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Title:

APT/LEDA RFQ AND SUPPORT FRAME STRUCTURAL ANALYSIS

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1. Introduction

This report documents structural analysis of the Accelerator Production of Tritium Low Energy Demonstration Accelerator (APT/LEDA) Radio Frequency Quadrupole (RFQ) accelerator structure and its associated support frame. This work was conducted for the Department of Energy in support of the APT/LEDA. The conceptual design of this RFQ is fully described in references 1.1 and 1.2.

Structural analysis of the RFQ was performed to quantify stress levels and deflections due to both vacuum loading and gravity loading. This analysis also verified the proposed support scheme geometry and quantified interface loads.

This analysis also determined the necessary stiffness and strength requirements of the RFQ support frame verifying the conceptual design geometry and allowing specification of individual frame elements. Complete structural analysis of the frame was completed subsequently.

This report details structural analysis of the RFQ assembly with regard to gravity and vacuum loads only. Thermally induced stresses from the Radio Frequency (RF) surface resistance heating were not considered.

The specified structural performance requirements for the RFQ and support frame are listed in table 1.1.

Table 1.1
RFQ and Support Frame Structural Performance Requirements

Parameter	Maximum Value	Load Case
RFQ von Mises stress	5,000 psi	all encountered
Major vane A1 disp.	.0005 in.	simple support, gravity loading
RFQ vane tip radial disp.	.00025 in.	Vacuum
RFQ displacement	.005 in.	static, gravity loading
RFQ displacement	.005 in.	100 lb_f point load applied to RFQ
RFQ displacement	.010 in.	250 lb_f point load applied to frame

2. Radio Frequency Quadrupole

The eight-meter long APT RFQ consists of four resonantly coupled segments, each joined end to end[2.1]. Each segment is composed of two sections, each approximately one meter long. Each section is fabricated from four separate Oxygen Free Electroless (OFE) copper vane machinings, which are furnace brazed together. Sections are joined end to end with high strength Glidcop™ alloy flanges. One flange is brazed to each end of each section. These flanges also provide external suspension points for the assembled and installed RFQ. Figure 2.0.1 depicts the assembled eight-meter RFQ schematic[2.2].

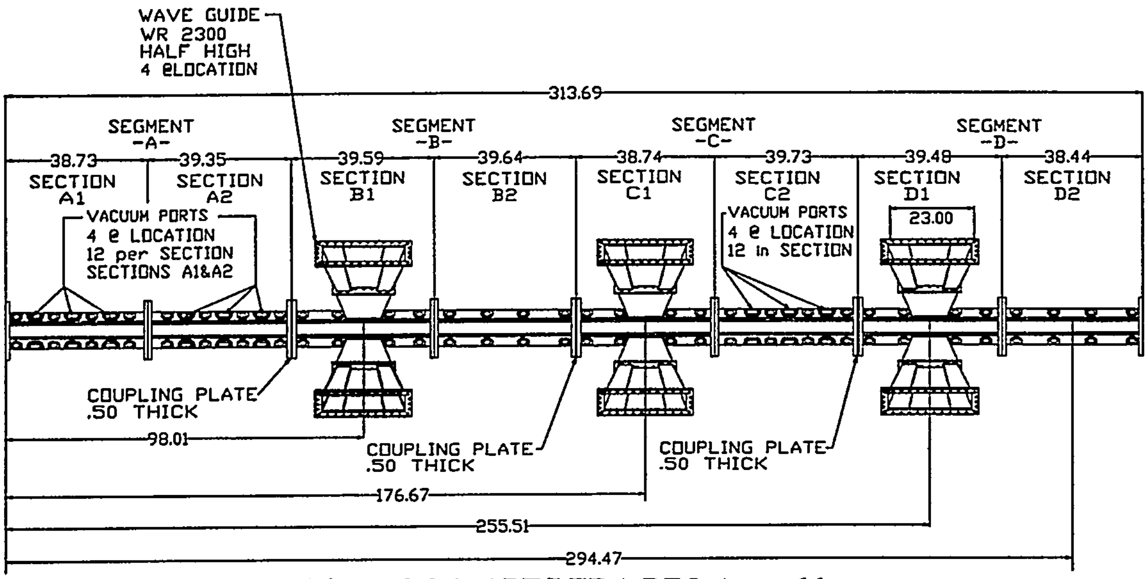


Figure 2.0.1, APT/LEDA RFQ Assembly

The majority of the RFQ is fabricated of OFE copper, base alloy C10100, procured to ASTM F68-93, class 2. This particular alloy possesses superior thermal conductivity, which minimizes thermal distortion and induced loads due to RF surface heating. A significant drawback of this material is its low allowable mechanical yield stress. This shortcoming necessitates careful study of all structural loads to insure suitable structural integrity.

The electro-magnetic resonant frequency of the RFQ cavity is defined by the geometry of the interior surface. Distortion of the RFQ interior will shift the cavity resonant frequency. Structural analysis is necessary to determine surface displacements during structural loading and thus quantify resonant frequency shift.

The two primary structural loads encountered by the RFQ are vacuum loading and gravity loading.

The RFQ interior is evacuated during operation inducing considerable loads. All vacuum loads are reacted solely by the RFQ structure; separate external structure is not utilized. Gravity loading acts on the RFQ while it is suspended in its support frame.

Each RFQ detail part is machined from rolled plate. Wrought sections typically exhibit slight anisotropy. Elastic modulus, Poisson's ratio and tensile strengths may vary up to 10 percent, dependent upon local material direction. After furnace brazing, all components will be fully annealed, thus any anisotropy present from the initial forming operations will be removed. All analysis described herein neglects the material anisotropy and assumes uniform isotropic material behavior.

Each RFQ section is formed of many separate detail components, all of which are brazed together. The joints are all very high quality joints made between accurately machined surfaces in a tightly controlled environment. The product is a joint that possesses stiffness and strength matching the parent material. This feature eased the modeling task by permitting the brazed assemblies to be modeled as one contiguous homogenous part.

Table 2.0.1
RFQ Room Temperature Material Mechanical Properties

Property	OFE Copper, ASTM F68-93	Glidcop™ AL-15 Alloy[2.3]
density	0.323 lb_f/in^3	0.321 lb_f/in^3
modulus of elasticity	16.5e6 psi	17.0e6 psi
Poisson's ratio	0.3	0.3
tensile yield strength	7,000 psi	37,000 psi
thermal expansion coeff.	9.5e-6 in/in °F	9.4e-6 in/in °F
thermal conductivity	226 Btu/hr-ft-°F	211 Btu/hr-ft-°F
condition	fully annealed	stress relieved

Glidcop™ alloy is similar to OFE copper concerning thermal properties but differs in its superior tensile strength. Highly stressed portions of the RFQ such as sealing surfaces for metallic seals or bolted flanges are fabricated of Glidcop™. Joints formed between Glidcop™ alloy and the OFE copper exhibit the same behavior, below the yield strength limit of OFE. The coefficient of thermal expansion for the two metals is similar so minimal residual stress is developed during the braze process thermal cycle. The mechanical properties for OFE and Glidcop™ are listed in table 2.0.1. Glidcop™ AL-15 is also designated in UNS as C15715.

2.1 RFQ Structural Analysis

The RFQ is a geometrically complicated structure. Numerous sizable vacuum ports, RF feed ports, slug tuner ports, and coolant channels have substantial impact on the structural behavior of RFQ; thus it was necessary to incorporate these features in each of the structural models. Figure 2.1.1.1 depicts one of the finite element meshes utilized. The models are very representative geometrically. However, small features with negligible mass or added structure such as bottom tapped fastener holes were not included in the model.

All models were generated with Patran, version 5.0, from an IGES file exported from Unigraphics. The IGES file was created from the Unigraphics A1 major vane machined part model, dated 29 January, 1996. Numerical solution and post processing were performed with Abaqus and Abaqus Post, version 5.5-1, respectively.

All modeling was performed utilizing elements with quadratic shape functions. In every case, separate meshes of higher mesh density were utilized to verify mesh quality and thus solution accuracy. Solution quality verification internal to the analysis code was also utilized.

Four separate analyses were performed, each is listed below.

1) Major vane A1, gravity loading
2) Section A1, vacuum loading
3) Section A1, structural characterization
4) RFQ Assembly, gravity loading

2.1.1 Major Vane A1

The major vane A1 is one of the two major vanes belonging to the first RFQ section. Each section is made of two major and two minor vanes. The vane model matched geometry after final machining. The model also represents the vane configuration during the final pre-braze alignment process. No secondary hardware, i.e., vane tips or coolant channel covers, have been added.

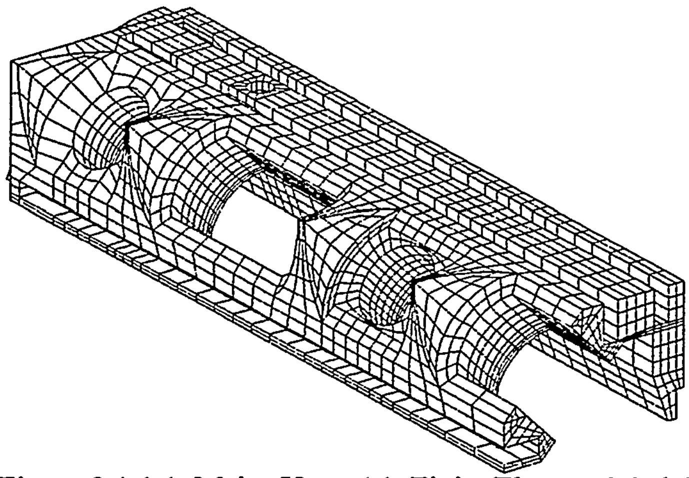


Figure 2.1.1.1, Major Vane A1, Finite Element Model

The model was subjected to gravity loading only. Simple statically determinate support is provided at the four threaded Keensert bosses. One of the Keensert bosses is present in the one-quarter symmetry mesh depicted in figure 2.1.1.1. This configuration and loading simulate handling, inspection and the final pre-braze alignment of the major vane machining. Due to symmetry about the vane length and width, modeling of only one quarter of the vane was necessary.

This quarter vane model consists of 5883 quadratic hex elements providing 89,000 degrees of freedom. The average element length dimension is .31 inches.

The induced stress and deflections due to the gravity load were calculated. Figures A.1 through A.4 depict deflection quantities, von Mises stress, and the deformed shape. The maximum deflection is 0.0003 inches, at the outer edges of the longitudinal vane center. The maximum von Mises stress is 260 psi.

2.1.2 Section A1, vacuum loading

Deflections and induced stresses due to vacuum loading were determined utilizing the model depicted in figure 2.1.2.1. The model depicted consists of 4181 quadratic hex elements providing 65,000 degrees of freedom. The average element length dimension is .58 inches.

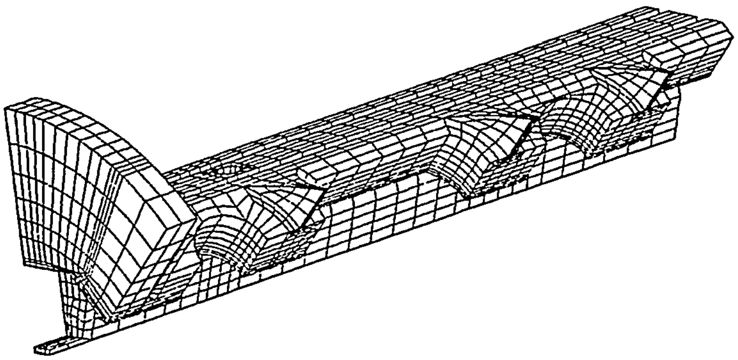


Figure 2.1.2.1, Section A1, Finite Element Model, Vacuum Load Case

Symmetry of the section and also loading permitted use of the one-sixteenth section model. Deflections normal to each of the cutting planes was restrained, simulating the symmetry at each cutting plane.

As depicted in the drawing, this model includes the Glidcop™ flange at each section end. This flange provides substantial radial stiffness to the RFQ and thus is important when considering vacuum loading.

This model is conservative in that, for simplicity, the coolant channel covers and flanging which is brazed at each vacuum and RF feed port was not included. The addition of these components will enhance stiffness and reduce overall displacements and induced stress levels. The RFQ vane tips were not included to simplify the model. The vane tips are located very close to the RFQ axis thus contribute little to the overall section stiffness.

A pressure of minus 14.7 psi was applied to all internal surfaces to mimic vacuum loading. A uniform pressure was applied to the axial symmetry cut simulating the compressive load acting along the RFQ. A uniform pressure of 4.0 psi was also applied to the circular flange surface where each slug tuner attaches. This uniform pressure simulates the vacuum load reaction induced by the slug tuner into it's mounting port. This procedure was not necessary for the oval vacuum pumping ports because these ports are structurally isolated with metal bellows assemblies.

A sea level vacuum load of 14.7 psi was utilized. Deflections and stress levels must be reduced by 11.3 /14.7 or 0.77 for vacuum loading at the elevation of Los Alamos. This scaling is permissible because at these load levels, structural behavior is linear elastic.

Figures A.5 and A.6 depict the vertical and lateral displacement quantities. The maximum calculated displacement is 0.0002 inches, at the longitudinal section center. Here, each vane tip will displace radially inward 0.0002 inches. This calculated value is greater than that for the actual hardware due to conservative simplifications made during analysis.

Von Mises stress is depicted in figure A.7. The von Mises stress maximum is 1140 psi, and occurs at the bottom of the longitudinal coolant passages. The calculated stress levels at this location are much greater than those, that will be encountered in service. The brazed coolant channel covers, which are not included in the model, will greatly reduce bending loads at the channel base. This bending load reduction will substantially reduce the associated stress levels.

2.1.3 Section A1, Structural Characterization

Overall structural behavior of a single RFQ section was used to develop an equivalent beam for the RFQ assembly. This was desired to simplify determination of overall system structural behavior and also determination of the support structure requirements for the entire 8 meter long RFQ. Simulating the RFQ assembly as a slender beam of uniform cross section greatly simplifies analysis of the RFQ and the RFQ when installed within its support frame. The brazed section assembly exhibits adequate uniform beam behavior permitting the equivalent uniform cross-section beam simplification.

The fully brazed section A1 assembly is depicted in figure 2.1.3.1. The finite element mesh utilized is depicted in figure 2.1.3.2. Symmetry permitted the use of a one half-symmetry model. Again, displacements normal to the symmetry cutting plane of zero were imposed.

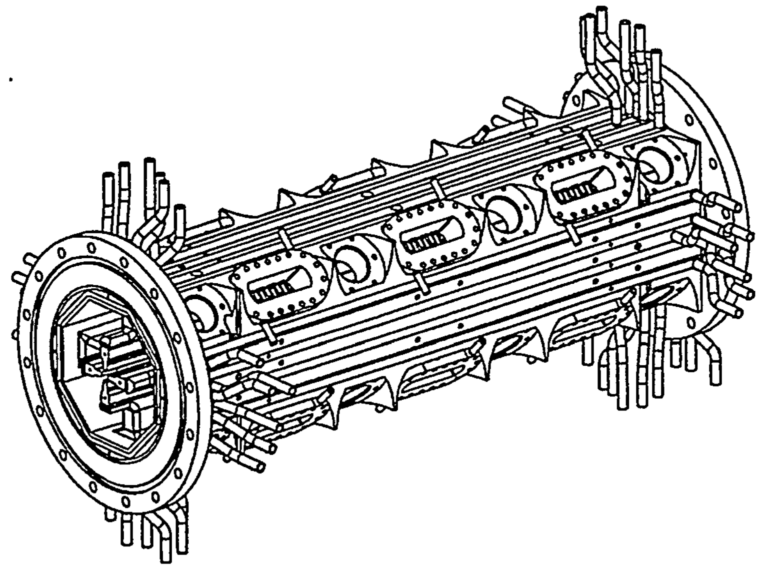


Figure 2.1.3.1, Section A1 Assembly

Three different load conditions were applied to this model to determine the associated simple beam cross section properties.

The first load case consisted of cantilever support for the section with a point load applied at the free end. The second load case consisted of cantilever support with a couple applied to the free end. The third load case consisted of a pure axial load. Tip deflection and rotation from the first two cases and the axial compression calculated with the third load case permitted calculation of approximate section properties for the equivalent beam. Figure A.8 depicts vertical displacement for the second load case. Figure A.9 depicts axial strain. The axial strain distribution is quite uniform along the length of the RFQ, just as the distribution would be for a constant cross-section beam loaded in bending.

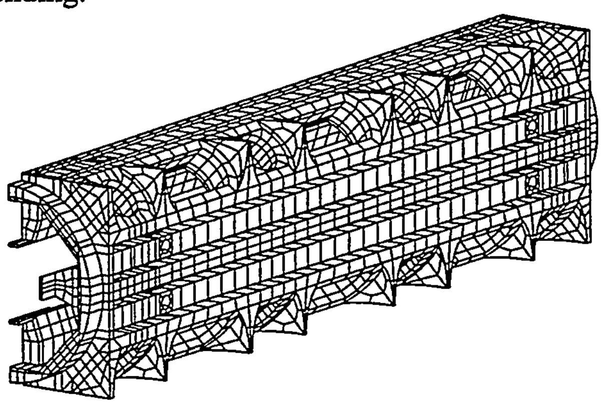


Figure 2.1.3.2, Section A1, Finite Element Model, Structural Characterization

The deformed shape of the derived simple beam model closely matches that of the complex 3-D model when loaded laterally. Shear deformation is very small relative to displacement due to bending. The deformed shape due to bending is reasonably smooth. The portions of the RFQ section where the vacuum ports or RF feed ports are located is not as stiff as the bulk RFQ but the deformed shape of the calculated constant cross section beam closely matches that of the actual RFQ section. Table 2.1.3.1 lists the nominal RFQ cross-section properties calculated.

Table 2.1.3.1
Nominal RFQ Cross-Section Properties

Area	Ixx	Iyy	J
26.4 in^2	212.6 in^4	212.6 in^4	425.2 in^4

The cross sectional area listed above corresponds to that necessary to provide the axial compliance exhibited by the detailed model. This area is less than the average cross sectional area of the actual RFQ. Calculations utilizing this quantity must incorporate a modified density of .602 lb_f/in^3 to accurately reflect the actual RFQ cross sectional weight. This modified weight also includes a contingent for all additional hardware that will be brazed of mechanically fastened to the completed RFQ.

The RFQ structural behavior when fully assembled will be notably improved. The bending stiffness of the section as studied is somewhat limited by the sizable vacuum ports and RF feed ports. These ports are large and substantially reduce bending stiffness. The completed RFQ will have additional components such as RF grills and interface flanging brazed or bolted to these ports. This additional hardware will enhance section stiffness and thus reduce displacements and induced stress levels.

The longitudinal coolant channel covers, which are brazed in place, will also enhance stiffness. These covers were not included in the model for simplicity. The calculated displacements and stress levels are conservative in this respect. The model utilized for this study, depicted in the figures, consists of 4300 quadratic hex elements providing 76,000 degrees of freedom. The average element length dimension for this model is .58 inches.

2.1.4 Complete RFQ Assembly

A simple beam element model of the assembled RFQ was constructed to study the support scheme with various loading conditions. The model incorporated appropriate boundary conditions simulating the actual configuration when the RFQ is installed within its support frame. This simple model consists of 42 quadratic 3-D beam elements providing 420 degrees of freedom. The properties for these beam elements were those described in section 2.1.3. The average element length dimension is 8.8 inches. An adjusted RFQ total weight of 5000 lb_f was used for this study. Shear and bending moment diagrams were created utilizing Mathematica, version 2.0.3, enhanced.

Tensile stress due to bending was calculated based on a uniform beam height of 9.658 inches. This is the nominal RFQ height as described by reference 2.4. The stress values calculated are based on a constant cross section beam simulating the RFQ. This approach neglects local stress concentration points present in the actual 3-D RFQ. This simplification is suitable when considering the very large margin, which exists between the calculated tensile stress values and the available material tensile yield strength.

Three particular load cases were studied. The first load case depicts typical in-service gravity loading. The two subsequent cases predict RFQ loading if one of the vertical supports is removed, for maintenance or repair. The three load cases are listed below.

1) Gravity loading, all vertical links installed
2) Gravity loading, center vertical link removed
3) Gravity loading, end vertical link removed

2.1.4.1 Complete RFQ, Gravity loading
The mount scheme for the RFQ is depicted in figure 3.01 and 3.2.1. Five total vertical links are spaced every two meters along the RFQ to support the gravity load. The support links do not introduce bending moments into the RFQ. Spherical joints are placed at each link end for this purpose. Figure 2.1.4.1.1 depicts the vertical "sag" (magnified) of the RFQ when suspended in this manner. The vertical and lateral support links are shown in this figure. The rotational and axial constraint links are not depicted but were included in the analysis. Maximum vertical displacement or "sag" occurs approximately 1.1 meters from either end of the RFQ. Displacement at these locations is 0.0012 in. Maximum bending tensile stress for this loading condition is 240 psi.

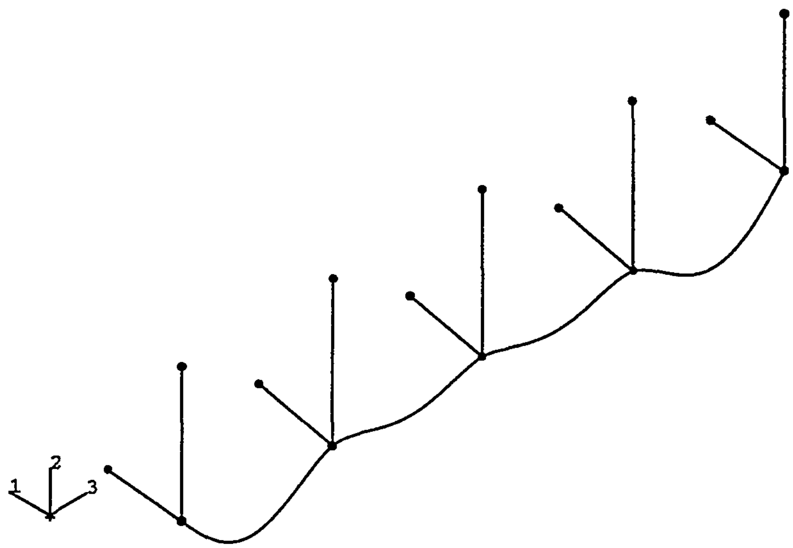


Figure 2.1.4.1.1, RFQ, Gravity Loading, Deformed Shape

Table 2.1.4.1.1 lists vertical support link tensions. Table 2.1.4.1.2 lists the maximum cross-section shear and bending moment and associated location. Figure 2.1.4.1.2 depicts bending moment and shear along the RFQ for this load case.

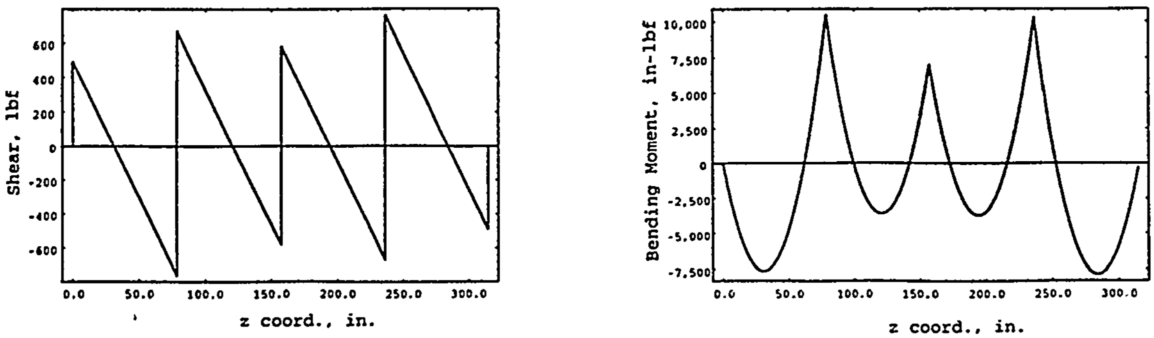
Table 2.1.4.1.1
RFQ Vertical Support Link Loads, Gravity Loading

Mount	Z coordinate	Load
1	0.0 m	497 lb_f
2	2.0 m	1413 lb_f
3	4.0 m	1182 lb_f
4	6.0 m	1413 lb_f
5	8.0 m	497 lb_f

Table 2.1.4.1.2
Maximum Cross-section Shear and Moment, Gravity Loading

Maximum shear force	Max. bending moment
758 lb_f	10,440 in-lb_f
@ mount point #2 and #4	@ mount point #2 and #4

Figure 2.1.4.1.2
RFQ Shear and Bending Moment, Gravity Loading



2.1.4.2 Complete RFQ, Gravity Loading, center link removed

This load case is identical to that described in the prior section except that the center vertical support link has been disconnected. This causes a maximum vertical displacement of .0121 inches at the RFQ center. The maximum tensile bending stress encountered is 630 psi.

Table 2.1.4.2.1
RFQ Vertical Support Link Loads
(gravity loading, center link disconnected)

Mount	Z coordinate	Load
1	0.0 m	274 lb_f
2	2.0 m	2226 lb_f
3	4.0 m	disconnected
4	6.0 m	2226 lb_f
5	8.0 m	274 lb_f

Table 2.1.4.2.2
Maximum Cross-section Shear and Moment
(gravity loading, center link disconnected)

Maximum shear force	Max. bending moment
1250 lb_f	27,606 in-lb_f
@ mount point #2 and #4	@ mount point #2 and #4

Figure 2.1.4.2.1
RFQ Shear and Bending Moment
(gravity loading, center link disconnected)

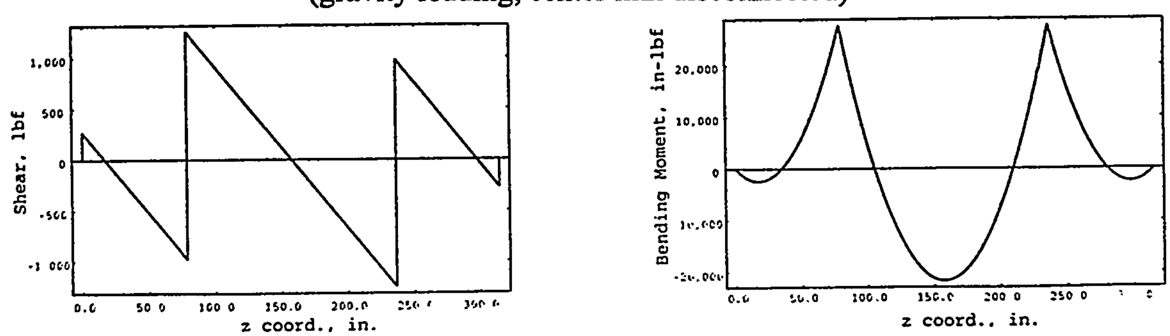


Table 2.1.4.2.1 lists support link tensions. Table 2.1.4.2.2 lists the maximum cross-section shear and bending moment with associated location present when the RFQ is supported in this manner. Figure 2.1.4.2.1 depicts bending moment and shear along the RFQ for this particular load case.

2.1.4.3 Complete RFQ, Gravity Loading, end link removed

This load case is identical to that described in section 2.1.4.1 except that the end vertical support link has been removed. Maximum vertical displacement of .0433 inches occurs at the cantilevered end. The maximum tensile bending stress encountered is 1120 psi.

Table 2.1.4.3.1 lists support link tensions. Table 2.1.4.3.2 lists the maximum cross-section shear and bending moment along the RFQ when the RFQ is supported in this manner. Figure 2.1.4.3.1 depicts bending moment and shear along the RFQ for this particular load case.

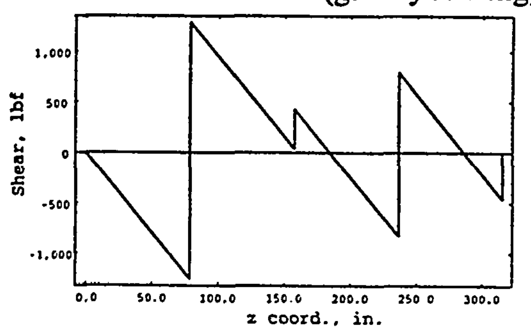
Table 2.1.4.3.1
RFQ Vertical Support Link Loads
(gravity loading, end link disconnected)

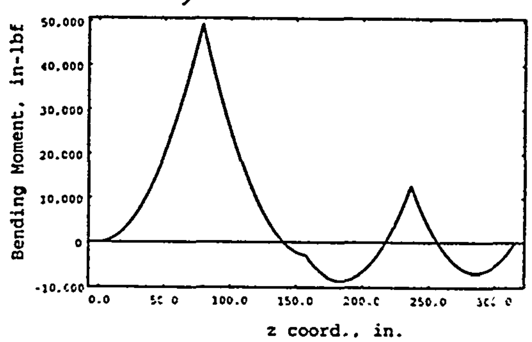
Mount	Z coordinate	Load
1	0.0 m	disconnected
2	2.0 m	2537 lb_f
3	4.0 m	388 lb_f
4	6.0 m	1614 lb_f
5	8.0 m	461 lb_f

Table 2.1.4.3.2
Maximum Cross-section Shear and Moment
(gravity loading, end link disconnected)

Maximum shear force	Max. bending moment
1287 lb_f	49,212 in-lb_f
@ mount point #2	@ mount point #2

Figure 2.1.4.3.1
RFQ Shear and Bending Moment
(gravity loading, end link disconnected)





3.0 RFQ Support Frame

The support frame, depicted in figure 3.0.1, provides all structural support for the RFQ assembly. The frame geometry was optimized to maximize available space around the RFQ for equipment and personnel access and also provide efficient structural support.

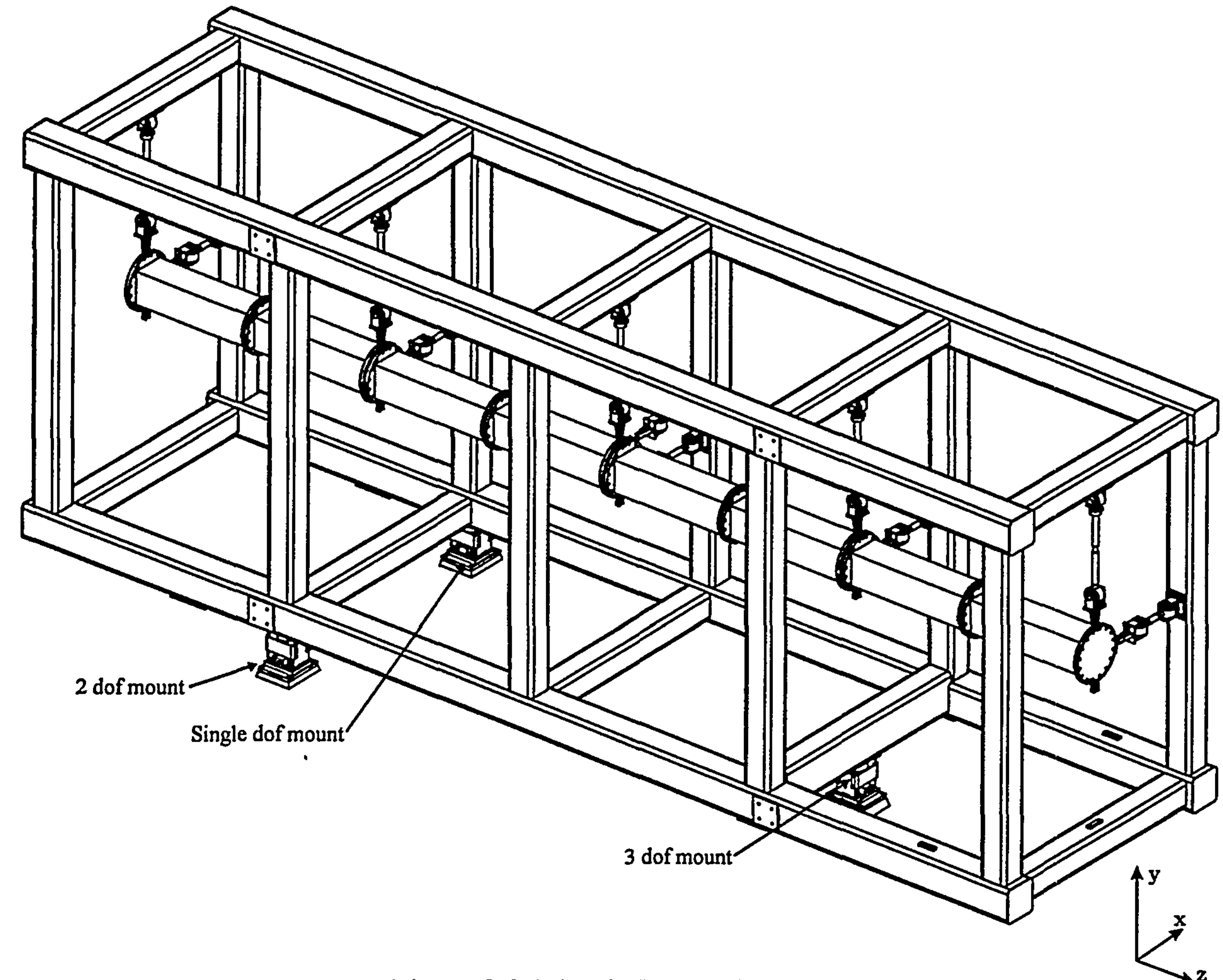


Figure 3.0.1, RFQ Support Frame

The dimensions to the frame member centerlines are 108.0 in. tall by 76.0 in. wide. Overall length, centerline to centerline is 8 meters or 315.0 inches, equally divided into four separate 2-meter cells. The RFQ is centered in the frame, at the nominal beamline height of 72.0 in. The lower edge of the frame is 13.0 in. above the facility floor.

3.0.1 Frame Configuration

The frame consists of lateral, longitudinal, and vertical members only. The design does not incorporate any canted members to accommodate shear loads acting in the lateral, longitudinal, or vertical directions. Instead these loads are reacted within the frame by inducing bending moments in the longitudinal, lateral and vertical members. This frame differs from a conventional truss in this respect. A conventional truss would be much more structurally efficient, transmitting all external forces predominantly as tensile or compressive loads in each member. The RFQ frame is less structurally efficient but provides ample access to the RFQ and associated support gear. Individual frame members were sized for appropriate stiffness and strength precluding the need for canted shear members.

The frame is a weldment, fabricated from AISC standard tube sections[3.1]. The frame is symmetric about its x, y, and z axis planes thus weld induced distortion is somewhat reduced. Only rectangular tube is utilized due to its structural efficiency in bending relative to round sections. Rectangular cross-section stock also eases the fabrication of joints. Simple cutting templates and weld fixtures allow quick fabrication of structurally efficient joints. Additional fabrication tooling is not required.

Table 3.0.1.1
Candidate Frame Configurations

Tube Size	Tube Wall Thickness	Frame Weight (approximate)	Max RFQ Static Deflection
12.0 in. x 12.0 in.	.50 in.	19,651 lb_f	-0.0030 in.
	.38 in.	15,001 lb_f	-0.0029 in.
	.25 in.	10,176 lb_f	-0.0028 in.
10.0 in. x 10.0 in.	.50 in.	16,141 lb_f	-0.0049 in.
	.38 in.	12,369 lb_f	-0.0048 in.
	.31 in.	10,439 lb_f	-0.0047 in.
	.25 in.	8,413 lb_f	-0.0046 in.
8.0 in. x 8.0 in.	.50 in.	12,632 lb_f	-0.0086 in.
	.38 in.	9,738 lb_f	-0.0081 in.
	.31 in.	8,211 lb_f	-0.0080 in.
	.25 in.	6,658 lb_f	-0.0078 in.
6.0 in. x 6.0 in.	.50 in.	9,123 lb_f	-0.0158 in.
	.38 in.	7,088 lb_f	-0.0148 in.
	.31 in.	6,018 lb_f	-0.0142 in.
	.25 in.	4,904 lb_f	-0.0137 in.

The particular frame member size and wall thickness was arrived at after consideration of structural behavior, fabrication ease and cost. Table 3.0.1.1 lists the different configurations considered.

This bounding study utilized a constant tube cross section for all frame members for each configuration.

Fabrication labor cost for the different configurations will be similar since each different frame configuration will have the same quantity of members and welded joints. The heavier wall tube may require multi-pass welds and will be more susceptible to weld induced distortion. Material cost is directly proportional to overall weight.

The configuration selected from those considered consists of 10.0 inch square tube for the longitudinal members, 8.0 inch square tube for all other members except the lower lateral member which attaches to the single kinematic support. See figure 3.0.1. This particular member is an 8.0 in. by 12.0 in. tall rectangular section. All tube wall is 3/8 inches. This configuration is a suitable compromise of stiffness, strength, ease of fabrication, cost, and reliability. The weight of this frame is approximately 10,600 lb_f.

Table 3.0.1.2 lists the AISC standard section properties for the three different sections to be utilized for this design. These closed section standard shapes are typically fabricated of ASTM-A500 cold formed steel. Grade B is the more common grade and is easily procured in small quantities.

Table 3.0.1.2
Frame Member Section Properties[3.1]

Section	Wall	Area	Ixx	Iyy	J
8.0 in. x 8.0 in. box	0.38 in	11.1 in^2	106.0 in^4	106.0 in^4	170.0 in^4
10.0 in. x 10.0 in. box	0.38 in	14.1 in^2	214.0 in^4	214.0 in^4	341.0 in^4
12.0 in. x 8.0 in. rect.	0.38 in	14.1 in^2	279.0 in^4	149.0 in^4	312.0 in^4

The mechanical properties for ASTM-A500 are listed in table 3.0.1.3. The tensile yield strength of welds and the surrounding weld heat affected zone will be that of ASTM-A500 in annealed condition. Annealed tensile strength is approximately 85% of the cold formed values.

Table 3.0.1.3
Frame Member Material Mechanical Properties[3.1]

Property	ASTM-A500, Grade B Cold Formed	ASTM-A500, Grade B Annealed
density	0.283 lb_f/in^3	0.283 lb_f/in^3
modulus of elasticity	30.0e6 psi	30.0e6 psi
Poisson's ratio	0.3	0.3
yield strength, min.	46,000 psi	39,000 psi
ultimate strength, min.	58,000 psi	49,000 psi

3.1 Frame Support Scheme

The frame is attached to the facility floor utilizing a pure kinematic support scheme. This approach provides a twofold benefit, first, ease of alignment, and second, minimal structural dependence on the facility floor. This scheme decouples most of the floor thermal or structural settling motions from the frame. A drawback is that the inherent stiffness in the facility floor is not utilized to aid supporting the RFQ. The frame must provide all stiffness and strength required by the RFQ.

The kinematic support utilizes six degrees of freedom only. Three separate mounts at the base of the frame will accomplish this. The first mount point behaves as a spherical joint, providing three degrees of restraint. The second mount point behaves as a revolute joint, with its axis pointing at the first mount, adding two more degrees of restraint. The third mount point behaves as a point contact providing the sixth degree of restraint. Complete alignment or positioning in space requires just six motions, one for each degree of freedom.

3.2 RFQ/Support Frame Interface

The method for supporting the RFQ within the support frame is depicted in figure 3.2.1. Use of a kinematic or statically determinant support configuration here is not feasible due to the lack of structural rigidity over the RFQ length. Overconstraint is required both vertically and laterally to maintain alignment and minimize dynamic motion.

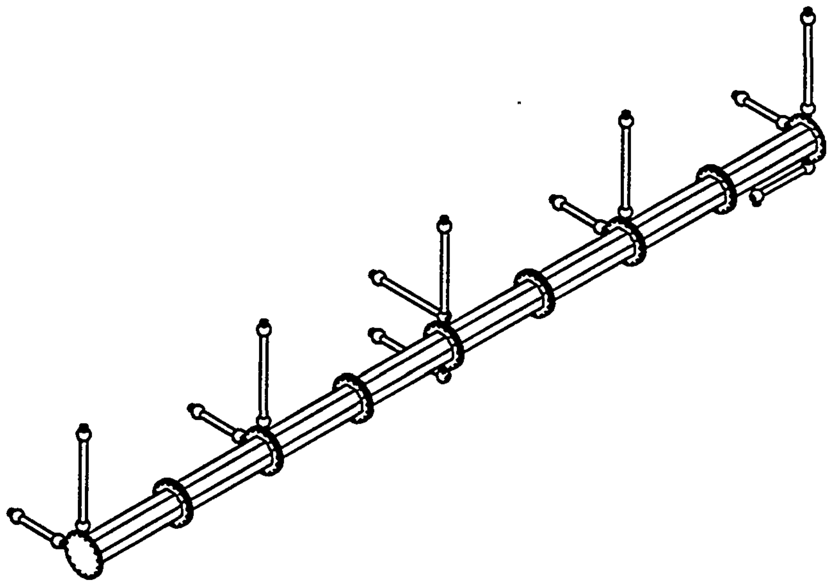


Figure 3.2.1, RFQ Support Scheme

The scheme utilizes five vertical and five lateral mount points plus one axial restraint and one rotational (about the beam axis) restraint. The system is configured with links incorporating spherical joints or flexures at each end. The use of spherical joints or flexures at the link ends precludes the introduction of bending moments into the RFQ.

The RFQ is supported vertically at five separate points, each approximately 2 meters apart. Some vertical deflection will be present between each mount point. Figure 2.1.4.1.1 depicts the gravity loaded shape of the RFQ when supported in this manner. Vertical displacement from the theoretical beam axis is minimized when the mount points are raised slightly with the vertical links to compensate for half of the maximum sag between mount points. With this approach, the maximum RFQ misalignment is 0.0006 inches.

The rotational restraint is accomplished utilizing a link pair. One is attached to the top of the center section flange and the other is attached to the bottom of the same flange. This scheme prevents rotation of the RFQ without inducing other loads or unwanted constraints. This pair also acts as a lateral constraint at this location. Mounting this link pair laterally instead of vertically eases alignment. The RFQ may be aligned vertically with this link pair disconnected. After vertical alignment, the RFQ may be aligned laterally with the other four lateral links. Subsequently, the lateral link pair is attached and additional lateral alignment may be performed, if required, and the RFQ rotational position may be set.

Lateral constraint at five locations on the RFQ was utilized instead of the minimum kinematic requirement of two to enhance lateral stiffness of the RFQ. The RFQ is quite structurally compliant without the added stiffness of its support frame. The enhanced lateral stiffness substantially raises the frequencies associated with lateral RFQ dynamic modes. This reduces dynamic response of the RFQ to the predominantly low frequency dynamic input present in facilities of this nature. The added stiffness also greatly reduces RFQ displacement for given live lateral loads. A drawback to the redundant lateral constraint is the extra effort required for RFQ alignment.

During operation, the RFQ will encounter a mean temperature rise of 20°F. This temperature increase corresponds to a total length increase of .019% or 0.060 inches. The axial constraint link for the RFQ is attached at the high energy end thus the axial expansion will grow from this point. The axial growth is perpendicular to every support link except the z constraint. Thus the slight thermal growth will have inconsequential impact on system alignment and will not induce any loads in the support frame.

3.3 Frame Structural Analysis

The frame, RFQ, and support links were all modeled utilizing 3-D beam elements. The RFQ was accurately represented with beam elements based on the modeling described above. A total RFQ weight of 5000 lb_f was utilized. This weight includes a contingent for externally mounted RFQ hardware.

Each welded joint was modeled as a rigid connection. Appropriate weld joint preparation and weld bead sizing will be utilized to maximize joint strength and stiffness and thus maximize overall structural efficiency.

Interface points such as attachment points for supports and RFQ links do not consider local deflections of the tube wall. Appropriate doublers and or bracketry must be added to spread these point loads and prevent significant local deformation at the tube wall.

The model is constrained with boundary conditions that accurately represent the kinematic support scheme. Figure 3.0.1 depicts the frame and the three support points. Table 3.3.1 lists the nominal reaction forces at each mount.

Table 3.3.1
Frame Support Reaction Forces

Mount	Lateral (x)	Vertical (y)	Longitudinal (z)
1	0.0	7666.0 lb_f	0.0
2	free	3952.0 lb_f	0.0
3	free	3952.0 lb_f	free

3.4 RFQ Alignment

The assembled RFQ is depicted in figure 3.2.1. Table 3.4.1 describes the vertical position of multiple points along the RFQ, when the RFQ is optimally aligned.

Table 3.4.1
RFQ Vertical Displacement

Z coordinate	Section	Location	Displacement
0.0 m	1	fwd. edge	0.0000
0.5 m	1	center	-0.0010
1.0 m	1 and 2	interface	-0.0012
1.5 m	2	center	-0.0007
2.0 m	2 and 3	interface	0.0000
2.5 m	3	center	-0.0002
3.0 m	3 and 4	interface	-0.0004
3.5 m	4	center	-0.0003
4.0 m	4 and 5	interface	0.0000
4.5 m	5	center	-0.0003
5.0 m	5 and 6	interface	-0.0004
5.5 m	6	center	-0.0002
6.0 m	6 and 7	interface	0.0000
6.5 m	7	center	-0.0007
7.0 m	7 and 8	interface	-0.0012
7.5 m	8	center	-0.0010
8.0 m	8	aft edge	0.0000

The stiffness of the RFQ assembly is small when compared to the stiffness of the support frame. This characteristic eases alignment. Small load changes that accompany adjustment of one of the support links induce small deformation of the support frame. This corresponds to very small or insignificant displacement of the other support links. Thus, relative to RFQ, the frame behaves as a rigid structure.

3.4.1 RFQ Alignment Sensitivity

The structural model of the frame with the RFQ installed was also used to study alignment sensitivity of the RFQ when installed in the frame. Of interest is the impact of adjusting one of the support links on the remaining four.

A arbitrary vertical displacement of 0.030 inches was applied to the RFQ at points where support links attach. This mimics mechanical adjustment of one support link, raising the RFQ .030 inches. Two separate cases were considered, first applying the displacement at the RFQ end support link and second application of the displacement at the middle support link.

Table 3.4.1.1
RFQ Alignment Sensitivity
(0.030 in. fixed displacement at RFQ end mount)

RFQ Mount	Z coord.	RFQ CL disp.	Frame disp.	Link Tension Change
#1	0.0 m	+0.0300 in.	-0.0018 in	271 lb_f
#2	2.0 m	+0.0019 in.	+0.0009 in	-562 lb_f
#3	4.0 m	-0.0012 in.	-0.0006 in	307 lb_f
#4	6.0 m	0.0000 in.	0.0000 in	-14 lb_f
#5	8.0 m	+0.0005 in.	+0.0005 in	-3 lb_f

Table 3.4.1.2
RFQ Alignment Sensitivity
(0.030 in. RFQ displacement at center mount)

RFQ Mount	Z coord.	RFQ CL disp.	Frame disp.	Link Tension Change
#1	0.0 m	-0.0013 in.	-0.0006 in.	375 lb_f
#2	2.0 m	+0.0049 in.	+0.0022 in.	-1468 lb_f
#3	4.0 m	+0.0300 in.	-0.0058 in.	2184 lb_f
#4	6.0 m	+0.0049 in.	+0.0021 in.	-1466 lb_f
#5	8.0 m	-0.0014 in.	-0.0007 in.	374 lb_f

Tables 3.4.1.1 and 3.4.1.2 list the results for this study, cases one and two respectively. Depicted in the tables is the mount number, mount coordinate, RFQ centerline displacement, corresponding frame displacement, and the difference in tension induced each link. Figure 3.4.1.1 depicts shear and bending moment induced in the RFQ for fixed displacement applied to the end link and figure 3.4.1.2 depicts the same information for the fixed displacement applied to the center support link. The tables clearly depict the increased relative stiffness of the frame when compared to the RFQ. This feature will substantially ease RFQ alignment.

The RFQ, due to the support link configuration, is less compliant laterally at its center than at either end. This is clear when comparing the two tables. Displacement of RFQ mount point one, as depicted in table 3.4.1.1, induces small displacements of the remaining mount points and small load changes in the remaining links. Case two, entailing lateral displacement at the center link, induces larger displacements of the other mount points and induces significant load changes in the support links.

Figure 3.4.1.1
RFQ Shear and Bending Moment
(0.030 in. RFQ displacement at end mount)

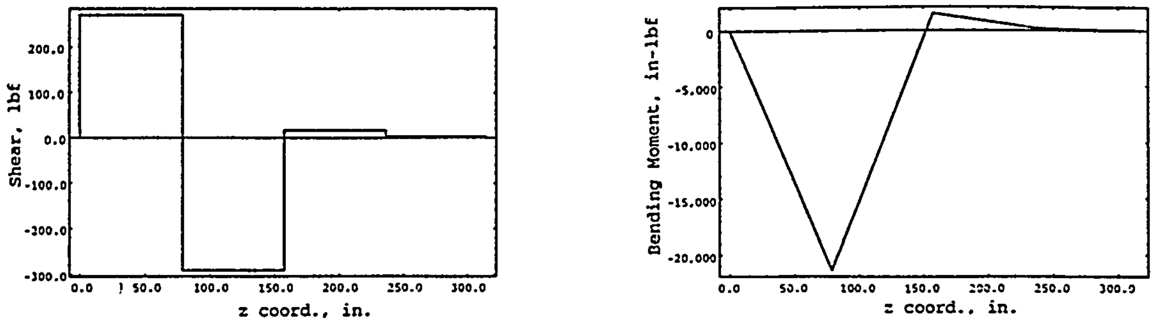
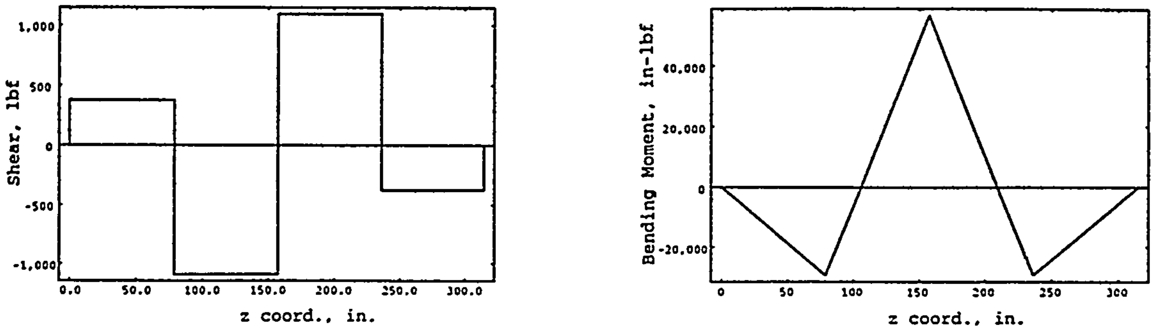


Figure 3.4.1.2
RFQ Shear and Bending Moment
(0.030 in. RFQ displacement at center mount)



The link tension changes calculated are on the order of the nominal link tension values when the RFQ is subject to gravity. Depending on the actual displacements required for each link for proper RFQ alignment, some links may be in compression instead of tension.

The displacement value of .030 inches was chosen arbitrarily. Fabrication and assembly tolerance of the RFQ assembly will determine exactly the displacement from the theoretical centerline the mechanical centerline varies over the length of the RFQ. RFQ performance criteria will specify the permissible centerline tolerance. Any mechanical tolerance above these values must be accommodated mechanically.

Only the vertical adjustment sensitivity was considered. Alignment behavior in the lateral direction will be similar. The RFQ behaves the same structurally but the lateral link mount points on the frame are somewhat more compliant. This is because the vertical frame members to which the lateral links attach are substantially longer than the lateral frame members.

The links used for this study were modeled as steel members having 1.0 square inch of cross section. Each end of each link was modeled as a perfect spherical joint, thus only axial loads were transmitted. No bending moments were induced.

3.5 Specific Support Frame Analyses

The comprehensive beam element model of the RFQ and support described above was utilized to study a variety of load cases. The primary load cases considered are listed below.

1) RFQ and frame, gravity loading
2) Wave guide RF window live load
3) 250 lb_f single point live load
4) RFQ sensitivity to point live loads
5) Assembly of the RFQ within the support frame
6) RFQ and frame, seismic analysis

3.5.1 RFQ and Frame, Gravity Loading

Gravity loading of the combined RFQ and frame assembly was performed to determine both displacements and associated induced loads. Figure A.10 depicts the frame deformed shape when loaded in this manner. Table 3.5.1.1 lists maximum frame member axial loads, shear and bending moments.

Table 3.5.1.1
RFQ Frame Member Maximum Axial, Shear, and Moment Values
(gravity loading)

Member Group	Maximum Axial Tension	Maximum Axial Compression	Maximum Shear	Maximum Moment
longitudinal (10x10 box sections)	408 lb_f	408 lb_f	730 lb_f	28,400 in-lb_f
vertical (8x8 box sections)	32 lb_f	2,470 lb_f	287 lb_f	15,200 in-lb_f
lateral (8x8 box and 8x12 rect.)	149 lb_f	149 lb_f	3,844 lb_f	23,700 in-lb_f

The stresses induced by the loads above are extremely low. The maximum individual stress value is 660 psi. This particular value occurs due to the 28,400 in-lb_f bending moment acting on the longitudinal members.

3.5.2 RF Wave Guide Window Live Load

This load case was evaluated to estimate the deformation associated with the installation of the twelve RF wave guide windows.

The RF window is a barrier, which is placed in the wave guide. This barrier maintains the vacuum on one side with ambient air on the other side. This vacuum barrier is maintained while allowing transmission of RF power. The RF windows for this application are unique in the immense quantity of RF power that they must transmit.

These particular RF windows are currently undergoing preliminary design. Exact weights and mount schemes are not yet known. A conservative estimate of the associated live loads and mount locations was made for this effort. Single 500 lb_f vertical loads were applied simultaneously to the top of each of the ten vertical frame members.

Figure A.11 is a deformed shape plot of the frame with the described live load only. The maximum RFQ vertical displacement for this load condition is .0081 inches. This maximum occurs at the RFQ high energy end.

3.5.3 250 lb_f Single Point Live Load

A single live vertical load of 250 lb_f was applied separately, at the lower corner of the frame. The load was applied to the frame at its down stream end. This end is more compliant due to proximity to the single kinematic frame support as opposed to the upstream end which has the remaining two supports. See figure A.12.

This load case was considered to determine maximum RFQ displacement due to a person standing on the frame. This event would occur during alignment, for example. This live load causes the lower corner point of the frame to drop .0039 inches. The largest displacement of the RFQ occurs also, as expected, at its downstream end. Here the RFQ centerline drops .0021 inches, and swings laterally .0010 inches. Total displacement is .0023 inches.

Figure A.12 depicts the deformed shape of the frame and RFQ assembly due to this particular load. This image is highly magnified. The point load tends to twist the frame about its axis. The single support at this end provides no reaction to the twist. The induced couple is reacted at the two frame supports at the low energy end.

3.5.4 RFQ Sensitivity to Point Live Loads

The sensitivity of the RFQ to small live loads at random locations was of interest. Random loads of low magnitude may be created, for example, during maintenance procedures.

The comprehensive beam element model described above was utilized. Single 100 lb_f point loads were applied to the RFQ independently. Table 3.5.4.1 lists the load, application point, direction, and corresponding RFQ displacement. The points chosen for load application were the high energy end of the RFQ and the joint between the last two sections, sections D1 and D2, see figure 2.0.1. The support frame is less stiff at the high energy end where these points are located due to the proximity to the single frame mount. Thus displacements at these positions will be the largest encountered for a given load applied anywhere on the RFQ.

Table 3.5.4.1
RFQ 100 lb_f Live Load Sensitivity

Load	Application point (z coordinate)	Application direction	RFQ displacement
100 lb_f	7.0 m	x	.0019 in.
100 lb_f	7.0 m	y	.0006 in.
100 lb_f	8.0 m	x	.0027 in.
100 lb_f	8.0 m	y	.0012 in.

The assembly possesses greater stiffness at the sections D1 and D2 joint relative to the RFQ end thus the associated displacements are smaller. Application of the point loads at the sections D1 and D2 interface induces maximum displacement of the RFQ near the center of section D2. When the point loads are applied at the end of the RFQ, the maximum RFQ displacement occurs at the load application point.

3.5.5 RFQ Assembly Loads

The frame serves both as an operational RFQ support and as an assembly fixture for the RFQ. Assembly and some of the performance verification procedures are most easily performed when the RFQ is mounted vertically.

Prior to assembly and installation of the RFQ within the support frame, the frame is mounted vertically in the assembly area. The frame is supported on temporary three legged support stands utilizing a trunnion mount scheme. The support stands are fastened with concrete anchors to the facility floor. This configuration is depicted in figure 3.5.5.1. The system is designed such that the RFQ and frame center of gravity are positioned slightly below the trunnion axis, providing dynamic stability. When configured as described, the frame is supported entirely at the two trunnion pins. One additional link, connecting the frame to the base of one support tripod is utilized to restrain rotation about the trunnion axis.

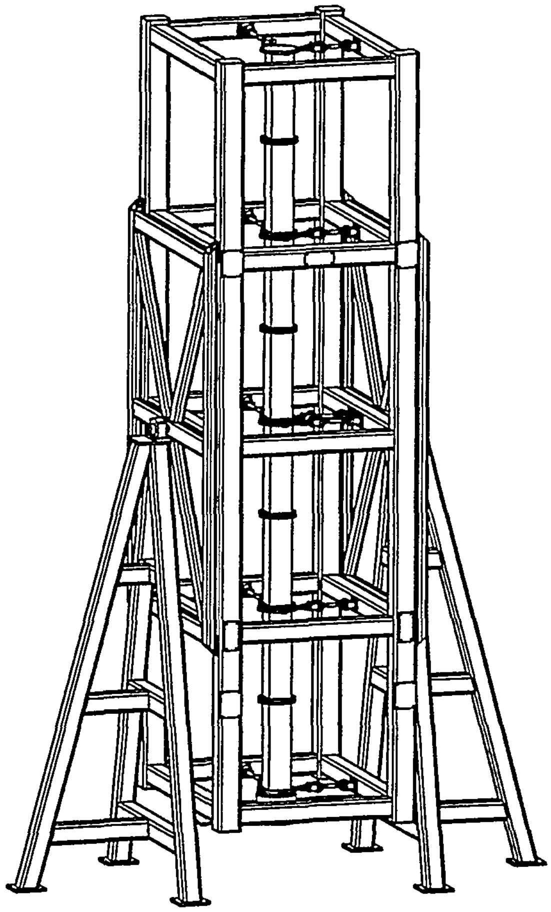


Figure 3.5.5.1, RFQ and Frame, Vertical Assembly Configuration

The RFQ is assembled in the frame one section at a time. Sections are installed sequentially from bottom to top. This procedure minimizes potential damage to the RFQ during assembly due to rigging and handling. Vertical assembly does not induce any cantilever bending loads in the RFQ and greatly eases positioning and joining of the individual sections.

Section A1, the first section to be installed, is mounted to an assembly fixture, which is fastened to the low energy end of the frame. This fixture has adjustment features to permit accurate alignment of section A1 to the frame theoretical axis. This fixture determines overall alignment of the entire RFQ during assembly.

The lateral and vertical support links will be installed sequentially as the sections are installed, to provide lateral support. Each link length will be adjusted so that essentially no force is imparted to the RFQ. This provides lateral stiffness if and when necessary, during assembly, but does not effect RFQ alignment. Each link incorporates very precise bearings and close tolerance threaded adjustment features to preclude any axial play.

After RFQ installation and testing is complete, the entire assembly is rotated 90 degrees about the trunnion axis to horizontal. Rotation is accomplished with the aid of the facility gantry crane and supplementary rigging. Appropriate rigging is utilized to insure slow, smooth rotation, and provide redundancy in the event of equipment failure.

Great care must be exercised during this operation to prevent overloading of the frame and introducing excessive loads into the RFQ. This is possible due to the ability of the rigging to overconstrain the frame, and due to the very large forces that the rigging equipment and the gantry crane are capable of producing. Incorporation of load cells or strain gages with the link assemblies would allow monitoring of all forces introduced to the RFQ. This safety feature would be very valuable during this particular operation.

After rotation to horizontal, while the assembly is suspended from the gantry crane, the trunnion support fixturing is removed. The assembly is then lowered to the facility floor. Four temporary casters are then installed on the lower longitudinal frame members, allowing easy transport of the RFQ assembly from the assembly area to its permanent position in the APT/LEDA tunnel.

Structural analysis of the complete assembly was performed while supported on the trunnion mount for both the vertical assembly configuration and the rotated horizontal configuration.

The RFQ loads are greatest when the RFQ and frame is positioned horizontally while supported on the trunnion mount. The RFQ assembly and frame deformed shape when supported in this manner is depicted in figure A.13. The RFQ vertical support link tensile loads for this configuration are listed in table 3.5.5.1. The tensile load in the center vertical support link is almost double its nominal tension of 1182 lb_f when the assembly is resting on its kinematic support. Figure 3.5.5.2 depicts shear and bending moment along the RFQ. The RFQ maximum shear and bending moments encountered are listed in table 3.5.5.2. The maximum RFQ tensile stress due to bending is 880 psi.

Table 3.5.5.1
RFQ Vertical Support Link Loads
(gravity loading, horizontal config., trunnion mount)

Mount	Z coordinate	Load
1	0.0 m	547 lb_f
2	2.0 m	916 lb_f
3	4.0 m	2079 lb_f
4	6.0 m	909 lb_f
5	8.0 m	550 lb_f

Table 3.5.5.2
Maximum cross-section shear and moment
(gravity loading, horizontal configuration, trunnion mount)

Maximum shear force	Max. bending moment
1,042 lb_f	38,622 in-lb_f
@ center mount point	@ center mount point

Figure 3.5.5.2
RFQ Shear and Bending Moment
(gravity loading, horizontal configuration, trunnion mount)

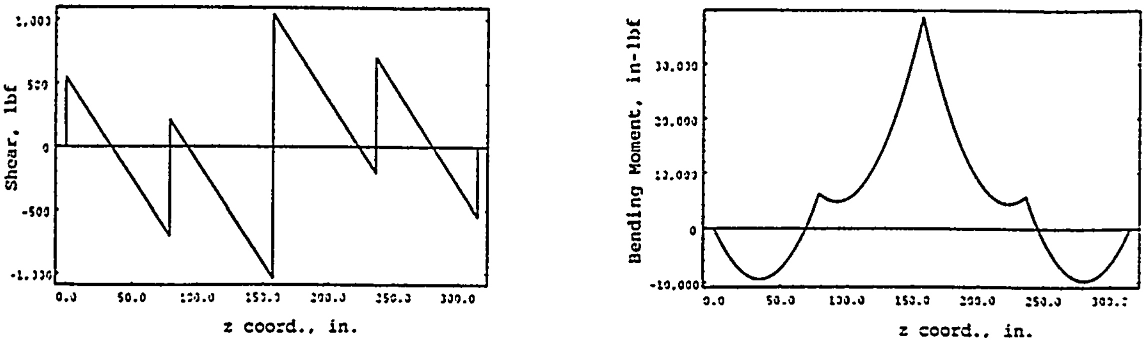


Table 3.5.5.3
RFQ Frame Member Maximum Axial, Shear, and Moment Values
(gravity loading, trunnion support)

Member Group	Maximum Axial Tension	Maximum Axial Compression	Maximum Shear	Maximum Moment
longitudinal (10x10 box sections)	1,446 lb_f	1,448 lb_f	1,584 lb_f	78,055 in-lb_f
vertical (8x8 box sections)	3,436 lb_f	4,461 lb_f	892 lb_f	46,330 in-lb_f
lateral (8x8 box and 8x12 rect.)	117 lb_f	129 lb_f	1,155 lb_f	26,150 in-lb_f

The loads induced in the frame for this particular configuration are very low. Table 3.5.5.3 lists the maximum tension, compression, shear and bending moment for each frame member group.

3.5.6 RFQ and Frame, Seismic Loading

Seismic analysis was completed for the RFQ and frame assembly. The requirement for this equipment is a performance category (PC) of 2, a seismic zone factor of 0.20 and an importance factor of 1.5[3.2].

The PC rating of 2 requires that during a seismic event, structural integrity is maintained sufficient only to ensure personnel safety. Structural failure is permitted as long as injury to persons working on or near the assembly is avoided. Risk to personnel would be collapse or toppling of the RFQ and frame.

The seismic requirements listed above impose a design lateral acceleration of .45g, applied in combination with standard gravitational acceleration. The specified lateral load must be considered to act in two perpendicular horizontal directions, but not concurrently. The accelerations are all applied statically. The requirement does not impose dynamic loading.

The RFQ and frame structure readily accommodates this modest acceleration. All induced stress levels are far below yield.

The lateral acceleration applied along the local x axis will cause the frame to topple. The high center of gravity of the assembly combined with the narrow frame width causes a low lateral stability.

The frame rests on a kinematic mount system. This mount scheme does not provide appropriate lateral and vertical structural restraint at each mount for the lateral acceleration listed above.

Appropriate structural restraint fittings or seismic clips must be utilized at each of the three frame supports to prevent toppling. The design of these fittings must not interfere with the operation of the kinematic mount system. Small displacements and rotations necessary for proper operation of the kinematic mounts must be accommodated without interference by the seismic clips.

Table 3.5.6.1
Frame Support Seismic Load Requirements

vertical (lifting)	vertical (compression)	lateral
1102 lb_f	9007 lb_f	3782 lb_f

The maximum vertical (lifting) and lateral loads that the frame support seismic clips must accommodate are listed in table 3.5.6.1. The values listed apply to each of the three frame supports. The values listed are nominal design values. An appropriate safety factor should be applied when designing hardware to meet these requirements.

3.6 RFQ and Support Frame Dynamics

Modal analysis of the RFQ and support frame assembly was performed. This analysis was performed utilizing the same beam element model that was used for the structural analysis described above. Again a 5000 lb_f total weight for the RFQ was utilized. This model accurately represents the kinematic frame support scheme and the link assemblies, which suspend the RFQ within the frame.

Estimates of system response due to background excitation were calculated. Accurate system response could not be calculated because vibratory input on the facility floor where the RFQ will be installed is not yet accurately known. Accurate measurement of this input can occur only after the facility is operational.

The first eight dynamic modes, associated frequencies and participation factors are listed in table 3.6.1. The first seven modes occur below 30 Hz. A total of 30 modes exist below 100 Hz. Prior measurement of the tunnel floor vibration spectrum during the GTA program revealed that 95.3% of the input displacement is present below 30 Hz.[3.3]. It is assumed that the dynamic input for an operational APT/LEDA will be similar to that measured for GTA.

Table 3.6.1
RFQ and Support Frame Dynamic Mode Description

Mode	Frequency	Participation Factor		
		x comp.	y comp.	z comp.
1	8.0 Hz	1.60	-0.01	0.00
2	13.4 Hz	0.70	-0.12	0.92
3	13.9 Hz	0.43	0.13	-0.83
4	23.2 Hz	-0.02	0.40	1.00
5	26.5 Hz	-0.04	0.85	-0.28
6	28.8 Hz	0.10	0.22	-0.07
7	29.7 Hz	-0.13	0.39	-0.11
8	32.7 Hz	0.59	-0.15	0.03

The first eight individual mode shapes are depicted in figure A.14. The red figures are the undeformed structure and the black overlay figures are the deformed shape. The associated frequency is listed with each particular figure.

The frame is less stiff in shear relative to conventional truss structures due to the lack of shear members and gussets. This is evident in the presence of the low frequency modes which each are due to overall shearing or twisting of the frame.

Estimates of RMS dynamic motion of the RFQ were calculated utilizing the dynamic input depicted in figure 3.6.1. This spectrum is identical to that developed from measurements taken for this facility during the GTA program except that for conservancy, the dynamic input was increased six dB over its entire frequency range. The associated RMS displacement for this modified curve is 7.7 micro-inches.

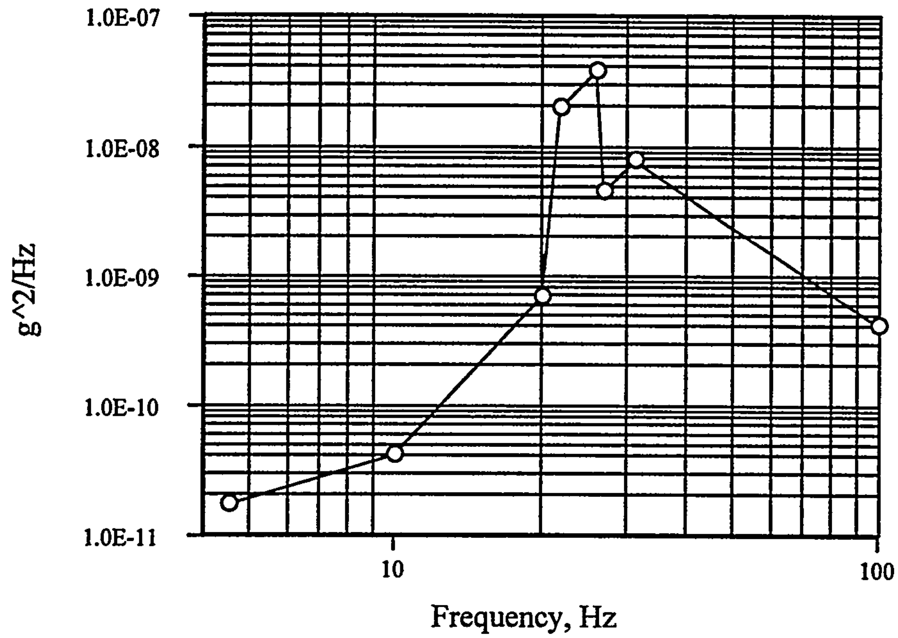


Figure 3.6.1, RFQ and Support Frame, Estimated Vibratory Input

Response calculations were performed utilizing a uniform structural damping factor of 2%. This corresponds to a dynamic gain at resonance of 25. This damping value is typical for a structure of this nature. The spectrum depicted was utilized as input independently along each of the three coordinate directions. Dynamic response was calculated considering all modes below 100 Hz but most of the response motion occurs due to the input and corresponding modes below 30 Hz. Table 3.6.2 lists the calculated maximum RMS displacement of the RFQ for each coordinate direction. Hand calculations were used to verify these values.

Table 3.6.2
Estimated RFQ RMS Displacement

Direction	Location of Maximum	RMS Displacement
x	high energy end	25.7 μ inch
y	low energy end	80.1 μ inch
z	low energy end	99.3 μ inch

The RMS displacement values calculated are very small when compared to the allowable static displacement values listed in table 1.1. After APT/LEDA is operational, the dynamic input at the floor where the RFQ assembly is installed may be measured and compared to the data depicted in figure 3.6.1. If this measured data is enveloped by the data utilized for this analysis, it may be assumed that the RMS displacement response of the RFQ is smaller than those listed in table 3.6.2.

As stated earlier, the finite element model utilized for this analysis accurately represents mass and stiffness for the RFQ as well as all frame structural members. The frame kinematic mount scheme as well as the RFQ support scheme within the frame is also represented accurately. The fidelity of the model to the actual assembly allows quite accurate calculation of the modes, mode shapes, and associated data.

3.7 Residual Stress Relief

The welding process induces residual stress within the weld and in the region immediately surrounding the weld that may approach the yield strength of the parent material. Small loads inducing low stress in these regions may then cause small amounts of plastic deformation. This may in turn cause alignment problems with the RFQ. This sequence of events may be prevented with suitable thermal stress relief of the frame assembly after all welding has been completed.

Thermal stress relief procedures for common low carbon steels, such as ASTM-A500, are listed in reference 3.4. Of importance is utilizing an appropriate temperature that relaxes residual stress but does not remove the enhanced strength provided by the cold-forming of the tube segments. Also of importance is allowing proper thermal soak time to allow full thermal penetration and proper residual stress relaxation.

The thermal stress relief process will relieve all inherent residual stress, including residual stress that may exist in the cold-formed tube sections. Some overall deformation or distortion of the weldment may occur during the heat treatment procedure. Suitable support fixturing or bracing may be required during heat treatment to minimize this consequence. Also, machining of any features on the frame that must be located accurately should be performed after the stress relief process. Subsequent welding should not be performed.

4.0 Conclusions

4.1 RFQ

The RFQ as designed meets all structural requirements specified in table 1.1.

The maximum displacement of major vane A1 due to gravity loading while simply supported is just .0003 inches. This value is sufficiently below the specified limit of .0005 inches.

Vacuum loading induces maximum calculated von Mises stress of about 1100 psi, 16% of tensile yield. Maximum calculated vane tip radial displacement due to vacuum is .0002 inches. These calculated stress and displacement values are greater than actual values which will be seen in service due to conservative simplifications utilized during modeling.

Gravity loading of the RFQ assembly is also suitably accommodated. The link support scheme incorporating spherical bearings at each link end performs very well. The support scheme adequately distributes the gravity load among the five vertical support points maintaining low induced stress levels. The maximum calculated bending stress due to gravity loading is 630 psi, just 9% of the available yield strength. Maximum sag of the RFQ due to gravity loading is just .0012 inches.

Structural characterization of the RFQ utilizing a detailed model of one RFQ section proved very valuable in evaluating the RFQ support scheme, alignment sensitivity, and also RFQ and support frame interaction.

4.2 Support Frame

The support frame design is an efficient design concerning RFQ access and simplicity. It meets every requirement with ample margin for RFQ deflection limits for the variety of loads imposed. Member sizing was dictated by the very small displacement requirements for the RFQ. This produced a frame that, for the same load conditions, possesses very low stress levels.

The maximum tensile stress encountered for the gravity load case, described in section 3.5.1, is 660 psi. This is far below the available tensile yield strength.

Maximum tensile stress encountered for all loading conditions occurs when the RFQ and frame assembly is supported on the trunnion mounts in a horizontal attitude. This occurs during RFQ assembly and is described in section 3.5.5. The maximum bending stress, which occurs in the longitudinal members, is 1830 psi. This value is just 4% of the available tensile yield strength. The maximum frame displacement encountered, .046 inches, also occurs for this particular load case.

5.0 Recommendations

The analysis completed for both the RFQ and its support frame was thorough. Several items were identified concerning the RFQ and support frame that could cause problems if not carefully considered. These items are described in detail below.

5.1 Spurious Loads Acting on the RFQ

A concern is unknown and unwanted forces acting on the RFQ. These forces may be introduced to the RFQ from several different sources:

1) Adjoining beamline hardware
2) Vacuum manifolding
3) Cooling system manifolding
4) RF wave guide interface

Adjoining beamline hardware, such as the ion source at the low energy end or the beam stop or CCDTL at the high energy end, must be structurally isolated from the RFQ. The vacuum interface must be designed such that when the system is evacuated, vacuum loads are not transmitted to or from the RFQ. The ion source must also accommodate the approximate .060 inches of axial thermal expansion at the RFQ entrance, while operational, without imparting load.

Vacuum manifolding must be designed such that it does not apply load to or restrain the RFQ. This is accomplished with appropriate bellows assemblies linking the RFQ to the manifolding. Bellows of appropriate compliance must be incorporated otherwise significant loads may be imparted. Each bellows must be positioned such that the tension load it develops is reacted appropriately. This is best accomplished by installing like bellows in pairs, one on either side of the RFQ. This arrangement, with the RFQ centered between two like bellows, applies zero net force to the RFQ.

The cooling system is similar to the vacuum system in that it to can cause unwanted loads or restraint. The use of appropriate flexible hose assemblies at interface points to the RFQ will structurally isolate the RFQ. The hoses must incorporate internal or external wire or cord braiding to react the developed axial extension load. Also, proper length and minimum bend radii must be maintained to minimize the loads developed as the hose assembly tends to straighten itself when pressurized. This effect is can be significant with large diameter hose assemblies.

The RF system is similar to the vacuum system in that evacuated manifolding, the RF waveguide, is attached to the RFQ. Again bellows are incorporated for structural isolation but a difference is that these bellows are much larger in cross section. Thus reaction forces are also much larger. These larger loads, approximately 1950 lb_f, must be accommodated appropriately. Also of concern with larger bellows is appropriate compliance.

An interesting experiment would be to monitor the RFQ alignment while, one, evacuating the RFQ and then, two, pressurizing the coolant system to operational coolant pressure. This would ascertain if the RFQ is displaced due to either of these systems.

5.2 RFQ Support Links

The links utilized in supporting the RFQ must be designed such that essentially no axial play exists.

Axial play will allow movement of the RFQ without an associated reaction force when link tension is at or near zero.

This will defeat the effect of the lateral and axial links for small lateral or axial RFQ displacements. These particular links typically have little or no tension thus under these circumstances the system will behave as if the links were not installed.

A similar situation occurs during RFQ assembly when the RFQ and frame is rotated from its vertical orientation to horizontal. During assembly the vertical support link lengths are set so no load is applied to the RFQ. As the assembly is rotated, the links begin to support the RFQ and finally support it fully at rotation completion. Axial play within these links will allow some motion of the RFQ without corresponding restraint. This can cause potentially large loads to be imparted at once during the rotation sequence.

5.3 Frame Fabrication

Selection of a fabricator who is appropriately certified by ASME and or AWS will confirm appropriate capability for the various fabrication and quality control procedures.

Proper tube section size, wall thickness, specific material and governing specification should be verified. Proper welds performed by AWS certified personnel, performed to the appropriate AWS specification must be verified.

Suitable verification of proper heat treatment, i.e. appropriate temperatures and corresponding thermal soak times is very important. Improper thermal stress relief would be very difficult to detect prior to installation but could prove disastrous once the RFQ and frame assembly was placed in service.

An inspection report of overall frame geometry and all feature geometry should be performed prior to delivery. Improper fixturing during welding or thermal stress relief can easily cause unwanted and unpredictable thermal distortion. Proper inspection will verify correct geometry as described by the fabrication drawings

5.4 RFQ and Frame Assembly Loads

As described in section 3.5.5, the RFQ and support frame is assembled vertically and subsequently rotated to horizontal, lowered, and transported to the APT/LEDA tunnel for final installation. The rotation, lowering, and transportation is performed with the aid of the facility overhead gantry crane and also temporary rigging equipment.

Extreme caution must be exercised to prevent inadvertent overloading of the RFQ and support frame assembly. Overhead cranes and rigging if applied in a structurally redundant manner are easily capable of overloading the RFQ and frame.

Application of rigging in a manner that is not structurally redundant will prevent the possibility of structural overloading. Non redundant rigging for the rotation step of the assembly sequence, for example, may not be permissible due to personnel safety requirements.

Load cells installed on the crane and on all winching type devices will allow monitoring of large applied loads. This procedure will greatly reduce the risk of overloading if redundant rigging is necessary.

5.5 Vibration Isolation

Dynamic excitation of the RFQ or associated components, of appropriate magnitude, could have adverse affects on beam quality.

Unfortunately, the vibratory input to which the RFQ assembly is subject can not be accurately measured until after the facility is complete and all mechanical equipment is installed.

Minimizing vibratory input to the RFQ as much as possible during the conceptual and detail design stages is prudent in mitigating potential operational vibratory problems. Mechanical equipment capable of significant vibratory input such as vacuum and roughing pumps, coolant pumps, and coolant flow metering valves should be mechanically isolated from the RFQ, if feasible.

Not mounting this type of equipment on the RFQ or support frame is optimal. The use of mechanically compliant interfacing, such as metal hose assemblies instead of rigid tubing, between this equipment and adjoining hardware will reduce transmitted dynamic energy. Also beneficial is the installation of this equipment throughout the facility on appropriate elastomeric mounts. This will dissipate portions of the dynamic energy that would otherwise be transmitted to its support structure.

Figures:

Tables:

References:

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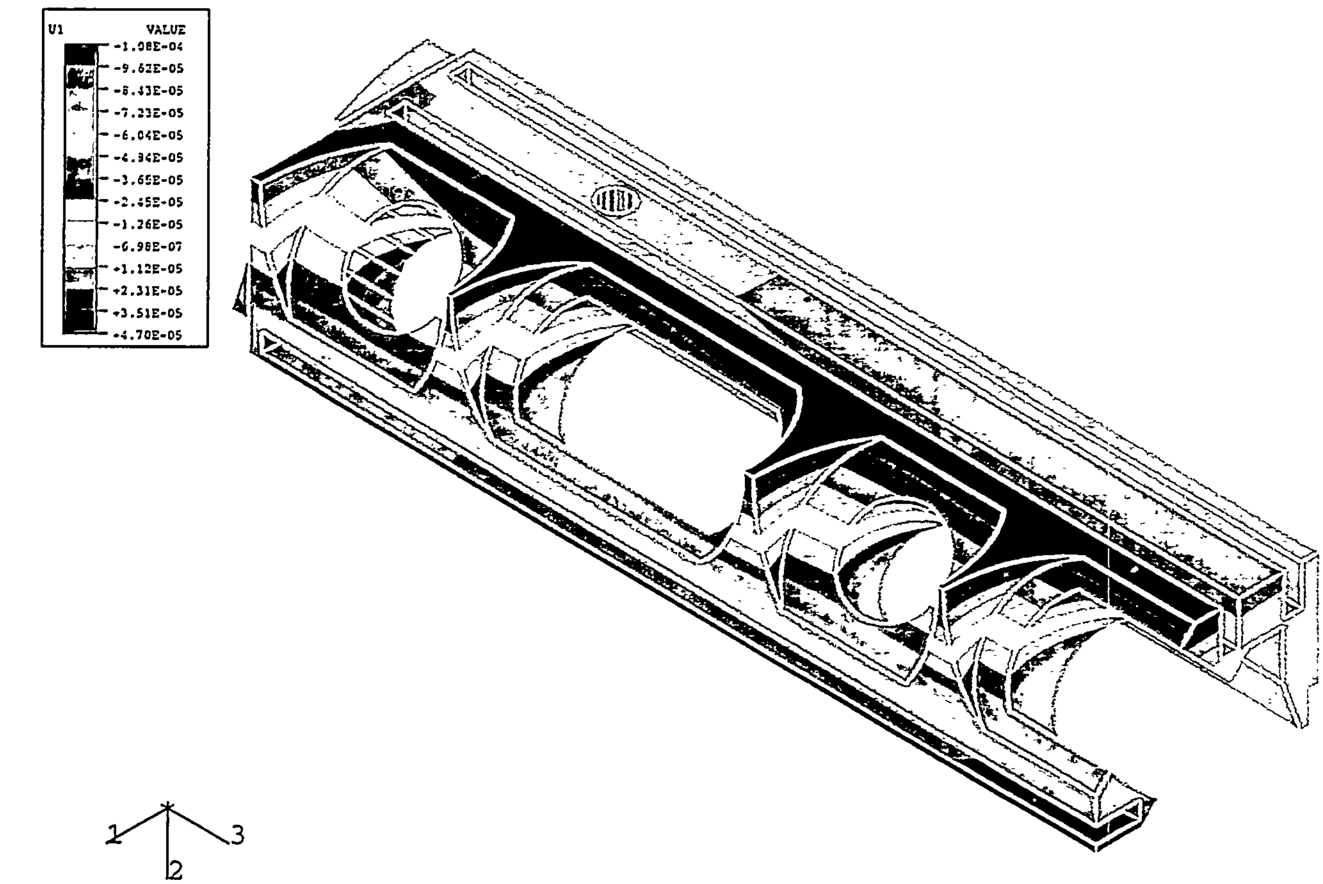


Figure A.1, Section A1 Major Vane, gravity loading, x displacement, inches

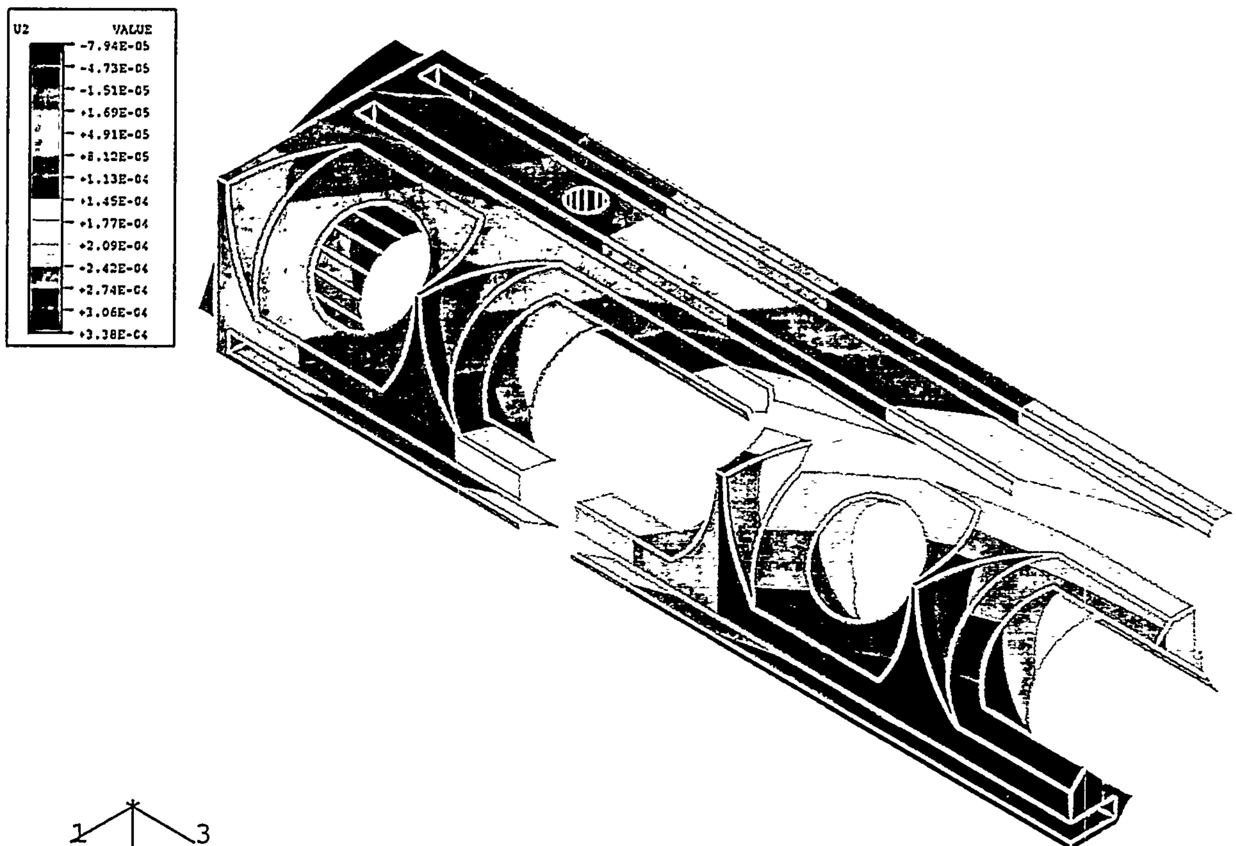


Figure A.2, Section A1 Major Vane, gravity loading, y displacement, inches

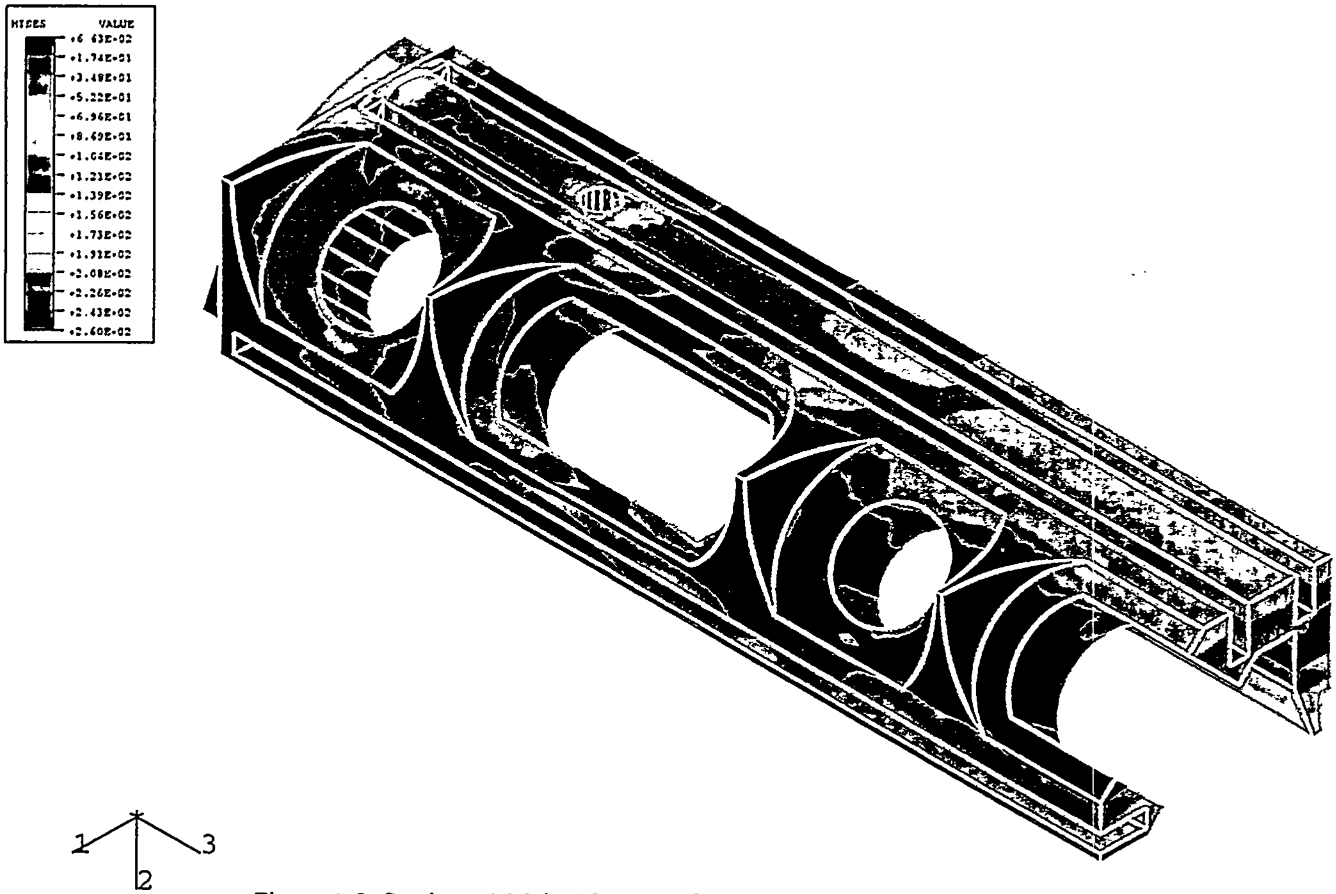


Figure A.3, Section A1 Major Vane, gravity loading, von Mises stress, psi

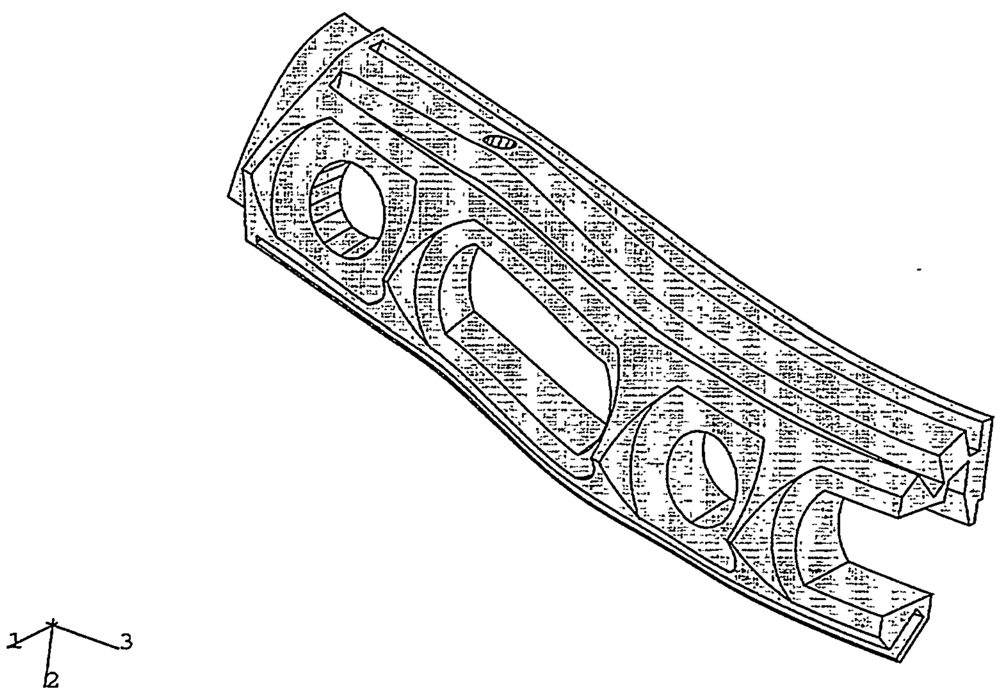


Figure A.4, Section A1 Major Vane, gravity loading, deformed shape (highly exaggerated)

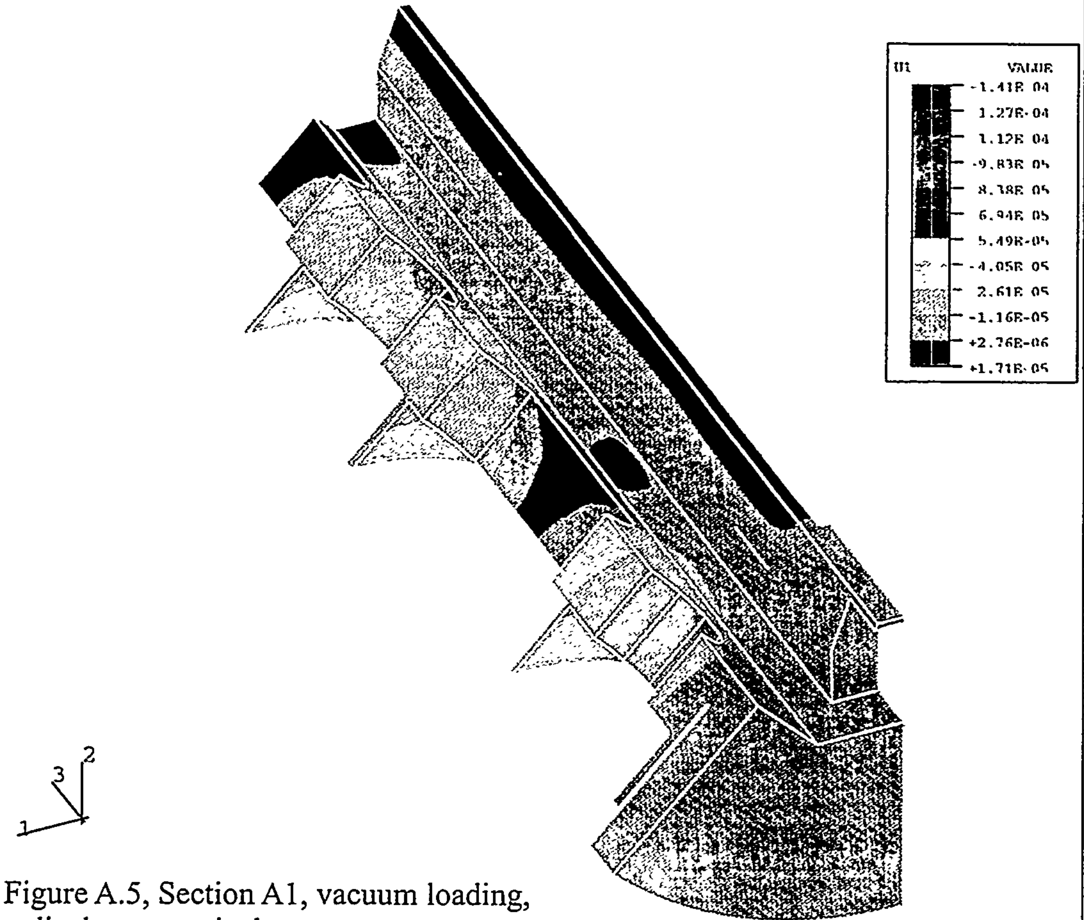


Figure A.5, Section A1, vacuum loading,
x displacement, inches

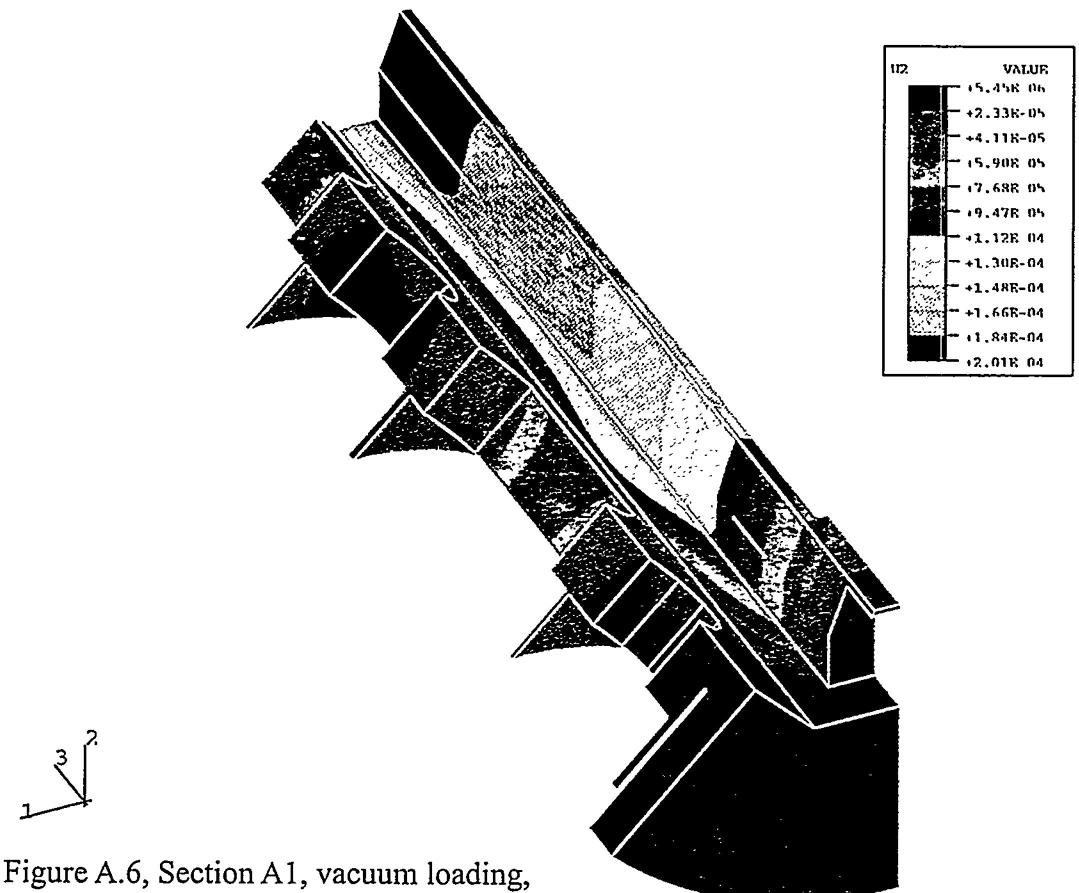


Figure A.6, Section A1, vacuum loading,
y displacement, inches

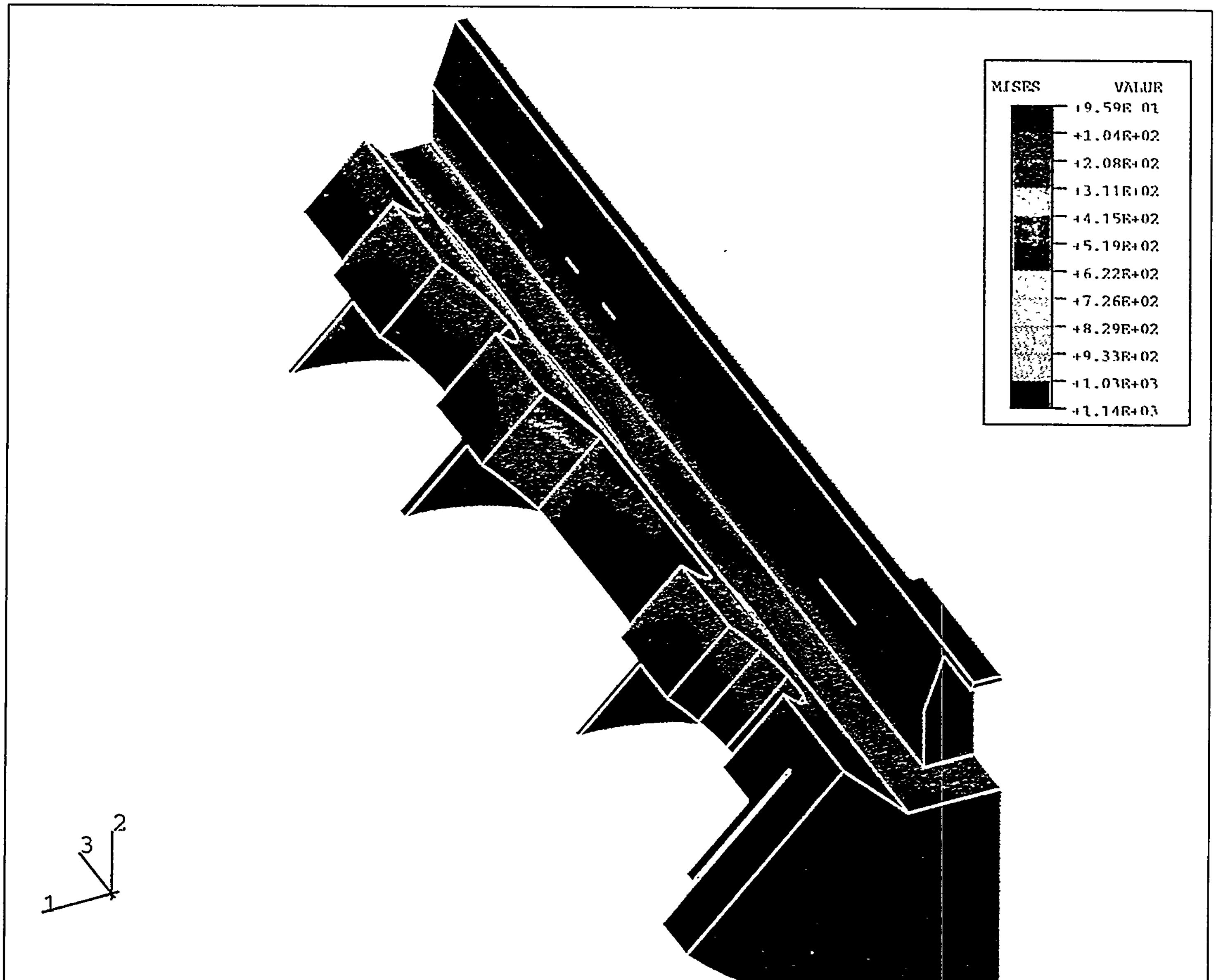


Figure A.7, Section A1, vacuum loading, von Mises Stress, psi

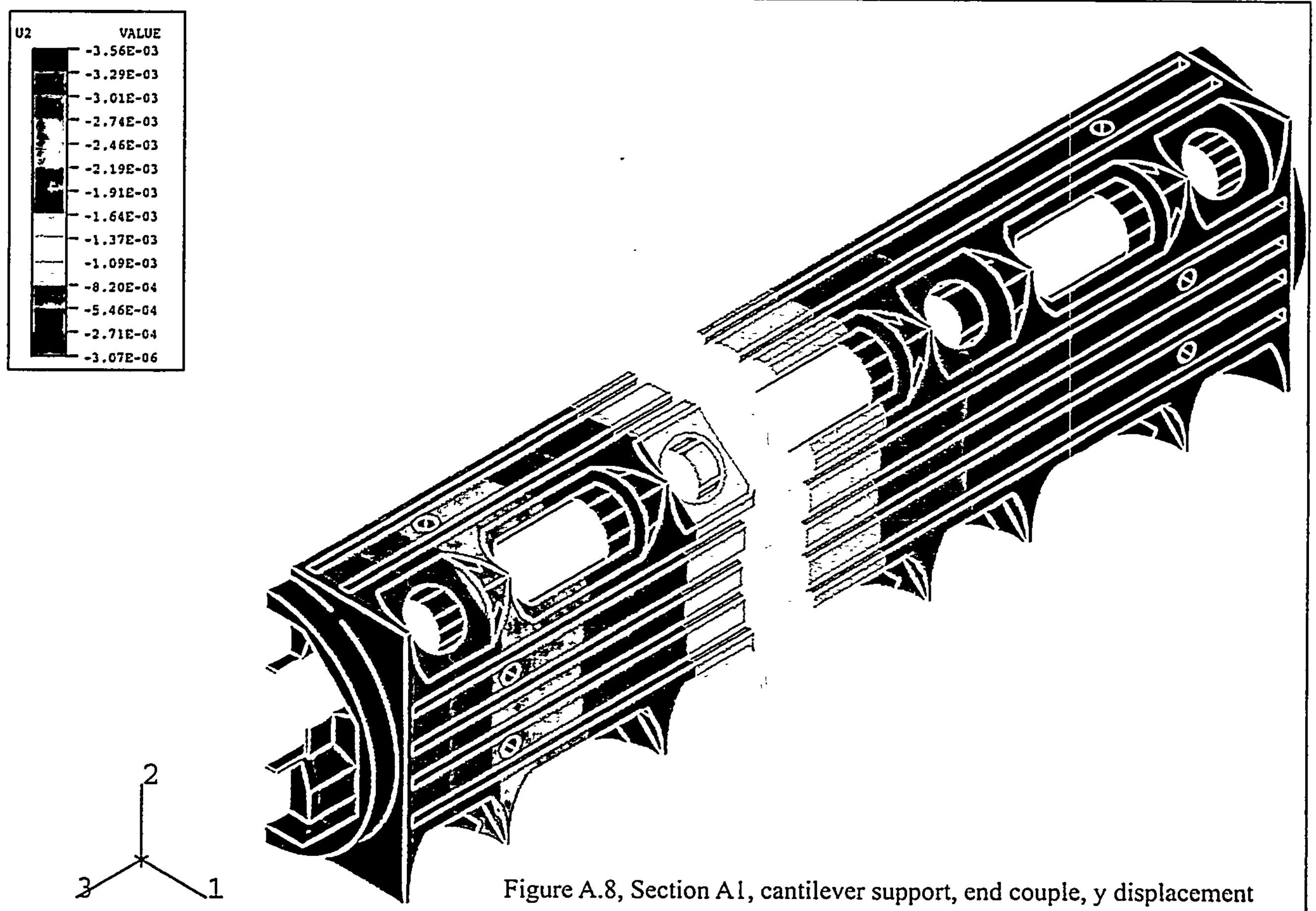


Figure A.8, Section A1, cantilever support, end couple, y displacement

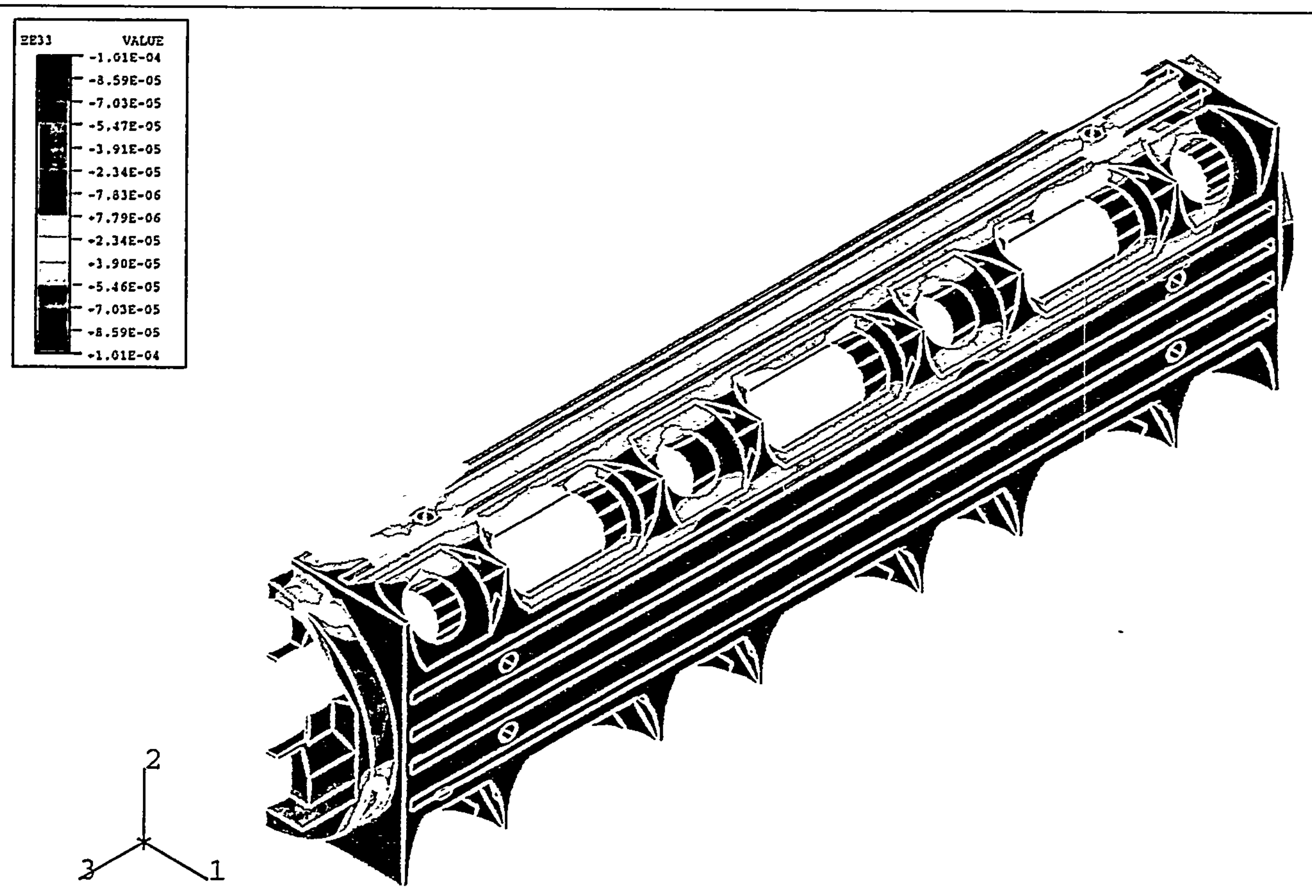


Figure A.9, Section A1, cantilever support, end couple, axial strain

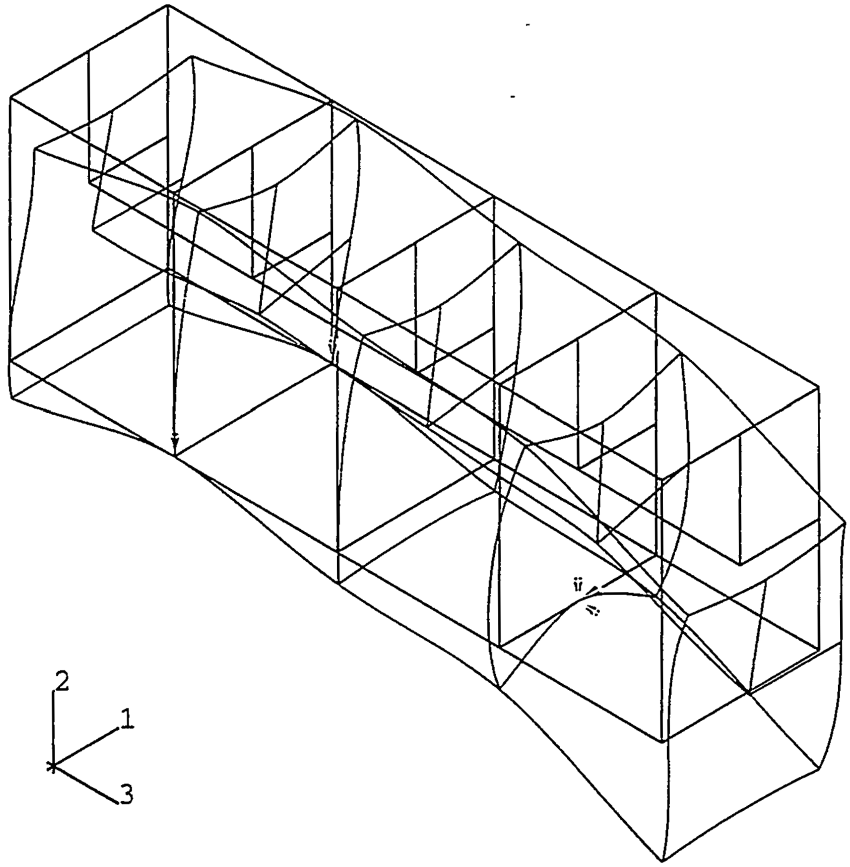


Figure A.10, RFQ and Support Frame, gravity loading, deformed shape

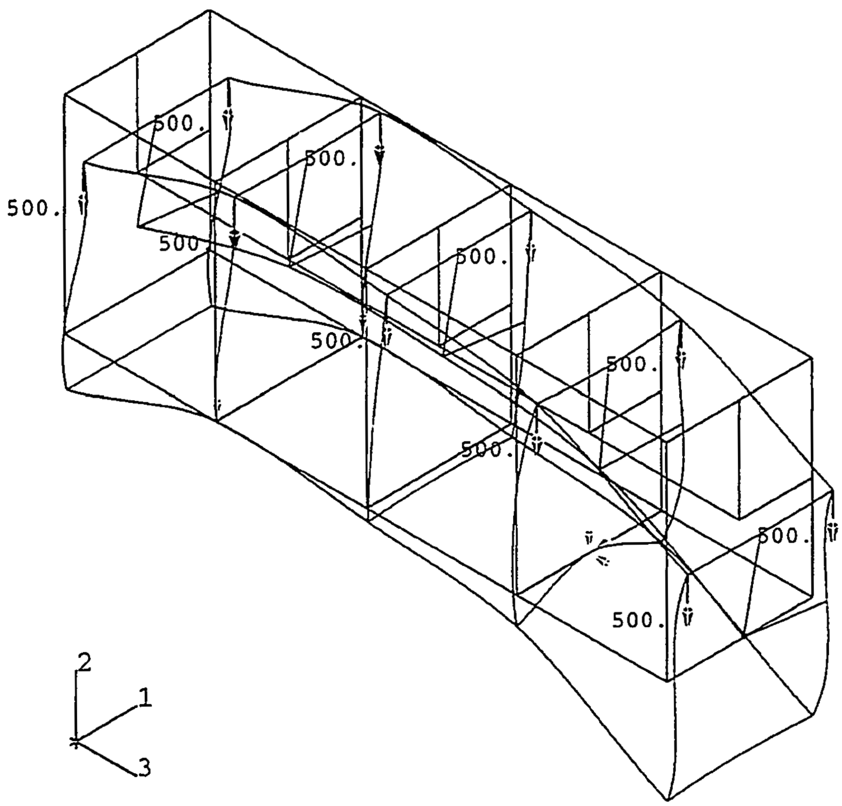
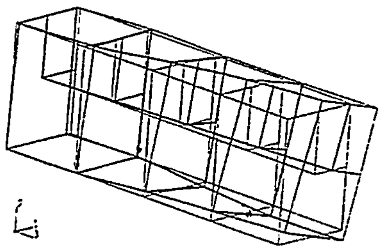
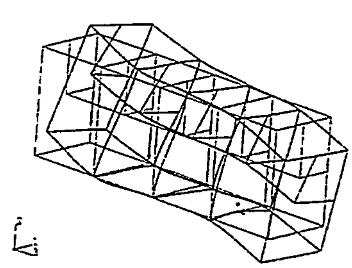


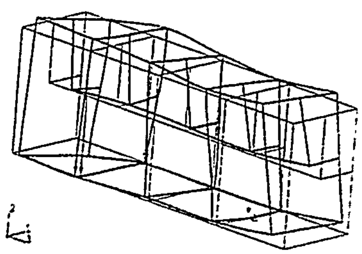
Figure A.11, RFQ and Support Frame, 500 lbf vertical point loads, deformed shape



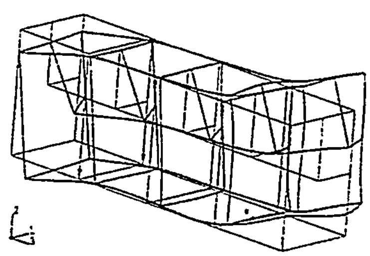
Mode 1, 8.0 Hz.



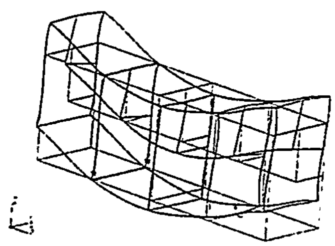
Mode 2, 13.4 Hz.



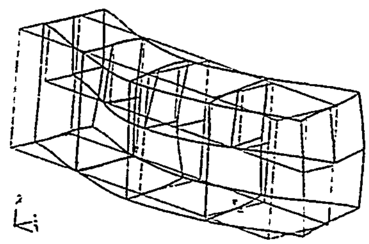
Mode 3, 13.9 Hz.



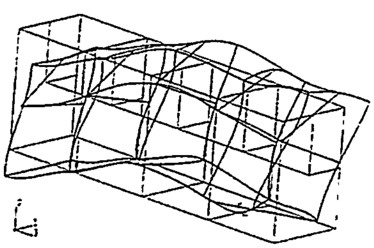
Mode 4, 23.2 Hz.



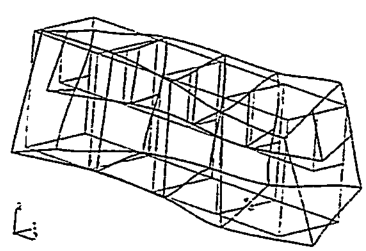
Mode 5, 26.5 Hz.



Mode 6, 28.8 Hz.



Mode 7, 29.7 Hz.



Mode 8, 32.7 Hz.

Figure A.14, RFQ and Support Frame Dynamic Mode Shapes and Frequencies

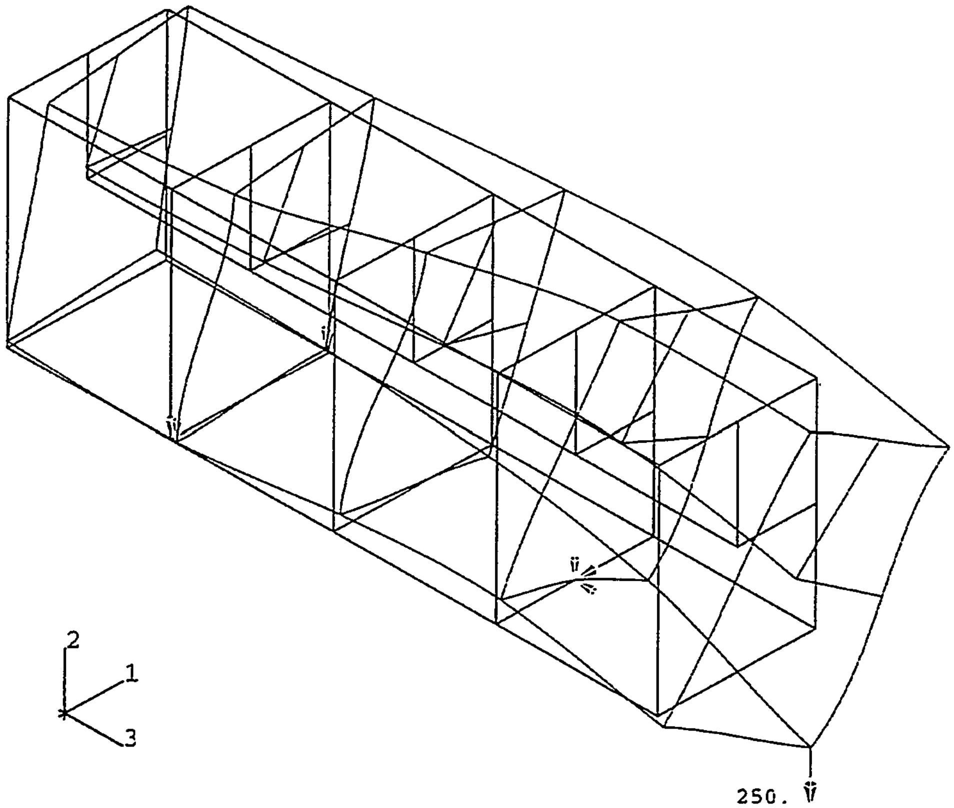


Figure A.12, RFQ and Support Frame, single 250 lbf point load, deformed shape

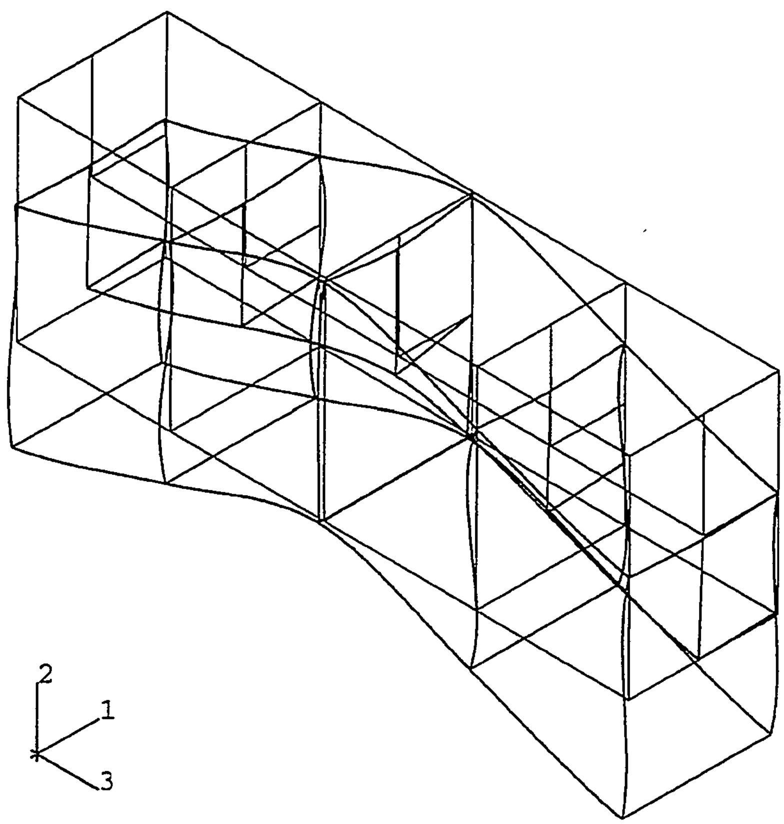


Figure A.13, RFQ and Support Frame, gravity loading, trunnion support, deformed shape