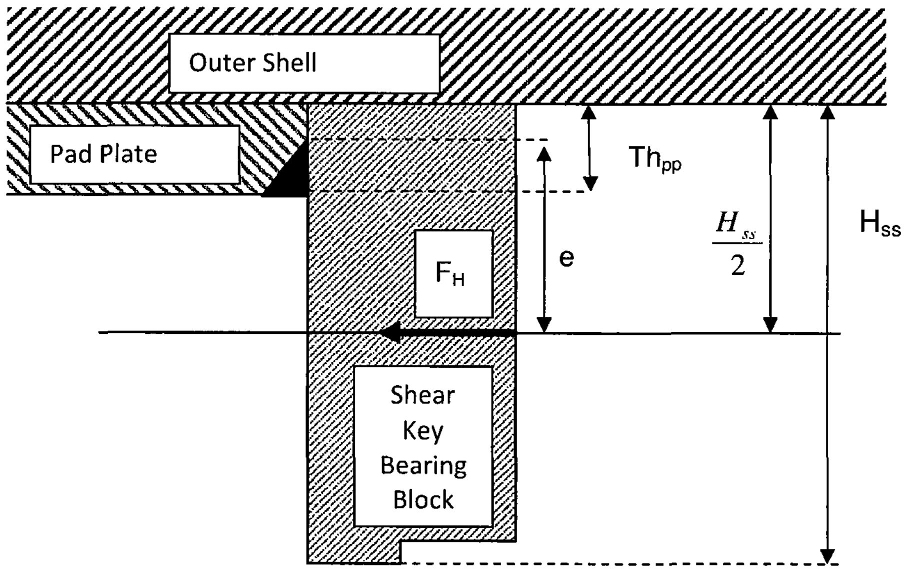

Figure 5: Shear Key Bearing Block and Pad Plate Weld Bending Length

The bending moment is applied at the middle of the shear key bearing block bearing area, therefore at a distance $\frac{H_{ss}}{2}$ from the outer shell:

The bending length is equal to

$$e = \frac{H_{ss}}{2} - 0.5 \times Th_{pp} = \frac{4.25}{2} - 0.5 \times 1 = 1.625 \text{ in}.$$

The bending moment M is therefore:

$$M_w = F_H \times e = 600{,}300 \times 1.625 = 975{,}488 \text{ in.lb}$$

The section modulus of the weld is computed by treating the weld as a line per unit thickness t_w [2.2]:

$$S_w = \left(bd + \frac{d^2}{3} \right) \times t_w.$$

$$S_w = \left(13.62 \times 9.62 + \frac{9.62^2}{3} \right) \times \frac{3}{8} = 60.70 \text{in}^3.$$

The bending stress is equal to:

$$\sigma_{wb} = \frac{M_w}{S_w} = \frac{975{,}488}{60.70} = 16070.6 \text{ psi}$$

5.2.5 Weld between the Pad Plate and the Outer Shell

The shear key pad plate is welded to the cask structure all around with a 0.5" groove weld (g_w) and 0.5" fillet weld (f_{wp}). The shear area in the base metal of the structural shell is:

$$S = b_{pp} \times d_{pp} - \{(d_{pp} - 2\times g_w)\times(b_{pp} - 2\times g_w)\} + 2\times(b_{pp} + d_{pp})\times\frac{\sqrt{2}}{2} f_{wp}$$
$$= 28\times21.21 - \{(21.21 - 2\times0.5)\times(28 - 2\times0.5)\} + 2\times(28 + 21.21)\times0.707x0.5$$
$$= 83.01 \text{ in}^2$$

The weld shear stress at the junction of the weld material and the cask structural shell is:

$$\frac{F_H}{S} = \frac{600{,}300}{83.01} = 7{,}231.7 \text{ psi}$$

6.0 RESULTS

6.1 Single Shoulder Trunnions

The stresses calculated for a load of 6 g are summarized in Table 6 and compared with allowable values (S_y). The stresses for a load of 10 g are also indicated in Table 6 (simple 10/6 ratio of the values calculated for 6 g) and compared with the allowable values (S_u).

Table 7 shows the weld stress values at the trunnion to cask shell weld. Base material and weld material stress allowables are based on appropriate Sy and Su values as indicated.

Table 6: Summary of Lifting Stresses – Single Shoulder Trunnions (ksi)

	Calculated (6 g)	Allowable (S_y)	Margin	Calculated (10 g)	Allowable (S_u)	Margin
Stress intensity in trunnion shoulder	36.8	43.3	0.18	61.3	94.2	0.54
Stress intensity in trunnion flange	22.7	43.3	0.91	37.9	94.2	1.49
Stress intensity in trunnion hub	26.9	43.3	0.61	44.8	94.2	1.10
Bolt tensile stress	80.3	140.3	0.75	80.3	165.0	1.05
Outer cask shell stress	29.5	43.3	0.47	49.2	94.2	0.91
Attachment Block Bearing Stress	15.7	22.4	0.43	26.2	66.2	1.53

Table 7: Summary of Weld Stresses – Trunnion Attachment Blocks (ksi)

Trunnion Weld	Calculated	Allowable	Margin
Cask Shell Base Metal Tension	12.76	43.3	2.39
Cask Shell Base Metal Shear	8.67	43.3	3.99
Weld Metal Stress Intensity	47.83	70.6	0.48
Attachment Block Base Metal Tension	10.71	22.4	1.09
Attachment Block Base Metal Shear	15.70	22.4	0.43

The results presented in Table 6 show that the smallest margin is at the trunnion shoulder, which implies that in case of failure, the trunnion itself will fail, but not the cask shell. This ensures that failure of any lifting device under excessive load would not impair the ability of the cask to meet the requirements of [2.6].

The minimum required engagement length is 1.406 in. According to [2.4], helicoils 1185–16CN–3000 are used. The maximum threaded length of the bolt is equal to 1.63 in, which is greater than the minimum required engagement length.

6.2 Shear Key Bearing Block

The stresses calculated for a longitudinal load of 10 g are summarized in Table 8 and compared with allowable values.

Table 8: Summary of Longitudinal Stresses – Shear Key Bearing Block (ksi)

		Calculated (10 g)	**Allowable (S_y or $0.6 \times S_y$)**	**Margin**
Shear key bearing block	Bearing stress	20.1	84.6	3.20
	Bending stress	3.4	84.6	24.08
	Shear stress	6.2	50.8	7.25
	Maximum stress intensity	12.8	84.6	5.63
	Bending stress in the weld with pad plate	16.1	22.4	0.39
Weld between pad plate and cask outer shell	Shear stress in base metal	7.2	13.4	0.86

7.0 CONCLUSIONS

All of the stresses calculated above are less than the allowable stresses.

7.1 Trunnion Assembly

Based on the above calculations, the trunnion design meets the requirements of 10CFR71.45 and ANSI N14.6.

7.2 Shear Key Assembly

Based on the above calculations, the design meets the requirements of 10CFR71.

8.0 LISTING OF COMPUTER FILES

Below is listing of computer file used for computing the trunnion and shear key assembly stresses.

File Name	Time	Description
TN- LC-0204-Rev2. xls	09/16/2013 2:49 PM	TN-LC transport cask trunnion, trunnion local stress and tie-down system stress evaluation.