	Orano Federal Services
	CALCULATION

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Project No.: 00225.03.0050	Project Name: DOE Atlas Railcar
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Title: Atlas Railcar Family 1 Conceptual Cradle Structural Calculation




Summary:

This calculation documents the suitability of the conceptual design of the Family 1 Atlas Railcar cradles. Family 1 includes: AREVA-TN: TN40, TN40HT, TN328 and Holtec: Hi-Star 100, Hi-Star 100HB, Hi-Star 180, Hi-Star 190SL, and Hi-Star 190XL casks.



Contains Unverified Input / Assumptions: Yes: No:

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Revision History

Rev.	Changes
0	Initial Issue
1	Revised calculation to add Holtec Hi-Star 190SL and Hi-Star 190XL casks. Update Table 2.2 to reduce conservatisms. Added the personnel barrier to the weight and CG of the Hi-Star 100 Cask. Revised the end stops for all remaining casks to accommodate rail car attachment changes. Revised the cradles for the Hi-Star 100 and Hi-Star 100HB to lower the casks to meet the AAR Plate E height requirements. Revised Table 5.1 to report cradle weight with 10% increase. Added Tables 5.3, Summary of Cradle Stresses and 5.4 Summary of Cradle Attachment Weld Stresses.
2	Revised to correct TOC and list of tables page numbers, and errors in Table 5.1 references on pages 25 and 27.
3	The weight of the end stop assembly for the HI-STAR 60 conceptual cradle design was previously calculated using simplifications which resulted in unrealistic weight and CG values. Revised Hi-Star 60 End Stop Weight and CG Calculation and updated Table 2.2, Table 5.5, and Table 6.1 and updated reference files.
4	The HI-STAR 60 conceptual central cradle was revised to increase weight. Updated Table 2.2, Table 4.1, Table 5.1, Table 5.2, Table 5.5 and Table 6.1
5	Table 5.3 was updated to correct the saddle section modulus for the HI-STAR 190XL and HI-STAR 190SL cradles.



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1.0 PURPOSE

This calculation evaluates and documents the structural capabilities of the Atlas Railcar Cradle design concepts for the Family 1 casks. Family 1 includes the following casks: AREVA TN:

TN-40, TN-40HT and TN-32B, Holtec International: Hi-Star 60, Hi-Star 100, Hi-Star 100HB (also referred to as the Hi-Star HB), Hi-Star 180, Hi-Star 190SL and, Hi-Star 190XL. This cask family (Family 1) is defined by the restraints defined/assumed for the cask. These casks all include end stops to restrain axial cask movement on the railcar during transport as shown in Figure 1.

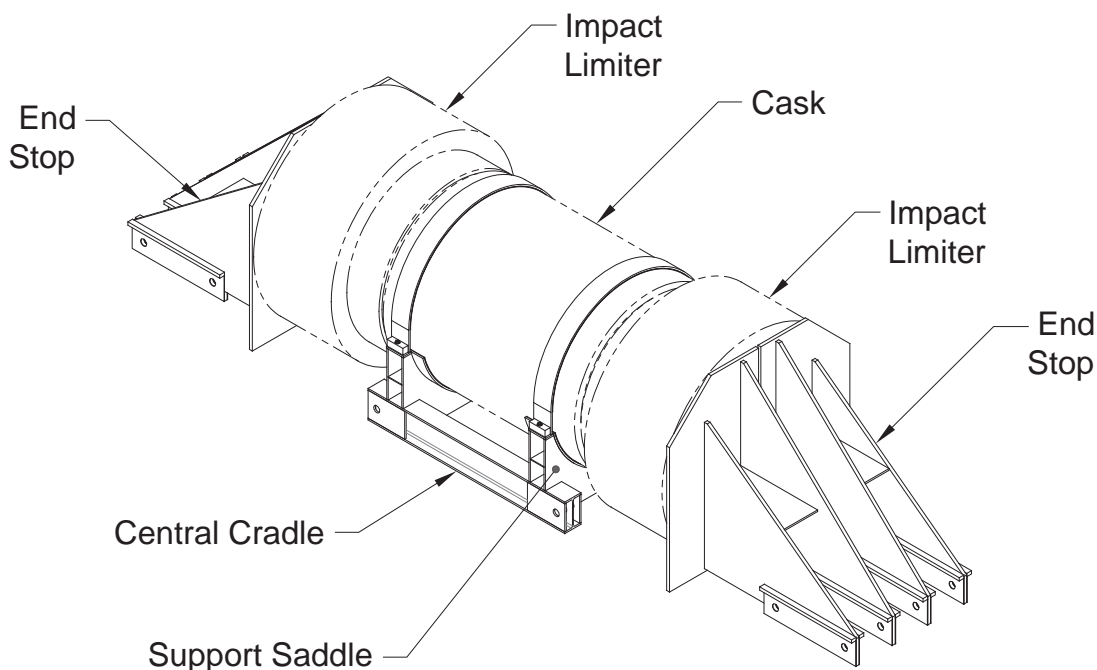


Figure 1: Typical Family 1 Cask and Cradle

The various designs, within Family 1, share the end stop requirement, however due to variations in the cask's geometries and licensing requirements, there are variations in the details.

The purpose of this design effort is the design of a railcar. In support of this, conceptual cradle designs are generated to define the height of each cask center-of-gravity above the bottom of the cradle and the weight on each rail car axle along with other information required to perform the analysis and provide simulated cask weights and supporting information needed for testing of the railcar.

This calculation also documents the loads to the railcar attachments due to the defined tie-down loads of ± 7.5 g Axial (Longitudinal), ± 2 g Vertical and ± 2 g Lateral applied independently per § 2.2.2.13 of [7.4].



As such, the cradle and end stop designs are only concepts and the design of the cradle and end stops will not be completed (these cask supports will be designed by each cask vendor). This evaluation serves only to validate this design concept.

The casks included here are grouped by the means of support for the transport cask on the rail car. All of the above casks are supported by a central support frame (used to react the vertical and lateral loads) and end stops (used to react the axial loads). All of the casks, with the exception of the Hi-Star 60 and Hi-Star 180 are rotated to the horizontal orientation for rail transport prior to placement on the rail car. The Hi-Star 60 and Hi-Star 180 are expected to have the option of this rotation on the rail car. In the case this is required (the facility has rail access to the cask loading location), a removable rotation fixture, such as is currently used by Holtec International is expected to be used. The loads on the rail car will be bounded by the loads from the heavier Magnatran cask (312 kip), a Family 2 cask vs. the Hi-Star 60 (164 kip) or Hi-Star 180 (309 kip) per Attachment A of [7.1].

The Family 1 support saddles are of similar design and the central cradle varies largely based on the cask length and height above the deck of the rail car. All of the Family 1 designs are shown in drawing Atlas Railcar Cradle Family 1 Conceptual Drawing [7.2]. The cradles for the AREVA-TN casks include slots in the cradle support to provide clearance for the tie-rods used to support impact limiter attachment.

Similarly, the end stops are all similar. For both the end stops and the central cradle, the attachment points to the rail car are the same.

Using these similarities, only the bounding loads for each component evaluated will be included and will thus bound all designs for Family 1.

Evaluation of the proposed attachment points and associated pins are included in the Attachment calculation [7.3].

The attachment lugs are located on the rail car deck [7.5]. The central cradle and end stops are pinned to the attachment lugs using 4 inch diameter pins. The holes in the four lugs used to attach the central cradle are slotted such that the lugs react only vertical and lateral loads. The holes in the lugs used to attach the end stops have round holes in the eight pair (four pair at each end) of lugs located nearer the center of the railcar and slotted holes for the remaining eight pair of attachment lugs, thus only the pin locations nearest the cask react the cask axial loads.

2.0 METHODOLOGY

2.1 Geometry

The Family 1 casks vary in outside diameter (at the cask support locations) from approximately 75-3/4 inches for the Hi-Star 60 cask to approximately 106-1/2 inches for the Hi-Star 190 casks. The largest diameter impact limiters are used on the TN-40 cask (144 inches) and the smallest are on the Hi-Star 60 (approximately 114-3/4 inches). The impact limiter diameter, with a 1 inch clearance, is the closest any cask may be located to the rail car deck. Some casks, due to their geometry, are located higher above the rail car deck, but in any case, the height above the deck is minimized in order to reduce the loads to the rail car as well as



minimize the height of the Center-of-Gravity (C.G.) for the system (cask, cask supports and rail car).

The component weights and C.G.'s for both the casks and cradle/end stop designs are documented in ten (10) spreadsheets [7.10 through 7.19]. The spreadsheets are also used to determine the loads on the rail car attachment points.

Materials of Fabrication:

The main support beams for the central cradle are W18 X 119 per ASTM A992. The remaining components (plate) are fabricated from ASTM A572, Grade 42 (for portions of the Hi-Star 190 SL & XL cradles), Grade 50, Grade 65 (for portions of the Hi-Star 190XL End stops). Material properties are shown in Table 2.3.

The loads specified in § 2.2 are design loads and use the material yield strength for the allowable stress per § 2.2.2.13 of the DBRD [7.4]. The acceptability of each component evaluated to the loads of § 2.2 will be determined by comparison with the yield strength and a Margin-of-Safety calculated as follows:

$$MS = \frac{\text{Allowable Load}}{\text{Applied Load}} - 1 \text{ or } \frac{\text{Allowable Stress}}{\text{Applied Stress}} - 1 \geq 0$$

2.2 Loads

Loads result from the accelerations specified in § 2.2.2.13 of [7.4]. The specified accelerations, listed in Table 2.1, are applied to each component/assembly. Each acceleration is applied separately. The resultant loads on the attachment points are developed in [7.10] through [7.19] and are summarized in Table 2.2. The component weights for the central cradle and end stops are increased by 10% in the determination of resultant loads per § 2.2.2.3(a) of [7.4].

**Table 2.1 – Applied Accelerations
(Tie Downs)**

Direction	Acceleration (g)
Longitudinal (Axial)	7.5
Vertical	2
Lateral	2

Notes:

1. Above values from § 2.2.2.13 of [7.4]. The values shown are the net accelerations.



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Table 2.2 – Summary of Loads

	HI-STAR 100 (kip)	HI-STAR 100HB (kip)	HI-STAR 180 (kip)	HI-STAR 190XL (kip)	HI-STAR 190SL (kip)	HI-STAR 60 (kip)	TN-32B (kip)	TN-40 (kip)	TN-40HT (kip)
Pin Block 1 / Pin Block 4									
vertical (+z)	155.5	108.1	209.9	283.6	258.8	105.3	161.6	167.1	149.5
vertical (-z)	-155.5	-108.1	-209.9	-283.6	-258.8	-105.3	-161.6	-167.1	-149.5
lateral (y)	303.3	212.2	408.5	555.0	507.5	211.1	277.4	287.1	256.4
Pin Block 5									
Axial (+x)	--	--	--	--	--	--	--	--	--
Axial (-x)	--	--	--	--	--	--	--	--	--
vertical (+z)	42.5	69.1	52.8	44.9	47.3	38.3	55.3	54.2	54.2
vertical (-z)	-703.1	-520.8	-739.6	-979.2	-901.0	-395.8	-739.6	-755.2	-687.5
lateral (y)	12.8	16.0	12.3	11.0	11.7	13.2	16.7	17.1	17.1
Pin Block 9									
Axial (+x)	611.1	441.8	648.4	858.3	788.9	390.2	584.5	599.6	544.9
Axial (-x)	-48.0	-60.0	-50.6	-41.3	-43.9	-49.5	-62.6	-64.1	-64.1
vertical (+z)	703.1	520.8	739.6	979.2	901.0	395.8	739.6	755.2	687.5
vertical (-z)	-42.5	-69.1	-52.8	-44.9	-47.3	-38.3	-55.3	-54.2	-54.2
lateral (y)	12.8	16.0	13.5	11.0	11.7	13.2	16.7	17.1	17.1
Pin Block 13									
Axial (+x)	47.9	59.8	50.7	41.3	43.7	49.5	62.7	63.9	63.9
Axial (-x)	-611.1	-441.8	-648.4	-858.3	-788.9	-390.2	-584.5	-599.6	-544.9
vertical (+z)	703.1	520.8	739.6	979.2	901.0	395.8	739.6	755.2	687.5
vertical (-z)	-21.6	-35.1	-26.8	-44.9	-47.3	-19.4	-55.3	-54.2	-54.2
lateral (y)	12.8	16.0	12.3	11.0	11.7	13.2	16.7	17.1	17.1
Pin Block 17									
Axial (+x)	--	--	--	--	--	--	--	--	--
Axial (-x)	--	--	--	--	--	--	--	--	--
vertical (+z)	21.6	35.1	52.8	44.9	47.3	19.4	55.3	54.2	54.2
vertical (-z)	-703.1	-520.8	-739.6	-979.2	-901.0	-395.8	-739.6	-755.2	-687.5
lateral (y)	12.8	16.0	13.5	11.0	11.7	13.2	16.7	17.1	17.1

Notes:

1. The loads are from [7.10] through [7.19]. Due to symmetry, the load magnitudes for pin locations 5 - 8, 9 - 12, 13 - 16 and 17 - 20, the loads are the same, therefore, Table 2.2 lists the loads at the first pin location in each group for each cask. Locations are defined in the attachment drawing [7.5].
2. An example calculation for P1 - P4 is shown in § 5.5 and for the axial loading for P5 - P20 in § 5.3

2.3 Allowable Stress

The acceptance criteria for the loads resulting from the accelerations shown in Table 2.1 is the material yield strength per § 2.2.2.13 of the DBRD [7.4]. The acceptance criteria for fillet welds



and partial penetration groove welds is 0.6 times the yield strength. Conservatively, the base material yield strength will be used.

2.4 Material Properties

Material Properties are shown in Table 2.3 below.

Table 2.3 – Material Properties for ASTM A992 and A572

ASTM Material	Yield Strength (ksi)	Ultimate Strength (ksi)
A992	50	65
A572, Grade 65	65	80
A572, Grade 50	50	65
A572, Grade 42	42	60

Notes:

1. Properties from American Society for Testing and Materials [7.6] and [7.7].
2. ASTM A572, Grade 42 is for materials greater than 4 inches in thickness.

2.5 Beam Properties

The longitudinal beam is a W18 x 119 with the following section properties (from AISC [7.8]):

$$A_b := 35.1 \text{ in}^2 \quad d := 19 \text{ in} \quad b_f := 11.3 \text{ in} \quad t_f := 1.06 \text{ in} \quad I_x := 2190 \text{ in}^4 \quad \text{and} \quad I_y := 253 \text{ in}^4$$

The beam is boxed at the ends (from the end of the beam to the first saddle) with 1 inch thick A572 plate. The composite beam has the following section properties:

$$S_{\text{maj}} = \left[2190 \text{ in}^4 + 2 \frac{1 \text{ in} (19 \text{ in} - 2 \times 1.06 \text{ in})^3}{12} \right] \frac{2}{19 \text{ in}} = 315 \text{ in}^3$$

$$S_{\text{min}} = \left[253 \text{ in}^4 + 2 \frac{(1 \text{ in})^3 (19 \text{ in} - 2 \times 1.06 \text{ in})}{12} + (1 \text{ in}) (19 \text{ in} - 2 \times 1.06 \text{ in}) \left[\frac{11.3 \text{ in} - 1 \text{ in}}{2} \right]^2 \right] \frac{2}{11.3 \text{ in}}$$

$$= 204 \text{ in}^3$$

3.0 ASSUMPTIONS

3.1 Justified Assumptions

- 3.1.1 Nominal dimensions are used throughout this calculation. This is standard practice.
- 3.1.2 The TN-40HT cask is not yet licensed for transportation. This cask is a version of the TN-40 used for high burnup fuel. The same impact limiter geometry and attachment method used on the licensed TN-40 cask is assumed. This is reasonable due to the relationship between the TN-40 and TN-40HT casks.



3.1.3 The TN-32B cask is not yet licensed for transportation. The same impact limiter geometry and attachment method used for the TN-40 cask is assumed. This assumption is reasonable due to the likeness of the TN-32 cask to both the licensed TN-40 and TN-68 casks. Both casks have similar impact limiters and impact limiter attachments. Additionally, this same assumption (as to the similarity of impact limiter geometry and impact limiter attachment) has been made on the TN-32B High Burnup (TN-32B HBU) demonstration cask project.

3.2 Unverified Inputs/Assumptions

None

4.0 DESIGN INPUTS

Table 4.1 – Design Inputs

Cask	Cask Weight ¹ Maximum (lb) (W _c)	Cask Vert CG ² from bottom of cradle (in) (d _{c_vcg})	Cradle Vert CG ³ from bottom of Cradle (in) (d _{cr_vcg})
HI-STAR 100 (_hs100)	279,893	66.0	25.2
HI-STAR 100HB (_hshb)	187,200	66.0	27.1
HI-STAR 180 (_hs180)	308,647	64.5	27.3
HI-STAR 190XL(_hs190XL)	420,769	64.5	21.8
HI-STAR 190SL(_hs190SL)	382,746	64.5	21.8
HI-STAR 60 (_hs60)	164,000	59.63	26.6
TN-32B (_TN32)	263,000	72.5	35.1
TN-40 (_TN40)	271,500	72.5	32.0
TN40HT (_TN40HT)	242,343	72.5	32.0

Notes:

1. Values from Attachment A of the Statement of Work [7.1] except values for the Hi-Star 190 casks are from RFI AFS-RFI-0015 [7.21].
2. Values from Cradle Family 1 Conceptual Drawing.
3. Values from [7.11] – [7.19].

5.0 CALCULATIONS

5.1 Check Bending of Longitudinal Beams

The longitudinal beams are attached to the railcar at the attachment lug locations (P1 - P4 on the attachment drawing [7.5]). The vertical loads are reacted by either the 1/2 inch thick shim plates (Item 6 on [7.5]) (downward) or the 4 inch diameter pins (upward). The loads on the beam are from the lateral and vertical accelerations only, the cask axial loads are reacted by



the end stops. The centers of the attachment lugs (and pins) are located 125 inches apart (see Figure 2).

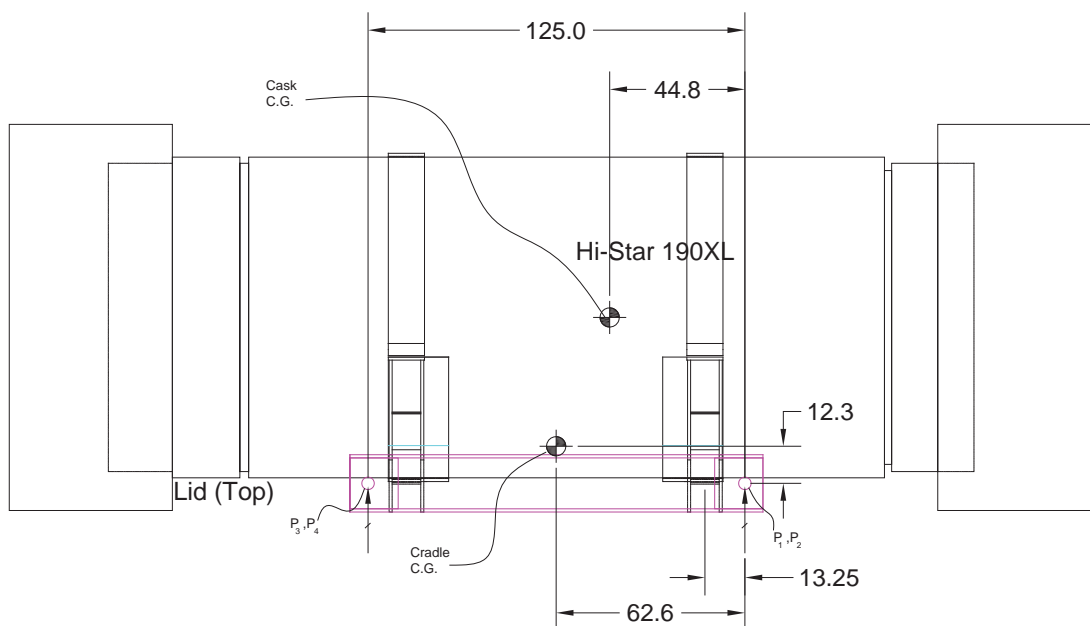


Figure 2: Hi-Star 190XL Free Body Diagram (FBD), Vertical

The vertical load is shared equally between the two beams and the lateral load is conservatively assumed to be reacted by only a single beam. The lateral load also causes a vertical load on the beam opposite the beam reacting the horizontal load. An example calculation of the moments is shown immediately below. The moments are calculated, using the same method as shown below for the remaining cradles and reported in Table 5.1.

The moment on the beam is simply the load at the attachment location (conservatively assume the center of the pin in lieu of the edge of the lug or shim plate) multiplied by the distance from the pin to the edge of the saddle. Conservatively, the dimension to the center of the saddle is used.

The force at the attachment is calculated by summing moments at pin location P1 as follows (the example is for the maximum moment case, the Hi-Star 190XL at the end near pin P3, see Figure 2 for FBD):

$$\begin{aligned} \text{Load}_{P3} &= a_d \frac{W_{C_{190XL}} \times d_{c_{hcg_{190XL}}} + W_{cr_{190XL}} \times d_{cr_{hcg_{190XL}}}}{2 \times 125 \text{ in}} \\ &= -2 \times \frac{420.769 \text{ kip} \times 44.8 \text{ inch} + 15 \text{ kip} \times 62.6 \text{ inch}}{2 \times 125 \text{ inch}} = -158.3 \text{ kip} \end{aligned}$$



The load at P1 is:

$$\begin{aligned} \text{Load}_{P1} &= \frac{a_d(W_{C_190XL} + W_{cr_190XL}) - 2 \times \text{Load}_{P3}}{2} \\ &= \frac{-2 \times (420.769 \text{ kip} + 15 \text{ kip}) - 2 \times (-158.3 \text{ kip})}{2} = -277.5 \text{ kip} \end{aligned}$$

The moment from the vertical load on the beam is: $M = \text{Load}_{P1} \times 13.25 \text{ inch} = 3,667 \text{ in}\cdot\text{kip}$ where 13.25 inch is the distance from the pin location to the center of the saddle. The horizontal load for the lateral load is double the vertical load (the load is reacted by a single beam). Additionally, the opposite beam reacts a vertical load for the righting moment from the lateral load. The vertical reactions at each end are proportional to the distance from the C.G. to the attachments.

Determine the vertical reactions resulting from the lateral acceleration by summing moments, counter clockwise positive. The restoring moment from the cask weight is conservatively neglected.

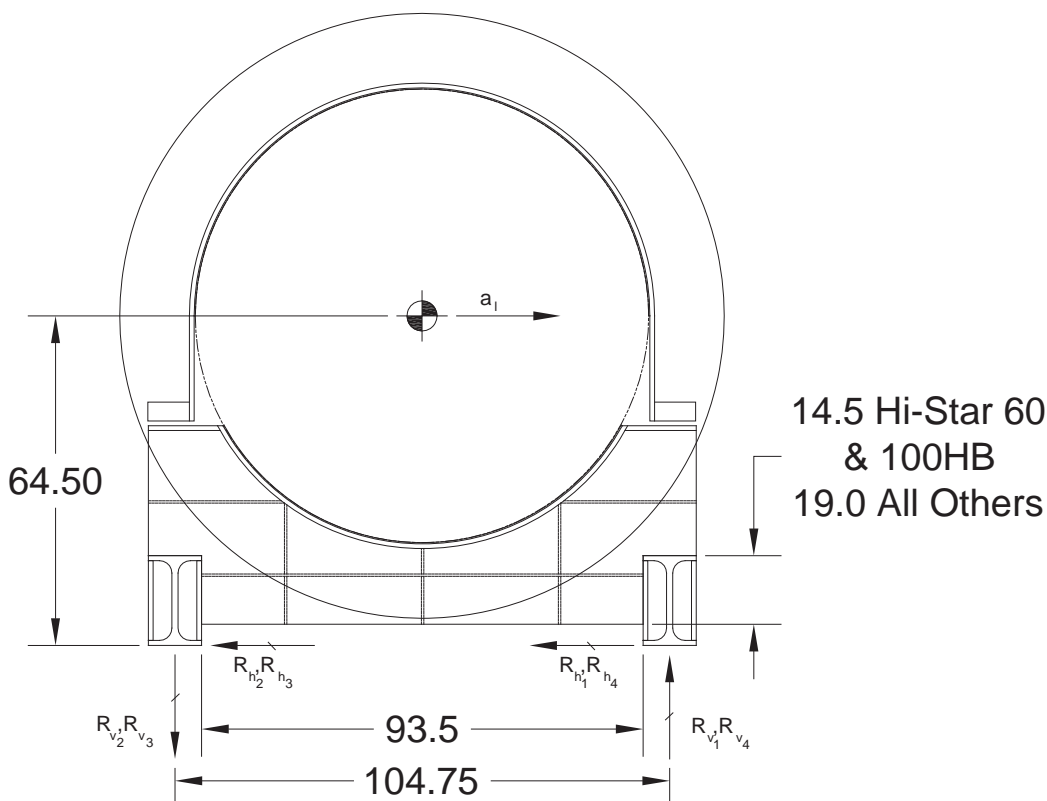


Figure 3 - Hi-Star 190XL Free Body Diagram (FBD), Lateral



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$$+\curvearrowright \quad \sum M_{P1} = 0 = -a_l (W_{c_190XL} d_{c_vcg_190XL} + W_{cr_190XL} d_{cr_vcg_190XL}) - 104.75 \text{ in} (R_{v2} + R_{v3})$$

where $a_l = 2 \text{ g}$ (Table 2.1), $d_{c_vcg_190XL} = 64.5 \text{ inches}$ (Table 4.1), $d_{cr_vcg_190XL} = 21.8 \text{ inches}$ (Table 6.1)

Sum forces in the vertical direction:

$$+\uparrow \quad \sum F_y = 0 = R_{v1} + R_{v4} - R_{v2} - R_{v3}, \text{ therefore } R_{v1} + R_{v4} = R_{v2} + R_{v3}$$

As noted above, the reactions on each beam are inversely proportional to the distance from the centroid. The combined longitudinal centroid for the Hi-Star 190XL cask and cradle is:

$$d_{hcg} = \frac{W_{c_190XL} \times d_{c_hcg_190XL} + W_{cr_190XL} \times d_{cr_hcg_190XL}}{W_{c_190XL} + W_{cr_190XL}} = \frac{420.769 \text{ kip} \times 44.8 \text{ inch} + 13.6 \text{ kip} \times 62.6 \text{ inch}}{420.769 \text{ kip} + 13.6 \text{ kip}} = 45.4 \text{ inch}$$

Using the CG and the distance between the pins of 125 inches, the following relationship is found for vertical reactions: $R_{v1} \times 45.4 \text{ inch} = R_{v4} (125 \text{ inch} - 45.4 \text{ inch})$ and the same relationship holds for R_{v2} and for R_{v3} respectively.

Substituting and solving for R_2 :

$$R_{v2} = \frac{a_l [W_{c_190XL} \times (d_{c_vcg_190XL} - 9.5 \text{ in}) + W_{cr_190XL} \times (d_{cr_vcg_190XL} - 9.5 \text{ in})]}{104.75 \text{ in} \left(1 + \frac{45.4}{125 - 45.4} \right)} = \frac{2 \times [420.769 \text{ kip} \times (64.5 \text{ inch} - 9.5 \text{ inch}) + 15.0 \text{ kip} \times (21.8 \text{ inch} - 9.5 \text{ inch})]}{104.75 \text{ in} \left(1 + \frac{45.4}{125 - 45.4} \right)} = 283.6 \text{ kip}$$

$$, R_{v3} = \frac{45.4}{125 - 45.4} R_{v2} = 161.8 \text{ kip. The corresponding moments are}$$

$M_{v2} = R_{v2} 12.75 \text{ inch} = 3,616 \text{ in} \cdot \text{kip}$ and $M_{v3} = R_{v3} 13.25 \text{ inch} = 2143 \text{ in} \cdot \text{kip}$ These moments resulting from the lateral acceleration are greater than the moments resulting from the vertical acceleration. However, these moments act on the strong axis of the longitudinal beams. The horizontal component of the lateral acceleration is also reacted by the single beam. Referring to Figure 2 and summing the forces in the horizontal direction (positive right),



$$\rightarrow + \sum F_h = a_l = (W_{c_190XL} + W_{cr_190XL}) - R_{h1} - R_{h4}, R_{h1} 45.4 \text{ in} = R_{h4} (125 \text{ in} - 45.4 \text{ in}).$$

Solving for R_{h1} : $R_{h1} := a_l \frac{(W_{c_190XL} + W_{cr_190XL})}{1 + \frac{45.4}{125 - 45.4}} = 555 \text{ kip}$ and the resulting moment is :

$M_{h1} = R_{h1} 13.25 \text{ in} = 7354 \text{ in} \cdot \text{kip}$ and the moment on the opposite end of the beam is:

$M_{h4} = R_{h1} \frac{45.4}{125 - 45.4} 12.75 \text{ in} = 4036 \text{ in} \cdot \text{kip}$ The moments resulting from the horizontal components are higher and the section modulus of the beam resisting this moment is lower, therefore, evaluation of the horizontal component is bounding for the beam.

The resulting stress for the composite W18X119 beam is: $\sigma_{\text{minor}} = \frac{M_{h1}}{S_{\text{min}}} = 36.0 \text{ ksi}$ where $S_{\text{min}} = 204 \text{ in}^3$ is from § 2.5.

The resulting Margin of Safety is: $MS = \frac{F_{y992}}{\sigma_{\text{minor}}} = 0.39 \rightarrow \text{Okay}$

The loads and moments on the central cradles are summarized in Tables 5.1 and 5.2, and demonstrate that the moment on the Hi-Star 190XL bounds the remaining cradles. Note that the values shown in the tables are for the vertical acceleration and are for comparison only (used to demonstrate the bounding cradle).

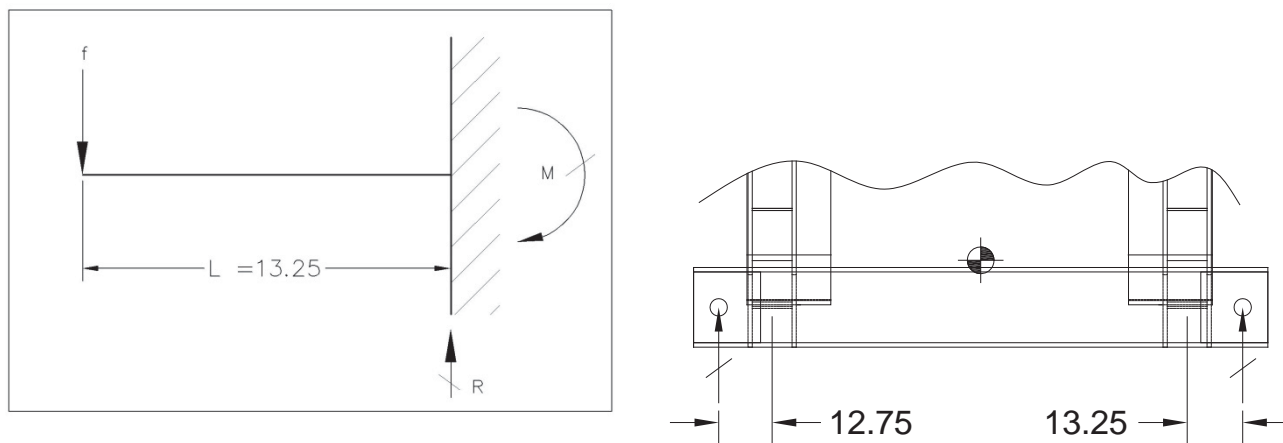


Figure 4 - Beam & Moment Diagram



Orano Federal Services

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Table 5.1 – Summary of Loads on Central Cradle

Cask	Cask Weight Maximum (lb) (W_c)	Cask CG from pin (P1) (in) (d_{c_hcg})	Central Cradle weight (kip) (W_{cr})	Central Cradle CG from P1 (in) (d_{cr_hcg})	Load at P3 (kip) ($Load_{P3}$)	Load at P1 (kip) ($Load_{P1}$)
HI-STAR 100($_{hs100}$)	279,893	62.9	22.6	66.8	151.7	149.6
HI-STAR 100HB($_{hshb}$)	187,200	59.9	16.5	60.2	97.7	106.0
HI-STAR 180($_{hs180}$)	308,647	44.4	10.1	62.6	114.2	204.1
HI-STAR 190XL($_{190XL}$)	420,769	44.8	15.0	62.6	158.3	277.5
HI-STAR 190SL($_{190SL}$)	382,746	44.6	14.7	62.6	143.3	253.5
HI-STAR 60($_{hs60}$)	164,000	50.9	17.7	68.2	76.4	105.3
TN-32B($_{TN32}$)	263,000	63.0	14.6	56.9	139.6	138.3
TN-40($_{TN40}$)	271,500	62.5	14.2	56.7	142.2	143.5
TN40HT($_{TN40HT}$)	242,343	62.5	14.2	56.7	127.6	128.9

Notes:

1. The loads in Table 5.1 and the moments in Table 5.2 result from the vertical acceleration on the cask/cradle. As such, the reactions are opposite the applied acceleration in all cases and since the applied accelerations are bi-lateral (± 7.5 g axial, ± 2 g vertical and lateral) only the magnitude is of importance.
2. In the table above, the column defines the main variable (such as W_c for cask weight) and the row defines the specific (such as $_{hs100}$). The variable name is, for this example, W_{c_hs100} and is the weight of the Hi-Star 100 cask.
3. The cradle weights shown in the above table include an additional 10% factor.



Table 5.2 – Summary of Moments on Central Cradle Beam

Cask	Distance from P1 to center of saddle (in) (d _{P1s})	Distance from P3 to center of saddle (in) (d _{P3s})	Moment	
			P3 End (in-kip) (M _{P3})	P1 End (in-kip) (M _{P1})
HI-STAR 100	13.375	12.625	1,916	2,001
HI-STAR 100HB	27.06	34.26	3,347	2,870
HI-STAR 180	13.25	12.75	1,456	2,704
HI-STAR 190XL	13.25	12.75	2,019	3,676
HI-STAR 190SL	13.25	12.75	1,827	3,359
HI-STAR 60	16.25	35.27	2,696	1,711
TN-32B	13.25	15.15	2,115	1,833
TN-40	13.25	15.15	2,154	1,901
TN40HT	13.25	15.15	1,933	1,708

5.2 Evaluate the Saddles for the Design Loads

The saddles support the vertical and lateral loads from the casks (the axial loads are reacted by the end stops).

The analysis below assumes a distributed load increasing toward the center of the cradle plates on the saddles. The saddles for the TN-40/TN-40HT and the TN-32 include cutouts for the tie-rods connecting the impact limiters. These cutouts reduce the depth of the saddles on these two cradles.

The weight of the TN-40 cask exceeds that of the TN-32 cask and the central cross-section of the TN-32 is less than that of the TN-40 [TN-40HT] cradle, therefore, the cross section of the TN-32 cradle will be used with the loads of the TN-40 cask, thus bounding both cradles.

The remaining cradles include reinforcement in the center. The reinforcement is comprised of two 3-1/4 inch thick doubler plates attached to each one inch thick vertical cradle support plate, except for the Hi-Star 190SL and Hi-Star 190XL cask cradles where a longer (50.7 inch long, ASTM A572, Grade 42) bar replaces the two one inch thick vertical cradle plates. The thickness of the bar is greater than 4 inches necessitating the use of grade 42 material.

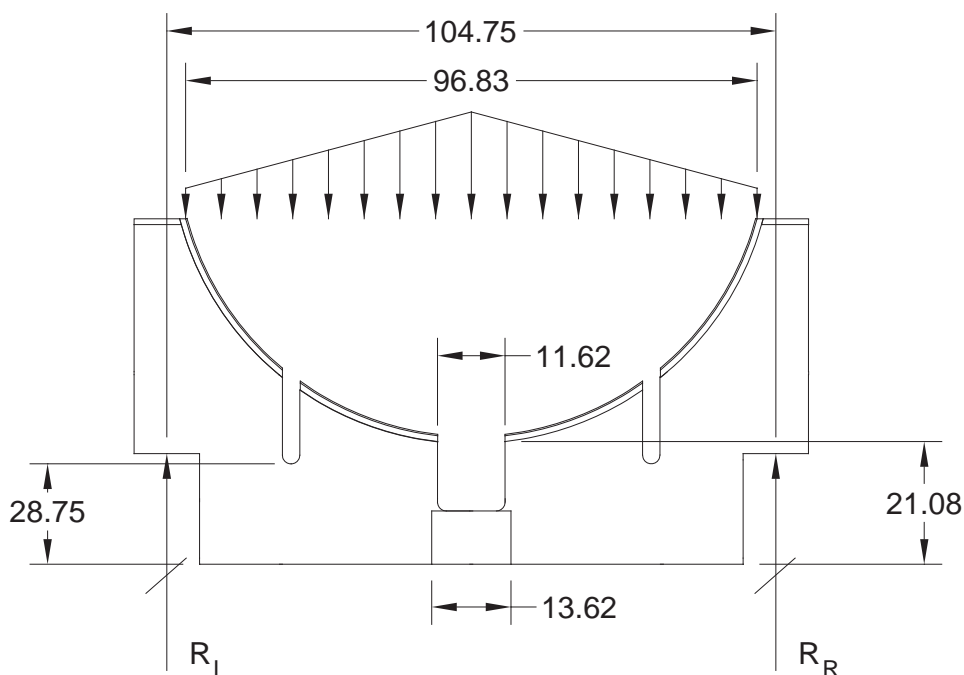


Figure 5 - TN-40 cradle Saddle with Major Points Identified - Vertical Loading

The saddle is modeled as a simply supported beam with a distributed load increasing toward the center. The moment is the highest at the center of the beam. The moment will be calculated using superposition, combining the moment calculated using case 8 (page VI-85) from Aluminum Design Manual [7.9] with the moment from the support offset to the edge of the cradle plate.

The moment at the center is:

$$M_{V_saddle} = a_d \frac{(W_{C_TN40}) 96.83 \text{ in}}{2 \times 6} + a_d \frac{104.75 \text{ in} - 96.83 \text{ in}}{2} \frac{W_{C_TN40}}{2}$$

$$M_{V_saddle} = 5457 \text{ in} \cdot \text{kip}$$

Where: $W_{C_TN40} = 271.5 \text{ kip}$ is from Table 5.1, 96.83 inches is the horizontal distance of the saddle plate ($2(48.875 + .25 + 1)\cos(15^\circ) = 96.83 \text{ in}$), 48.875 is the radius of the TN-32 Cask, .25 and 1 are the thickness of the rubber and the cradle plate and $a_d = 2g$ is the vertical acceleration.

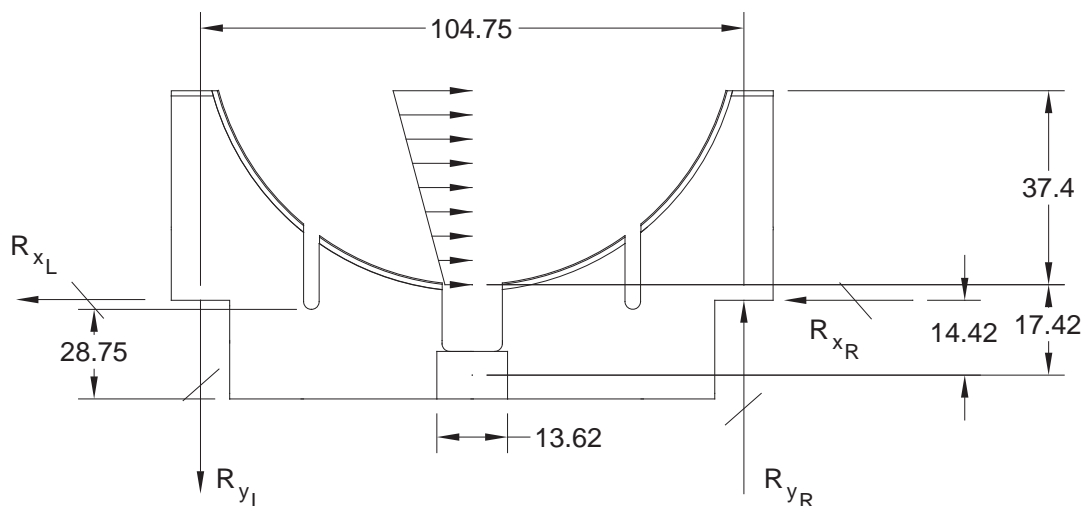


Figure 6 - TN-40 cradle Saddle with Major Points Identified - Lateral Loading

In addition to the vertical loading, the lateral acceleration would also cause a moment on the central area of the saddle. Figure 6 above shows the loading where a triangular load distribution is assumed. In the lateral load case shown above, the load from cask weight is modeled as a triangle with the area equal to the weight of the cask. Each saddle supports one half of the cask weight and the saddles are supported by the W18 X 119 longitudinal beams. The first step is to determine the loads.

The triangular distribution is equivalent to the entire weight of the cask applied at the centroid of the area or 1/3 of the length from the top of the saddle.

Summing the moments (positive clockwise):

$$\sum M_R = 0 = \left(17.42 + \frac{2 \times 37.4}{3} \right) \frac{W_{c_TN40}}{2} - 104.75 R_{yL} - 14.42 R_{xL} - 14.42 R_{xR}$$

$R_{yL} = 2 \frac{17.42 + \frac{2 \times 37.4}{3}}{104.75} \frac{W_{c_TN40}}{2} = 110 \text{ kip}$ where the moment resulting from the horizontal reactions is conservatively neglected, the multiplier of 2 accounts for the applied lateral acceleration and the divisor of 2 accounts for the load sharing between the two saddles.

The resulting moment is simply the force multiplied by the distance:

$$M_{L_saddle} = R_{yL} \frac{104.75 \text{ in}}{2} = 5761 \text{ in} \cdot \text{kip}$$



The TN-40 saddle, at the center section, is 9.15 inches tall (see Drawing 3015137, Sheet 1, Zone A7 [7.2]) and in addition to the 1 inch thick saddle plate, includes two 3-1/4 inch thick doublers.

The corresponding section modulus of the plates at the center is:

$$S_{\text{saddle}} = 2 \left[\frac{1 \text{ in} (9.15 \text{ in})^2}{6} + \frac{3.25 \text{ in} (9.15 \text{ in})^2}{6} \right] = 118.6 \text{ in}^3. \text{ The moment due to the lateral load is bounding and the resulting stress is: } \sigma_{b_TN40} = \frac{M_{L_saddle}}{S_{\text{saddle}}} = 48.6 \text{ ksi}$$

The Corresponding Margin of Safety is: $MS = \frac{F_{y572_50}}{\sigma_{b_TN40}} - 1 = 0.03$ where $F_{y572_50} = 50 \text{ ksi}$ is the material of the cradle and doubler plate.

The Hi-Star 190SL and 190XL have a two piece doubler plate (each 5 inches thick) forming the center section of the cradle. This section is 11-1/2 inches wide, 50.7 inches long and 10 inches thick. The thickness limit of ASTM A572 for Grade 50 material requires this bar to be fabricated from multiple pieces, two ASTM A572, Grade 42 plates with a yield strength of 42 ksi were chosen to achieve the total 10 inch thickness.

The TN40 doubler plate is only 2 inches longer than the 11.62 inch wide cutout. Assuming the same moment is present at the point where the doubler plate ends, the stress is:

$$\sigma_{b2_TN40} = \frac{M_{L_saddle}}{S_{2_saddle}} = 38.9 \text{ ksi where}$$

$$S_{2_saddle} = 2 \frac{1 \text{ in} (21.08 \text{ in})^2}{6} = 148.1 \text{ in}^3. \text{ This is the shortest unreinforced section of the saddle plates and because the maximum moment was used, bounds all other sections.}$$

The resulting margin of safety is: $MS = \frac{F_{y572_50}}{\sigma_{b2_TN40}} - 1 = 0.285$ where $F_{y572_50} = 50 \text{ ksi}$ is from

Table 2.3.



Table 5.3 – Summary of Saddle Stress

Cask	R _{cask} (in)	Saddle Angle (deg)	Width (in)	Moment (in-kip)		Distance (in)		S _{cradle} (in ³)	Stress (ksi)	
				Vert	Hor	To cask Bottom	To Saddle Top		Vert	Hor
HI-STAR 100	48	20	92.56	4,016	2,839	9.625	31.2	93.5	30.4	43.0
HI-STAR 100HB	48	20	92.56	4,029	2,637	7.375	31.2	87.5	30.1	46.0
HI-STAR 180	53.15	14.72	105.23	5,339	4,919	5.675	39.3	111	44.3	48.1
HI-STAR 190XL	53.15	14.72	105.23	7,279	6,827	6.25	39.3	191.7	35.6	38.0
HI-STAR 190SL	53.15	14.72	105.23	6,621	6,210	6.25	39.3	191.7	32.4	34.5
HI-STAR 60	37.875	20	73.53	4,570	2,098	9.25	24.5	106.7	19.7	42.8
TN-32B	48.875	15	96.83	5,286	5,662	19.125	35.9	118.6	47.7	44.6
TN-40	50.5	14.67	100.13	5,158	5,749	17.42	37.4	118.6	48.5	43.5
TN40HT	50.5	14.67	100.13	4,604	5,132	17.42	37.4	118.6	43.3	38.8

Note: The allowable stress for all cradle components except the Hi-Star 190SL & 190XL is 50 ksi. The allowable stress for the Hi-Star 190SL & 190XL is 42 ksi.

Sample Calculation - Weld attaching the Saddle to the Longitudinal Beams

The attachment weld is a 3/4 inch fillet weld on each outer side of the saddle plates (See Drawing 3015137, Sheet 2, Zone B3, Section B-B [7.2]). The two legs are horizontal across the beam flange and vertical along the 1 inch thick beam closure plate. Referring to Figure 3 and summing the moment about the weld on the right hand (R_{v1}, R_{v4}) beam.

$$+\circlearrowleft \sum M_{Rv1} = 0 = -a_1 W_{c_hshb} [d_{c_vcg_hshb} - 19in + (14.5in - 10.43in)] + 2F_{Rv23}(93.5in + 2 \times 2.5in)$$

Solving for F_{Rv23} (the load reacted by the weld):

$$R_{v23} = \frac{a_1 W_{c_hshb} [d_{c_vcg_hshb} - 19in + (14.5in - 10.43in)]}{2(93.5in + 2 \times 2.5in)} = 97 \text{ kip}$$

where a₁=2 is for the 2g lateral load, the 2 in the denominator is for the number of saddles sharing the load, d_{c_vcg_hshb} = 66.0 inches is the height of the Hi-Star 100HB cask above the bottom of the cradle from Table 4.1, 93.5 inches is the distance between the Item 1 beams

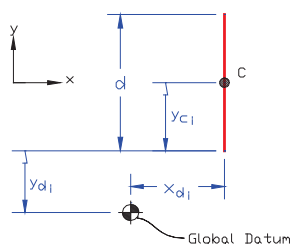
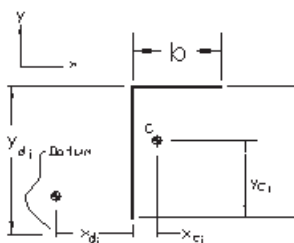


and 19 inches is the height of the Item 1 beams from Figure 3 and 2.5 inches (rounded from 2.47 inches) and 10.43 inches is the location of the weld centroid (calculated below). The calculated values for all of the casks are shown in Table 5.4 following this sample calculation.

Calculate fillet weld properties

Each of the two welds are comprised of two legs, the vertical and the horizontal. The horizontal leg is the width of the W18 X 119 flange. On all cradles except the Hi-Star 60 and the Hi-Star 100HB, the vertical leg of the weld is the height of the W18 X 119 beam (19 inches). On the two exceptions, the saddle plates are shorter to provide clearance to the shear key on the Railcar. These two welds have a vertical leg 14.5 inches long as shown in Figure 3. The distance between the welds is the same for all cradles. The Hi-Star 100HB cask is heavier than the Hi-Star 60

The complete weld is shown below:



Weld Geometry

Weld Throat:

$$h = \frac{.75 \text{ in}}{\sqrt{2}} = 0.53 \text{ in}$$

Dimensions:

$d = 14.5 \text{ in}$ where d is the length of the vertical leg of the weld as shown in Figure 3.

Weld Properties

(Weld Number $i := i + 1, i = 1$)

Weld Area:

$$A_i = d \cdot h = 7.7 \text{ in}^2$$

Weld Centroid:

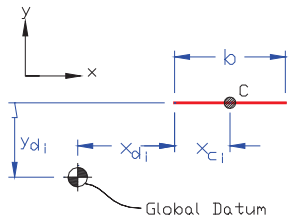
$$x_{d_i} = 0 \text{ in}$$

Weld Offset

$$X_{d_i} = 0 \text{ in}$$

$$Y_{d_i} = 0 \text{ in}$$

$$y_{c_i} = \frac{d}{2} = 7.25 \text{ in}$$



Weld Geometry

Weld Throat: $h = 0.53$ in

Dimensions: $b = b_f = 11.3$ in where b_f is the flange width of the W18 X 119 beam

Weld Properties

(Weld Number $i := i + 1, i = 2$)

Weld Area: $A_i = b \cdot h = 6$ in²

Weld Centroid: $x_{d_i} = \frac{b}{2} = 5.65$ in

$y_{c_i} = 0$ in

Weld Offset

$X_{d_i} = 0$ in

$Y_{d_i} = d$

Composite Section Properties:

(Welds $j := 1 \dots i, i = 2$)

Area: $A_c = \sum_j A_j = 13.7$ in²

Centroid:

$$x_c = \frac{\sum_j (x_{d_j} + X_{d_j}) A_j}{A_c} = 2.47$$

$$y_c = \frac{\sum_j (y_{c_j} + Y_{d_j}) A_j}{A_c} = 10.43$$

The weld shear stress is: $\tau_{weld} = \frac{R_{v23}}{A_c} = 7.1$ ksi and the Resulting Margin of Safety

$$Is: MS = \frac{0.6 \times F_{y572-50}}{\tau_{weld}} - 1 = 3.23$$

→ Okay



Table 5.4 – Cradle Attachment Weld Stresses

Cask	Cask Weight Maximum (W_c) (lb)	Vertical Weld Leg Length (in)	Weld Centroid		Vertical Load (R_{v23}) (kip)	Weld Area (in ²)	Weld Stress (ksi)	Margin of Safety
			Hor (x) (in)	Ver (y) (in)				
HI-STAR 100 (_hs100)	279,893	19.0	2.11	13.04	152	16.1	9.4	2.19
HI-STAR 100HB (_hshb)	187,200	14.5	2.47	10.43	97	13.7	7.1	3.23
HI-STAR 180 (_hs180)	308,647	19.0	2.11	13.04	163	16.1	10.1	1.97
HI-STAR 190XL(_190XL)	420,769				222	16.1	13.8	1.17
HI-STAR 190SL(_190SL)	382,746				202	16.1	12.5	1.40
HI-STAR 60 (_hs60)	164,000	14.5	2.47	10.43	74	13.7	5.4	4.56
TN-32B (_TN32)	263,000	19.0	2.11	13.04	160	16.1	9.9	2.03
TN-40 (_TN40)	271,500				165	16.1	10.2	1.91
TN40HT (_TN40HT)	242,343				147	16.1	9.1	2.26

5.3 Evaluate the End Stops

The end stops are constructed of largely the same materials and the construction is similar. The end stops are constructed largely from ASTM A572, Grade 50 plate, 2 inches thick except at the attachment locations where a 1/4 inch thick doubler is attached on each side of the 2 inch plate and the stiffener plates are 1 inch thick. The pin attachment plates at the base of the Hi-Star 190XL are constructed from (2) 1-1/4 inch thick ASTM A572, Grade 65 plates in lieu of the 2 inch thick plate with (2) 1/4 inch thick doubler plate as is typical of the remaining end stops.

The plates are pinned to the rail car attachment lugs using Ø 4 inch pins in Ø 4.13 inch holes or slots (the slots are in the attachment lugs at the pin locations closest to the end of the rail car and allow axial motion while the round holes serve to react the axial load from the cask).

A pair of end stops is located at each end of the rail car. Each end stop is comprised of 2, 2 inch thick vertical plates and a face plate (adjacent to the cask's impact limiters) of 2 inch thick plate or 2, 1 inch thick plates (total thickness 2 inches). There are additional 1 inch thick plates placed between the vertical plates to act as stiffeners (as shown in Figure 7).

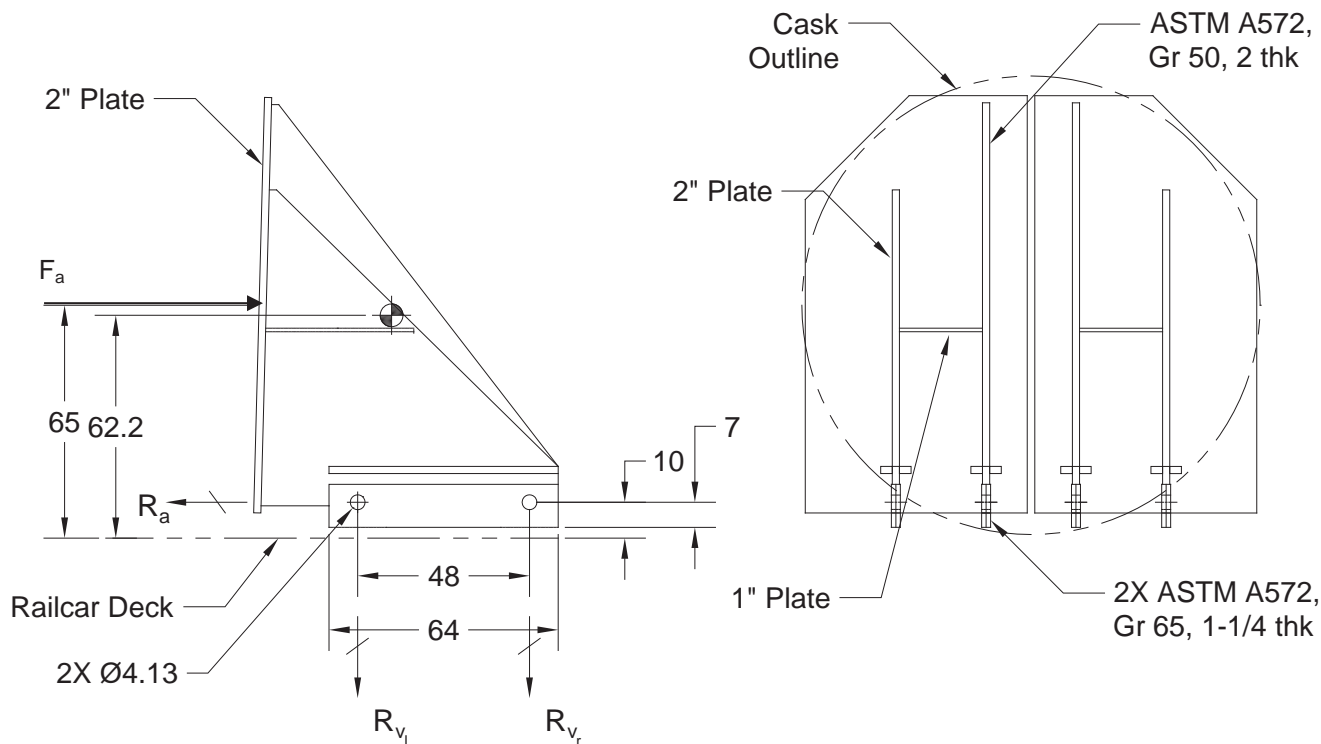


Figure 7- End Stop - Hi-Star 190XL

Evaluate Bending on the Vertical Plates

The maximum moment on any plate is at the pin attachment locations and all end stops are configured identically in this area, therefore, the cask/end stop with the largest applied moment bounds all others.

The combination of cask height, weight and central cradle weight for the Hi-Star 190XL produces the highest moment load (see Table 5.5 below). The combined moment is:

$$\begin{aligned}
 M_{ES} &= a_{ax} [(W_{C_{190XL}} + W_{cr_{190XL}})(d_{c_{vcg_{190XL}}} - 9.5in) + 2 \times W_{ES_{190XL}} \times (d_{ES_{190XL}} - 10in)] \\
 &= 7.5 \times [(420.769kip + 15.0kip)(64.5inch - 9.5inch) + 2 \times 11kip \times (62.2inch - 10inch)] \\
 &= 188 \times 10^3 in \cdot kip
 \end{aligned}$$

Where $a_{ax}=7.5$ g is the axial acceleration, $W_{C_{190XL}} = 420.769$ kip is the cask weight, $W_{cr_{190XL}} = 15.0$ kip is 110% of the central cradle weight both from Table 5.1, $d_{c_{vcg_{190XL}}} = 64.5 + .5 = 65$ inches, $W_{ES_{190XL}} = 11$ kip from Table 6.1, $d_{ES_{190XL}} = 62.2$ inches is the end stop vertical centroid location and 10 inches are from Figure 7 and 0.5 inches is the offset from the rail car deck provided by the shim plate located between the lugs.



The vertical reaction at the pin location is found by dividing the moment above by the distance between the holes. $R_{vL} = M_{ES} \frac{1}{4 \times 48 \text{in}} = 979.2 \text{ kip}$ where the 4 accounts for the number of lugs sharing the load and 48 inches is the distance between the holes from Figure 7.

The axial load on the end stop pins (R_a) is simply the axial load equally distributed over the number of pins sharing the load. As discussed in § 1.0, only the 4 end stop pin locations nearest the cask react the axial load (the holes in the lugs furthest away from the pins are slotted and only react vertical loading).

$$R_a = a_{ax} [W_{c_{190XL}} + W_{cr_{190XL}} + 2 \times W_{ES_{190XL}}] / 4$$

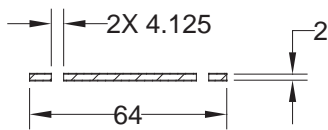
$$= 7.5 \times [420.769 \text{kip} + 15.0 \text{kip} + 2 \times 11 \text{kip}] / 4 = 858.3 \text{kip}$$

where $W_{ES_{190XL}} = 11 \text{ kip}$ is from

Table 6.1.

The moment is reacted by four vertical end stop plates, conservatively neglecting the doublers. The length of the plates through the pins is 64 inches and the corresponding section modulus, through the holes, (for one plate) is:

$$S_{ES} = \frac{2 \text{ in} (64 \text{ in})^3}{12} - 2 \left[\frac{2 \text{ in} (4.125 \text{ in})^3}{12} + 2 \text{ in} (4.125 \text{ in}) \left(\frac{64 \text{ in}}{2} - 8 \text{ in} \right)^2 \right] = 1068 \text{ in}^3$$



The end stops are divided into two halves on each end and are symmetric. There are two vertical plates on each end stop half (refer to Figure 7). The moment reacted by each plate is therefore, one quarter the total calculated above and the maximum bending stress is:

$$\sigma_{b_ES} = \frac{M_{ES}}{4 S_{ES}} = 43.8 \text{ ksi}$$

and the corresponding margin of safety is:

$$MS = \frac{F_{y572_50}}{\sigma_{b_ES}} - 1 = 0.142 \quad \rightarrow \quad \text{Okay}$$

The end stops for all designs with the exception of the Hi-Star 190SL and 190XL are comprised of a 2 inch thick plate with 1/4 inch thick doublers on each side. The material is ASTM A572, Grade 50. The Hi-Star 190XL end stop is constructed using 2, 1-1/4 inch thick ASTM A572, Grade 65 plates (for the same overall 2-1/2 inch thickness). Conservatively, a thickness of 2 inches and ASTM A572, Grade 50 was used in the calculations to qualify all end stops.

Stiffeners were added between the vertical plates on this design concept. If buckling or crippling is identified as a concern in the detailed design, additional stiffeners may be added.



Table 5.5 – Moments on End Stops

Cask	Cask Weight Maximum (W _c) (lb)	Cask Vert cg from bottom of cradle (d _{c_vcg}) (in)	Central Cradle weight (W _{cr}) (kip)	Moment at Base of End Stop (M _{ES}) (10 ³ in-kip)
HI-STAR 100 (_hs100)	279,893	66.0	22.6	136
HI-STAR 100HB (_hshb)	187,200	66.0	16.5	100
HI-STAR 180 (_hs180)	308,647	64.5	10.1	142
HI-STAR 190XL(_190XL)	420,769	64.5	15.0	188
HI-STAR 190SL(_190SL)	382,746	64.5	14.7	173
HI-STAR 60 (_hs60)	164,000	59.63	17.7	76
TN-32B (_TN32)	263,000	72.5	14.6	142
TN-40 (_TN40)	271,500	72.5	14.2	145
TN40HT (_TN40HT)	242,343	72.5	14.2	132

Note: The cradle weights shown the above table include an additional 10% factor.

Evaluate Shear Tear-out

The same moment is reacted by the plate in shear at the attachment pin locations, however, the attachment loads for the attachment locations closest to the cask include both the vertical and axial loads acting at a single pin location. The highest combined load occurs for the Hi-Star 190XL cask. Evaluation of this load bounds all other designs. The loads conservatively include the self weight of the end stops. The shear force, at one of the pin locations is:

$f_s = \sqrt{R_a^2 + R_{v1}^2} = \sqrt{(858.3 \text{ kip})^2 + (979.2 \text{ kip})^2} = 1302 \text{ kip}$ where 858.3 kip and 979.2 kip are the maximum attachment lug loads from Table 2.2 for Pin Block 9 on the Hi-Star 190XL cask.

Note: The lug located further from the cask (e.g. P8) has a slotted hole and reacts only a vertical load. The distance to the edge of a plate, parallel to the applied load, is:

$$d_{\min} = \frac{7 \text{ in}}{\cos\left(a \tan\left(\frac{858.3}{979.2}\right)\right)} - \frac{4.125 \text{ in}}{2} = 7.2 \text{ in}$$

where 7 inches is the distance from the center of

the hole to the bottom edge of the plate. The shear area is:

$$A_{s_ES} = 2 \times 2.5 \text{ in} \times d_{\min} = 36.0 \text{ in}^2$$

where 2.5 inches is the thickness of the plates at the

lower end stop attachment and the resulting shear stress is: $\tau_{ES} = \frac{f_s}{A_{s_ES}} = 36.2 \text{ ksi}$



and the Resulting Margin of Safety is: $MS = \frac{0.6 \times F_{y572_65}}{\tau_{ES}} - 1 = 0.08 \rightarrow \text{Okay}$

where $F_{y572_65} = 65$ ksi is from Table 2.3 and the 0.6 multiplier is defined in § 2.3. Using the same method, the shear stress for the Hi-Star 190SL end stop is 33.1 ksi and for the Hi-Star 180 (the next highest end stop pin load) is 27.8 ksi. The Hi-Star 180 meets the allowable shear stress of 30 ksi for ASTM A572, Grade 50.

5.4 Evaluate Strap Attachment Fasteners

The straps are attached using 2, 1 1/2-6 UNC ASTM A490 bolts threaded into nuts welded to the underside of the saddle plate for all cradles except the Hi-Star 190 cradles which use (2) 1 3/4-5 ASTM A574 Hex Head Cap Screws and compatible nuts.

Determine the required strength for the attachment bolts

The bolts react the load from the vertical load case or 2 g up. All cradle designs include 2 or more saddles and straps, therefore, sharing the load between two tie down straps bounds all load cases.

The maximum cask weight, from Table 5.1 $W_{c_190XL} = 420.769$ kip. The load on a single bolt is:

$f_{bolt} = 2 \frac{W_{c_190XL}}{2 \times 2} = 210$ kip where the multiplier of 2 is for the 2g up load case and the two's in the denominator are for the number of saddle straps and number of bolts on each strap.

The bolts have a tensile area of: $A_{bolt} = 1.9$ in² from ASTM A574 [7.22]. The stress on each

bolt is: $\sigma_{bolt} = \frac{f_{bolt}}{A_{bolt}} = 111$ ksi. The yield strength of the bolt will be used as the allowable

strength. The margin of safety is: $MS = \frac{F_{ybolt}}{\sigma_{bolt}} - 1 = 0.216 \rightarrow \text{Okay}$

where $F_{y_bolt} = 135$ ksi is from ASTM A574 for a 1 3/4-5 UNC bolt. The cradles for other than the Hi-Star 190 casks use 1-1/2-6 UNC ASTM A490 bolts [7.20] with a yield strength of 130 ksi and a maximum bolt stress of 110 ksi for the Hi-Star 180 cask.

5.5 Example Calculation of Attachment Lug Loads – Central Cradle

The Railcar attachment lug loads are shown in Table 2.2. An example calculation for the lug loads is shown below. The examples are for the Hi-Star 100 Cask and do not necessarily constitute the bounding lug load.

The lug loads result from the applied tiedown accelerations shown in Table 2.1. Lugs P1 - P4 are used to attach the central cradle. These lugs are slotted and will not react the axial loads

resulting from the ± 7.5 g axial acceleration. These lugs react only the vertical and lateral loads.



The load on lug P1 due to the vertical acceleration is determined by summing moments about the P3-P4 end of the central cradle:

$$+\cup \quad \sum M_{P34} = 0 = a_u \left[\begin{array}{l} -W_{c_hs100} (125 \text{ in} - d_{c_hcg_hs100}) \\ -W_{cr_hs100} (125 \text{ in} - d_{cr_hcg_hs100}) \end{array} \right] + (F_{P1v} + F_{P2v}) 125 \text{ in}$$

The reactions at P1 and P2 are the same (the cradle is laterally symmetric). Rearranging and solving for F_{P1v} :

$$+\uparrow \quad F_{P1v} = a_u \frac{W_{c_hs100} (125 \text{ in} - d_{c_hcg_hs100}) + W_{cr_hs100} (125 \text{ in} - d_{cr_hcg_hs100})}{2 \times 125 \text{ in}}$$

$$F_{P1v} = 149.6 \text{ kip}$$

where: $a_u = 2 \text{ g}$ is the upward vertical acceleration (Table 2.1), $W_{c_hs100} = 279893 \text{ lbf}$ is the weight of the Cask (Table 4.1), $W_{cr_hs100} = 20.5 \text{ kip}$ is the weight of the central cradle (Table 5.1), $d_{c_hcg_hs100} = 62.9 \text{ inch}$ and $d_{cr_hcg_hs100} = 66.8 \text{ inch}$ are the distances of the centroids from lug P1 for the cask and central cradle respectively (Table 5.1) and 125 inches is the longitudinal distance between the pins of the central cradle (Figure 2).

The vertical reactions at lugs P1/P2 and P3/P4 are inversely proportional to the distance from the combined centroid of the cask and central cradle. The combined centroid is:

$$d_{hcg_hs100} = \frac{W_{c_hs100} d_{c_hcg_hs100} + W_{cr_hs100} d_{cr_hcg_hs100}}{W_{c_hs100} + W_{cr_hs100}} = 63.1 \text{ in.}$$

The load on the lugs at the opposite end of the central cradle are found by summing moments about the

$$\text{combined centroid: } \sum M_{\text{comb}} = 0 = 2 F_{P1v} d_{c_hcg_hs100} - 2 F_{P3v} (125 \text{ in} - d_{c_hcg_hs100})$$

where $F_{P3v} = F_{P4v}$ due to lateral symmetry. Solving for F_{P3v} ,

$$F_{P3v} = F_{P1v} \frac{d_{c_hcg_hs100}}{125 \text{ in} - d_{c_hcg_hs100}} = 151.7 \text{ kip}$$

There is a vertical load on lugs P1 - P4 in reaction to the lateral acceleration. The vertical load on lug P1 is found by summing moments about the line formed by lugs P2-P3:

$$\sum M_{P23} = 0 = -a_l \left[\begin{array}{l} -W_{c_hs100} (d_{c_vcg_hs100} - 10 \text{ in}) \\ -W_{cr_hs100} (d_{cr_vcg_hs100} - 10 \text{ in}) \end{array} \right] + (F_{P1vl} + F_{P4vl}) 104.75 \text{ in}$$

The vertical loads on the ends are again inversely proportional to the distance from the combined centroid. Substituting and solving for F_{P1vl} finds:

$$F_{P1vl} = -a_l \frac{W_{c_hs100} (d_{c_vcg_hs100} - 10 \text{ in}) + W_{cr_hs100} (d_{cr_vcg_hs100} - 10 \text{ in})}{104.75 \text{ in} \left(1 + \frac{d_{hcg_hs100}}{125 \text{ in} - d_{hcg_hs100}} \right)} \quad \text{where:}$$

$a_l = 2 \text{ g}$, $W_{c_hs100} = 279.893 \text{ kip}$, $W_{cr_hs100} = 22.6 \text{ kip}$, $d_{c_vcg_hs100} = 66.5 \text{ inch}$ and

$d_{cr_vcg_hs100} = 25.7 \text{ inch}$ are the vertical centroid heights above the deck for the cask and cradle



respectively from Table 4.1 including the 0.5 inch offset from the deck to the bottom of the cradle, $d_{hcg_hs100} = 63.1$ inch is the combined cradle / cask CG calculated above and 10 inches is the offset from the railcar deck to the hole in the lug as shown in Figure 2 and .5 inches is the offset from the deck to the bottom of the cradle.

$F_{P1vl} = -152.6$ kip, $F_{P4vl} = F_{P1vl} \frac{d_{hcg_hs100}}{125 \text{ in} - d_{hcg_hs100}} = -154.9$ kip F_{P4vl} has the greater magnitude and is reported in Table 2.2.

The lateral load on the central cradle attachment lugs is simply a sum of the forces calculation with the proportional load sharing as above. As discussed in § 5.1, the only one of the central cradle beams reacts the lateral load.

$$\sum F_{lat} = 0 = -a_1(W_{c_hs100} + W_{cr_hs100}) - F_{P1l} - F_{P4l} \text{ and } F_{P4l} = F_{P1l} \frac{d_{hcg_hs100}}{125 \text{ in} - d_{hcg_hs100}}$$

Solving for F_{P1l} yields: $F_{P1l} = a_1 \frac{W_{c_hs100} + W_{cr_hs100}}{1 + \frac{d_{hcg_hs100}}{125 \text{ in} - d_{hcg_hs100}}} = 297.5$ kip and

$$F_{P4l} = F_{P1l} \frac{d_{hcg_hs100}}{125 \text{ in} - d_{hcg_hs100}} = 303.3 \text{ kip}$$

6.0 RESULTS AND CONCLUSIONS

Table 6.1 – Summary of Cradle and End Stop Weights and C.G.'s

Cask	Central Cradle weight (kip)	Central Cradle cg from Bottom of Cradle (in)	End Stop weight (Each) (kip)	End Stop CG from Deck (in)	Total Cradle CG from Bottom of Cradle (in)
HI-STAR 100	22.6	25.2	12.8	52.7	44.5
HI-STAR 100HB	16.5	27.1	16.0	65.5	57.2
HI-STAR 180	10.1	27.3	13.5	60.0	54.4
HI-STAR 190XL	15.0	21.8	11.0	62.2	51.6
HI-STAR 190SL	14.7	21.8	11.7	61.9	52.0
HI-STAR 60	17.7	26.6	13.2	47.1	41.6
TN-32B	14.6	35.1	16.7	52.3	48.8
TN-40	14.2	32.0	17.1	50.7	47.0
TN40HT	14.2	32.0	17.1	50.7	47.0

Notes: 1. There are four (4) end stops for each configuration, two (2) on each end. As discussed in § 5.3, two (2) end stops are located at each end. Total end stop weight is four (4) times the value shown in Table 6.1.

2. The values shown for the weights of the central cradle and end stops include an additional 10% factor.

All stresses are below the maximum allowable stress as shown above. The cradles are acceptable for their intended use.



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6.1 Results of applicable literature searches

A literature search was not required for this calculation.



7.0 REFERENCES

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