LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO- T050071-00-E ADVANCED LIGO April 26, 2005

Advanced LIGO Quad Suspension Installation Fixtures Design Review

Oddvar Spjeld

Distribution of this document:
LIGO Science Collaboration

This is an internal working note
of the LIGO Project.

California Institute of Technology
LIGO Project – MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW17-161
175 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 1970
Mail Stop S9-02
Richland WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

http://www.ligo.caltech.edu/

1. INTRODUCTION

The intent of this review is to discuss the following before detailed drawings are created:

- Have the design requirements for the quad suspension installation fixtures been met?
- Has there been adequate analysis of stress and deflection for all load scenarios?
- Will the fixtures be practically functional during installation? (operators)
- Issues/concerns regarding binding of linear drives, follower shafts, Lazy Susan, tilt, etc.
- Manufacturing feasibility, production cost efficiency, etc.
- Other comments, suggestions for changes and improvements.

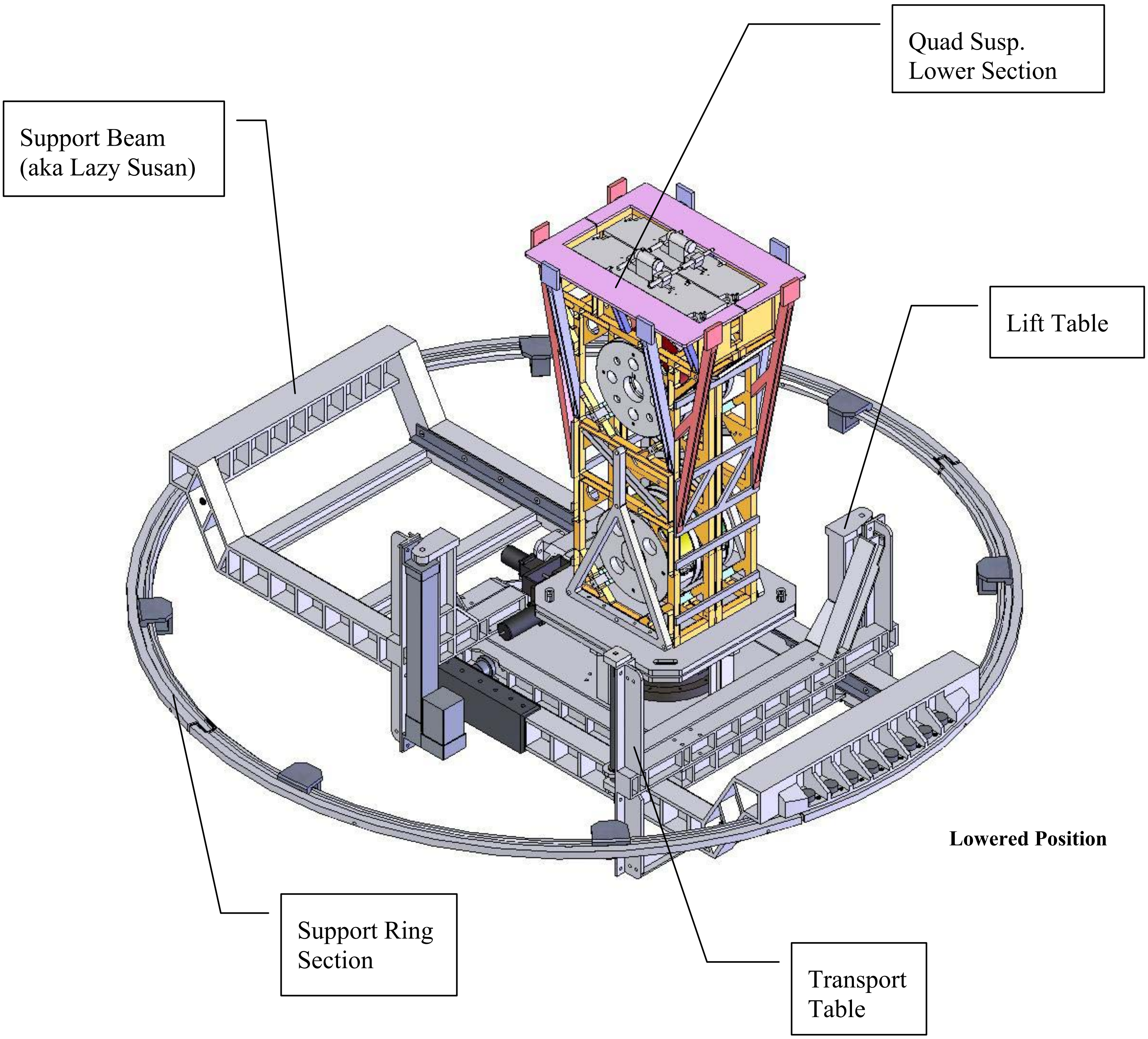
2. PURPOSE

The purpose of the quad suspension installation fixtures is to receive the lower quad section from the articulated arm through the BSC chamber door, position the section below the upper section while supporting the structure securely, then lift it to the correct height and perform fine adjustments (linear and angular) of the complete suspension assembly.

3. DESIGN REQUIREMENTS SUMMARY

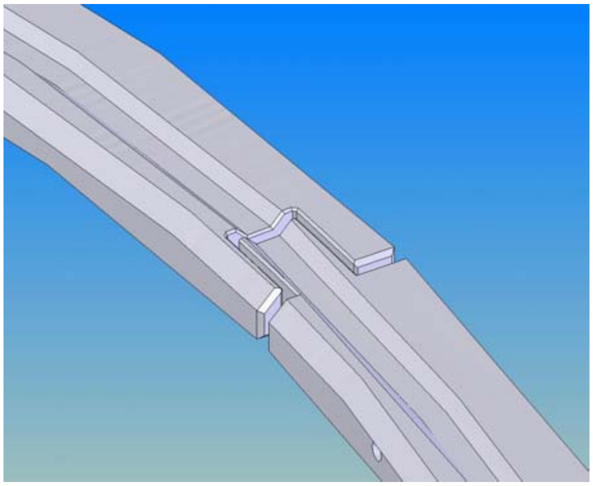
1. Load Capacity – minimum 2,750 lbs with a maximum vertical deflection of .0005 in and maximum stress of less than half of the tensile yield strength of the fixture material.
2. All material utilized should be in compliance with the LIGO Vacuum Compatible Materials List (E960050-B), however other materials may be considered as these are class B assemblies. Weight should be minimized.
3. All fixtures are to clear seismic and chamber parts while in use. The fixtures must fit through the BSC chamber door before and after installation.
4. The fixtures should be able to receive and securely support the lower suspension section transferred horizontally through the BSC chamber door (by the articulated arm).
5. Course alignment by horizontal linear translation 120 inches and horizontal angular rotation +/- 30 degrees.
6. Vertical translation of the lower suspension section with a maximum lift range of 12 inches, with a sensitivity of .005 in. The backlash should not exceed this resolution.
7. Fine alignment in horizontal X-Y-translation within a range of +/- 2 inches with a sensitivity of .005 inches or less, vertical plane tilt alignment of +/- 2 degrees with a resolution of 1.0 arc second and a horizontal angular rotation of +/- 10 degrees with a resolution of 1.0 arc second.

4. DESIGN

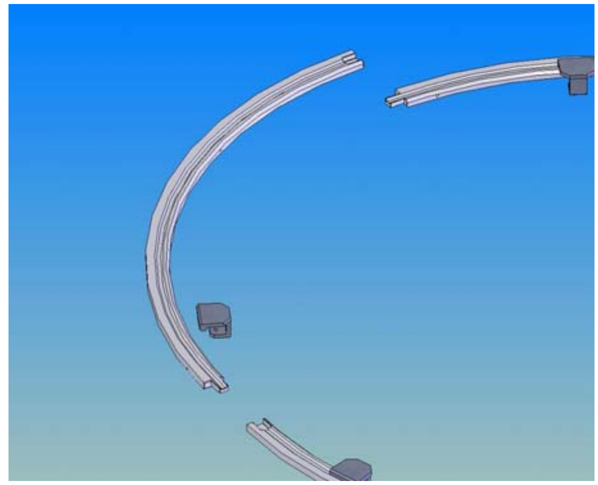


1. Support Ring Section – a total of four 90 degree angle sections of a cylinder will be joined at clamped down to the existing support flange inside the BSC chambers. The sections have a track on which the ball transfers attached to the support beam will roll. There are .125 clearance gaps between the sections and interlocks to accommodate for a non-cylindrical chamber walls. There is also a .25 in clearance between the existing chamber wall diameter and the support ring section outer diameter. The clamps press down into the track of the

ring sections and are intended to secure the support rings to the chamber flange, as well as to eliminate any buckling due to unevenness in ring sections or chamber flange.

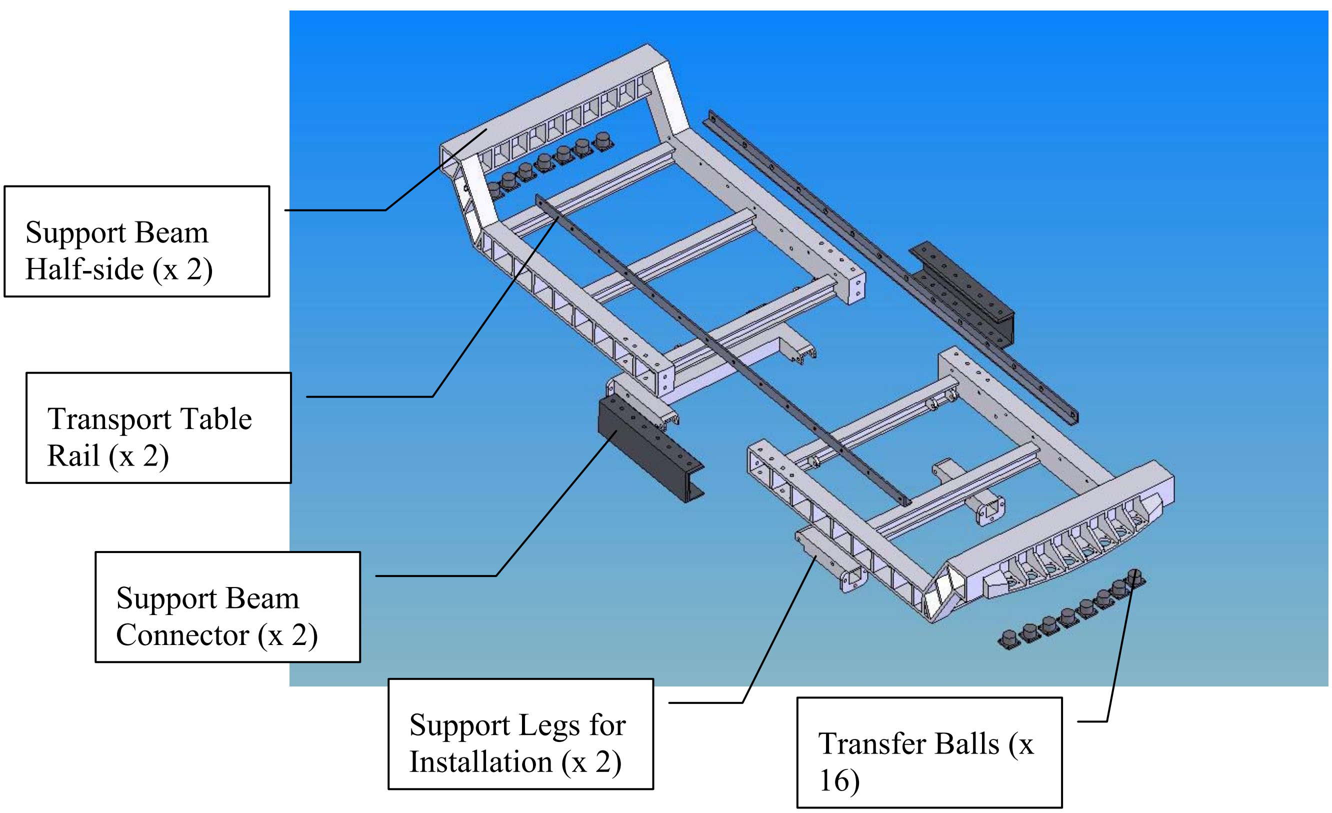


Support Ring Section Interlock



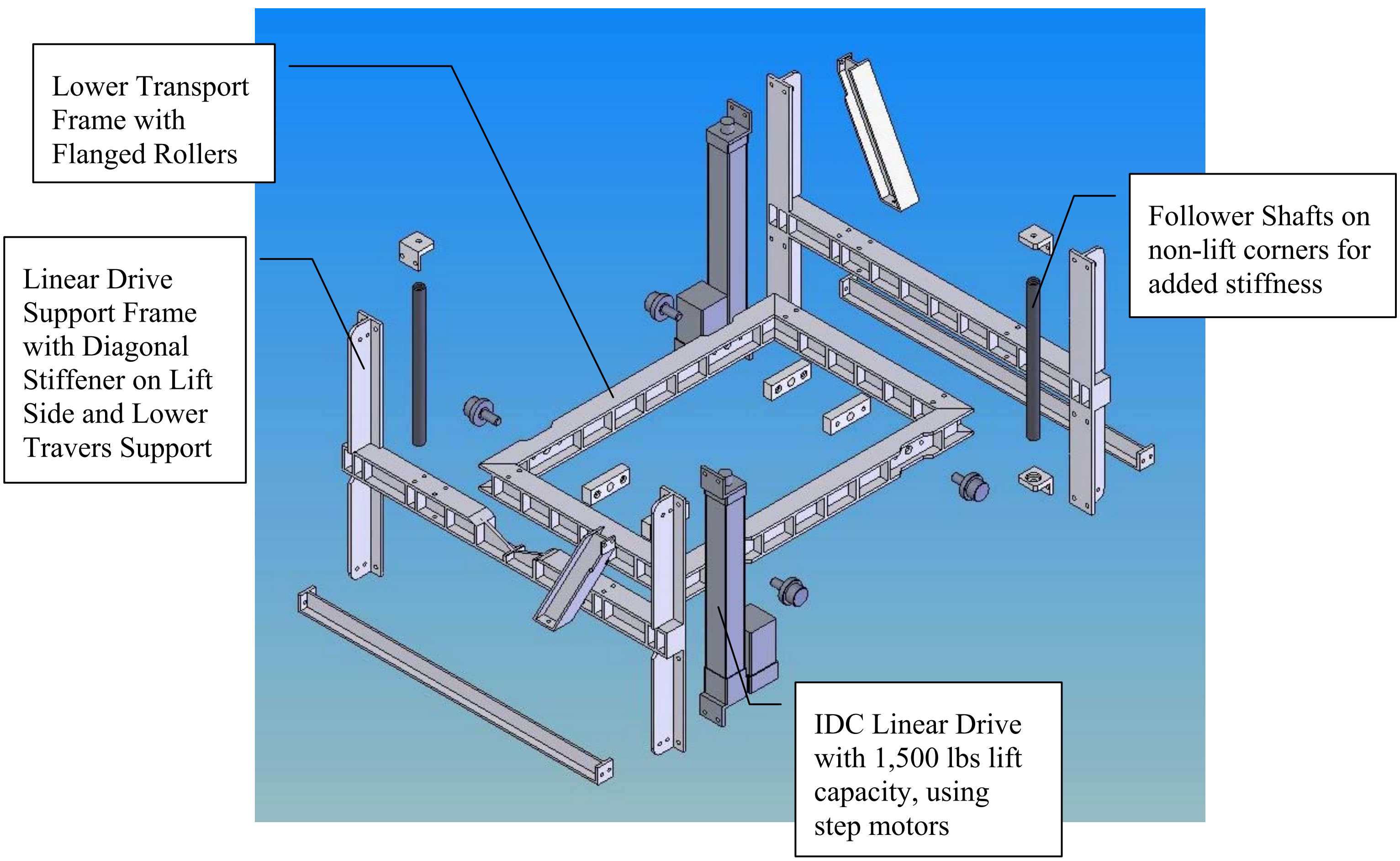
Support Ring Section Exploded w/Clamps

2. Support Beam – based on the support beam for the initial LIGO suspension installation fixtures, but lowered, widened and stiffened to accommodate larger load and provide sufficient clearance for the lower quad suspension section to be installed.

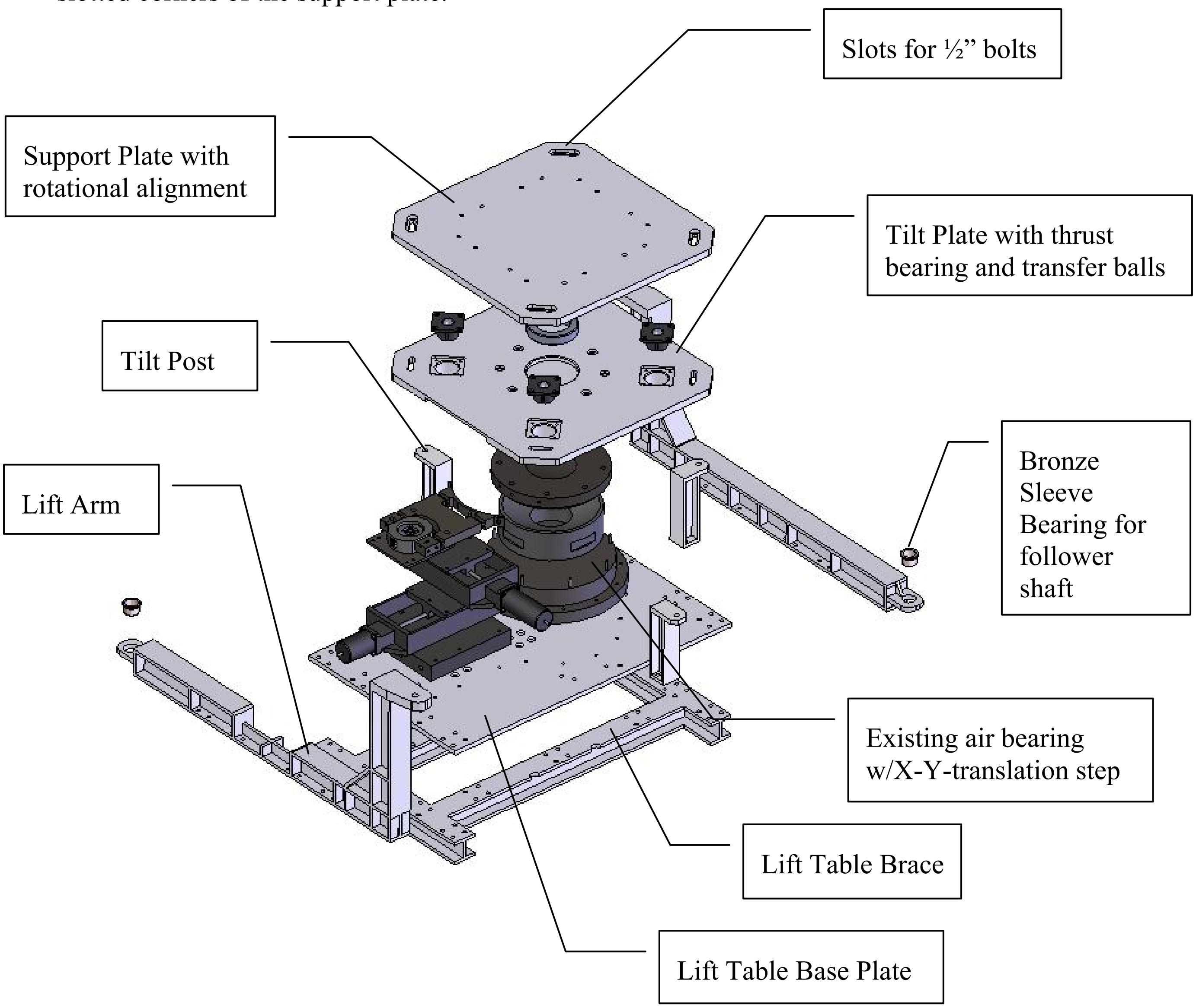


The support beam consists of two half-sides which will be brought in to the chamber separately and then joined, using pivoting support legs with adjustable height, with a stainless steel connector on each beam side as shown above. After the two half-sides have been connected, the support legs will swing up and out of the way. Note: The support legs are not designed to support any payload during installation of the quad suspension. The weight of the support beam and the payload is transferred to the existing chamber flange through a total of 16 off-the-shelf transfer balls, each with a load capacity of 300 lbs. The transfer balls will roll in the track of the support ring sections as mentioned above. The two transport table rails will be attached to the inside of the beam sections and will carry the load of the transport and lift table as well as the payload.

3. <u>Transport Table</u> – consists of the lower transport frame with four mounted adjustable stainless steel rollers which will roll on the support beam rails, and two linear drive support frames mounted to each side of the transport frame. The linear drive frames will support two IDC Linear Drives with Step Motors, each with a lift capacity of 1,500 lbs. The drives will be synchronized in a master-slave control system to avoid binding. On the opposite corners there will be two follower shafts mounted to the drive frames, which will add stiffness during lift. To minimize deflection, a diagonal stiffener as well as a lower travers support have been added to each drive support frame.

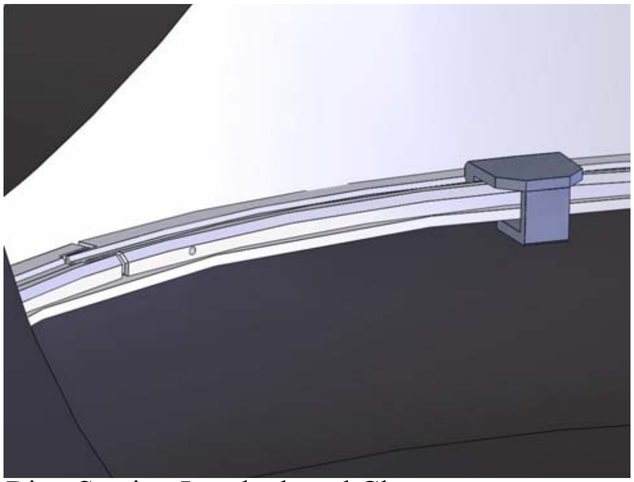


4. Lift Table – consists of a base-plate attached to a load supporting brace and two lift arms which bolts through the base-plate and attaches to the brace. The lift arm has an extended post which attaches to the linear drive. A recycled existing air bearing assembly complete with the X-Y-translation step for fine alignment is attached to the lift table base-plate. A tilt plate is attached to the air-bearing. Tilt is achieved by pushing on the bottom of the tilt plate with a set screw from either of the three tilt posts. Tilt is limited by the flexure of the X-Y-translation step attached to the air bearing. A high load capacity thrust bearing is embedded on top of the tilt plate, as well as four equally spaced transfer balls, to provide rotational alignment of the support plate. The rotational alignment may be limited by the slotted corners of the support plate.

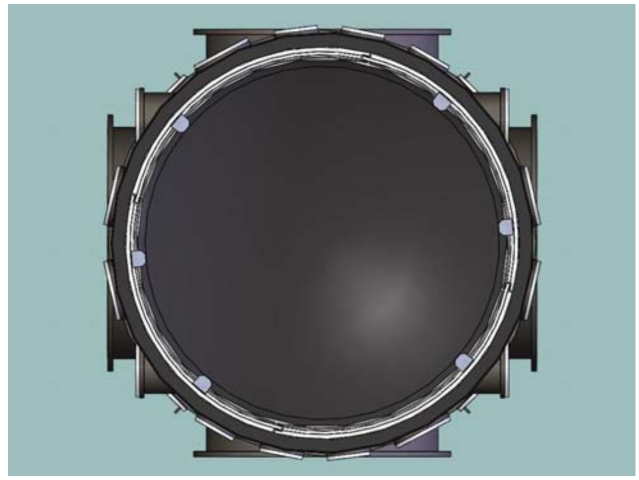


5. INSTALLATION

1. Support Ring Sections – insert the four sections through the BSC chamber door and position them on top of the existing flange, interlocking each section and using two clamps per section. The distance from the outer edge of the ring section and the chamber wall can be adjusted by set screws threaded through the inner edge of the ring sections. Clamps should be positioned with the desired placement of the support beam in mind.

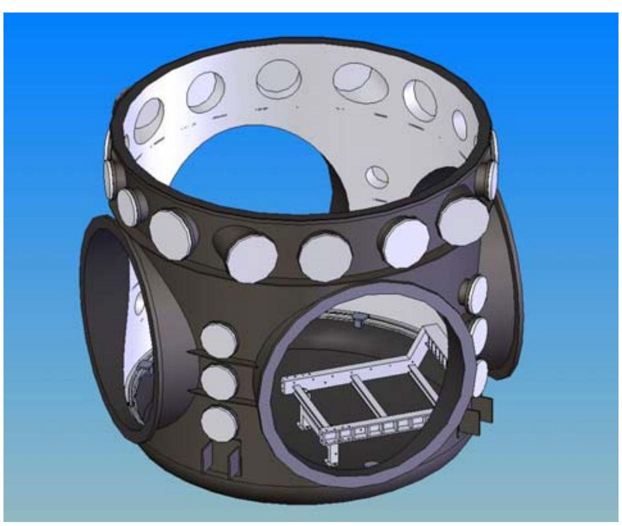


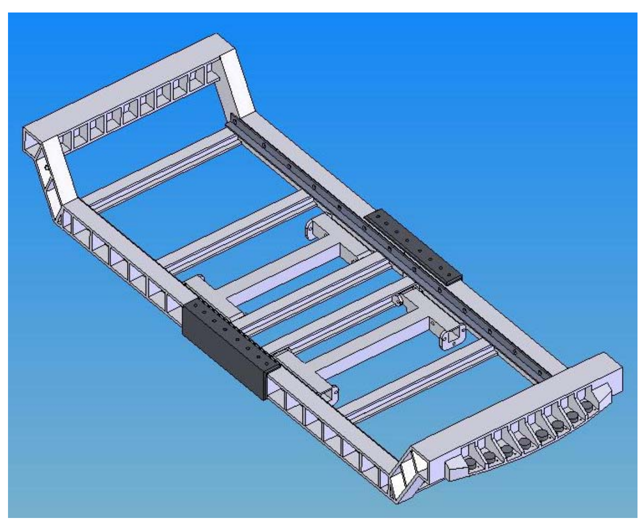
Ring Section Interlock and Clamp



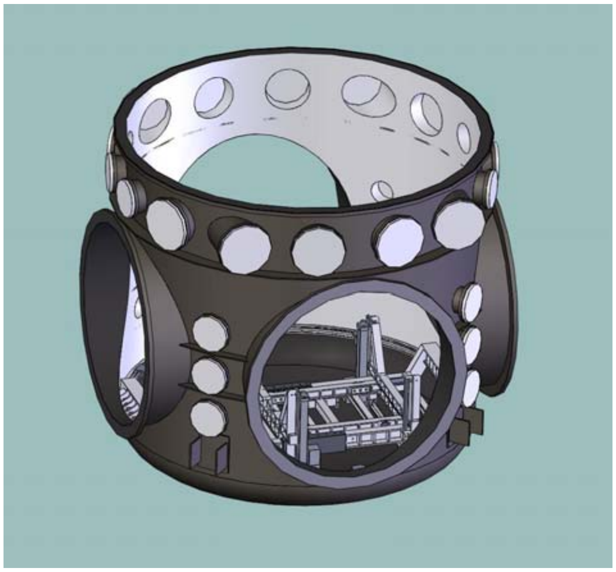
All four support ring sections installed

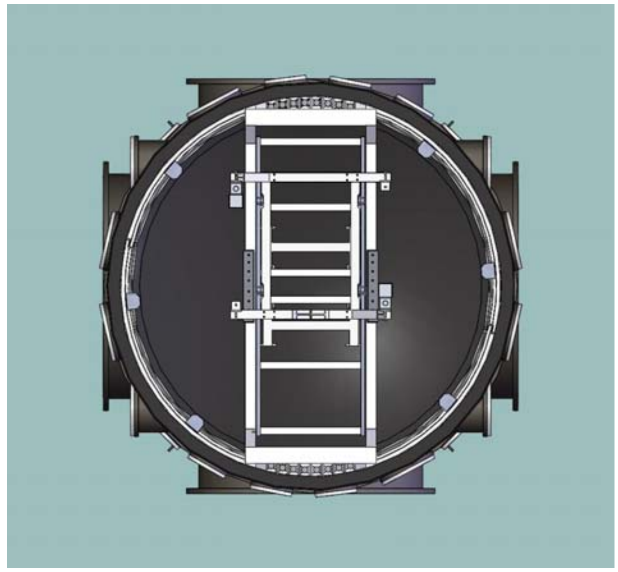
2. Support Beam Section – attach all transfer ball assemblies to both beam sections, then insert one of the support beam half-sides through the BSC chamber door with a fork-lift truck, placing the cylindrical end with the transfer balls into the track of the support ring sections. While supporting the beam section with the fork-lift truck, fold down the support legs so that the section rests on the bottom of the surface. Then insert the second beam section into the chamber and align it opposite of the first section, again supported on the fold-down legs. Level the two sections by use of the adjustable support legs. Carefully insert the two L-shaped rails through the chamber door and align holes pattern to the holes inside of each beam side, attach using flat head socket head bolts. Attach the two support beam sections by use of the stainless steel connection braces, and fold up the two pivoting support legs.





3. Transport Table – insert the pre-assembled transport table through the chamber door with a fork-lift truck and position it carefully onto the support beam, aligning the flanged rollers onto the rails, adjusting the distance from the roller flange to the support beam wall if necessary. Use the set screws located on the sides of the linear drive supports to pin down the transport table and lock its position before attaching the lift table. Note: - the same set screws will be used to lock the transport table in place while transferring the lower suspension section onto the support plate.



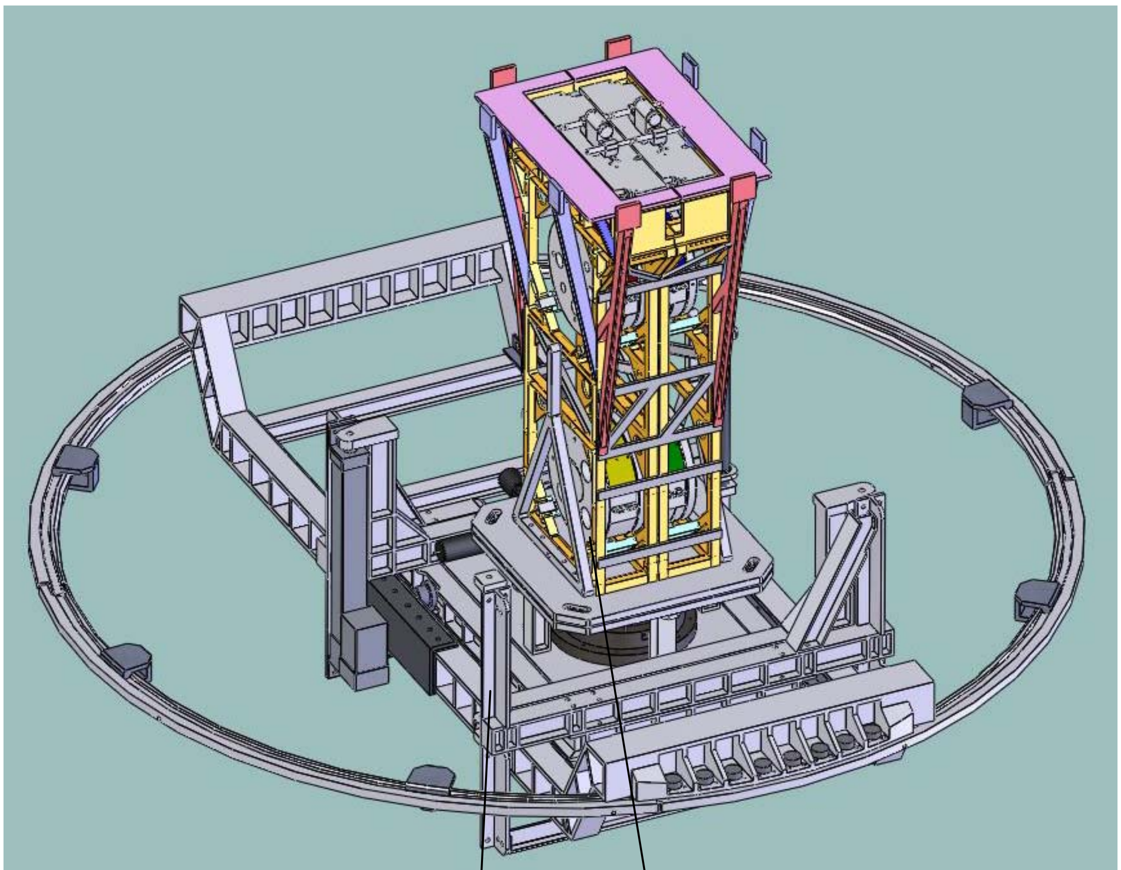


4. Lift Table – remove the follower shafts and shaft brackets on the transport table, then insert the pre-assembled lift table into the chamber door by use of fork-lift truck and carefully align the lift arms to the linear drive connections. Attach the lift arms to the drives and insert the follower shafts through the bronze sleeves on the lift arms, then secure the shafts with the L-shaped attachment brackets to the transport table drive support frames.

5. Control System – connect controllers for the linear drives and X-Y-translation steps. Check control operation, alignment and vertical range by driving the lift table to maximum lift.

6. OPERATION

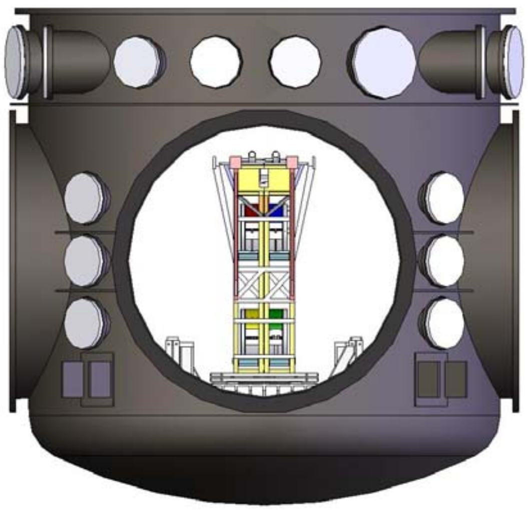
1. Receive and secure lower suspension section – position the transport table as close as possible to the chamber door where the suspension section will be transferred. Lock its position by use of the set screws pinning the table to the support beam. Lock the position of the support plate by tightening down the bolts between the tilt plate and support plate to avoid rotation and tighten the set screws in the tilt posts. With the lift table in its lowest position, carefully position the lower suspension section cage onto the support plate by use of the articulated arm. Install the lower suspension cage supports onto the support plate and bolt and attach it to the suspension cage, then release the connection between the suspension cage and the articulated arm and carefully withdraw the arm through the chamber door.



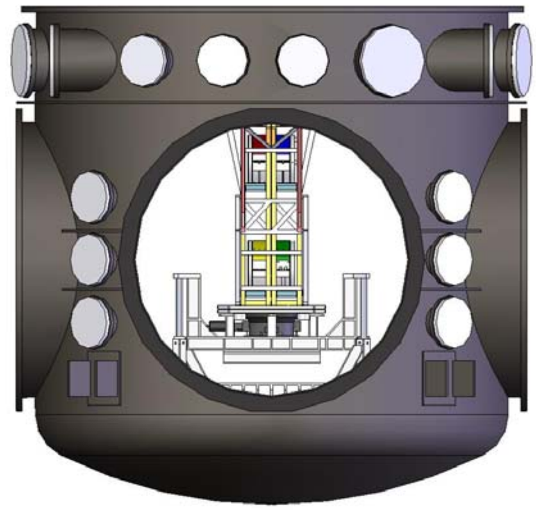
a) Move transport table as close to chamber door as possible and lock position by use of set screws pinning the linear drive frame to the support beam. Also lock position of Lazy Susan by using set screws to pin its position to the chamber flange.

b) Lock tilt and rotational motion of support plate and carefully transfer the lower suspension section onto the support plate. Install the cage support frames (triangles) to the support plate and attach cage to the frames.

2. Horizontal linear and rotational positioning of lower suspension section – release set screws locking the position of the transport table and the Lazy Susan and carefully slide transport table and/or rotate Lazy Susan until the suspension section is in approximate position directly below the upper section. Once again lock the position of the transport table and Lazy Susan before lifting the suspension section. Note: - it will take one minute using maximum speed to raise the lift table to its highest position.



Lift table in lowered position

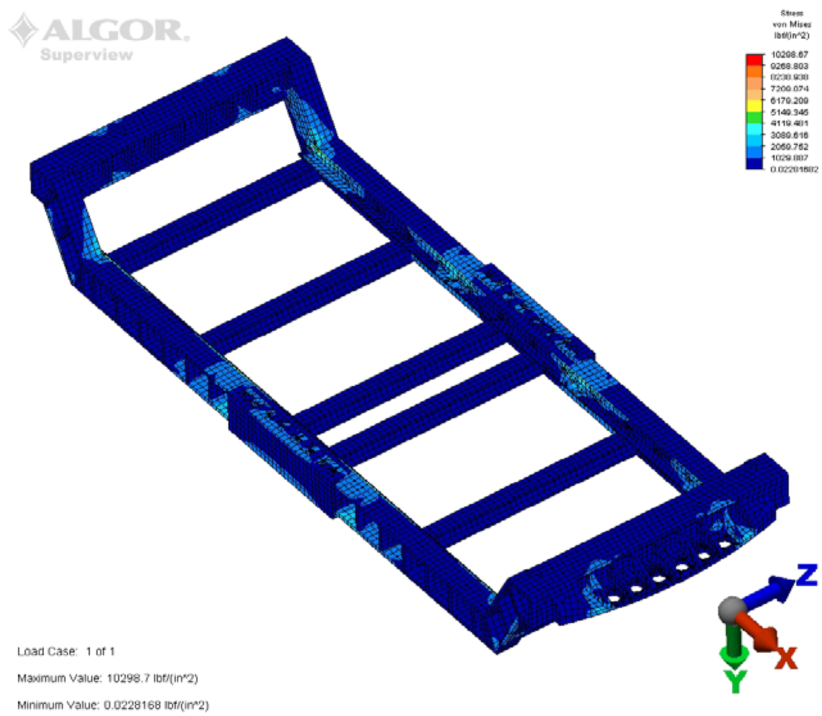


Lift table with maximum lift (15 inches)

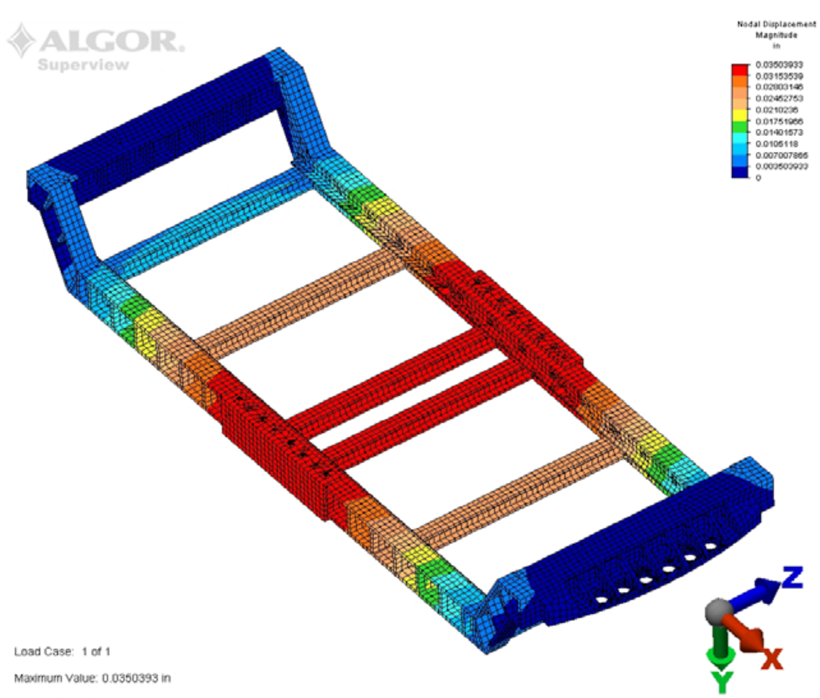
3. Horizontal X-Y-translational and rotational motion and vertical plane tilt fine alignment – with the lower suspension section lifted to approximately 1-2 inches below the upper section, release set screws locking the tilt and rotational motion of the support plate. Carefully raise the lower section to meet the upper while using the X-Y-translation step and the air bearing to align the section. Use rotational and tilt alignments as necessary. Attach the lower section to the upper and detach the support frames from the lower suspension section cage and lower the lift table. Carefully remove fixtures following reverse directions of installation.

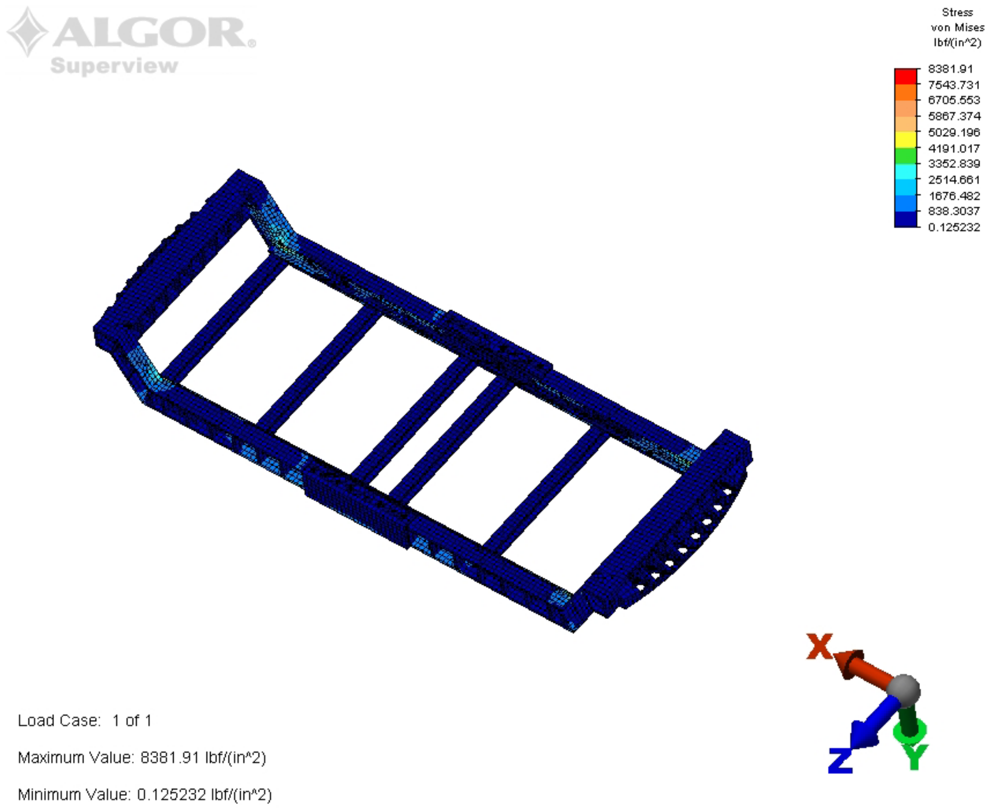
7. ANALYSIS

1. Support Beam – von Mises stress and deflection analysis of the support beam assembly, including connectors and rails have been studied for centered and offset load scenarios.

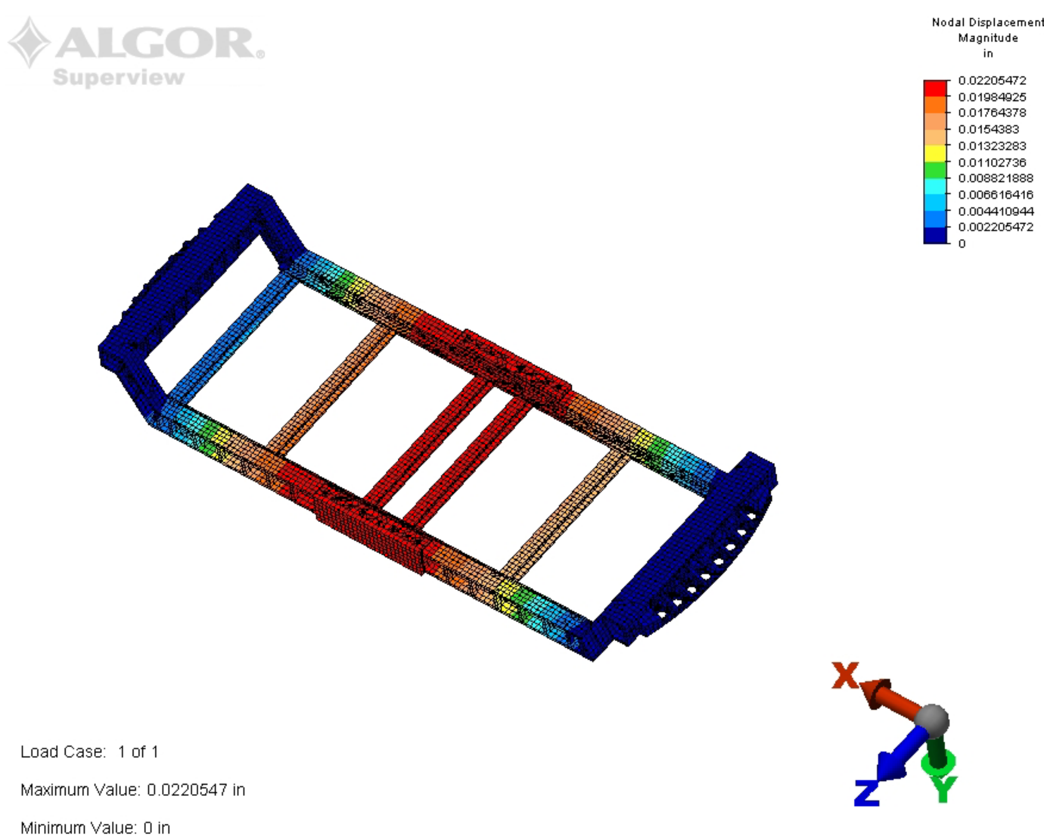


Stress and deflection analysis for a 3,000 lbs load evenly distributed on four load points centered on the stainless steel rails, estimates a maximum stress of 10,300 psi and a maximum deflection of .035 inches at the center of the beam.

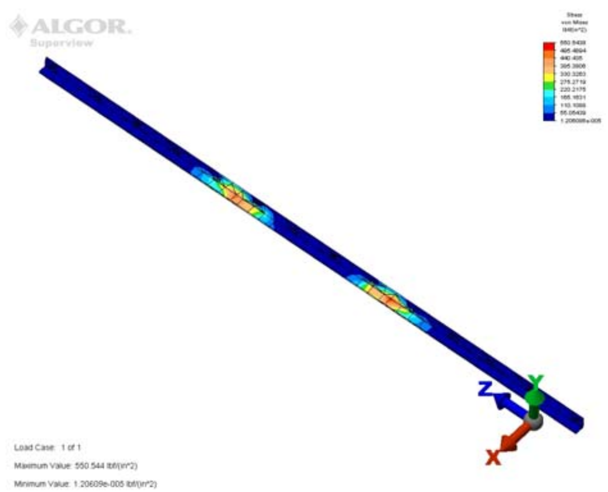


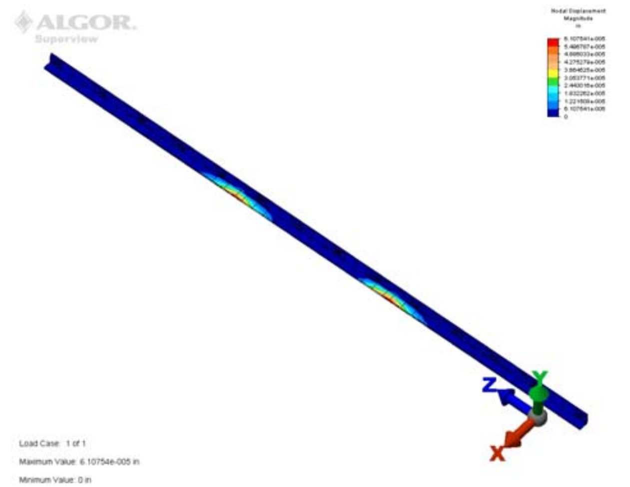


Stress and deflection analysis for a 3,000 lbs load at the maximum possible offset of the transport table evenly distributed on four load points on the stainless steel rails, estimates a maximum stress of 8,400 psi and a maximum deflection of .022 inches at the center of the beam.



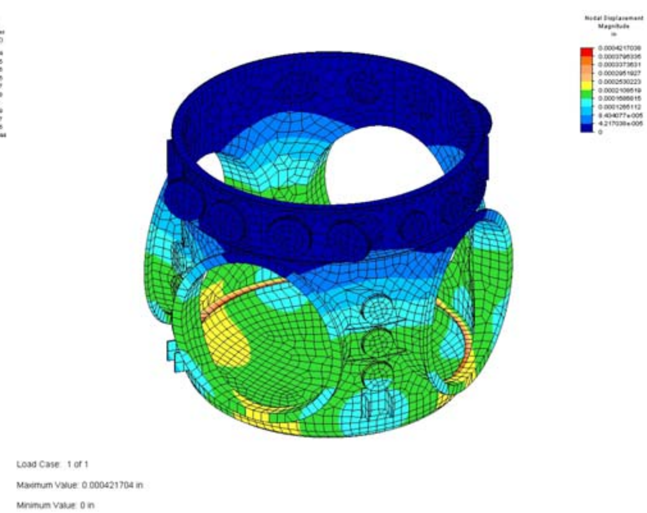
2. Support Beam Rails – von Mises stress and deflection analysis of the support beam rails for a evenly distributed four point load centered on the rails.





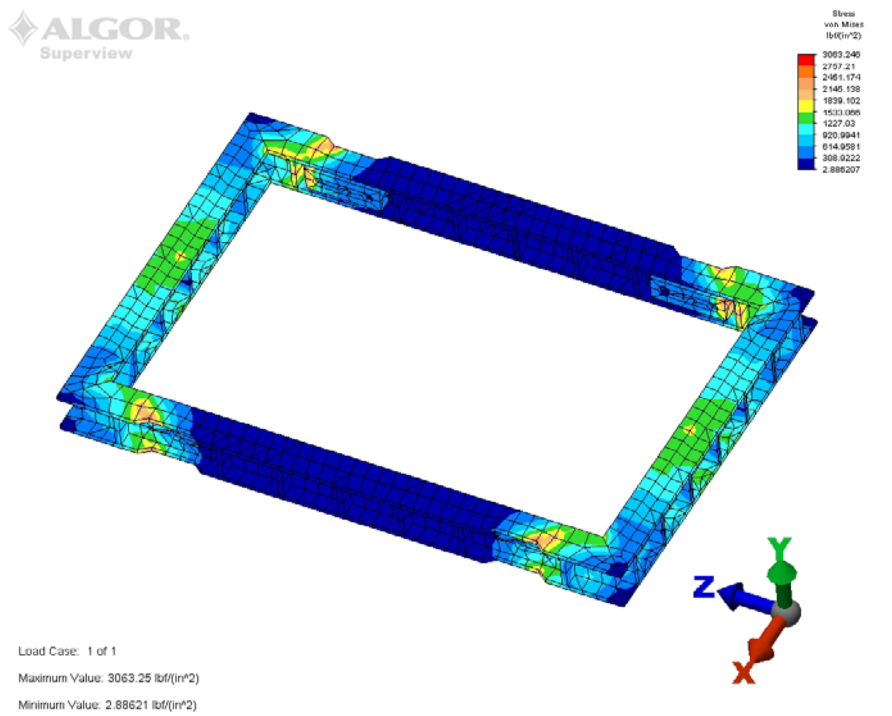
This analysis indicates no significant stress or displacement on the rails due to a 3,000 lbs load.

3. BSC Chamber and Flange – von Mises stress and deflection analysis of the BSC chamber and inner flange from a 3,500 lbs load evenly distributed on upper surface of the flange.

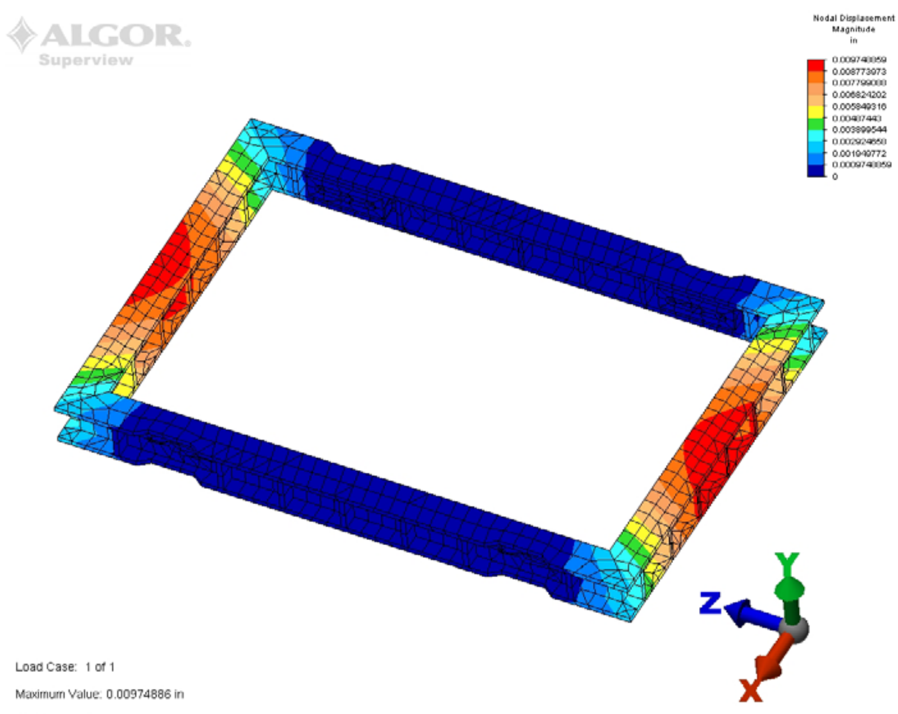


This analysis indicates no significant stress or displacement on the flange or chamber due to a 3,500 lbs load.

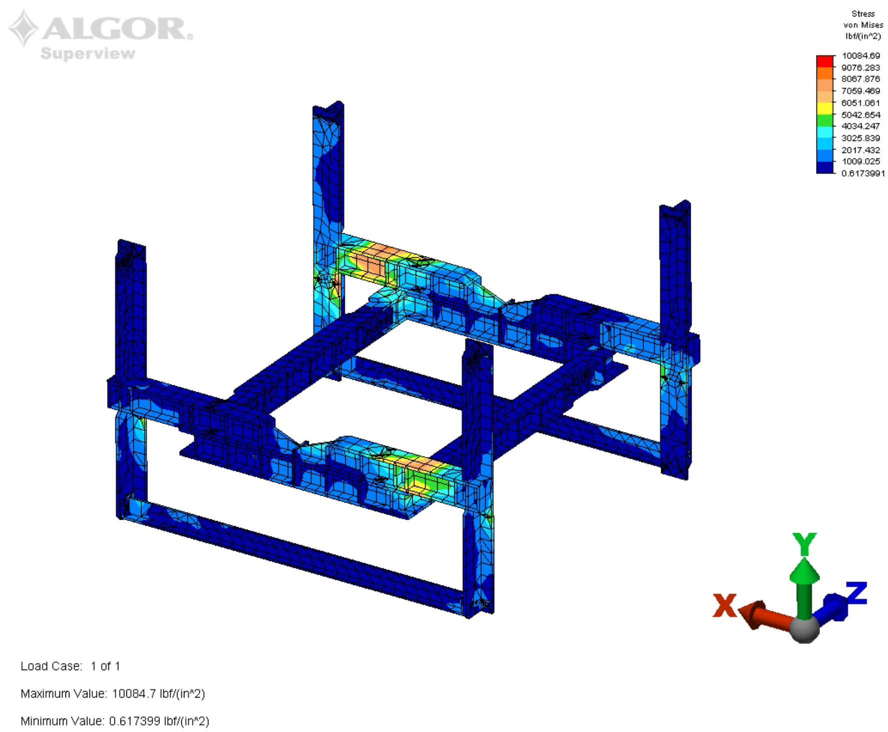
4. <u>Lower Transport Table Frame</u> – von Mises stress and deflection analysis of the lower transport table frame, load distributed evenly on each side of the frame where linear drive support frames attach.



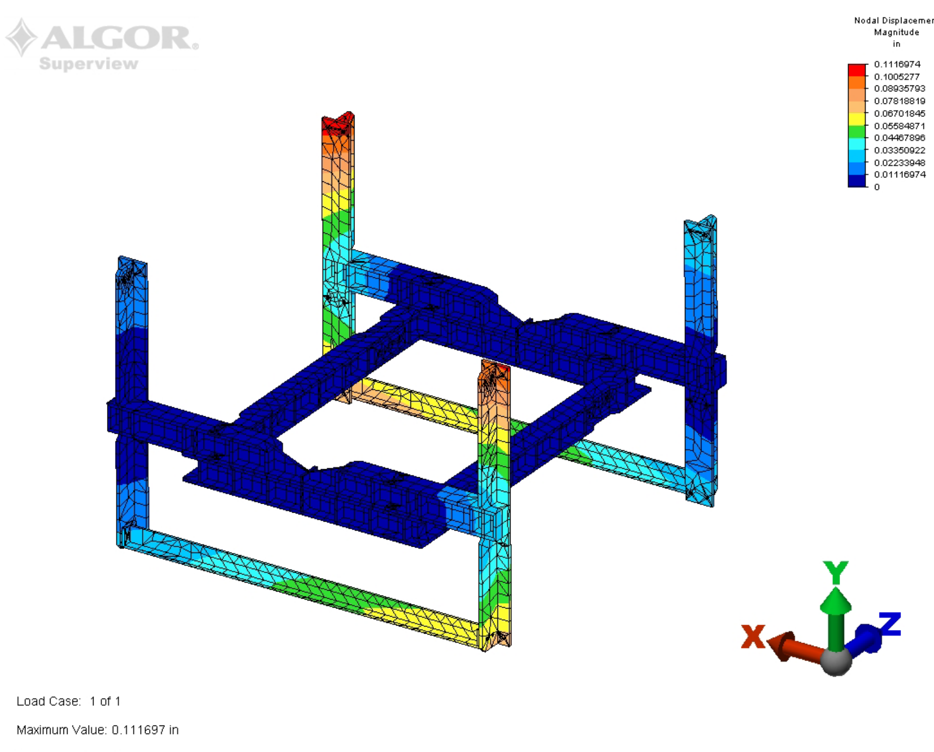
An evenly distributed load of 3,000 lbs, estimates a maximum stress of 3,100 psi and a maximum deflection of .001 inches.



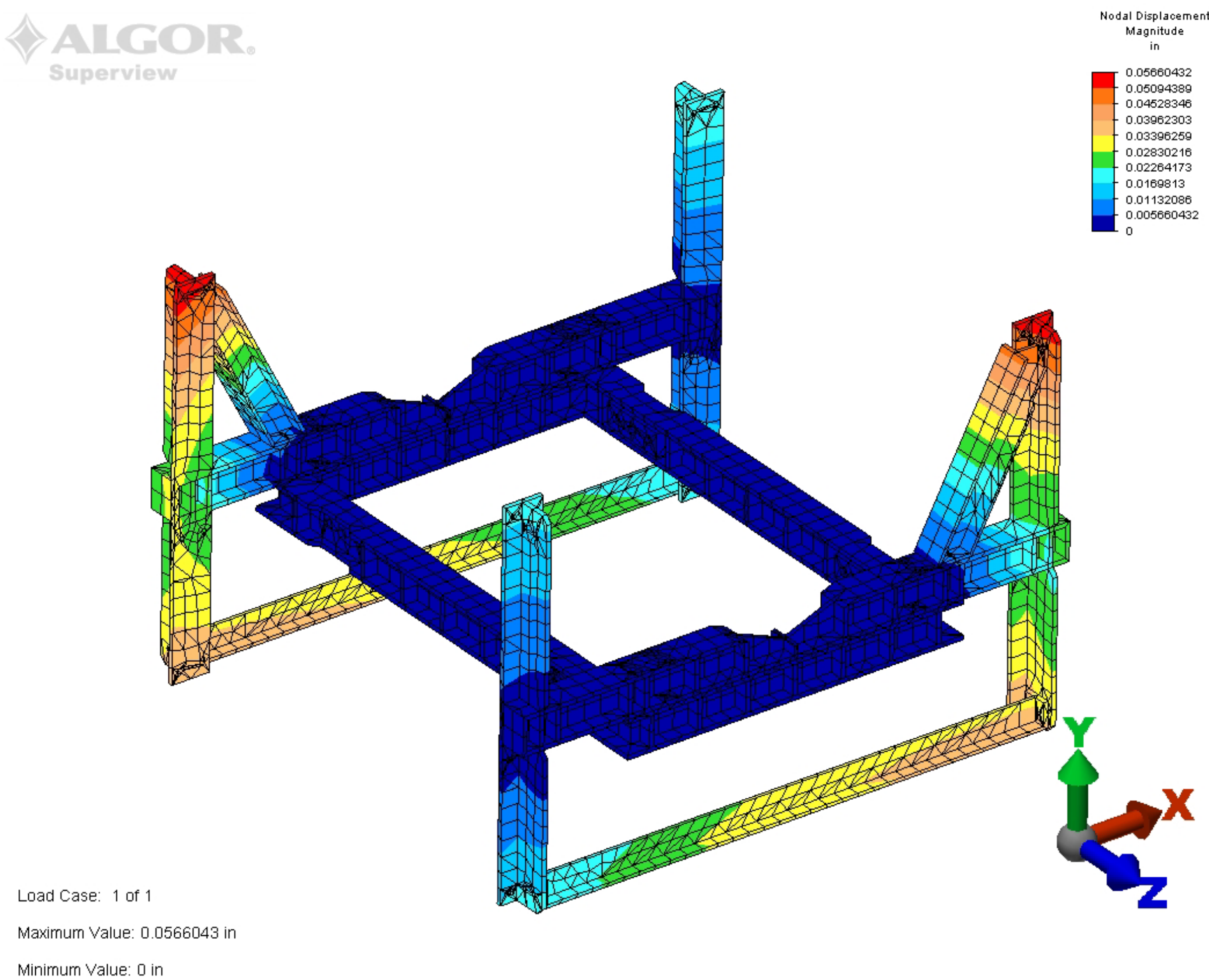
5. Transport Table – von Mises stress and deflection analysis of the transport table, with a -1,500 lbs vertical load on each drive support arm and a + 250 lbs vertical load on the follower shaft corners.



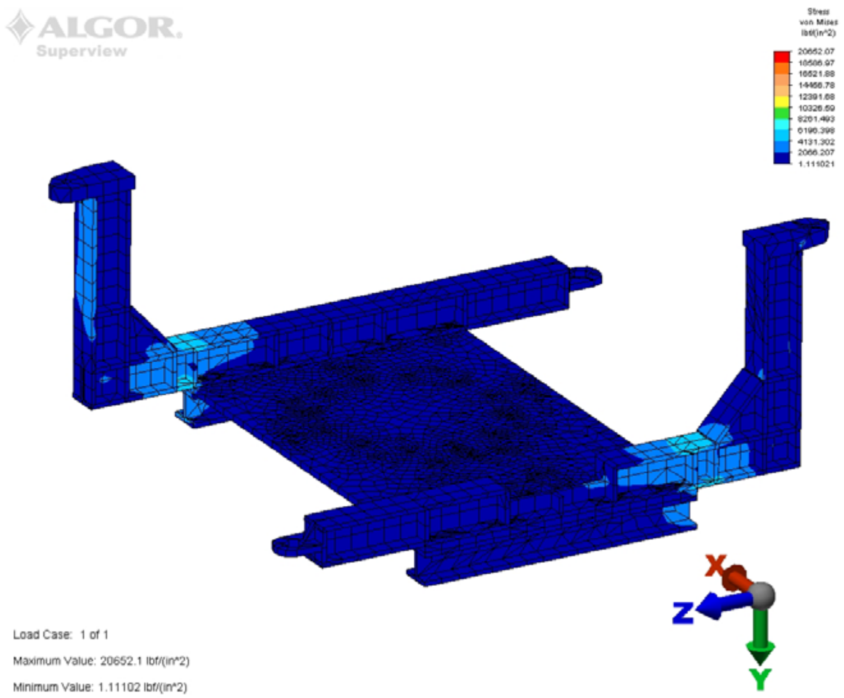
This load scenario yields an estimated maximum stress of 10,100 psi and a maximum deflection at the tip of the drive support arms of .112 inches, which is unacceptable considering the attachment of the linear drives.



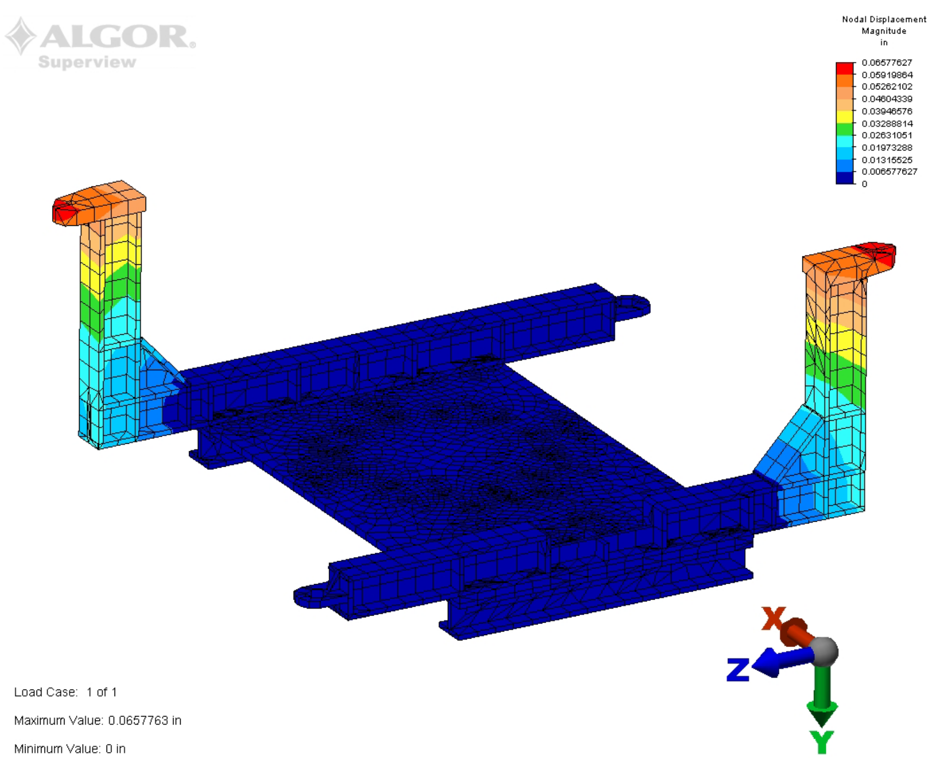
After adding two diagonal stiffeners to each of the drive support arms, the deflection of the arm tips were reduced to a maximum of .057 inches. Considering this as a worst case scenario and the additional stiffness gained to the structure from the linear drives, this result was considered acceptable.



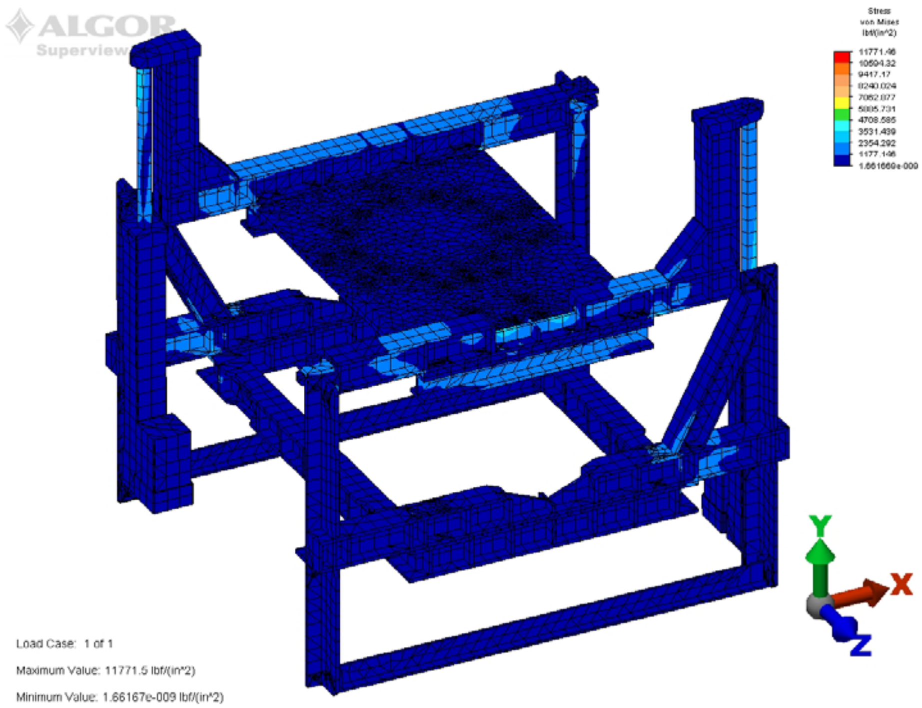
6. Lift Table – von Mises stress and deflection analysis of the lift table, with a + 1,500 lbs vertical load on each lift arm, a - 250 lbs vertical load on each of the follower shaft corners and a - 2,500 lbs vertical payload evenly distributed on the lift table surface.



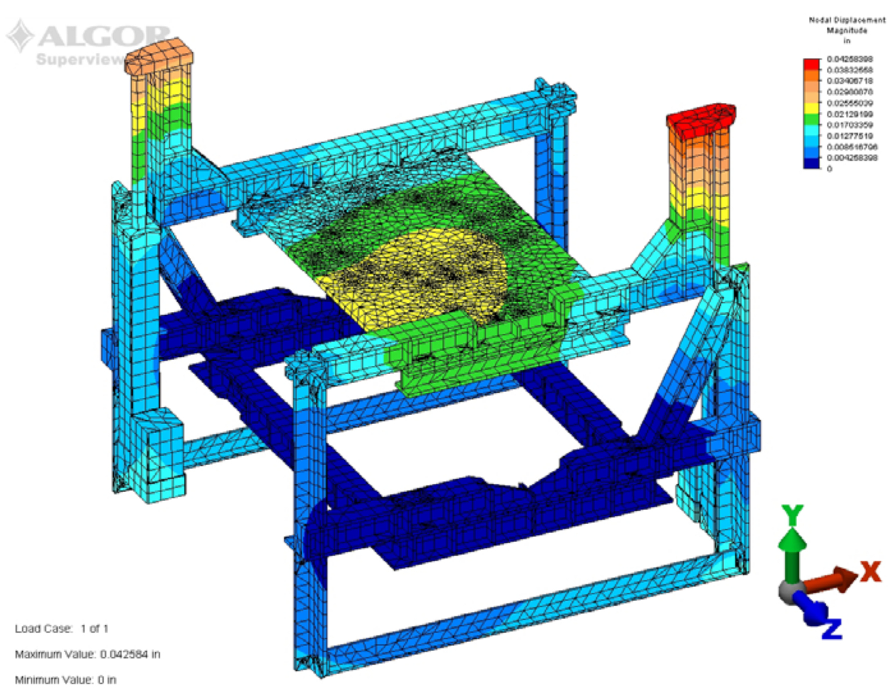
This load scenario yields an estimated maximum stress of 20,650 psi and a maximum displacement of .067 inches at the tip of the lift arms. The yield strength of Al 6061-T4 is 21,000 psi, which means that the worst scenario load case would borderline yield and thus do not satisfy the design requirements of a safety factor of two. Al 6061-T6 has a yield strength of 40,000 psi and would satisfy the design requirement, but may loose strength during heat treatment. However, it seems to be the only acceptable material selection for the lift table.



6. <u>Transport and Lift Table – Raised Position</u> - von Mises stress and deflection analysis of the transport and lift table assembly in maximum raised position, with a + 1,500 lbs vertical load on each lift arm, a - 250 lbs vertical load on each of the follower shaft corners and a - 2,500 lbs vertical payload evenly distributed on the lift table surface.



The estimated maximum stress for this load scenario is 11,770 psi and the maximum displacement is .043 inches at the tip of the lift arms.



8. MASS ESTIMATES

Lazy Susan

Support Beam Section	2 x	113 lbs	=	226 lbs
Beam Connection	2 x	28 lbs	=	56 lbs
Support Legs	2 x	10 lbs	=	20 lbs
Transfer Balls	16 x	1 lbs	=	16 lbs
Rails	2 x	16 lbs	=	32 lbs
Total Mass (without fasteners)				350 lbs

Support Ring

Support Ring Section	4 x	20 lbs	=	80 lbs
Beam Connection	8 x	4 lbs	=	32 lbs
Total Mass (without fasteners)				112 lbs

Transport Table

Lower Frame w/ Rollers	1 x	45 lbs	=	45 lbs
Drive Support Frame	2 x	23 lbs	=	46 lbs
Linear Drives	2 x	30 lbs	=	60 lbs
Lower Travers Support	2 x	4 lbs	=	8 lbs
Diagonal Stiffeners	2 x	3 lbs	=	6 lbs
Total Mass (without fasteners)				165 lbs

Lift Table

Lift Table Base Plate	1 x	36 lbs	=	36 lbs
Lift Table Support Brace	1 x	24 lbs	=	24 lbs
Lift Table Support Arm	2 x	17 lbs	=	34 lbs
Air Bearing Assembly	1 x	60 lbs	=	60 lbs
X-Y-Translation Step	1 x	30 lbs	=	30 lbs
Support and Tilt Plates	1 x	82 lbs	=	82 lbs
Tilt Support	3 x	1 lbs	=	3 lbs
Total Mass (without fasteners)				269 lbs
Total Mass of Installation Fixtures				**896 lbs**

9. COST ESTIMATES

Lazy Susan

Support Beam Section	2 x	$5,000	=	$10,000
Beam Connection	2 x	$400	=	$800
Support Legs	2 x	$800	=	$1,600
Ball Transfer	16 x	$100	=	$1,600
Rails	2 x	$700	=	$1,400
Total Estimated Cost				$15,400

Support Ring

Support Ring Section	4 x	$1,200	=	$4,800
Ring Clamp	8 x	$200	=	$1,600
Total Estimated Cost				$6,400

Transport Table

Lower Frame w/ Rollers	1 x	$1,800	=	$1,800
Drive Support Frame	2 x	$1,800	=	$3,600
Linear Drives w/Contrl.	2 x	$5,000	=	$10,000
Lower Travers Support	2 x	$750	=	$1,500
Diagonal Stiffeners	2 x	$400	=	$800
Total Estimated Cost				$17,700

Lift Table

Lift Table Base Plate	1 x	$800	=	$800
Lift Table Support Brace	1 x	$1,200	=	$1,200
Lift Table Support Arm	2 x	$1,500	=	$3,000
Air Bearing Assembly	1 x	0	=	0
X-Y-Translation Step	1 x	0	=	0
Support and Tilt Plates	1 x	$2,500	=	$2,500
Tilt Support	3 x	$250	=	$750
Total Estimated Cost				$8,250
Total Estimated Cost (+ 10% margin for cleaning)				**$52,525**