Appendix L – Atlas Railcar Cask and Cradle Dynamic Modeling Inputs (CALC-3015934)

AREVA

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CALCULATION

Document No.:	CALC-3015934	Rev. No.	001	Page 1 of 53
Project No.:	00225.03.0050	Project Name:	DOE Atlas Railcar	
Title:	Atlas Railcar Cask and Cradle Dynamic Modeling Inputs			

Summary:

The Department of Energy (DOE) has contracted AREVA Federal Services (AFS) to design the Atlas railcar. This contract includes designing conceptual transport package cradles for 17 spent nuclear fuel transportation casks. AFS has partnered with Transportation Technology Center, Inc. (TTCI) to perform dynamic modeling of the 17 railcar cask and cradle designs. This calculation generates the Atlas Railcar cask and cradle inputs required for the dynamic modeling to be performed by the TTCI. Additional requested dynamic modeling inputs are generated in Appendix B.

This document is not safety related.

Safety ☐ Non-Safety ☒

Contains Unverified Input / Assumptions: Yes: ☐ No: ☒

Software Utilized: SolidWorks **Software Active in AFS EASI: Yes: ☒ NA*: ☐** *Not Applicable per Section 5.7 of AFS-EN-PRC-002	**Version:** **- 2014 x64 Edition, SP 5.0**	**Storage Media: Yes: ☒ No: ☐**
Error Reports & Associated Corrective Actions Reviewed: Yes: ☒ No: ☐		**Location:** COLDStor
Software Utilized: Microsoft Excel **Software Active in AFS EASI: Yes: ☐ NA*: ☒** *Not Applicable per Section 5.7 of AFS-EN-PRC-002	**Version:** **- 2010**	**Storage Media: Yes: ☒ No: ☐**
Error Reports & Associated Corrective Actions Reviewed: Yes: ☐ No: ☒		**Location:** COLDStor

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AFS-EN-FRM-002 Rev. 05 (Effective January 31, 2018)
Reference: AFS-EN-PRC-002

Orano Federal Services
MAR 05 2018
Records Management

Revision History

Rev.	Changes
000	Initial release
001	Revised project background for editorial changes.

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1.0 PURPOSE

1.1 Project Background

The United States Department of Energy (DOE) is laying the groundwork for implementing an integrated nuclear waste management system. This includes preparing for future large-scale transport of spent nuclear fuel (SNF) and high-level waste (HLW); since transport will be a necessary component of any integrated nuclear waste management system. With this project the DOE will provide for the transportation of SNF and HLW by means of a specific railcar (named by the DOE as the Atlas railcar) to carry SNF and HLW casks.

As part of this project, the DOE has contracted AREVA Federal Services (AFS) to design the Atlas railcar, including a single set of standardized attachment components (railcar tie-down interface) and transport package conceptual cradle designs for the 17 SNF transportation casks (herein referred to as "packages") listed in Attachment A of the Statement of Work (SOW) [1]. The DOE Atlas railcar (and by extension to subsystems, the package cradles) must be designed and built to satisfy the requirements of Association of American Railroads (AAR) Standard S-2043 [2] and the AFS Design Basis Requirements Document (DBRD) [3]. The standardized attachment components are part of the railcar and must also meet the AAR S-2043 requirements.

AFS has chosen to divide the 17 packages into 4 families based on the package tie-down methods. The packages contained in each of these four families are listed below:

- Family 1 TN-32B, TN-40, TN-40HT, HI-STAR 60, HI-STAR 100, HI-STAR 100HB (also referred to as HI-STAR HB), HI-STAR 180, HI-STAR 190SL, and HI-STAR 190XL.
- Family 2 MAGNATRAN®, NAC-STC™, NAC-UMS UTC™, and the TN-68.
- Family 3 MP-197, MP-197HB, and the TS125.
- Family 4 MP-187.

As part of the work to be completed to design the Atlas railcar to the AAR S-2043 requirements, dynamic modeling will be performed by Transportation Technology Center, Inc. (TTCI).

1.2 Calculation Purpose

This calculation generates the Atlas Railcar cask and cradle inputs required for the dynamic modeling to be performed by TTCI. Additional dynamic modeling inputs for railcar permanent attachment hardware and railcar ballast are generated in Appendix B.

1.3 Atlas Railcar Cradles

The Atlas Railcar has been designed to transport the 17 packages listed in Section 1.1. Each package is secured to the railcar using a cradle and the standardized attachment components discussed in Section 1.4. An example of a cradle for Family 1 is shown in Figure 1-1.

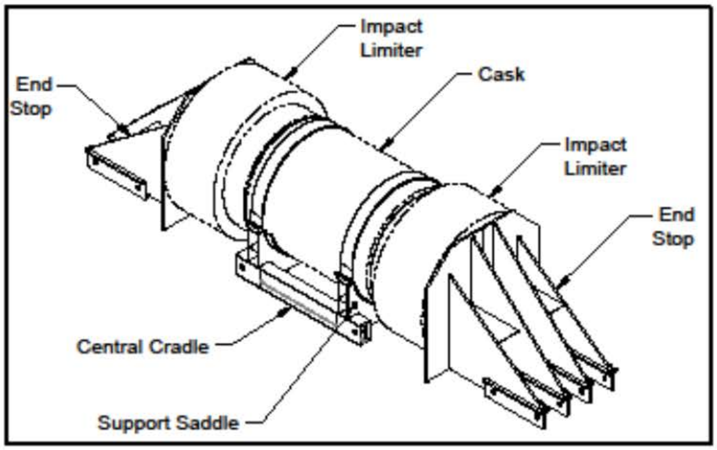

Figure 1-1: Atlas Railcar Family 1 Cradle

1.4 Atlas Railcar Standardized Attachment Components

The Atlas Railcar standardized attachment components are depicted in AFS Drawing DWG-3015278 [4] and are shown in Figure 1-2 below. There are four center pin attachment blocks welded to the railcar that are used for all cradle designs. The cradles are secured laterally and vertically using four attachment pins inserted through the center pin attachment blocks. Longitudinal support for cradle Families 2 through 4 is provided by shear blocks welded to the railcar. Family 1 cradles use end stop assemblies to support the cask longitudinally. The end stop assemblies are attached to the railcar using pins through the eight end stop attachment blocks.

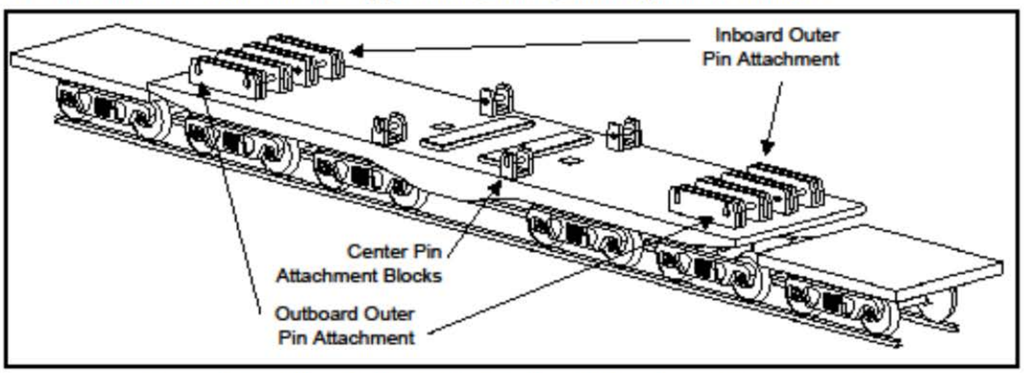

Figure 1-2: Atlas Railcar Standardized Attachment Components

2.0 METHODOLOGY

The inputs required for TTCI dynamic modeling include the cradle, cask, and end stop weights, centers of gravity, and mass moments of inertia. Previously hand-calculated values for cradle and end stop weights and centers of gravity are used with SolidWorks models to determine cradle and end stop mass moments of inertia. Additional hand calculations are performed to integrate cask weights, centers of gravity, and mass moments of inertia with their associated cradles to determine combined system properties for use by TTCI.

2.1 Acceptance Criteria

This calculation is used as an input for further analysis and does not have acceptance criteria.

3.0 ASSUMPTIONS

3.1 Unverified Inputs/Assumptions

None.

3.2 Justified Assumptions

1. Personnel barriers are not included within SolidWorks models since they are less than 2% of the total cask and cradle weight. If a personnel barrier is less than 2% of total cask and cradle weight, it can be considered to have a negligible effect on mass moments of inertia [17].
2. Casks are treated as right cylinders for calculation of mass moments of inertia. The cask center of gravity is not assumed to be at the symmetric center and thus must be accounted for in each calculation. Impact limiter geometry is ignored but impact limiter weight is included in each calculation.

4.0 DESIGN INPUTS

4.1 Transportation Package Design Inputs

Weight and center of gravity (cg) inputs are taken from the following calculations and are listed in the tables below.

1. Atlas Railcar Family 1 Conceptual Cradle Structural Calculation [5]
2. Atlas Railcar Family 2 Conceptual Cradle Structural Calculation [6]
3. Atlas Railcar Family 3 Conceptual Cradle Structural Calculation [7]
4. Atlas Railcar Family 4 Conceptual Cradle Structural Calculation [8]

Table 4-1: Cradle Design Inputs – Families 2-4

Cask	Family	Nominal Cradle Weight (lb)	Cradle Vertical cg from Cradle Bottom (in)(7)	Cradle Longitudinal cg from Center Pin Location (in)	Cradle Lateral cg from Railcar Center (in)(8)
NAC-STC	2	42,000(1)	27(1)	70(1)	0
NAC-UMS UTC	2	42,000(1)	27(1)	70(1)	0
MAGNATRAN	2	42,000(1)	27(1)	70(1)	0
MP187	4	32,500(2)	28.5 (2)	125/2 = 62.5(5)	0
MP197	3	26,000(3)	17 (3)	125/2 = 62.5(6)	0
MP197HB	3	26,000(3)	17.5 (3)	125/2 = 62.5(6)	0
TN-68	2	27,000(4)	26 (4)	54(4)	0
TS125	3	30,000(3)	24.5 (3)	125/2 = 62.5(6)	0

Notes:

1. Values are taken from Section B-1 of [6].
2. Values are taken from Table 4-1 of [8].
3. Values are taken from Table 5.3-1 of [7]
4. Values are taken from Table B-3 of [6].
5. The MP187 cradle is symmetric and is centered on the attachment pins locations.
6. Per Section 5.2 of [7], the family 3 cradles are symmetrically designed and the longitudinal cradle cg is at the cradle geometric center. The cradle is centered on the attachment pin locations.
7. Cradle bottom is 0.5" above railcar deck due to standardized attachment components shim plate.
8. Determined by inspection.

Casks in family 1 require an axial support (end stops) to support the cask. The total cradle system includes a central cradle and two sets of axial end stops. Weights for the cradles and corresponding end stops are listed separately.

Table 4-2: Cradle Design Inputs – Family 1 Central Cradles

Cask	Nominal Central Cradle Weight (lb)(1)	Central Cradle Vertical cg from Cradle Bottom (in)(1)(3)	Central Cradle Longitudinal cg from Center Pin Location (in)(1)	Central Cradle Lateral cg from Railcar Center (in)(2)
HI-STAR 100	20,545	25.2	66.8	0
HI-STAR 100HB	15,000	27.1	60.2	0
HI-STAR 180	9,182	27.3	62.6	0
HI-STAR 60	15,364	27.3	65.1	0
TN-32B	13,272	35.1	56.9	0
TN-40	12,909	32.0	56.7	0
TN-40HT	12,909	32.0	56.7	0
HI-STAR 190SL	13,364	21.8	62.6	0
HI-STAR 190XL	13,636	21.8	62.6	0

Notes:

1. Values are taken from Tables 5.1 and 6.1 of [5]. Masses are nominalized from reported maximums by dividing by 1.1.
2. Determined by inspection.
3. Cradle bottom is 0.5" above railcar deck due to standardized attachment components shim plate.

Table 4-3: Cradle Design Inputs – Family 1 End Stops

Cask	Nominal End Stop Weight per End (lb)(1)(2)	End Stop Vertical cg from Railcar Deck (in)(1)	End Stop Longitudinal cg from Outboard Outer Pin Location (in)	End Stop Lateral cg from Railcar Center (in)(12)
HI-STAR 100	23,273	52.7	61.2(3)	0
HI-STAR 100HB	29,091	65.5	69.0(4)	0
HI-STAR 180	24,545	60.0	83.1(5)	0
HI-STAR 60	34,182	67.9	53.1(6)	0
TN-32B	30,364	52.3	90.7(7)	0
TN-40	31,091	50.7	86.9(8)	0
TN-40HT	31,091	50.7	86.9(9)	0
HI-STAR 190SL	21,273	61.9	61.5(10)	0
HI-STAR 190XL	20,000	62.2	57.5(11)	0

Notes:

1. Values are taken from Table 6.1 of [5]. Masses are nominalized from reported maximums by dividing by 1.1.
2. The ends stop weight listed in Table 6.1 of [5] is for one of four end stops, two are used on each end of the railcar. The weight listed here is for one end (2 times the values listed in Table 6.1).
3. Value taken from "CALC 3015133_Hi-Star 100_Railcar Loads.2.17.17.xlsx" [5].
4. Value taken from "CALC 3015133_Hi-Star 100HB_Railcar Loads.2.9.17.xlsx" [5].
5. Value taken from "CALC 3015133_Hi-Star 180_Railcar Loads.2.9.17.xlsx" [5].
6. Value taken from "CALC 3015133_Hi-Star 60_Railcar Loads.2.9.17.xlsx" [5].
7. Value taken from "CALC 3015133_TN-32B_Railcar Loads.2.9.17.xlsx" [5].
8. Value taken from "CALC 3015133_TN-40_Railcar Loads.2.9.17.xlsx" [5].
9. Value taken from "CALC 3015133_TN-40HT_Railcar Loads.2.9.17.xlsx" [5].
10. Value taken from "CALC 3015133_Hi-Star 190SL_Railcar Loads.2.2.17.xlsx" [5].
11. Value taken from "CALC 3015133_Hi-Star 190XL_Railcar Loads.2.1.17.xlsx" [5].
12. Determined by inspection for each set of end stops.

5.0 CALCULATIONS

5.1 TTCI Modeling Inputs

Inputs required for dynamic modeling to be performed by the TTCI are generated in the following sections. Values are taken from other calculations (with references provided in each table) or are calculated as noted.

5.1.1 Transportation Cask TTCI Dynamic Modeling Inputs

The mass moments of inertia for the transportation casks are not listed in the publically available SARs. The mass moments of inertia (MMI) are calculated using equations from [10] for a right circular cylinder using the cask mass, cask length, and cask radius.

$$Rotational\ MMI\ Longitudinal\ Axis = \frac{1}{2}(Cask\ mass)(Cask\ radius)^2$$

$$Rotational\ MMI\ Lateral\ Axis = Rotational\ MMI\ Vertical\ Axis$$
$$= \frac{1}{12}(Cask\ mass)(3(Cask\ radius)^2 + (Cask\ length)^2) + (Cask\ mass)(Longitudinal\ cg)^2$$

The diameter of the cylinder is taken to be the diameter of the cask. All mass moments of inertia are calculated at the cask center of gravity (thus the longitudinal center of gravity must be accounted for since it is different than the symmetric center of gravity). The cask weights and center of gravity locations are shown in Table 5-1. The mass moments of inertia for the casks using the loaded weights are shown in Table 5-2 and the mass moments of inertia using the empty cask weights are in Table 5-3.

Table 5-1: Cask Modeling Inputs – Weight and cg

Cask	Maximum (Loaded) Cask Weight (lb)(1)	Minimum (Empty) Cask Weight (lb)(2)	Cask Vertical cg from railcar deck (in)(3)	Cask Longitudinal cg from railcar center (in)	Cask Lateral cg from railcar center (in)
NAC-STC	254,589	188,767	68.00	2.25(8)	0
NAC-UMS UTC	255,022	178,798	68.00	1.65(8)	0
MAGNATRAN	312,000	208,000	68.00	6.90(8)	0
HI-STAR 100	279,893	179,710	66.50	0.40(9)	0
HI-STAR 100HB	187,200	-(4)	66.50	2.60(9)	0
HI-STAR 180	308,647	-(5)	65.00	18.10(9)	0
HI-STAR 60	164,000	142,530(6)	60.13	11.60(9)	0
HI-STAR 190SL	382,746	282,746	65.00	17.90(9)	0
HI-STAR 190XL	420,769(12)	304,369	65.00	17.70(9)	0
MP187	271,300	190,200	65.00	0(10)	0
MP197	265,100	176,710	62.50	1.15(11)	0
MP197HB	303,600	179,000	64.50	1.63(11)	0
TN-32B	263,000	-(7)	73.00	0.50(9)	0
TN-40	271,500	-(7)	73.00	0(9)	0
TN-40HT	242,343	-(7)	73.00	0(9)	0
TN-68	272,000	-(5)	78.00	6.10(8)	0
TS125	285,000	196,118	73.30	5.00(11)	0

Notes:

1. The loaded cask weight is taken from the DOE SOW Attachment A [1].
2. The empty cask weights are taken from the DOE SOW Attachment A [1] except where noted. Some empty weights are not available.
3. The cask vertical cg is taken from AFS Calculation CALC-315276-002 [9]. Revised values taken from [5] and [8] for families 1 and 4. Values from [5] and [8] are increased 0.5" due to standardized attachment components shim plate.
4. Per the DOE SOW Attachment A [1], the HI-STAR 100HB cask is already loaded and will not be shipped empty.
5. The DOE SOW Attachment A [1] lists an empty weight of less than the loaded weight. An empty weight is provided in the public information; however, this is not a bounding empty condition weight and will not be listed here.
6. The DOE SOW Attachment A [1] lists an empty weight of <164,000 pounds. An empty weight of 142,530 pounds is listed in Section 1.2.1.3 of the HI-STAR 60 SAR, Rev 2 (Docket 71-9336) [16].
7. Per the DOE SOW Attachment A [1], the TN-40 is authorized for a single use shipment and would not be shipped empty. Per [1] this is also assumed to be the case for the TN-32B and TN40HT.

8. Value calculated using values derived from "Minimum/Maximum Combined CG distance from rear cradle pins, X (in)" in Tables B-2 and B-4 of CALC-3015134 [6] and the distance between attachment pins of 125 inches per [4]. Cask cg is the bounding value farthest from railcar center.

9. Value calculated using "Cask CG from pin near cask bottom (P1) (in) (dc_hcg)" from CALC-3015133 Table 5.1 [5] and the distance between attachment pins of 125 inches per [4].

10. The MP187 cask cg is at the center of the attachment points [8].

11. Value calculated using "Cask Length (in)" and Cask Longitudinal CG (in)" from Table 4.1-1 of CALC-3015135 [7]. Where available, bounding values were used. Casks are geometrically centered on their respective cradles.

12. Loaded cask weight adjusted from DOE SOW Attachment A per AFS-RFI-00225-0015-00 [22]

Table 5-2: Cask Modeling Inputs – Loaded Mass Moment of Inertia

Cask	Maximum (Loaded) Cask Weight (lb)	Cask Length (in)(1)	Cask Radius (in)(2)	Rotational Mass Moment of Inertia ($lb*in^2$), Loaded Cask around cg		
				Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
NAC-STC	254,589	193.0	49.50	311903349	947506003	947506003
NAC-UMS UTC	255,022	209.3	46.45	275118052	1069221548	1069221548
MAGNATRAN	312,000	214.0	55.00	471900000	1441500320	1441500320
HI-STAR 100	279,893	203.3	48.00	322436736	1125282050	1125282050
HI-STAR 100HB	187,200	128.0	48.00	215654400	364683072	364683072
HI-STAR 180	308,647	174.4	53.15	435951927	1101392609	1101392609
HI-STAR 60	164,000	158.9	37.88	117661341	425971047	425971047
HI-STAR 190SL	382,746	214.5	53.25	542650102	1861480626	1861480626
HI-STAR-190XL	420,769	237.0	53.25	596558399	2399616416	2399616416
MP187	271,300	201.5	46.25	290163828	1063031116	1063031116
MP197	265,100	208.0	45.75	277435434	1094842179	1094842179
MP197HB	303,600	210.3	48.88	362688818	1301071121	1301071121
TN-32B	263,000	184.0	48.88	314186954	899169893	899169893
TN-40	271,500	183.8	49.76	336124819	932390115	932390115
TN-40HT	242,343	183.8	50.50	309017618	836753630	836753630
TN-68	272,000	197.3	49.00	326536000	1055741027	1055741027
TS125	285,000	210.4	47.10	316123425	1216555513	1216555513

Notes:

1. The cask length is taken as the "Length without Impact Limiters" from the DOE SOW Attachment A [1].

2. The cask radius is taken as half of the "Diameter without Impact Limiters" from the DOE SOW Attachment A [1].

Table 5-3: Cask Modeling Inputs – Empty Mass Moment of Inertia

Cask	Minimum (Empty) Cask Weight (lb)	Cask Length (in)[(1)]	Cask Radius (in)[(2)]	Rotational Mass Moment of Inertia (lb*in^2), Empty Cask around cg		
				Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
NAC-STC	188,767	193.0	49.50	231263171	702535717	702535717
NAC-UMS UTC	178,798	209.3	46.45	192887506	749639930	749639930
MAGNATRAN	208,000	214.0	55.00	314600000	961000213	961000213
HI-STAR 100	179,710	203.3	48.00	207025920	722506234	722506234
HI-STAR 100HB	-	128.0	48.00	-	-	-
HI-STAR 180	-	174.4	53.15	-	-	-
HI-STAR 60	142,530	158.9	37.88	102257749	370205203	370205203
HI-STAR 190SL	282,746	214.5	53.25	400871977	1375131813	1375131813
HI-STAR 190XL	304,369	237.0	53.25	431528661	1735795291	1735795291
MP187	190,200	201.5	46.25	203424844	745258084	745258084
MP197	176,710	208.0	45.75	184932537	729798421	729798421
MP197HB	179,000	210.3	48.88	213838269	767100562	767100562
TN-32B	-	184.0	48.88	-	-	-
TN-40	-	183.8	49.76	-	-	-
TN-40HT	-	183.8	50.50	-	-	-
TN-68	-	197.3	49.00	-	-	-
TS125	196,118	210.4	47.10	217535066	837152400	837152400

Notes:

1. The cask length is taken as the "Length without Impact Limiters" from the DOE SOW Attachment A [1].
2. The cask radius is taken as half of the "Diameter without Impact Limiters" from the DOE SOW Attachment A [1].

5.1.2 Cradle TTCI Dynamic Modeling Inputs

Weight and cg

The cradle TTCI dynamic modeling inputs are calculated in the following tables. Cradle nominal weights and cg locations are listed in Table 5-4 for Families 2-4. Values for this table are taken from Table 4-1. Cradle and end stop nominal weights and cg locations are listed in Table 5-5 and Table 5-6 for Family 1. Values for these tables are taken from Table 4-2 and Table 4-3.

Mass Moment of Inertia

The mass moments of inertia for the cradles are not currently provided in the cradle structural calculations. The mass moments of inertia for each cradle are calculated using SolidWorks. All mass moments of inertia calculations are done using models built in accordance with drawings [11], [12], [13], [14], and [15]. Hand-calculated cradle masses and center of gravities are used, overriding those calculated by SolidWorks. SolidWorks model materials are defined using densities taken from reference [19]. Each model is composed mostly of carbon steel (0.28 lb/in^3), with some components constructed of stainless steel (0.29 lb/in^3), bronze (0.32 lb/in^3), aluminum (0.10 lb/in^3), and rubber (assumed 0.04 lb/in^3). Although cradle masses are overridden within SolidWorks, materials (specifically, material densities) must be defined to establish relative weight distribution within each model.

Results from Solidworks are listed in Appendix A and shown in Table 5-7 through Table 5-9 below.

Table 5-4: Cradle Modeling Inputs – Weight and cg – Families 2-4

Cask	Nominal Cradle Weight (lb)(1)	Cradle Vertical cg from Railcar Deck (in)(2)	Cradle Longitudinal cg from Railcar Center (in)(3)	Cradle Lateral cg from Railcar Center (in)
NAC-STC	42,000	27.5	7.5	0
NAC-UMS UTC	42,000	27.5	7.5	0
MAGNATRAN	42,000	27.5	7.5	0
MP187	32,500	29.0	0	0
MP197	26,000	17.5	0	0
MP197HB	26,000	18.0	0	0
TN-68	27,000	26.5	8.5	0
TS125	30,000	25.0	0	0

Notes:

1. Nominal weight values rather than maximum or minimum weight values are used in each SolidWorks calculation.
2. The cg is taken from Table 4-1 and increased by 0.5 inches due to the standardized attachment components.
3. The cradle longitudinal cg is adjusted to the center of the railcar by taking the value from Table 4-1 and adjusting using the distance between the pins (125 inches per [4]), x = abs(125/2-d).

Table 5-5: Cradle Modeling Inputs – Weight and cg – Family 1 Central Cradle

Cask	Nominal Central Cradle Weight (lb)[(1)]	Central Cradle Vertical cg from Railcar Deck (in)[(2)]	Central Cradle Longitudinal cg from Railcar Center (in)[(3)]	Central Cradle Lateral cg from Railcar Center (in)
HI-STAR 100	20,545	25.7	4.3	0
HI-STAR 100HB	15,000	27.6	2.3	0
HI-STAR 180	9,182	27.8	0.1	0
HI-STAR 60	15,364	27.8	2.6	0
TN-32B	13,272	35.6	5.6	0
TN-40	12,909	32.5	5.8	0
TN-40HT	12,909	32.5	5.8	0
HI-STAR 190SL	13,364	22.3	0.1	0
HI-STAR 190XL	13,636	22.3	0.1	0

Notes:

1. Nominal weight values rather than maximum or minimum weight values are used in each SolidWorks calculation.
2. The cg is taken from Table 4-2 and increased by 0.5 inches due to the standardized attachment components.
3. The cg is adjusted to the center of the railcar by taking the value from Table 4-2 and adjusting using the distance between the pins (125 inches per [4]), x = abs(125/2-d).

Table 5-6: Cradle Modeling Inputs – Weight and cg – Family 1 End Stops

Cask	Nominal End Stop Weight per End (lb)[(1)]	End Stop Vertical cg from Railcar Deck (in)	End Stop Longitudinal cg from Railcar Center (in)[(2)]	End Stop Lateral cg from Railcar Center (in)
HI-STAR 100	23,273	52.7	197.8	0
HI-STAR 100HB	29,091	65.5	190.0	0
HI-STAR 180	24,545	60.0	175.9	0
HI-STAR 60	34,182	67.9	205.9	0
TN-32B	30,364	52.3	168.3	0
TN-40	31,091	50.7	172.1	0
TN40HT	31,091	50.7	172.1	0
HI-STAR 190SL	21,273	61.9	197.5	0
HI-STAR 190XL	20,000	62.2	201.5	0

Notes:

1. Nominal weight values rather than maximum or minimum weight values are used in each SolidWorks calculation.
2. The cg is adjusted to the center of the railcar by taking the value from Table 4-3 and adjusting using the distance between the outer pins (125+148.5+148.5+48+48 inches per [4]), x = abs((125+148.5+148.5+48+48)/2-d).

Table 5-7: Cradle Modeling Results – Families 2-4

Cask	Nominal Cradle Weight (lb)	Calculated Rotational Mass Moment of Inertia ($lb*in^2$)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
NAC-STC	42,000	107420031	177507865	245802070
NAC-UMS UTC	42,000	108344606	215505187	283962578
MAGNATRAN	42,000	107996979	214855254	284549589
MP187	32,500	76512209	102544674	129466464
MP197	26,000	53452254	53944950	83293680
MP197HB	26,000	57567432	90162852	119270004
TN-68	27,000	70617158	73796861	112935016
TS125	30,000	63572366	130481182	160163420

Table 5-8: Cradle Modeling Results – Family 1 Central Cradle

Cask	Nominal Central Cradle Weight (lb)	Calculated Rotational Mass Moment of Inertia, ($lb*in^2$)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
HI-STAR 100	20,545	43074602	50542232	67971425
HI-STAR 100HB	15,000	36189820	27793388	44375308
HI-STAR 180	9,182	25366782	28726632	37587666
HI-STAR 60	15,364	33624685	29949688	46509586
TN-32B	13,272	36398191	41030969	53446863
TN-40	12,909	33491643	36922579	48700012
TN-40HT	12,909	33491643	36922579	48700012
HI-STAR 190SL	13,364	31907634	40984186	51573243
HI-STAR 190XL	13,636	32560720	41818848	52626918

Table 5-9: Cradle Modeling Results – Family 1 End Stops

Cask	Nominal End Stop Weight per End(lb)	Calculated Rotational Mass Moment of Inertia, (lb*in^2)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
HI-STAR 100	23,273	31791742	41822972	40285039
HI-STAR 100HB	29,091	37918666	78764969	78321041
HI-STAR 180	24,545	42279179	51551205	52133252
HI-STAR 60	34,182	38475171	72009557	70568374
TN-32B	30,364	56558696	78818952	69306526
TN-40	31,091	57912871	80706101	70965920
TN-40HT	31,091	57912871	80706101	70965920
HI-STAR 190SL	21,273	38400939	34801023	35530098
HI-STAR 190XL	20,000	36701031	29459126	29937032

5.1.3 Combined Cask and Cradle System TTCI Dynamic Modeling Inputs

The mass moments of inertia dynamic modeling inputs are to be reported to TTCI for each combined cask and cradle system. System mass moments of inertia are found using hand calculation and evaluated around the combined system center of gravity. The combined system center of gravity is a function of the mass and center of gravity of each cask and cradle and is calculated using the follow equations [10]:

$$cg_x = \frac{m_{Cask} * cg_{x,Cask} + m_{Cradle} * cg_{x,Cradle}}{m_{Cask} + m_{Cradle}}$$

$$cg_y = \frac{m_{Cask} * cg_{y,Cask} + m_{Cradle} * cg_{y,Cradle}}{m_{Cask} + m_{Cradle}}$$

$$cg_z = \frac{m_{Cask} * cg_{z,Cask} + m_{Cradle} * cg_{z,Cradle}}{m_{Cask} + m_{Cradle}}$$

Mass moments of inertia for each combined system are calculated using the individual cask and cradle mass moments of inertia and application of the parallel axis theorem. The combined system mass moments of inertia are calculated using the following equations [10]:

$$\begin{aligned} \text{Rotational MMI Longitudinal } (x) \text{ Axis} &= \left[MMI_{x,Cask} + m_{Cask}\left(\left(cg_{y,System} - cg_{y,Cask}\right)^2 + \left(cg_{z,System} - cg_{z,Cask}\right)^2\right)\right] \\ &+ \left[MMI_{x,Cradle} + m_{Cradle}\left(\left(cg_{y,System} - cg_{y,Cradle}\right)^2 + \left(cg_{z,System} - cg_{z,Cradle}\right)^2\right)\right] \end{aligned}$$

$$\begin{aligned} \text{Rotational MMI Lateral } (y) \text{ Axis} &= \left[MMI_{y,Cask} + m_{Cask}\left(\left(cg_{x,System} - cg_{x,Cask}\right)^2 + \left(cg_{z,System} - cg_{z,Cask}\right)^2\right)\right] \\ &+ \left[MMI_{y,Cradle} + m_{Cradle}\left(\left(cg_{x,System} - cg_{x,Cradle}\right)^2 + \left(cg_{z,System} - cg_{z,Cradle}\right)^2\right)\right] \end{aligned}$$

$$\begin{aligned} \textit{Rotational MMI Vertical } (z) \textit{ Axis} &= \left[MMI_{z,Cask} + m_{Cask}\left(\left(cg_{x,System} - cg_{x,Cask}\right)^2 + \left(cg_{y,System} - cg_{y,Cask}\right)^2\right)\right] \\ &+ \left[MMI_{z,Cradle} + m_{Cradle}\left(\left(cg_{x,System} - cg_{x,Cradle}\right)^2 + \left(cg_{y,System} - cg_{y,Cradle}\right)^2\right)\right] \end{aligned}$$

Combined system mass moments of inertia are calculated for both loaded and empty casks.

Table 5-10: Combined Cask and Cradle Dynamic Modeling Inputs, Loaded Cask

Cask	Mass (lb)	cg relative to Railcar Deck Center (in)			Calculated Rotational Mass Moment of Inertia (lb*in^2)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)	Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
NAC-STC	296,589	3.0	0.0	62.3	478458289	1185142470	1194301767
NAC-UMS UTC	297,022	2.5	0.0	62.3	442611789	1345109965	1354418225
MAGNATRAN	354,000	7.0	0.0	63.2	640614030	1717085951	1726063235
HI-STAR 100	300,438	0.7	0.0	63.7	397372649	1207976714	1193544596
HI-STAR 100HB	202,200	2.6	0.0	63.6	272858531	413492021	409059629
HI-STAR 180	317,829	17.6	0.0	63.9	473658043	1145347597	1141869297
HI-STAR 60	179,364	10.8	0.0	57.4	165969346	471741939	473618516
HI-STAR 190SL	396,110	17.3	0.0	63.6	598102106	1930100576	1917145263
HI-STAR-190XL	434,405	17.1	0.0	63.7	653201069	2469608514	2456334633
MP187	303,800	0.0	0.0	61.1	404290112	1203189865	1192497580
MP197	291,100	1.0	0.0	58.5	378835181	1196765935	1178167173
MP197HB	329,600	1.5	0.0	60.8	472040039	1443081392	1420404755
TN-32B	276,272	0.7	0.0	71.2	368257664	958202003	952945378
TN-40	284,409	0.3	0.0	71.2	389829387	989940166	981504675
TN-40HT	255,252	0.3	0.0	71.0	362612405	894191649	885865939
TN-68	299,000	6.3	0.0	73.3	462297386	1194823592	1168817519
TS125	315,000	4.5	0.0	68.7	443017091	1411036566	1377397504

Table 5-11: Combined Cask and Cradle Dynamic Modeling Inputs, Empty Cask

Cask	Mass (lb)	cg relative to Railcar Deck Center (in)			Calculated Rotational Mass Moment of Inertia (lb*in²)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)	Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
NAC-STC	230,767	3.2	0.0	60.6	395035510	937342825	949284722
NAC-UMS UTC	220,798	2.8	0.0	60.3	357018322	1022095262	1034766443
MAGNATRAN	250,000	7.0	0.0	61.2	479913875	1233184943	1245562383
HI-STAR 100	200,255	0.8	0.0	62.3	280791826	804020200	790758089
HI-STAR 100HB	-	-	-	-	-	-	-
HI-STAR 180	-	-	-	-	-	-	-
HI-STAR 60	157,894	10.7	0.0	57.0	150378708	415774553	417838177
HI-STAR 190SL	296,110	17.1	0.0	63.1	456046355	1443425893	1430748206
HI-STAR-190XL	318,005	16.9	0.0	63.2	487885669	1805453195	1792464977
MP187	222,700	0.0	0.0	59.7	315910218	883775924	874724549
MP197	202,710	1.0	0.0	56.7	284281794	829670349	813122076
MP197HB	205,000	1.4	0.0	58.6	320494050	906412081	886430884
TN-32B	-	-	-	-	-	-	-
TN-40	-	-	-	-	-	-	-
TN-40HT	-	-	-	-	-	-	-
TN-68	-	-	-	-	-	-	-
TS125	226,118	4.3	0.0	66.9	341808710	1028985354	997966315

5.2 Cradle to Railcar Clearances

The interface clearances between the cradle and the railcar are shown in Table 5-12 and are calculated below using the following drawing references:

DWG-3015278-002 [4]

DWG-3015137-001 [11]

DWG-3015138-000 [12]

DWG-3015277-000 [13]

DWG-3015139-000 [14]

DWG-3015140-001 [15]

Table 5-12: Maximum Cradle to Railcar Clearances

	Longitudinal	Lateral	Vertical
Maximum Clearance	0.86 inches	0.78 inches	0.432 inches
Minimum Clearance	0.14 inches	0.16 inches	0.128 inches

5.2.1 Longitudinal Clearance

The conceptual cradle designs for Families 2-4 are supported longitudinally by the shear blocks welded to the railcar. The conceptual cradle designs for Family 1 are supported longitudinally by the end stop assemblies which are shimmed to remove any gap. Therefore, there is no clearance in the longitudinal direction for the Family 1 conceptual cradle designs.

For the cradles in Families 2-4, the longitudinal interface is shown in Figure 5-1 and evaluated in the table below:

Table 5-13: Cradle to Rail Longitudinal Clearance

DWG-3015278-002 (Cradle Attachment Components)	DWG-3015138-000, DWG-3015139-000, DWG-3015140-001, DWG-3015277-000 (Conceptual Cradle Families 2-4 Drawings)	
Distance between shear blocks = 36.00±.12	Distance between shear blocks =(80.25±.12) – (44.75±.12) = 35.5±.24 =35.5±.12 =35.5±.125 =(80.25±.12) – (44.75±.12) = 35.5±.24	 DWG-3015138-000 DWG-3015139-000 DWG-3015140-001 DWG-3015277-000

The minimum gap is:

$$min\ clearance = (36.00 - .12) - (35.5 + .24) = .14\ inches$$

The maximum gap is

$$max\ clearance = (36.00 + .12) - (35.5 - .24) = .86\ inches$$

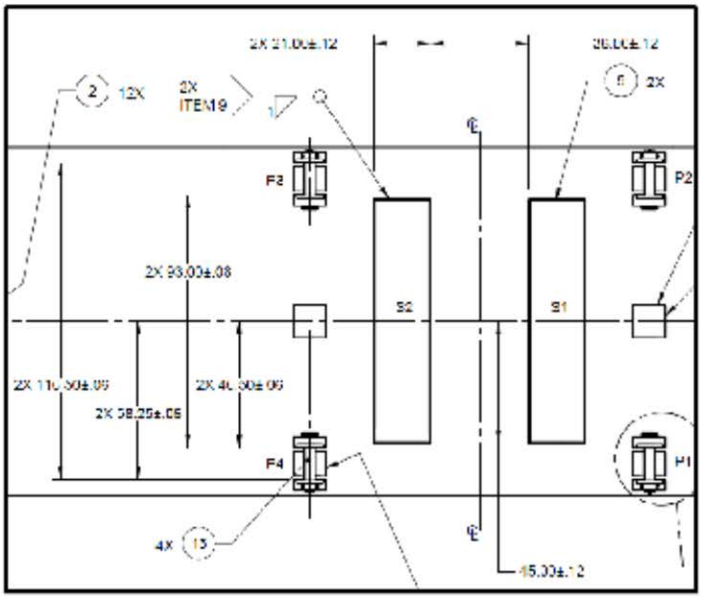

Figure 5-1: Attachment Components Interface

5.2.2 Lateral Clearance

All of the conceptual cradle designs are supported laterally by the center pin attachment blocks. The structural evaluation of the attachment components is performed in CALC-3015276 [9]. From Section 5.2.7 of [9], the conceptual cradle I-beam width is 11.265 inches. The lateral interface is shown in Figure 5-1 and evaluated in the table below:

Table 5-14: Cradle to Railcar Lateral Clearance

DWG-3015278-002 (Cradle Attachment Components)	DWG-3015137-001, DWG-3015138-000, DWG-3015139-000, DWG-3015140-001, DWG-3015277-000 (Conceptual Cradle Drawings)
Edge of inboard center pin attachment blocks dimension = 93.00±.06	Inside edged of cradle I-beams =93.50±.25 DWG-3015137-001 =93.50±.25 DWG-3015138-000 =93.50±.12 DWG-3015139-000 =93.50±.25 DWG-3015140-001 =93.50±.25 DWG-3015277-000
Edge of outboard center pin attachment blocks = 116.50±.06	Outside of cradle I-beams =93.50±.25+2(11.265) = 116.03±.25

At the inboard center pin attachment to cradle I-beam interface:

The minimum gap is:

$$min\ clearance = (93.50 - .25) - (93.00 + .06) = .19\ inches$$

The maximum gap is

$$max\ clearance = (93.50 + .25) - (93.00 - .06) = .81\ inches$$

At the outboard center pin attachment to cradle I-beam interface:

The minimum gap is:

$$min\ clearance = (116.50 - .06) - (116.03 + .25) = .16\ inches$$

The maximum gap is

$$max\ clearance = (116.50 + .06) - (116.03 - .25) = .78\ inches$$

The cradle will contact the outboard edge of the center pin attachment blocks first. The maximum, worst-case clearance (cradle pushed to one side laterally) is 0.78 inches.

5.2.3 Vertical Clearance

All of the conceptual cradle designs are supported vertically by the center pin attachment blocks. Revised dimensions are per reference [18]. A pinned connection is used with an Ø4.000±.002 pin. The Ø4.13±.06 hole on the cradle is round while the cradle connection is a 4.37+.06/-.00 slotted hole. The maximum clearance can be calculated using the minimum of the slot and hole maximum conditions and the smallest pin diameter. This assumes the hole/slot size is not reduced from misalignment which would reduce the clearance.

The maximum vertical clearance is

$$max\ clearance = (4.37 + .06) - (4.000 - .002) = .432\ inches$$

The minimum vertical clearance can be calculated using the minimum condition hole and slot sizes, with the maximum sized pin, and the maximum misalignment per the hole locations.

The minimum cradle hole size is: 4.13-.06= 4.07

The minimum center pin attachment block slot height is: 4.37-.00 = 4.37

The maximum misalignment comes from the tolerance on the cradle and pin block hole/slot vertical locations.

The center pin attachment block tolerance height from base plate = 9.50±.03

The cradle hole height from base plate (bottom of cradle) = 9.50±.06

The maximum misalignment = .03+.06 = .09

This half difference in slot height – cradle hole = (4.37-4.07)/2 = .15

The minimum through hole due to misalignment = 4.07 – (.09-.15) = 4.130 inches

The maximum pin diameter is 4.002 inches.

$$min\ clearance = 4.130 - 4.002 = .128\ inches$$

6.0 COMPUTER SOFTWARE USAGE

File listings are generated using the "Get-ChildItem" command in PowerShell. File listings include date and time of most recent save, file size in bytes, and file name. Each SolidWorks calculation model consists of a large number of part models as well as associated assembly models and drawings. The results of each SolidWorks mass moments of inertia calculation are saved both as a .pdf text output as well as a .jpeg screen capture. The screen captures are included in Appendix A.

COMPUTER RUN RECORD	
Run description	See input/output file names and the discussions in the body of the calculation
Software used	SolidWorks 2014 x64 Edition
Computer name	EGONSIOROWSKI1
Hardware (processor name)	Intel® Xeon® CPU E5-1650 v2 @ 3.50 GHz
Operating system	64-bit Windows 7 Enterprise, Service Pack 1
Unique run identifier	See input/output file names and associated date/time stamps
List of input/output files	See input/output file names

Due to the large size of the SolidWorks model file listing (~800 lines), the file listing is contained in "SolidWorks Model Listing.txt". The mass moments of inertia calculation output files are listed below.

```
    Directory: \Results

Mode                LastWriteTime     Length Name

d----         3/20/2017   1:28 PM            Family 1
d----         3/20/2017   1:28 PM            Family 2
d----         3/20/2017   1:28 PM            Family 3
d----         3/20/2017   1:28 PM            Family 4
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-a---          3/8/2017  12:48 PM     139240 Hi-Star 100 Cradle.JPG
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COMPUTER RUN RECORD	
Software used	Excel 2010

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7.0 RESULTS/CONCLUSIONS

Results of this calculation are shown in Section 5.

7.1 Literature Search and other Background Data

A formal literature search was not applicable to this scope of work. All required background information is given under Section 1.1, *Project Background*.

8.0 REFERENCES

1. Department of Energy Contract DE-NE0008390 (Conformed through Mod 5), Part 1, Section C, *Statement of Work*.
2. Association of American Railroads, *Manual of Standards and Recommended Practices, Section C – Car Construction Fundamentals and Details*, Standard S-2043, *Performance Specification for Trains Used to Carry High-Level Radioactive Material*, 2008
3. AREVA Federal Services Engineering Information Record, EIR-3014611, *Design Basis Requirements Document (DBRD) for the DOE Atlas Railcar*, Rev. 8.
4. AREVA Federal Services Drawing, DWG-3015278, *Atlas Railcar Cradle Attachment Components Drawing*, Rev. 2.
5. AREVA Federal Services Calculation, CALC-3015133, *Atlas Railcar Family 1 Conceptual Cradle Structural Calculation*, Rev. 2
6. AREVA Federal Services Calculation, CALC-3015134, *Atlas Railcar Family 2 Conceptual Cradle Structural Calculation*, Rev. 0
7. AREVA Federal Services Calculation, CALC-3015135, *Atlas Railcar Family 3 Conceptual Cradle Structural Calculation*, Rev. 0
8. AREVA Federal Services Calculation, CALC-3015136, *Atlas Railcar Family 4 Conceptual Cradle Structural Calculation*, Rev. 1

9. AREVA Federal Services Calculation, CALC-3015276, *Atlas Railcar Cradle Attachment and Combined Center of Gravity Calculation*, Rev. 3
10. Beer, Johnson, *Vector Mechanics for Engineers, Statics*, Sixth Edition, McGraw-Hill, Boston, 1996.
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12. AREVA Federal Services Drawing, DWG-3015138, *Atlas Railcar, Cradle Family 2 (NAC), Conceptual Drawing*, Rev. 1
13. AREVA Federal Services Drawing, DWG-3015277, *Atlas Railcar, Cradle Family 2 (TN-68), Conceptual Drawing*, Rev. 0.
14. AREVA Federal Services Drawing, DWG-3015139, *Atlas Railcar, Cradle Family 3, Conceptual Drawing*, Rev. 0
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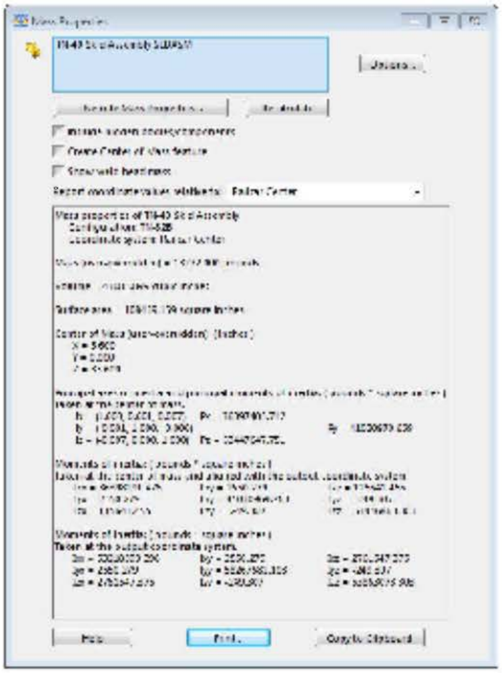
16. Docket 71-9336, *Safety Analysis Report for on the HI-STAR 60 Transportation Package*, Non-Proprietary Version, Rev 3, May 2009.
17. Klein, Slade "FW: TTCI data needed from AFS for modeling", Message to Erik Gonsiorowski, February 2017, E-mail
18. Klein, Slade "FW: Atlas Cradle to Railcar Interface", Message to Erik Gonsiorowski, February 2017, E-mail
19. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code, Section II, Part D, "Properties (Customary), Table PRD", 2015
20. AREVA Federal Services Calculation, CALC-3018954, *Atlas Railcar Conceptual Ballast Load Structural Calculation*, Rev. 1
21. AREVA Federal Services Drawing, DWG-3018955, *Atlas Railcar Ballast Load Conceptual Drawing*, Rev. 0
22. AREVA Federal Services Request For Information, AFS-RFI-00225-0015-00, November 2016

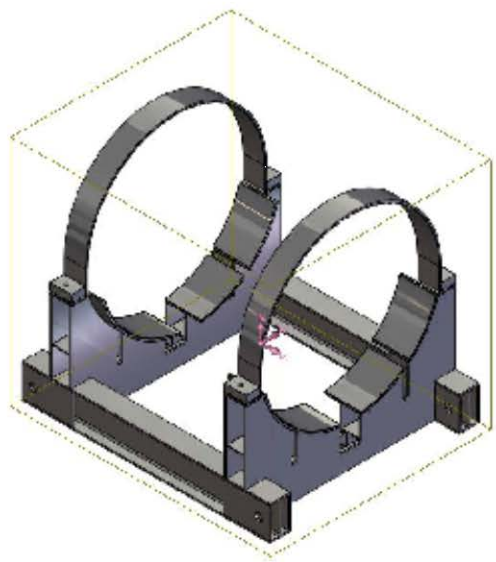
APPENDIX A: SOLIDWORKS CALCULATION OUTPUTS

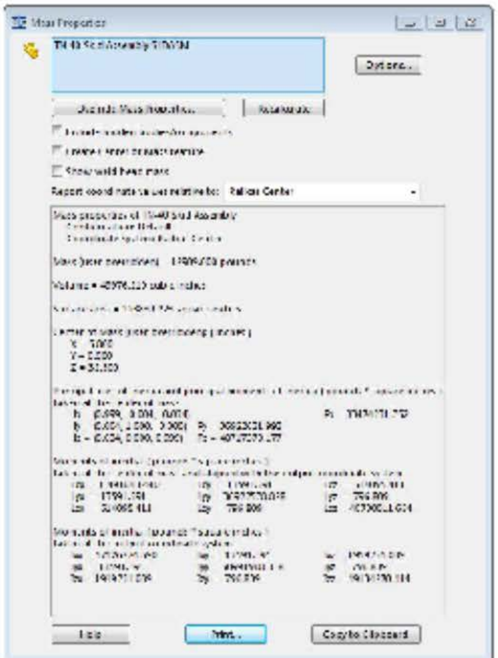
The mass moment of inertia for each cradle design is calculated within SolidWorks. The personnel barrier geometries are not included in each model but are included in the assembly masses. The mass moments of inertia are taken at the center of gravity of each model and aligned with the output coordinate system. The cradle masses and center of gravities are overridden within SolidWorks using hand-calculated values (overriding the center of gravity does not change the output of interest).

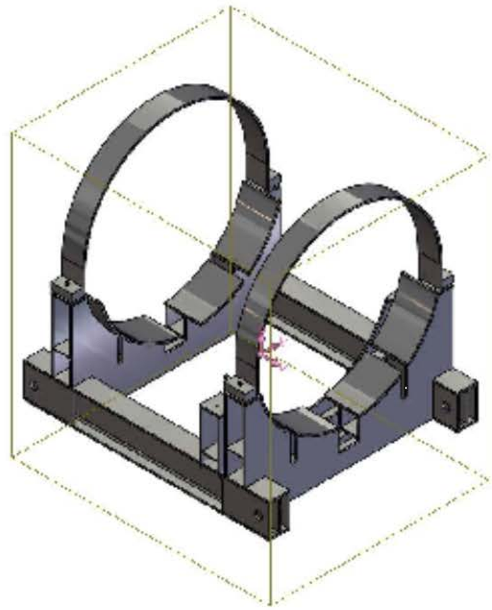
A.1 Family 1 Conceptual Cradles

A.1.1 TN-40, TN-40HT and TN-32B

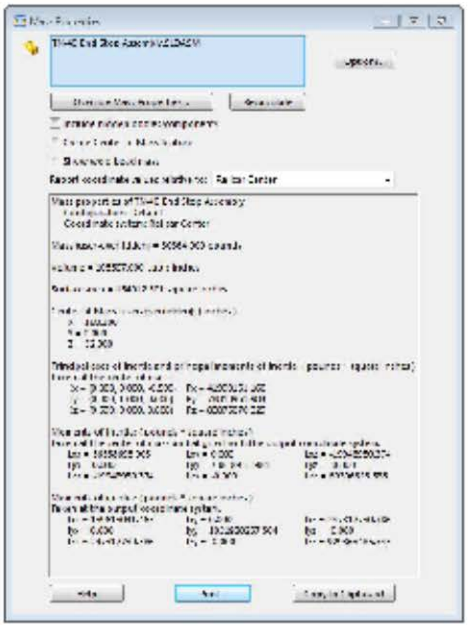


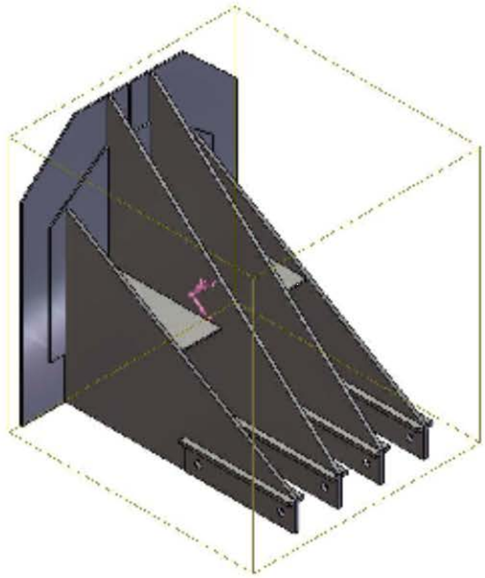


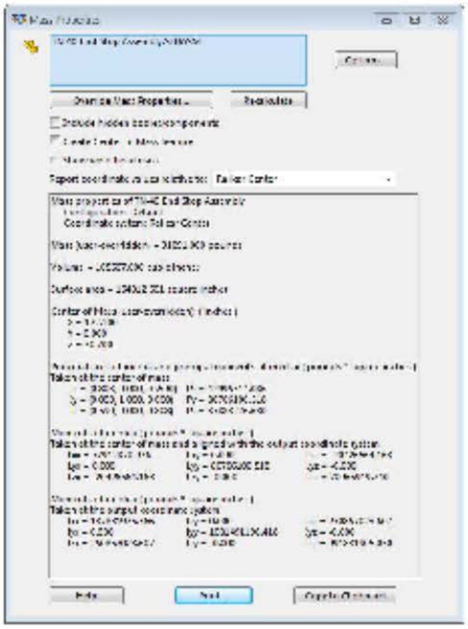


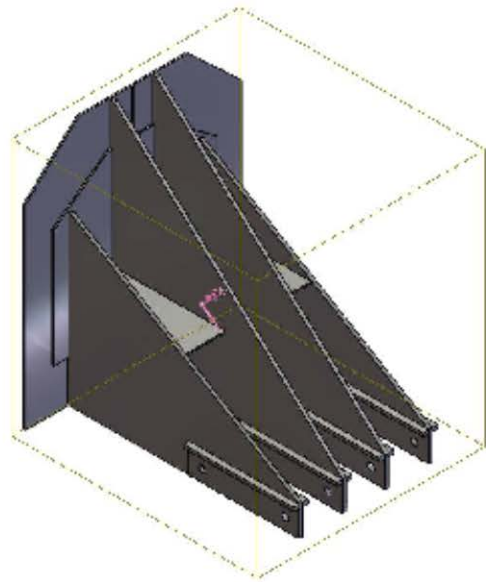


Cask	Nominal Central Cradle Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in^2)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
TN-32B	13,272	36398191.476	41030969.263	53446863.383
TN-40	12,909	33491643.440	36922578.828	48700011.654
TN-40HT	12,909	33491643.440	36922578.828	48700011.654



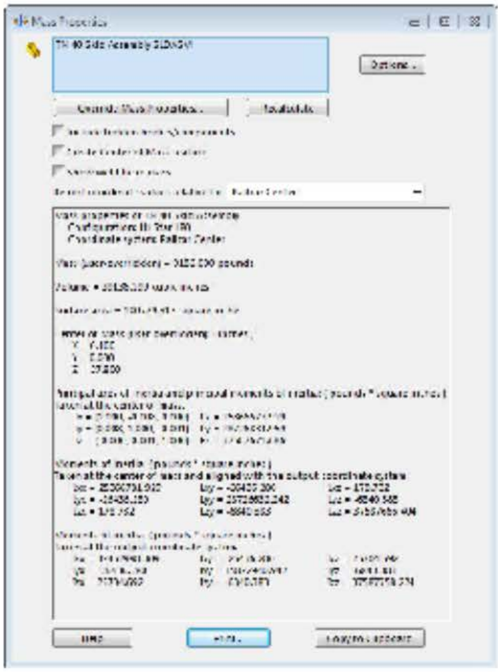


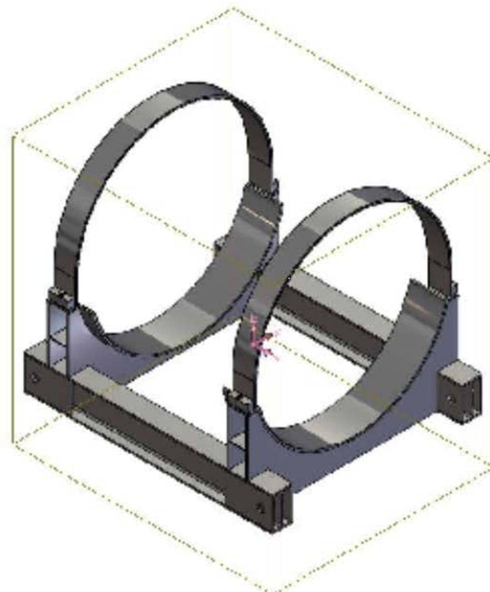




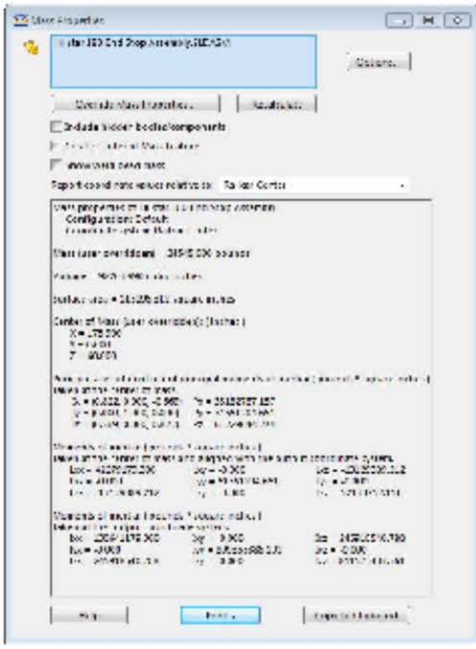
Cask	Nominal End Stop Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in²)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
TN-32B	30,364	56558695.903	78818951.984	69306525.585
TN-40	31,091	57912870.976	80706100.518	70965919.740
TN-40HT	31,091	57912870.976	80706100.518	70965919.740

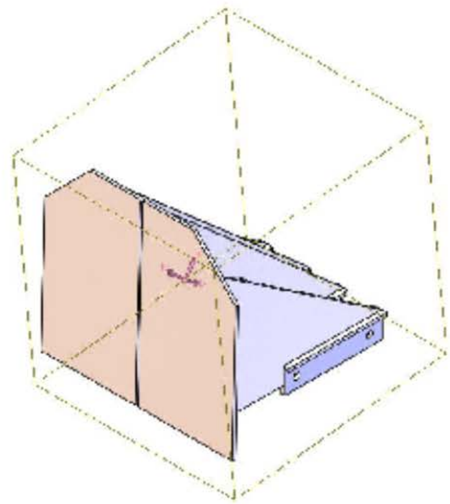
A.1.2 HI-STAR 180





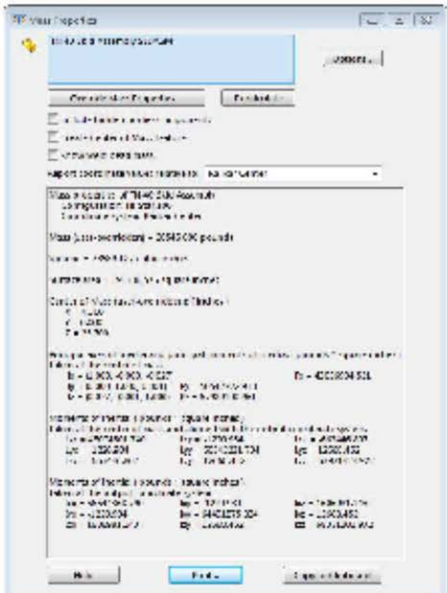
Cask	Nominal Central Cradle Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in²)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
HI-STAR 180	9,182	25366781.929	28726632.242	37587666.404

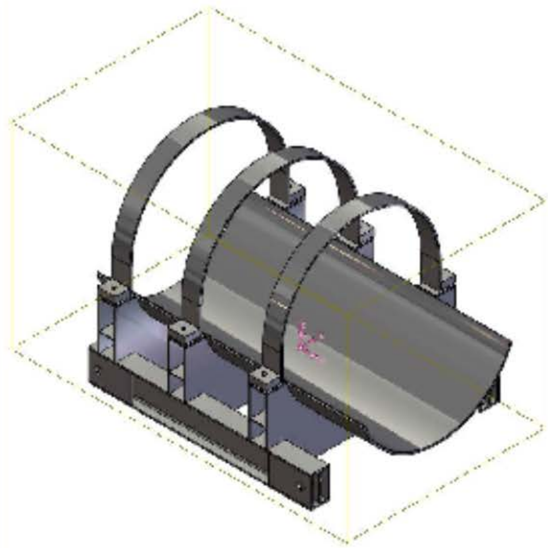




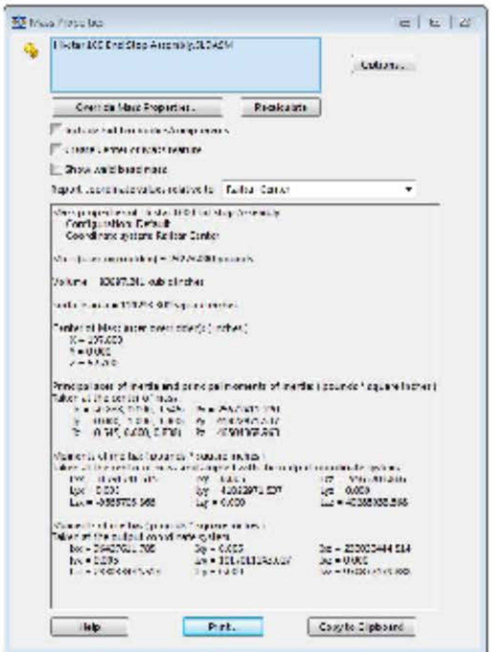
Cask	Nominal End Stop Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in²)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
HI-STAR 180	24,545	42279179.300	51551204.651	52133252.111

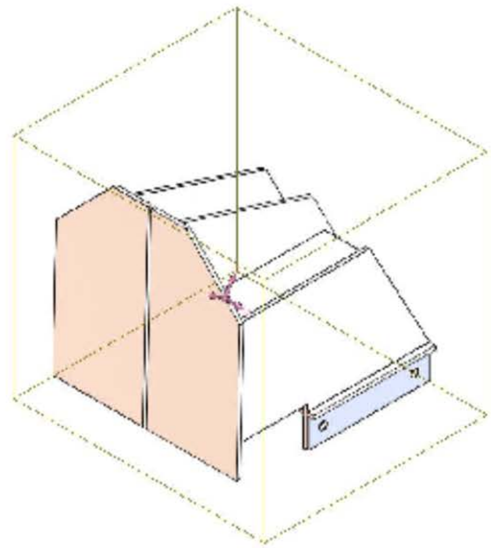
A.1.3 HI-STAR 100





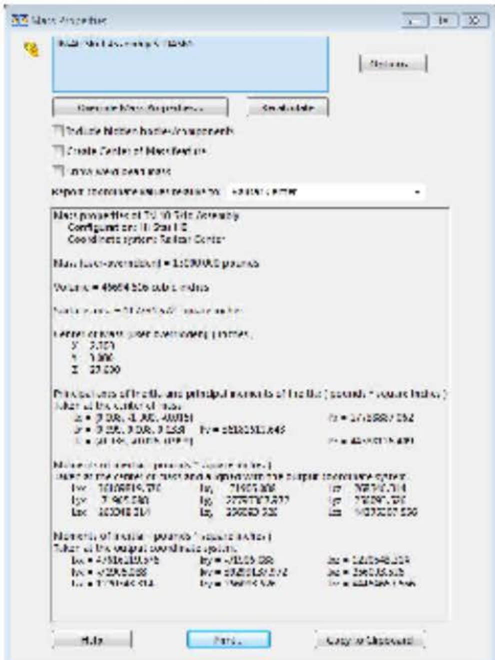
Cask	Nominal Central Cradle Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in²)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
HI-STAR 100	20,545	43074601.740	50542231.734	67971424.922

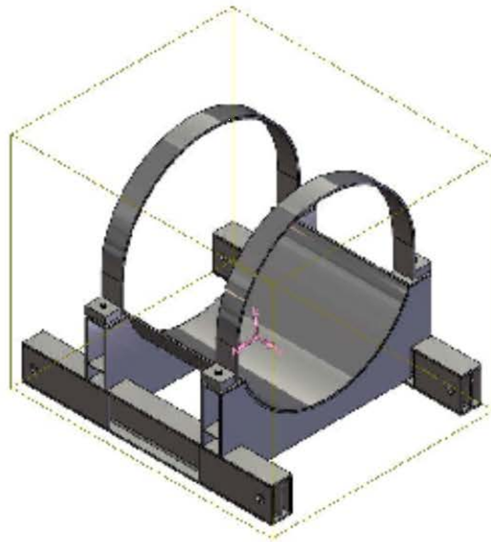




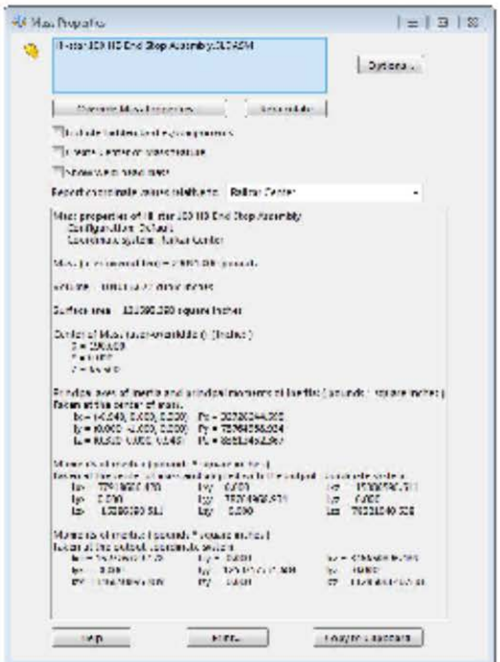
Cask	Nominal End Stop Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in²)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
HI-STAR 100	23,273	31791741.615	41822971.537	40285038.568

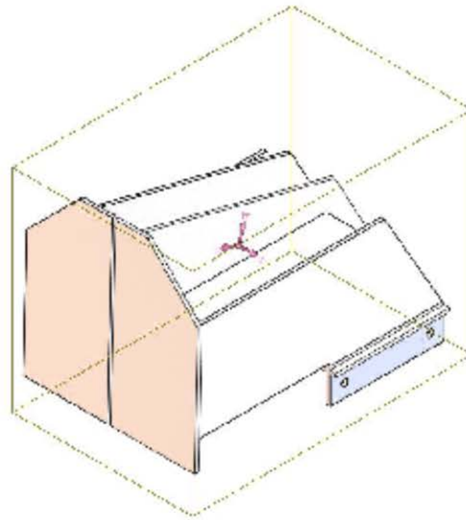
A.1.4 HI-STAR 100HB





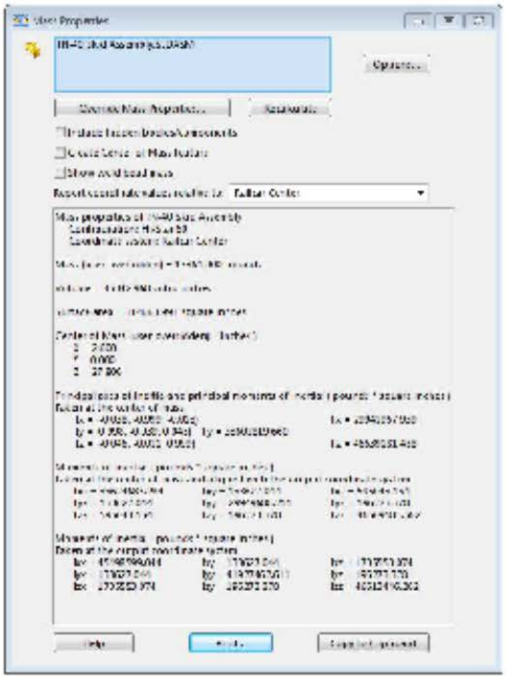
Cask	Nominal Central Cradle Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in²)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
HI-STAR 100HB	15,000	36189819.576	27793387.972	44375307.556

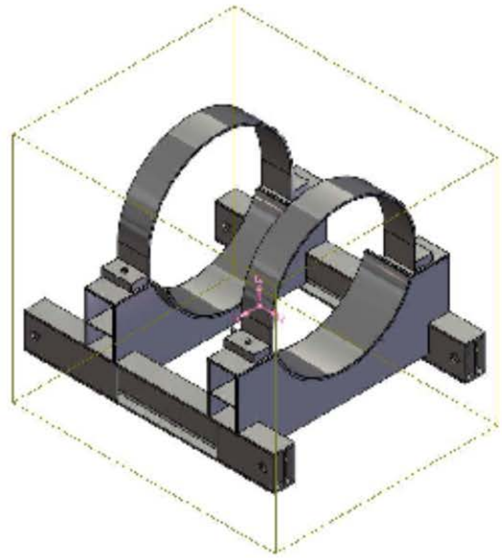




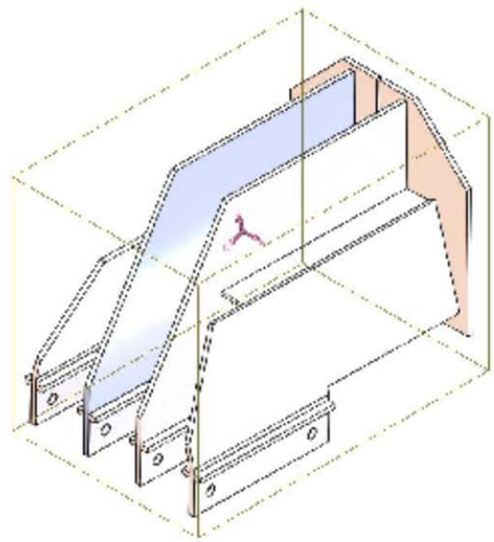
Cask	Nominal End Stop Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in²)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
HI-STAR 100HB	29,091	37918666.428	78764968.934	78321040.538

A.1.5 HI-STAR 60



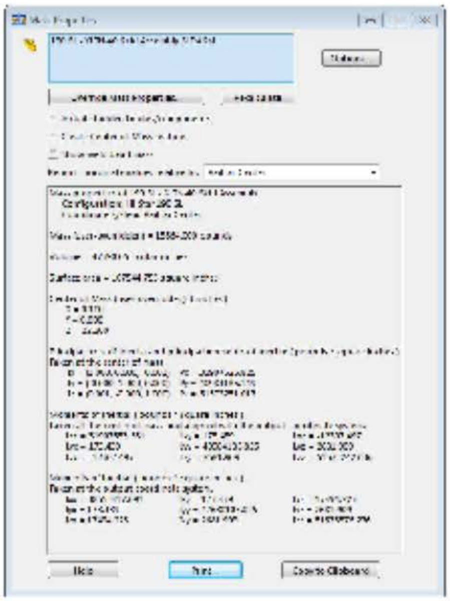


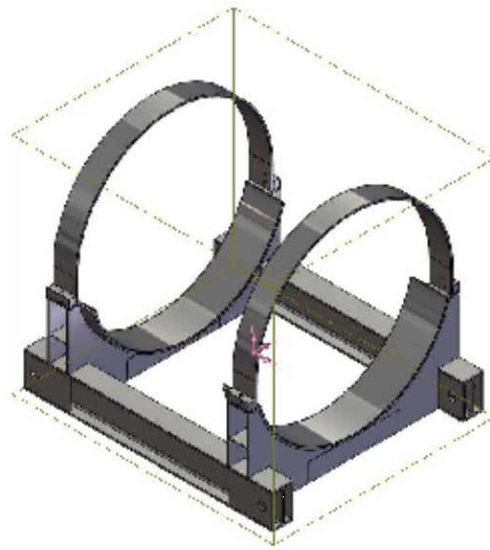
Cask	Nominal Central Cradle Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in²)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
HI-STAR 60	15,364	33624685.284	29949688.211	46509585.562



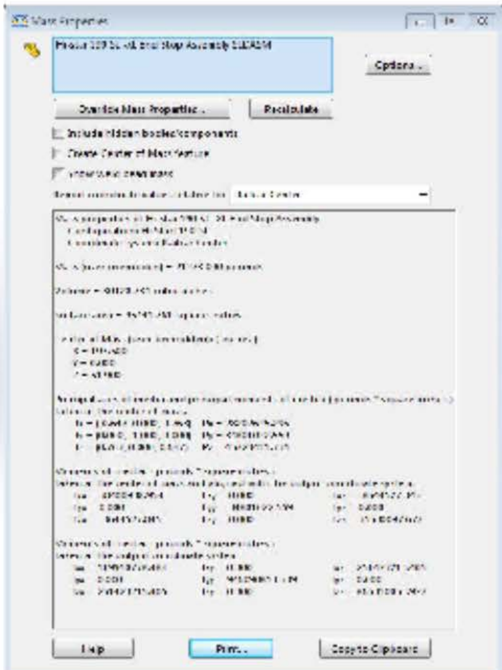
Cask	Nominal End Stop Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in²)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
HI-STAR 60	34,182	38475171.497	72009557.099	70568374.259

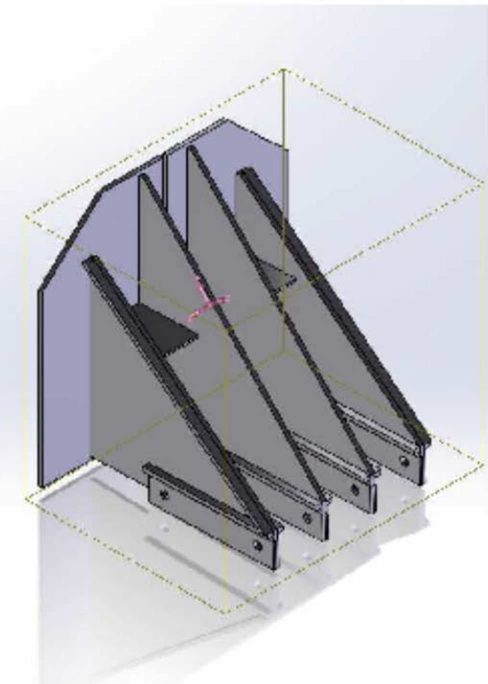
A.1.6 HI-STAR 190SL





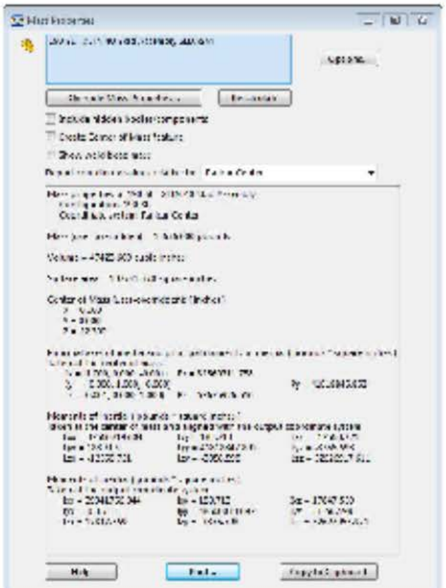
Cask	Nominal Central Cradle Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in^2)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
HI-STAR 190SL	13,364	31907633.531	40984185.825	51573242.636

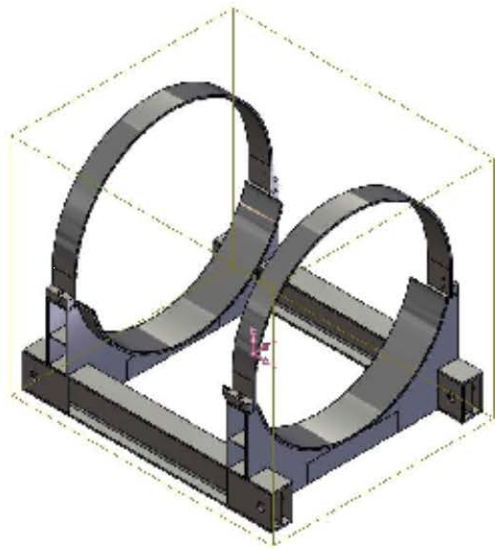




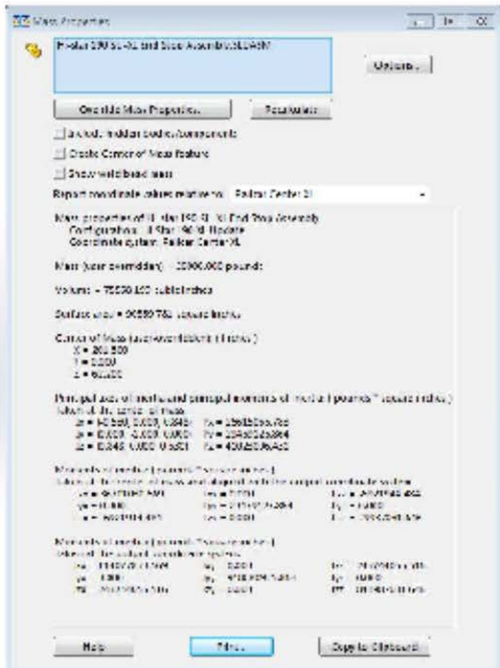
Cask	Nominal End Stop Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in²)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
HI-STAR 190SL	21,273	38400938.954	34801022.559	35530097.677

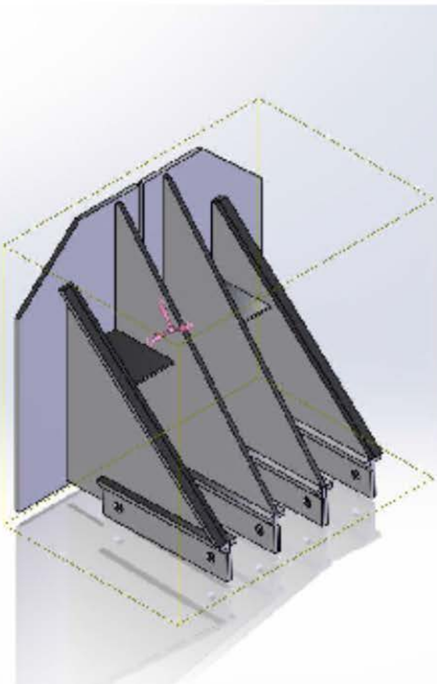
A.1.7 HI-STAR 190XL





Cask	Nominal Central Cradle Weight (lb)	Calculated Rotational Mass Moment of Inertia, ($lb*in^2$)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
HI-STAR 190XL	13,636	32560719.604	41818847.892	52626917.611

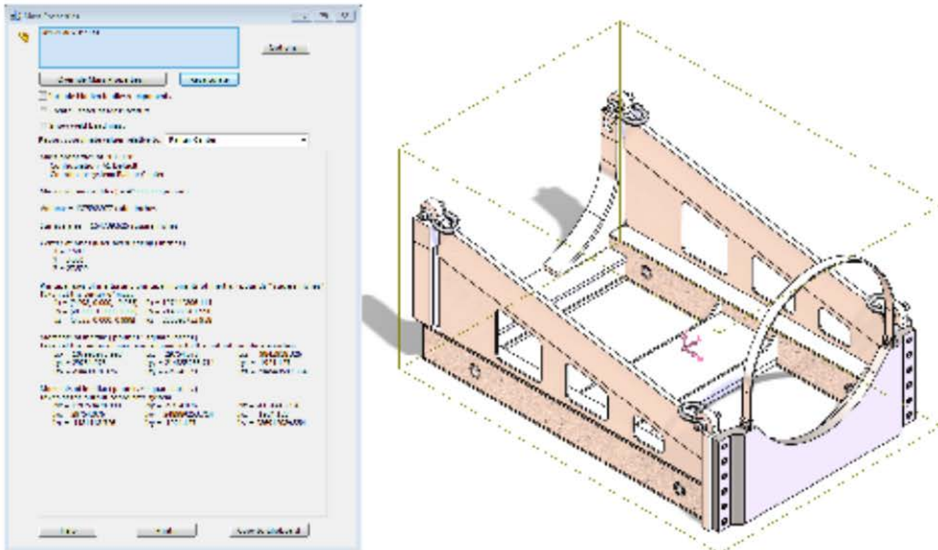




Cask	Nominal End Stop Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in²)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
HI-STAR 190XL	20,000	36701030.569	29459125.864	29937031.646

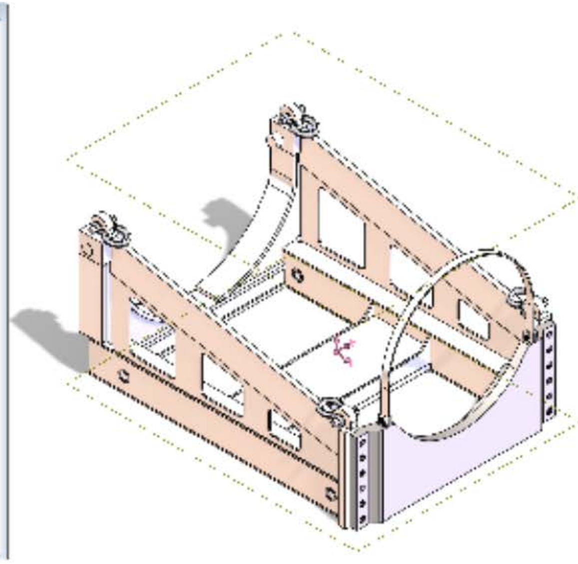
A.2 Family 2 Conceptual Cradles

A.2.1 NAC MAGNATRAN



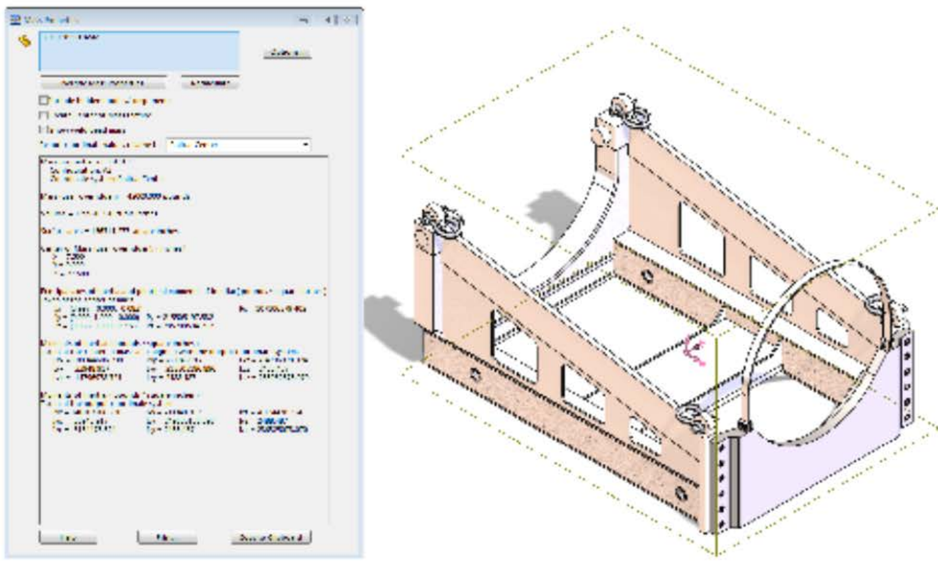
Cask	Nominal Cradle Weight (lb)	Calculated Rotational Mass Moment of Inertia, ($lb*in^2$)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
MAGNATRAN	42,000	107996978.993	214855253.714	284549589.354

A.2.2 NAC STC



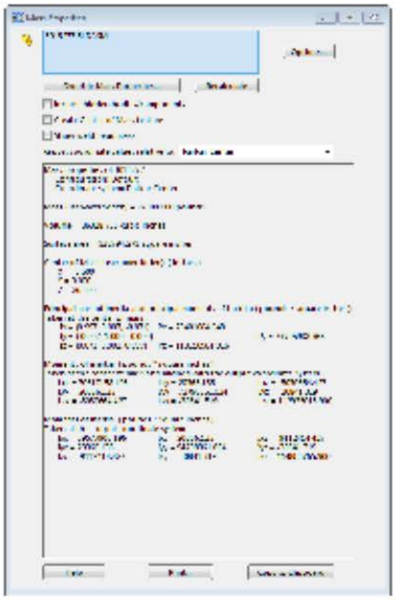
Cask	Nominal Cradle Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in^2)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
NAC-STC	42,000	107420031.027	177507864.928	245802070.276

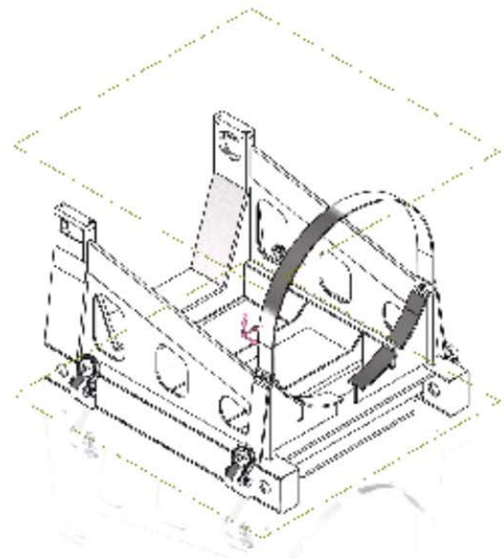
A.2.3 NAC-UMS UTC



Cask	Nominal Cradle Weight (lb)	Calculated Rotational Mass Moment of Inertia, ($lb*in^2$)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
NAC-UMS UTC	42,000	108344606.230	215505186.896	283962578.070

A.2.4 TN-68

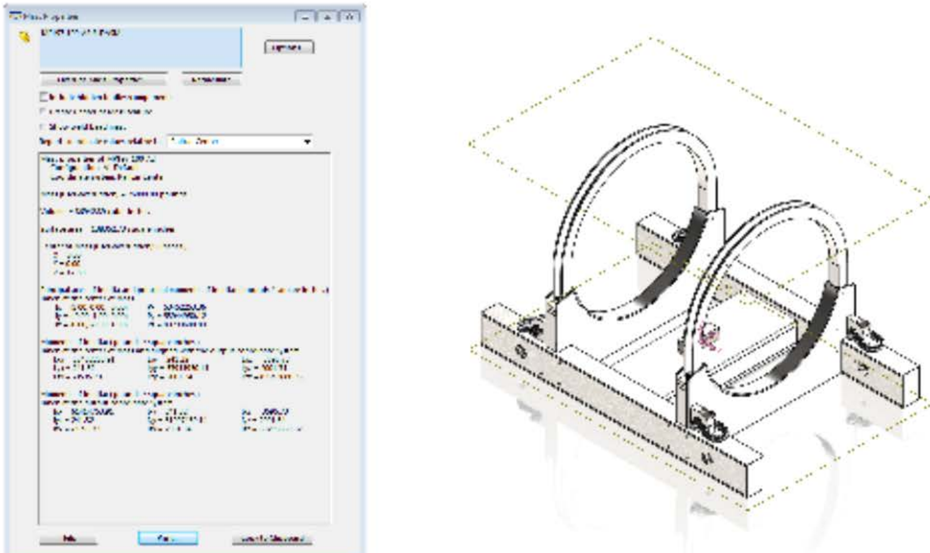




Cask	Nominal Cradle Weight (lb)	Calculated Rotational Mass Moment of Inertia, ($lb*in^2$)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
TN-68	27,000	70617158.196	73796861.034	112935015.900

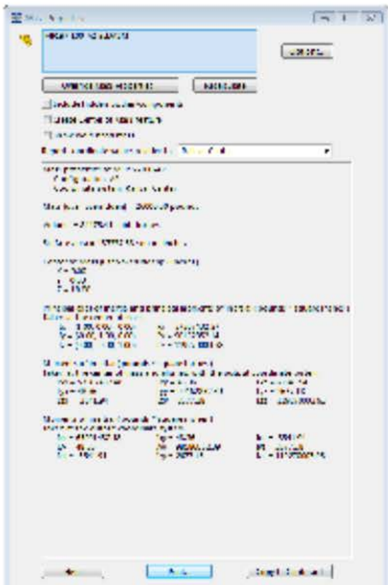
A.3 Family 3 Conceptual Cradles

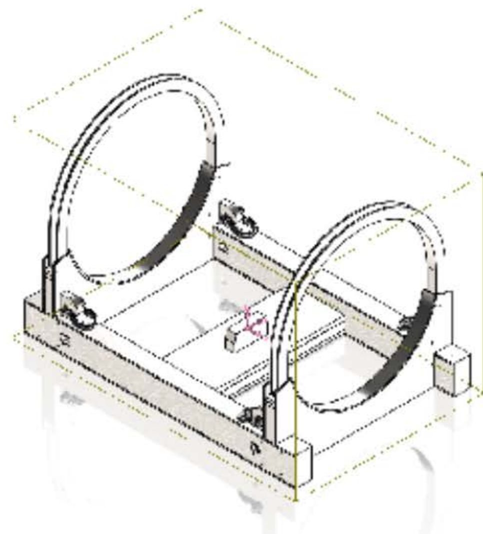
A.3.1 MP197



Cask	Nominal Cradle Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in^2)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
MP197	26,000	53452253.91	53944950.14	83293680.32

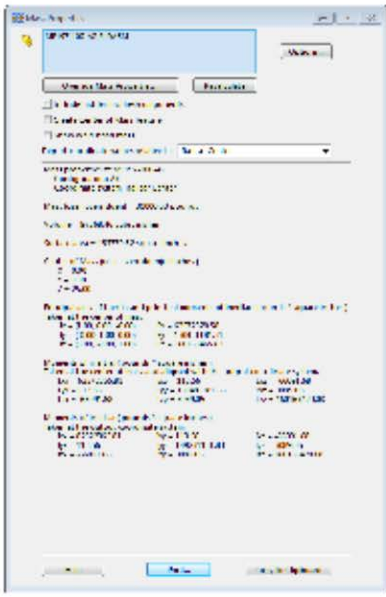
A.3.2 MP197HB

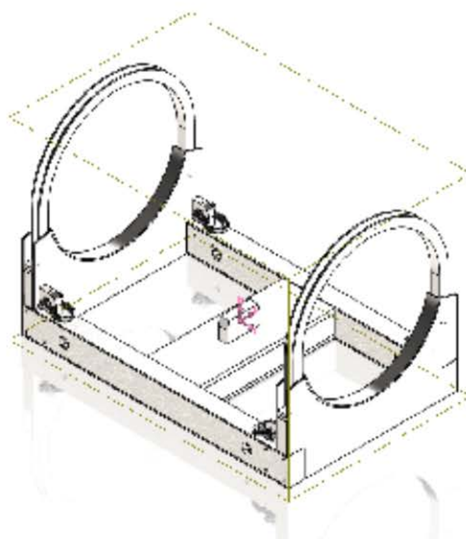




Cask	Nominal Cradle Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in²)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
MP197HB	26,000	57567432.48	90162852.39	119270003.93

A.3.3 TS125

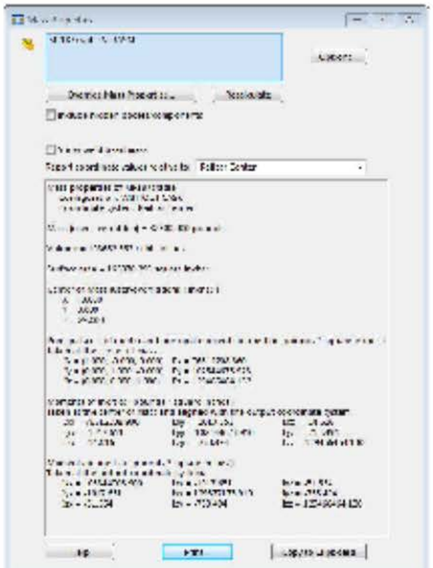


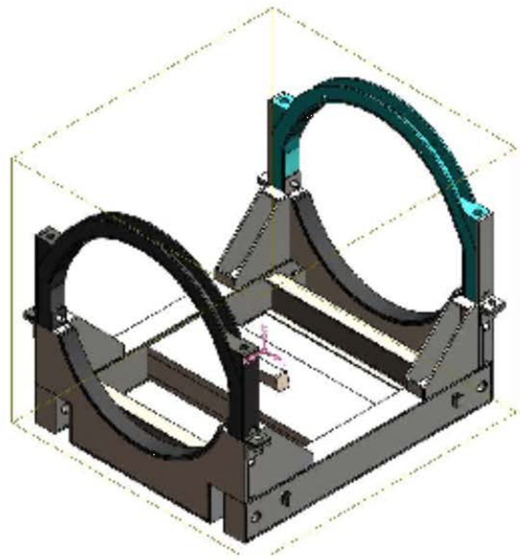


Cask	Nominal Cradle Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in^2)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
TS125	30,000	63572365.81	130481181.83	160163420.08

A.4 Family 4 Conceptual Cradle

A.4.1 MP187



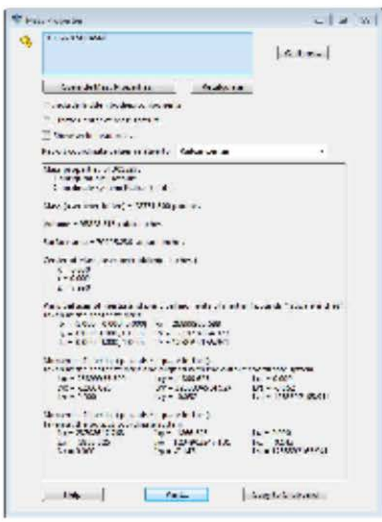


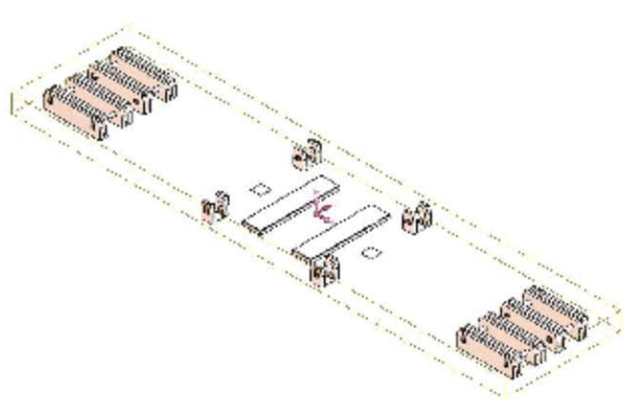
Cask	Nominal Cradle Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in²)		
		Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
MP187	32,500	76512208.900	102544673.910	129466464.130

APPENDIX B: ADDITIONAL DYNAMIC MODELING INPUTS

B.1 Attachment Hardware Permanently Attached to the Railcar Deck

Permanently attached railcar hardware must be accounted for in TTCI's cask and cradle dynamic models. The mass moments of inertia for the permanently attached railcar hardware are calculated in SolidWorks. The hardware models are built in accordance with drawing [4]. Hand-calculated hardware mass and center of gravity from Table 9-1 in [9] are used, overriding values calculated by SolidWorks. The hardware mass is 28,331.6 pounds with a vertical center of gravity of 7.99 inches from the railcar deck (hardware is symmetrical along longitudinal and lateral axes). The model is composed of carbon steel (0.28 lb/in^3) and stainless steel (0.29 lb/in^3) to establish the model weight distribution. Mass moments of inertia are evaluated around the railcar deck center and are shown below.

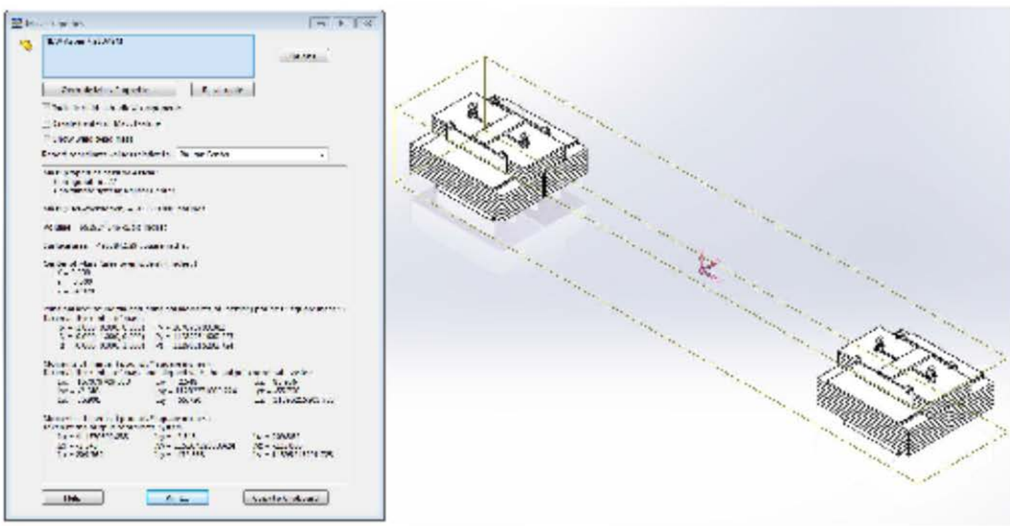




Nominal Hardware Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in^2)		
	Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
28331.6	26899955.590	1233094554.924	1258392165.941

B.2 Ballast Load

The Atlas railcar will require additional mass, a ballast load, to be able to be transported without a cask and cradle loading. The mass moments of inertia for the ballast load are calculated in SolidWorks. The hardware is built in accordance with drawing [21]. Hand-calculated load mass and center of gravity from Table 4-2 in [20] are used, overriding values calculated by SolidWorks. The load mass is 200,500 pounds for a ballast load pair (one assembly at each end of the railcar). The vertical center of gravity is 32.42 inches from the bottom of the ballast assembly (each ballast load is symmetrical along the longitudinal axis; a pair is symmetrical along the lateral axis). The ballast load pin hole center is 7.5 inches from the bottom of the ballast assembly [21], while the attachment hardware pin hole center is 10 inches from the railcar deck [4]. Thus, the vertical center of gravity of the ballast assembly is (32.42-7.5+10) = 34.92 inches from the railcar deck. The model is composed of carbon steel (0.28 lb/in^3) and stainless steel (0.29 lb/in^3) to establish the model weight distribution. Mass moments of inertia are evaluated around the railcar deck center and are shown below.



Nominal Ballast Weight (lb)	Calculated Rotational Mass Moment of Inertia, (lb*in^2)		
	Longitudinal Axis (x)	Lateral Axis (y)	Vertical Axis (z)
200,500	167079709.083	11282231600.224	11395215201.723