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Second Target Station Project: Moderator Reflector Assembly Fastener Analysis

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July 2026

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MODERATOR REFLECTOR ASSEMBLY FASTENER ANALYSIS

Jim Janney

July 2026

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CONTENTS

ABSTRACT

While all of the pressure boundaries of the Moderator Reflector Assembly are fully welded, fasteners are used for alignment, support, and structurally connecting dissimilar metals within the assembly. These fasteners include threaded rods, screws, and pins and must be shown to support the expected loads from preloading, lifting, seismic, and pressure loading.

1. INTRODUCTION

The Second Target Station (STS) Moderator Reflector Assembly (MRA) contains 2 liquid hydrogen moderators which are optimized to provide high brightness cold neutron beams to the instruments. The liquid hydrogen is contained within aluminum hydrogen vessels which are supported by titanium pins within the vacuum vessel portion of the aluminum reflector vessels. As seen in Figure 1.1, the reflector vessels are bolted to a stainless steel backbone which supports and aligns the reflector vessels. The backbone is supported by 3 alignment blocks which align to pins and rest on mating surfaces in the core vessel shielding. The backbone also supports an MRA shield block, which is bolted to the top of the backbone with threaded rods. A seismic block is bolted to the back of the shield block just below the top surface and interfaces to a pin in the core vessel shielding to prevent the MRA from tipping over during a potential seismic event since the MRA is not secured down. Finally, a threaded rod is threaded into the shield block over the MRA center of gravity to provide a lifting feature for remote handling of the MRA.

While the MRA has been analyzed according to the intent of the ASME BPVC, Section VIII, Division 2 using finite element analysis methods [1], this analysis is focused on the pressure boundaries of the reflector vessels and the backbone. The fasteners connecting parts of the MRA can be verified to support the applied loads with hand calculations as shown in this document. Because the fasteners employed in the MRA are not used to maintain pressure enclosure but instead to hold components of the assembly together, we will not use ASME BPVC bolting analysis methods but instead use general purpose fastener calculations.

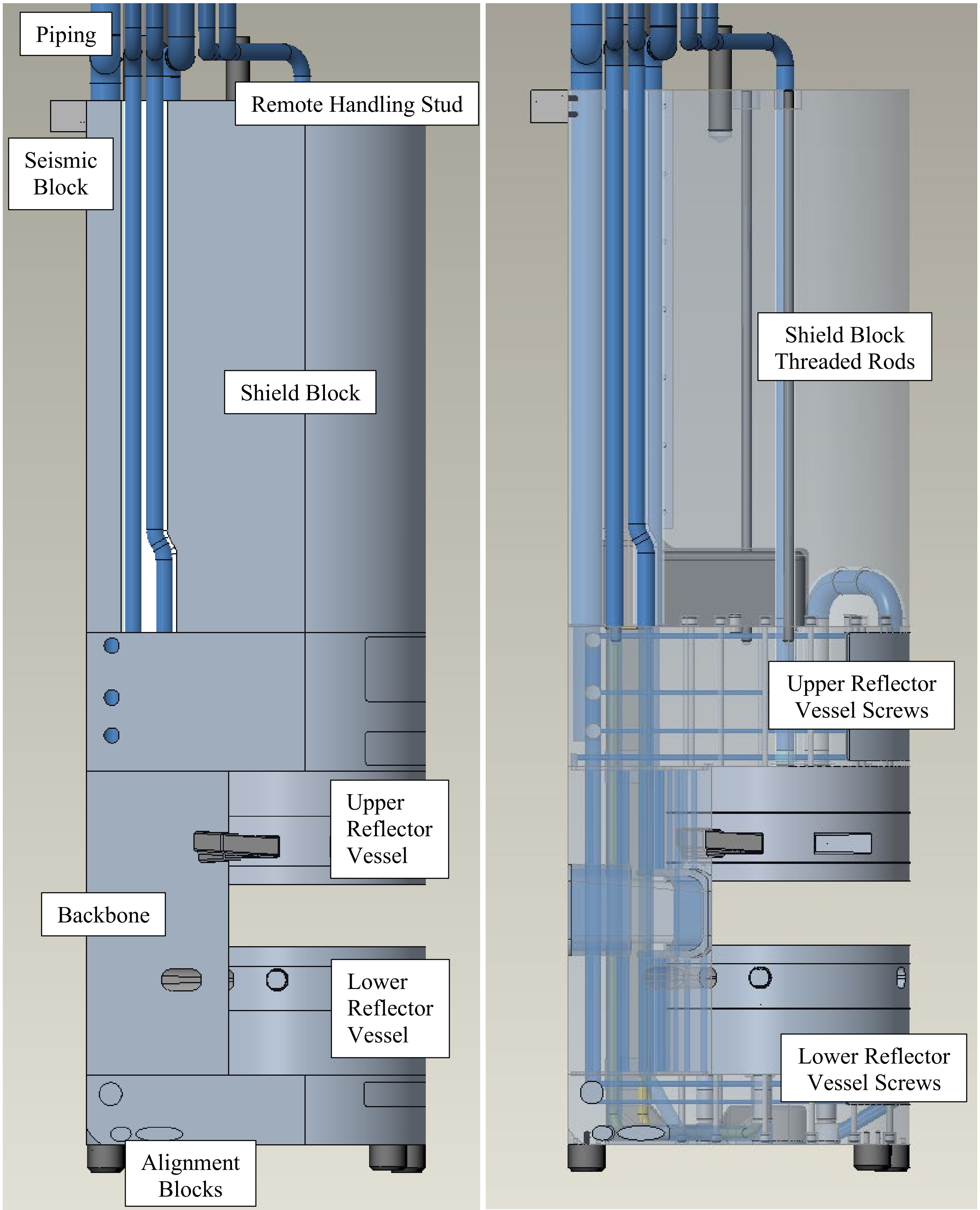

Figure 1.1 Moderator Reflector Assembly Geometry (left) and Transparent View to show Fasteners (right)

2. MATERIAL PROPERTIES

2.1 COMPONENT PROPERTIES AND MASSES

Table 2.1 Component Properties and Masses

Component	Material	Specification	Min. Yield Strength (MPa)	Min. Tensile Strength (MPa)	Mass (kg)
Shield Block	Carbon Steel	ASTM A36	250	400	1105
Backbone	316L Stainless Steel	ASTM A240	170	485	637
Upper Reflector Vessel	6061-T6 Aluminum	ASTM B-247	221	241	37
Lower Reflector Vessel	6061-T6 Aluminum	ASTM B-247	221	241	41
Piping	316L/Invar				93
Total					1913

2.2 FASTENERS

Table 2.2 Fastener Sizes and Material Properties

Fastener	Size	Material	Specification	Min. Yield Strength (MPa)	Min. Tensile Strength (MPa)
Remote Handling Stud	1.5-8 UN	316 Stainless Steel	ASTM A193, B8M, Class 1 or 1D	205	515
Shield Block Threaded Rods	5/8-11 UNC	316 Stainless Steel	ASTM A193, B8M, Class 1 or 1D	205	515
Shield Block Alignment Pins	18mm OD	316 Stainless Steel	ISO 2338	205	515
Reflector Vessel Screws	3/8-16 UNC	316 Stainless Steel	ASTM F837, Mark F837E	276	552
Alignment Block Screws	5/16-18 UNC	316 Stainless Steel	ASTM F837, Mark F837E	276	552
Alignment Block Pins	10mm OD	316 Stainless Steel	ISO 2338	205	515
Seismic Block Pins	10mm OD	316 Stainless Steel	ISO 2338	205	515
Seismic Block Screws	5/16-18 UNC	316 Stainless Steel	ASTM F837, Mark F837E	276	552
Hydrogen Vessel Pins	3mm OD	Ti 15-3-3-3	AMS 4914	690	703

3. PRELOAD

3.1 SHIELD BLOCK THREADED RODS

The shield block threaded rods are 5/8"-11 UNC rods with a length of 870.4 mm and a thread engagement of 22.2 mm. The preload of 8.96 kN is ensured by compressing flat 3 MW Components CDS-126389S Belleville washers in series [2]. The washer stack also ensures maintenance of preload under any differential thermal expansion. The rods are threaded into the backbone, which is made of the same material.

First, we will calculate the tensile stress in the rods and compare it to the minimum yield strength.

$$\sigma = \frac{F}{\pi * \frac{d_{minor}{}^2}{4}} = \frac{8.96kN}{\pi * \frac{(13.1mm)^2}{4}} = 66.6\ MPa$$

$$FOS_{yield} = \frac{\sigma_{yield}}{\sigma} = \frac{205MPa}{66.6MPa} = 3.08$$

Next, we will check the shear yield of the stud threads using the formula given in [3].

$$\tau = \frac{F}{(\pi * d_{pitch} * l_{eng})/_3} = \frac{8.96kN}{(\pi * 14.2mm * 22.2mm)/_3} = 27.1\ MPa$$

$$FOS_{yield} = \frac{0.577 * \sigma_{yield}}{\tau} = \frac{0.577 * 205MPa}{27.1MPa} = 4.36$$

Finally, we will check the thread pullout of the hole threads.

$$\tau = \frac{F}{(\pi * d_{pitch} * l_{eng})/_3} = \frac{8.96kN}{(\pi * 14.2mm * 22.2mm)/_3} = 27.1\ MPa$$

$$FOS_{yield} = \frac{0.577 * \sigma_{yield}}{\tau} = \frac{0.577 * 170MPa}{27.1MPa} = 3.62$$

The shielded block threaded rods have been shown to support the preload with a minimum factor of safety of 3.08.

3.2 REFLECTOR VESSEL SCREWS

The reflector vessels screws are 3/8"-16 screws with a thread engagement of 13.55 mm. The preload of 3.98 kN is ensured by compressing flat 3 MW Components CDS-753856S Belleville washers in series [2]. The washer stack also ensures maintenance of preload under any differential thermal expansion. The screws are threaded into the reflector vessels, which are made of Al-6061 T6 but feature helicoil inserts made of 316 stainless steel.

First, we will calculate the tensile stress in the screws and compare to the minimum yield strength.

$$\sigma = \frac{F}{\pi * \frac{{d_{minor}}^2}{4}} = \frac{3.98kN}{\pi * \frac{(7.60mm)^2}{4}} = 87.7\ MPa$$

$$FOS_{yield} = \frac{\sigma_{yield}}{\sigma} = \frac{273MPa}{87.7MPa} = 3.11$$

Next, we will check the shear yield of the screw threads.

$$\tau = \frac{F}{(\pi * d_{pitch} * l_{eng})/_3} = \frac{3.98kN}{(\pi * 8.35mm * 13.55mm)/_3} = 33.6\ MPa$$

$$FOS_{yield} = \frac{0.577 * \sigma_{yield}}{\tau} = \frac{0.577 * 273MPa}{33.6MPa} = 4.69$$

4. LIFTING LOADS

4.1 REMOTE HANDLING STUD

The remote handling stud is a 1.5"-8 UN threaded rod with 61.9 mm of engagement located over the center of gravity of the MRA which is responsible for carrying the whole 1913 kg mass of the MRA upon installation lifting. The stud is threaded into the shield block. Note that the factor of safety for the threaded rod must be greater than 3 because it is used for lifting.

First, we will calculate the tensile stress in the stud and compare it to the minimum yield strength.

$$\sigma = \frac{F}{\pi * \frac{{d_{minor}}^2}{4}} = \frac{1913kg * 9.81\frac{N}{kg}}{\pi * \frac{(34.26mm)^2}{4}} = 20.4\ MPa$$

$$FOS_{yield} = \frac{\sigma_{yield}}{\sigma} = \frac{205MPa}{20.4MPa} = 10.1$$

Next, we will check the shear yield of the stud threads.

$$\tau = \frac{F}{(\pi * d_{pitch} * l_{eng})/_3} = \frac{1913kg * 9.81\frac{N}{kg}}{(\pi * 35.8mm * 61.9mm)/_3} = 8.09\ MPa$$

$$FOS_{yield} = \frac{0.577 * \sigma_{yield}}{\tau} = \frac{0.577 * 205MPa}{8.09MPa} = 14.6$$

Finally, we will check the thread pullout of the hole threads.

$$\tau = \frac{F}{(\pi * d_{pitch} * l_{eng})/_3} = \frac{1913kg * 9.81\frac{N}{kg}}{(\pi * 35.8mm * 61.9mm)/_3} = 8.09\ MPa$$

$$FOS_{yield} = \frac{0.577 * \sigma_{yield}}{\tau} = \frac{0.577 * 250MPa}{8.09MPa} = 17.8$$

4.2 SHIELD BLOCK THREADED RODS

The mass of the MRA below the shield block is supported by the 4 shield block threaded rods during lifting. The arrangement of the threaded rods is shown in Figure 4.1. Although the piping is attached to the backbone and supported by the shield block, we will assume the full piping load is supported by the threaded rods, giving a suspended load of 808 kg from the rods. Note that the preload on a single threaded rod is greater than the lifting load on the threaded rods so that lifting will simply reduce the contact force on the mating surfaces but will not change the load seen by the fasteners. Nonetheless, we will calculate the stress that would be applied by the lifting load to obtain a safety factor for lifting. We will assume that the lifting load is divided evenly between the 4 fasteners.

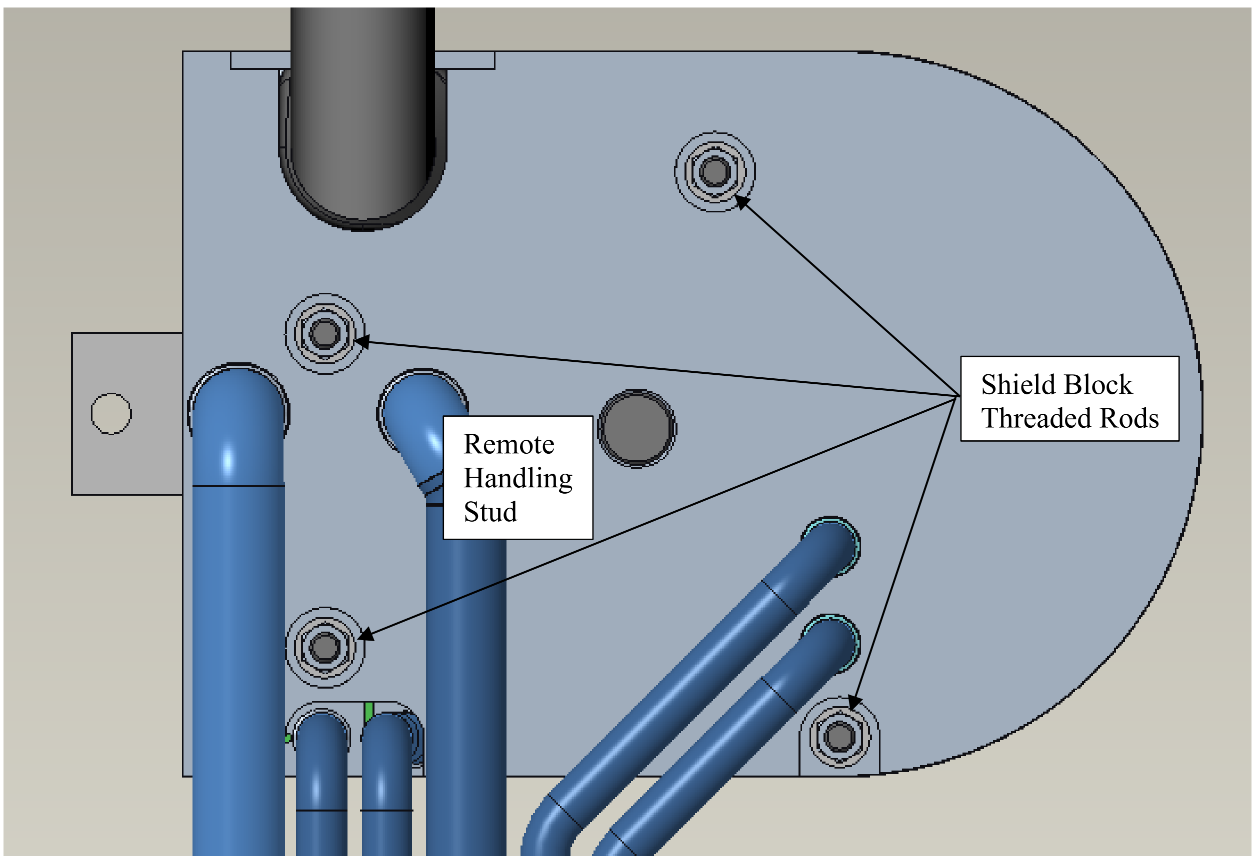

Figure 4.1 MRA Shield Block Threaded Rod Configuration from the Top.

First, we will calculate the tensile stress in the rods and compare to the minimum yield strength.

$$\sigma = \frac{F}{4\pi * \frac{{d_{minor}}^2}{4}} = \frac{808kg * 9.81\frac{N}{kg}}{4\pi * \frac{(13.1mm)^2}{4}} = 14.7\ MPa$$

$$FOS_{yield} = \frac{\sigma_{yield}}{\sigma} = \frac{205MPa}{14.7MPa} = 13.9$$

Based on the preload calculation in section 4.1, the tensile stress in the rods is the limiting factor in this joint and thread pullout will not be analyzed.

4.3 UPPER REFLECTOR VESSEL SCREWS

The 12 upper reflector vessels screws support the mass of the upper reflector vessel at all times, including during lifting. The screw arrangement is shown in Figure 4.2. Note that the preload on the upper reflector vessel screws is much greater than the force caused by supporting the 37 kg upper reflector vessel so that there is significant contact force between the vessel and the mating backbone surface. Nonetheless, we will calculate the stress that would be applied by the lifting load to obtain a safety factor for lifting. We will assume that the lifting load is divided evenly between the 12 screws.

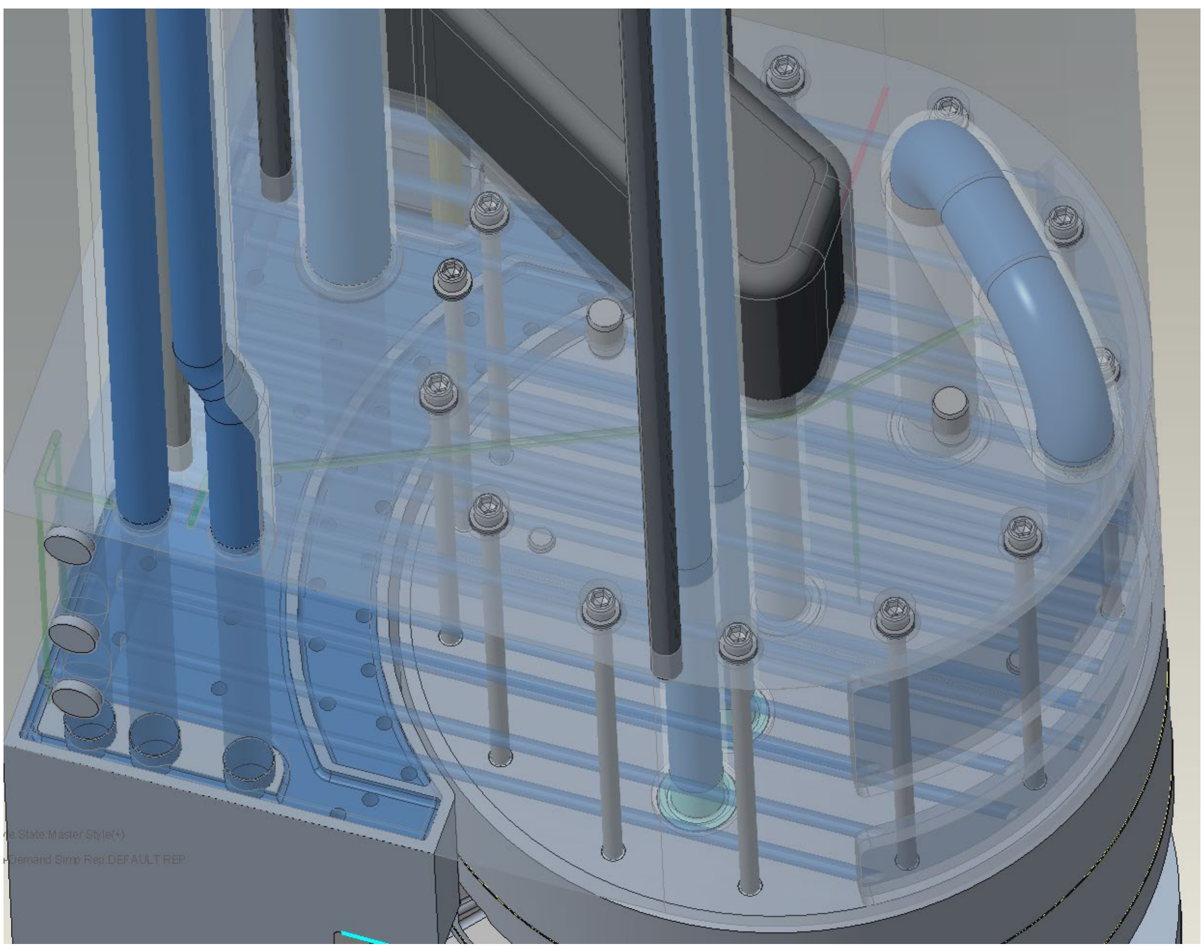

Figure 4.2 Upper Reflector Vessel Screw Arrangement with Upper Backbone and Shield Block Transparent.

First, we will calculate the tensile stress in the screws and compare it to the minimum yield strength.

$$\sigma = \frac{F}{12\pi * \frac{d_{minor}{}^2}{4}} = \frac{37kg * 9.81\frac{N}{kg}}{12\pi * \frac{(7.60mm)^2}{4}} = 0.666\ MPa$$

$$FOS_{yield} = \frac{\sigma_{yield}}{\sigma} = \frac{273MPa}{0.666MPa} = 410$$

Based on the preload calculation in section 4.2, the tensile stress in the screws is the limiting factor in this joint and thread pullout will not be analyzed.

5. SEISMIC LOADS

The seismic loads applied to the Moderator Reflector Assembly are based on the guidance of the NPH BOD [4]. The equivalent static loads for the design basis earthquake are derived in Appendix A. Seismic loads are only considered for the MRA while it is in its installed position and not during lifting. While in the installed configuration, the components within the MRA are not suspended from fasteners, so the vertical equivalent static load is generally not considered and the horizontal equivalent static load is applied in the worst case direction.

5.1 SHIELD BLOCK

The seismic block will be conservatively assumed not to be loaded when calculating the restraint of the shield block relative to the backbone under seismic loading. As a result, full equivalent static load will be carried through the shield block to backbone interface.

5.1.1 Shield Block Tipping

First, we evaluate whether the shield block will tip off the backbone under the static horizontal equivalent load without restraint from the threaded rods. If restraint from the threaded rods is required, the normal force between the shield block and the backbone would be reduced. We will sum the moments about the edge of support of the shield block closest to the center of gravity, assuming no restraint from the threaded rods, as shown in Figure 5.1. The normal force is a distributed force but we will assume a point force for convenience since we are only interested in determining if the force is positive, which would indicate the shield block will not tip even ignoring restraint from the threaded rods.

$$\sum M = F_g * l_{cg} - F_{horiz} * h_{cg} - F_n * l_{cg} = 0$$

Rearranging to solve for F_n gives,

$$F_n = \frac{F_g * l_{cg} - F_{horiz} * h_{cg}}{l_{cg}} = \frac{1198kg * 9.81\frac{N}{kg} * 185.4mm - 0.308 * 1198kg * 9.81\frac{N}{kg} * 430.3mm}{185.4mm}$$

$$F_n = 3.35kN$$

Since the normal force between the shield block and the backbone remains positive, the shield block will not tip without restraint and the full preload from the threaded rods is applied as normal force between the backbone and shield block.

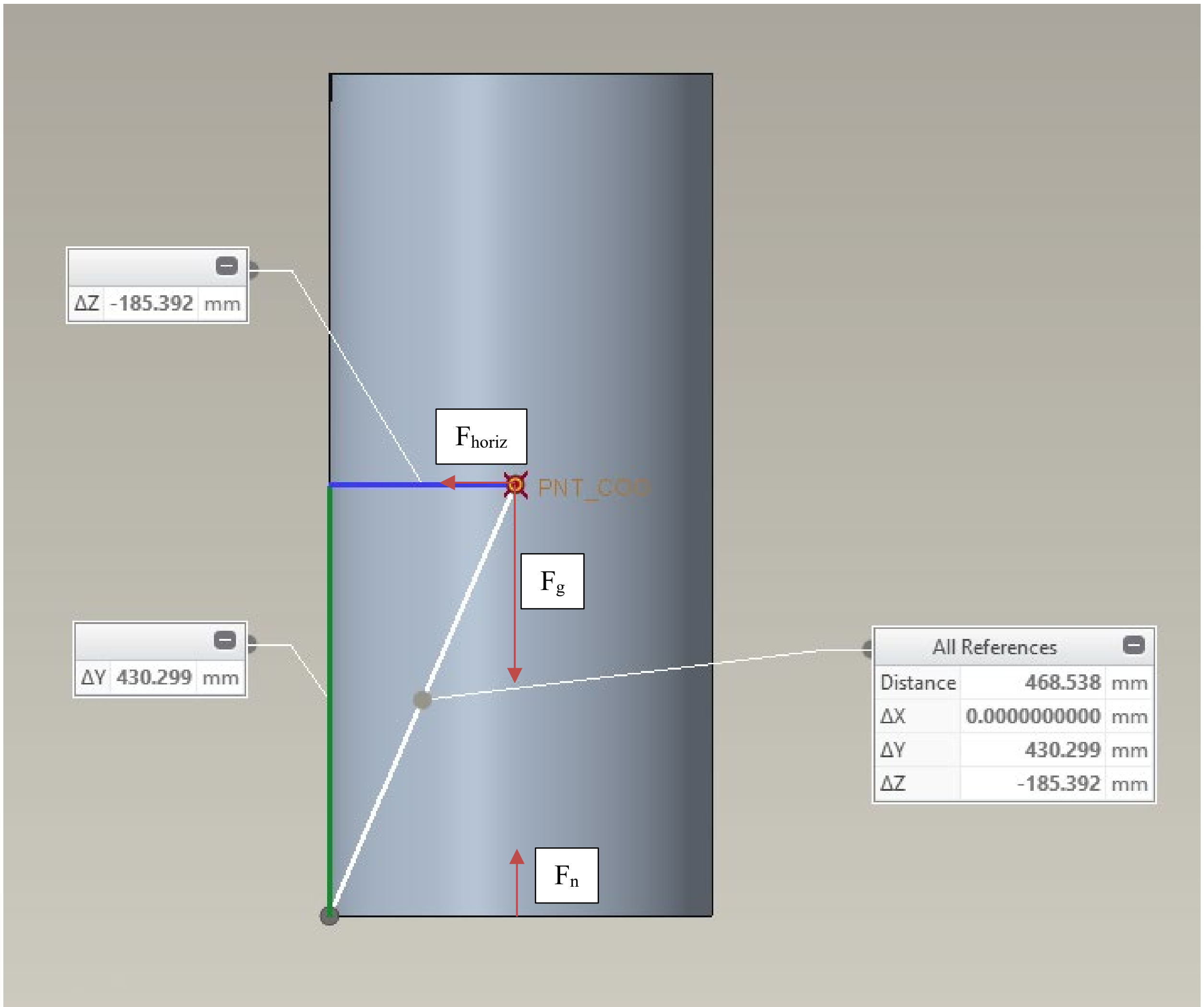

Figure 5.1 Shield Block Free Body Diagram with Horizontal Static Equivalent Load Applied

5.1.2 Friction from Preload

The first way the MRA shield block is restrained against horizontal seismic loading is the friction force between the shield block and the backbone caused by preload from the 4 threaded rods. Note, we will ignore the additional potential friction force caused by the gravity load of the shield block. The mass used to calculate the shield block horizontal equivalent static load will include the piping since the piping is partially supported by the shield block. We will assume a friction factor of 0.4 between the nickel coated A36 carbon steel shield block and the 316 stainless steel backbone.

$$F_{horiz} = 0.308 * m * 9.81\frac{N}{kg} = 0.308 * 1198kg * 9.81\frac{N}{kg} = 3.62kN$$

$$F_{slip} = \mu * 4 * F_{pre} = 0.4 * 4 * 8.96kN = 14.3kN$$

$$FOS_{slip} = \frac{F_{slip}}{F_{horiz}} = \frac{14.3kN}{3.62kN} = 3.95$$

5.1.3 Shear of Alignment Pin

The MRA shield block is also restrained against horizontal seismic loading by the pins used to align the shield block to the backbone. The pins are 18 mm diameter and made from 316 stainless steel. One of the pins is mated into a slotted hole in the shield block to prevent over constraint, so only the shear area of one pin will be considered to restrain horizontal seismic loading.

$$\tau = \frac{F_{horiz}}{\pi \frac{d^2}{4}} = \frac{3.62kN}{\pi * \frac{(18\,mm)^2}{4}} = 13.1MPa$$

$$FOS_{shear} = \frac{0.577 * \sigma_{yield}}{\tau} = \frac{0.577 * 205MPa}{13.1MPa} = 8.99$$

5.2 UPPER REFLECTOR VESSEL

The upper reflector vessel is restrained against horizontal seismic loading by the friction force between the reflector vessel and the backbone caused by preload from the 12 screws. Note, we will account for the reduction in friction force caused by the gravity load of the upper reflector vessel. We will assume a friction factor of 0.4 between the Al 6061-T6 reflector vessel and the 316 stainless steel backbone. We will not take any credit for the water and vacuum connections between the components as these are not meant to be structural connections.

$$F_{horiz} = 0.308 * m * 9.81\frac{N}{kg} = 0.308 * 37kg * 9.81\frac{N}{kg} = 112N$$

$$F_{slip} = \mu * \left(12 * F_{pre} - F_g\right) = 0.4 * \left(12 * 3.98kN - 37kg * 9.81\frac{N}{kg}\right) = 19.0kN$$

$$FOS_{slip} = \frac{F_{slip}}{F_{horiz}} = \frac{19.0kN}{112N} = 170$$

5.3 LOWER REFLECTOR VESSEL

The lower reflector vessel is restrained against horizontal seismic loading by the friction force between the reflector vessel and the backbone caused by preload from the 12 screws. Note, we will ignore the additional potential friction force caused by the gravity load of the lower reflector vessel. We will assume a friction factor of 0.4 between the Al 6061-T6 reflector vessel and the 316 stainless steel backbone. We will not take any credit for the water and vacuum connections between the components as these are not meant to be structural connections.

$$F_{horiz} = 0.308 * m * 9.81\frac{N}{kg} = 0.308 * 41kg * 9.81\frac{N}{kg} = 124N$$

$$F_{slip} = \mu * 12 * F_{pre} = 0.4 * 12 * 3.98kN = 19.1kN$$

$$FOS_{slip} = \frac{F_{slip}}{F_{horiz}} = \frac{19.1kN}{124N} = 154$$

5.4 ALIGNMENT BLOCKS

The seismic block will be conservatively assumed not to be loaded when calculating the restraint of the MRA under seismic loading. As a result, full equivalent static load of the MRA will be carried through the alignment blocks. We will conservatively ignore friction forces between the alignment blocks and the vessel systems flat surfaces and alignment pins they interface. The direction of the horizontal seismic equivalent static load which causes the largest loading in the alignment blocks is along the direction of the proton beam due to the angles of the alignment blocks as shown in Figure 5.2. In this loading, the alignment block closest to the target restrains no load as the load is parallel to the slot. The remaining 2 alignment blocks share the seismic load equally, but must react a much larger normal load due to the angle of the slots.

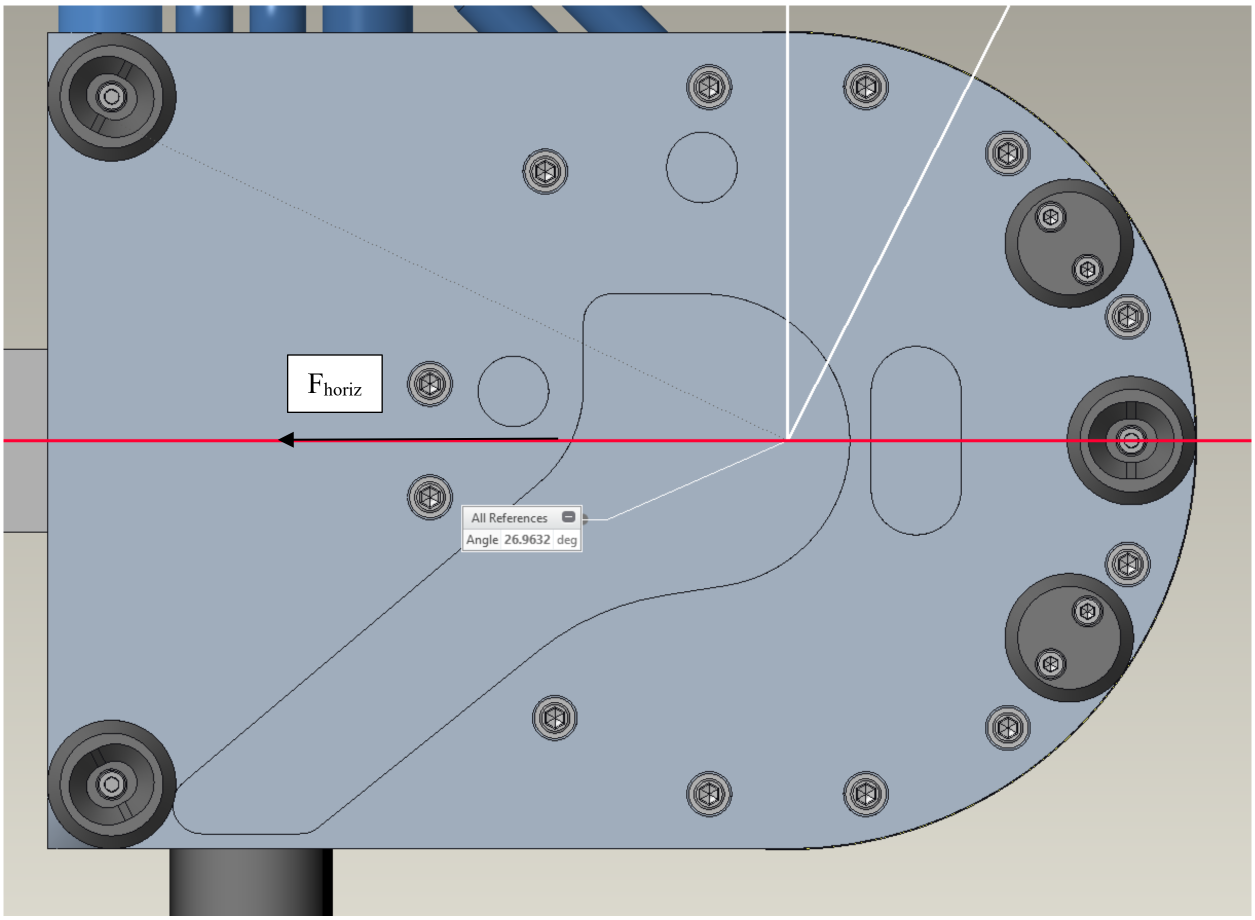

Figure 5.2 Worst Case Direction for Horizontal Seismic Loading for MRA Alignment Blocks

$$F_{horiz} = 0.308 * m * 9.81\frac{N}{kg} = 0.308 * 1913kg * 9.81\frac{N}{kg} = 5.78kN$$

$$F_{norm} = \frac{F_{horiz}/2}{sin(\alpha)} = \frac{5.78kN/2}{sin(26.96°)} = 5.60kN$$

The normal force is reacted by the 2 10 mm diameter 316 stainless steel dowel pins which align the alignment block to the backbone as shown in Figure 5.3. Even though one of the dowel interface holes is slotted to avoid over constraint, it is slotted perpendicular to the normal force, so the load is assumed to be shared between the 2 dowel pins. Note, the 20 mm alignment pins are not analyzed in this document as they are Vessel Systems scope but the maximum normal force calculated will be recorded in the MRA-Vessel Systems Interface Sheet.

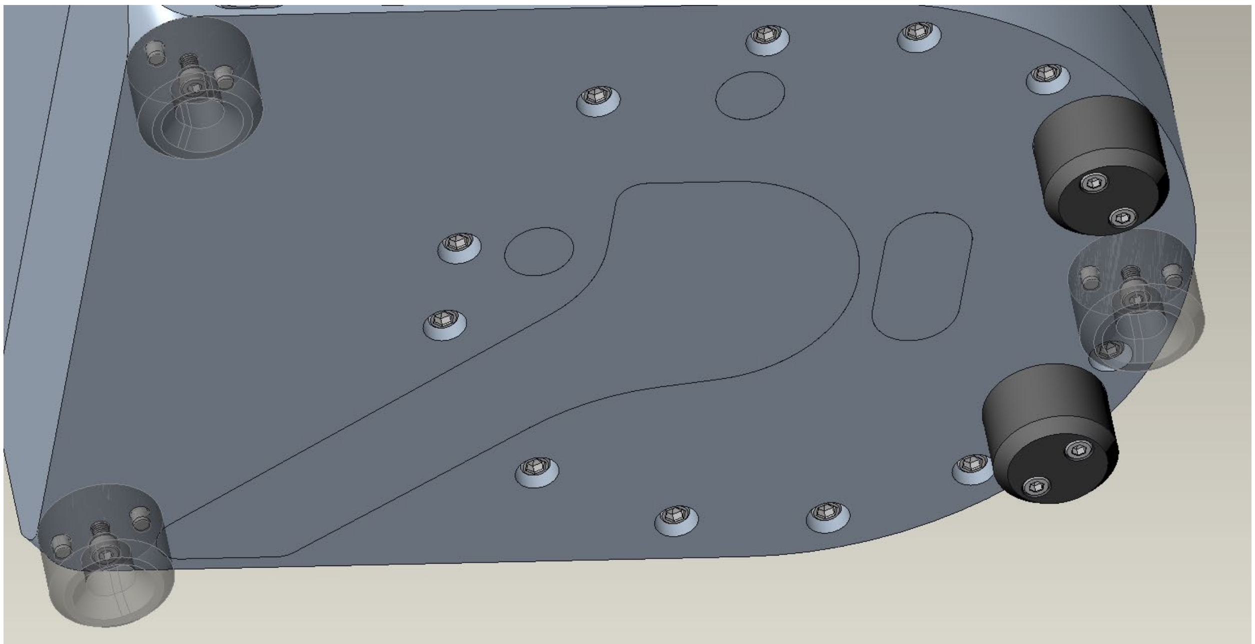

Figure 5.3 MRA Alignment Block Pin Arrangement

$$\tau = \frac{F_{norm}}{2\pi \frac{d^2}{4}} = \frac{5.60kN}{2\pi \frac{(10\ mm)^2}{4}} = 35.6MPa$$

$$FOS_{shear} = \frac{0.577 * \sigma_{yield}}{\tau} = \frac{0.577 * 205MPa}{35.6MPa} = 3.32$$

5.5 SEISMIC BLOCK

The seismic block exists only to prevent the MRA from tipping due to the equivalent horizontal static load from an earthquake. The worst case direction for the equivalent static load is in the direction where the center of gravity is closest to the outside of the base of support, which is only 78.07 mm as shown in Figure 5.4. In order to calculate the required restraint force to prevent tipping we will sum the moments about the axis of the outside of the base of support closest to the center of gravity, as shown in Figure 5.5.

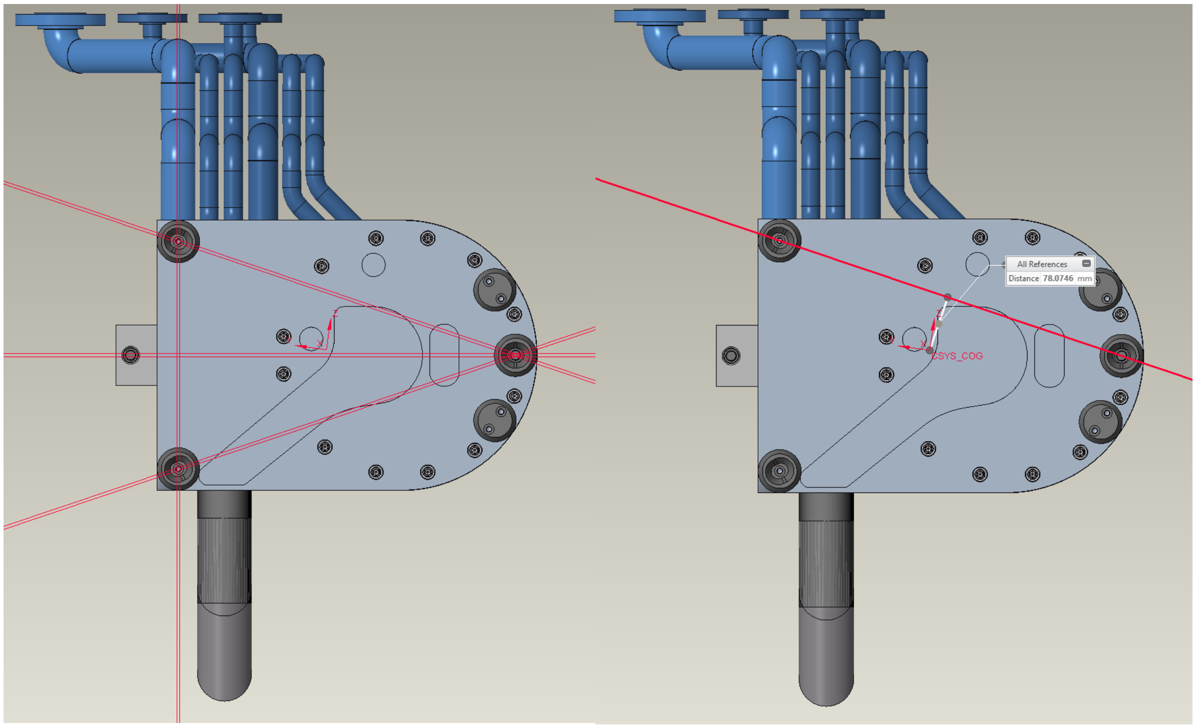

Figure 5.4 Center of Gravity Relative to the Outside Base of Support (left) and the Distance from the CG to the Closest Base of Support (right)

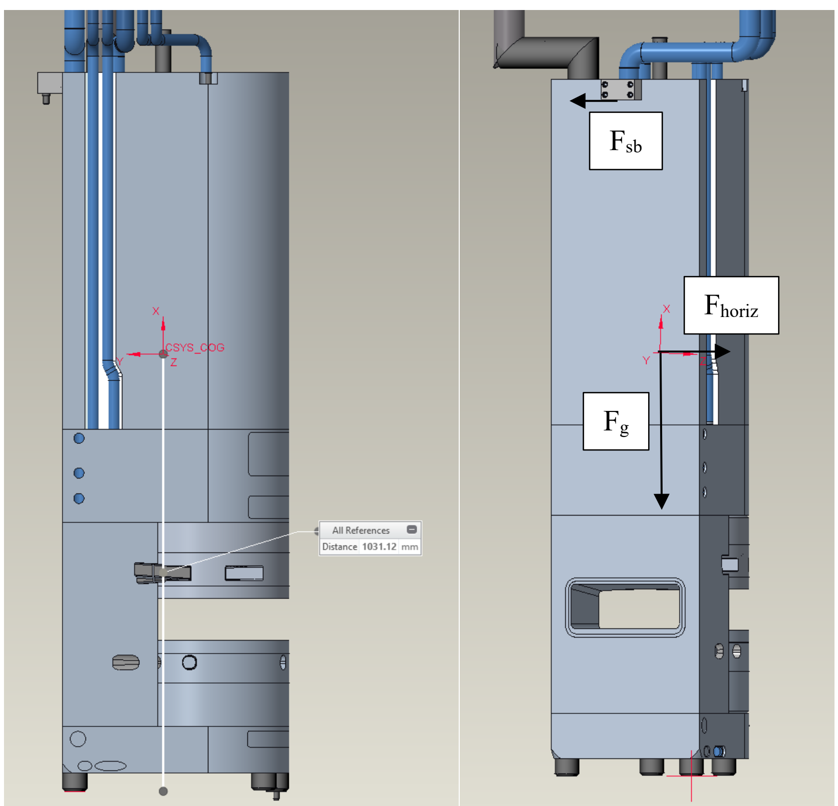

Figure 5.5 MRA CG Height (left) and Free Body Diagram Projected Normal to the Axis of the Closest Base of Support (right)

$$\sum M = F_g * l_{cg} - F_{horiz} * h_{cg} + F_{sb} * h_{sb} = 0$$

Rearranging to solve for F_{sb} gives,

$$F_{sb} = \frac{F_{horiz} * h_{cg} - F_g * l_{cg}}{h_{sb}} = \frac{0.308 * 1913kg * 9.81\frac{N}{kg} * 1031mm - 1913kg * 9.81\frac{N}{kg} * 78.07mm}{1645mm}$$

$$F_{sb} = 2.73kN$$

The seismic block is located with 2 10 mm diameter stainless steel alignment pins as shown in Figure 5.6; however, one of the holes is slotted. We will assume the component of the seismic block force parallel to the seismic block interface is carried by shear in a single pin.

$$\tau = \frac{F_{sb} * cos(\alpha)}{\pi\frac{d^2}{4}} = \frac{2.73kN * \cos(18.633°)}{\pi * \frac{(10\,mm)^2}{4}} = 32.9MPa$$

$$FOS_{shear} = \frac{0.577 * \sigma_{yield}}{\tau} = \frac{0.577 * 205MPa}{32.9MPa} = 3.59$$

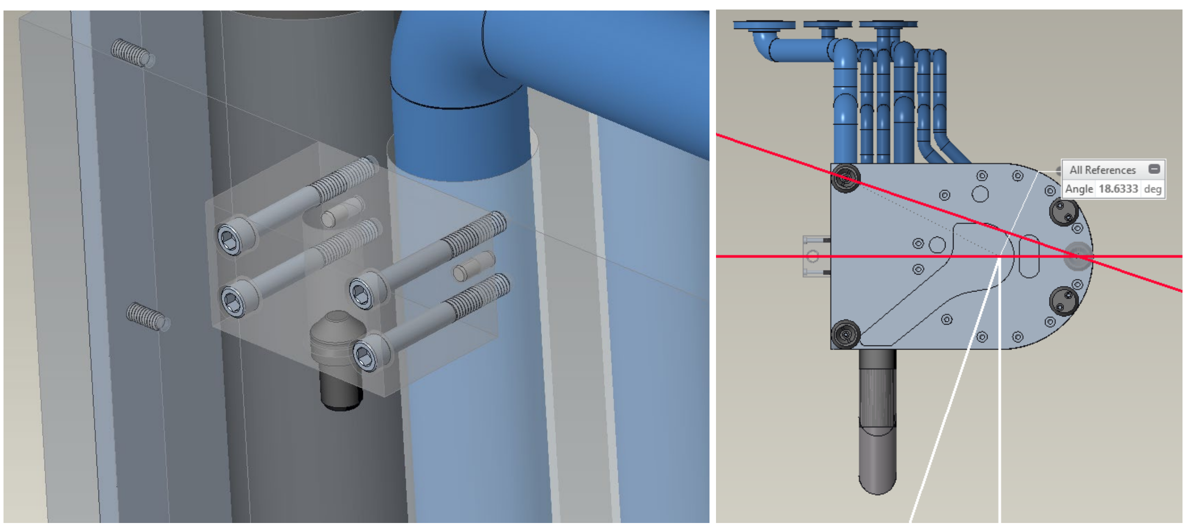

Figure 5.6 Seismic Block Fastener Arrangement (left) and Angle of Maximum Seismic Block Force Relative to Seismic Block (right)

The component of the seismic block force normal to the seismic block interface is assumed to be equally shared by the qty:4 5/16"-18 seismic block screws with 14.2 mm of engagement.

$$\sigma = \frac{F_{sb} * sin(\alpha)}{4 * \pi * \frac{d_{minor}^{\ 2}}{4}} = \frac{2.73kN * \sin(18.633°)}{4 * \pi * \frac{(6.23mm)^2}{4}} = 7.16\,MPa$$

$$FOS_{yield} = \frac{\sigma_{yield}}{\sigma} = \frac{276MPa}{7.16MPa} = 38.5$$

We will also check for thread shear failure of the screws and the mating holes.

$$\tau = \frac{F}{4 * {(\pi * d_{pitch} * l_{eng})}/{3}} = \frac{2.73kN * \sin(18.633°)}{4 * {(\pi * 6.89mm * 14.2mm)}/{3}} = 2.13\ MPa$$

$$FOS_{yield} = \frac{0.577 * \sigma_{yield}}{\tau} = \frac{0.577 * 276MPa}{2.13MPa} = 74.9$$

$$\tau = \frac{F}{4 * {(\pi * d_{pitch} * l_{eng})}/{3}} = \frac{2.73kN * \sin(18.633°)}{4 * {(\pi * 6.89mm * 14.2mm)}/{3}} = 2.13\ MPa$$

$$FOS_{yield} = \frac{0.577 * \sigma_{yield}}{\tau} = \frac{0.577 * 250MPa}{2.13MPa} = 67.8$$

5.6 HYDROGEN VESSEL PINS

Each hydrogen vessel is supported by 6 Ti 15-3-3-3 alignment pins, 3 each top and bottom, with 3 mm diameters as shown in Figure 5.7. The pins are restrained in slots in the surrounding vacuum vessel, which is a part of the reflector vessel, to allow for thermal contraction of the hydrogen vessel at its 20K operating temperature.

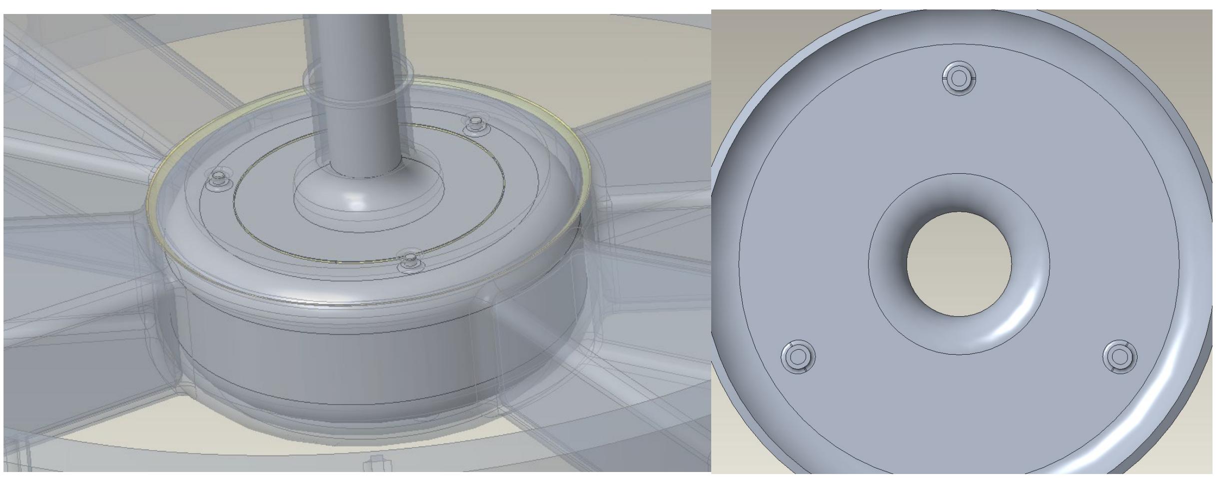

Figure 5.7 Hydrogen Vessel Pin Arrangement (left) and Vacuum Vessel slot arrangement (right)

5.6.1 Upper Hydrogen Vessel

The upper hydrogen vessel has a mass of 0.43 kg including the liquid hydrogen within it during operation. The equivalent static horizontal load causes the highest pin loads when it is aligned parallel to 2 of the restraining slots, causing the load to be reacted evenly among the other 4 remaining slots which are angled 60 degrees from the load. We will conservatively neglect friction.

$$F_{horiz} = 0.308 * m * 9.81\frac{N}{kg} = 0.308 * 0.43kg * 9.81\frac{N}{kg} = 1.30N$$

$$F_{norm} = \frac{F_{horiz}/_{4}}{sin(\alpha)} = \frac{1.30N/_{4}}{sin(60°)} = 0.375N$$

$$\tau = \frac{F_{norm}}{\pi \frac{d^2}{4}} = \frac{0.375N}{\pi \frac{(3\ mm)^2}{4}} = 0.0531MPa$$

$$FOS_{shear} = \frac{0.577 * \sigma_{yield}}{\tau} = \frac{0.577 * 690MPa}{0.0531MPa} = 7500$$

Since the pins are much higher strength than the surrounding aluminum, we will also evaluate shear in the boss that holds the pin. We will conservatively assume only the material in the projection of the pin will participate in restraining shear and only in the connection to the vacuum vessel body.

$$\tau = \frac{F_{norm}}{d * t_{boss}} = \frac{0.375N}{3mm * 1mm} = 0.125MPa$$

$$FOS_{shear} = \frac{0.577 * \sigma_{yield}}{\tau} = \frac{0.577 * 221MPa}{0.125MPa} = 1020$$

5.6.2 Lower Hydrogen Vessel

The lower hydrogen vessel has a mass of 0.33 kg including the liquid hydrogen within it during operation. Because of the smaller mass and similar pin arrangement, and extremely high factors of safety to yielding for the upper hydrogen vessel, we will not evaluate the lower hydrogen vessel further.

6. PRESSURE LOADS

6.1 REFLECTOR VESSEL SCREWS

While the bolts that attach the reflector vessels do not actually hold back any internal pressure loads, they do prevent displacement of the reflector vessels from causing separation between the backbone and the reflector vessel mating surfaces, which could load water and vacuum connections. Although this separation has been analyzed using FEA analysis [1], we will provide a conservate assessment which bounds the possible loading seen by the reflector vessel screws. The internal pressure of the reflector vessels is supported by the 25 mm thick wall which interfaces to the backbone. We will conservatively assume that this plate takes no load and the full internal pressure load on the surface is transferred to the screws holding the reflector vessel to the backbone. We will use the MAWP of the reflector vessel water passages of 5 bara and assume the core vessel is operating in vacuum mode. The load is assumed to be evenly distributed among the 12 screws for each reflector vessel. It should be noted that this conservative approach gives screw loads just higher than the preload and the FEA analysis shows no appreciable separation.

$$F_{pres} = P * \pi * \frac{d^2}{4} = 5e5Pa * \pi * \frac{(351mm)^2}{4} = 48.4kN$$

$$\sigma = \frac{F_{pres}}{12 * \pi \frac{d_{minor}}{4}^2} = \frac{48.4kN}{12\pi * \frac{(7.60mm)^2}{4}} = 88.9\ MPa$$

$$FOS_{yield} = \frac{\sigma_{yield}}{\sigma} = \frac{273MPa}{88.9MPa} = 3.07$$

Based on the preload calculation in section 4.2, the tensile stress in the screws is the limiting factor in this joint and thread pullout will not be analyzed.

7. FASTENER FATIGUE

Cyclic loads on the MRA fasteners could be driven by water pressure changes or thermal cycles associated with beam perturbations. Water pressure changes are expected to be less than 4 per year and less than 20% of the MAWP in magnitude, so they will be ignored. Potential thermal cycle fatigue will be explored in more detail. The MRA is required to show a lifetime of 5 years or greater with an expected 10000 beam trips per year [4].

7.1 SHIELD BLOCK THREADED RODS

The shield block threaded rods pass through the full thickness of the shield block to connect to the backbone. The screws are only cooled by thread contact to the backbone and head contact to the top of the shield block. While the MRA shield block is only cooled by contact to the backbone, the A36 shield block material has significantly higher thermal conductivity (50.0 W/m-K vs 16.3 W/m-K) as well as lower coefficient of thermal expansion (11.7E-6/°C vs. 16.0E-6/°C), so the threaded roads are expected to elongate more than the shield block during beam operations. 3 belleville washers in series provide preload and have an active height of 1.68 mm before the preload is fully removed. While the preload is expected to be maintained in anticipated thermal conditions, we will conservatively assume that the preload is fully released during every thermal cycle for this fatigue calculation. Therefore, the expected stress range is 66.6 MPa and the corresponding stress amplitude is 33.3 MPa. According to Figure 7.1 (Figure 3-F.3M, ASME BPVC Section VIII, D2 [5]), the endurance limit for 316 Stainless Steel is greater than 90 MPa stress amplitude, so the threaded rods are not expected to have a lifetime limit from fatigue.

7.2 REFLECTOR VESSEL SCREWS

The reflector vessel screws pass through the full thickness of the upper and lower backbone to connect into each reflector vessel. The screws are only cooled by thread contact to the reflector vessels and head contact to the outside of the backbone, so the screws will be hotter than the surrounding water cooled backbone. 3 belleville washers in series provide preload and have an active height of 1.07 mm before the preload is fully removed. While the preload is expected to be maintained in anticipated thermal conditions, we will conservatively assume that the preload is fully released during every thermal cycle for this fatigue calculation. Therefore, the expected stress range is 87.7 MPa and the corresponding stress amplitude is 43.9 MPa. According to Figure 7.1 (Figure 3-F.3M, ASME BPVC Section VIII, D2 [5]), the endurance limit for 316 Stainless Steel is greater than 90 MPa stress amplitude, so the screws are not expected to have a lifetime limit from fatigue.

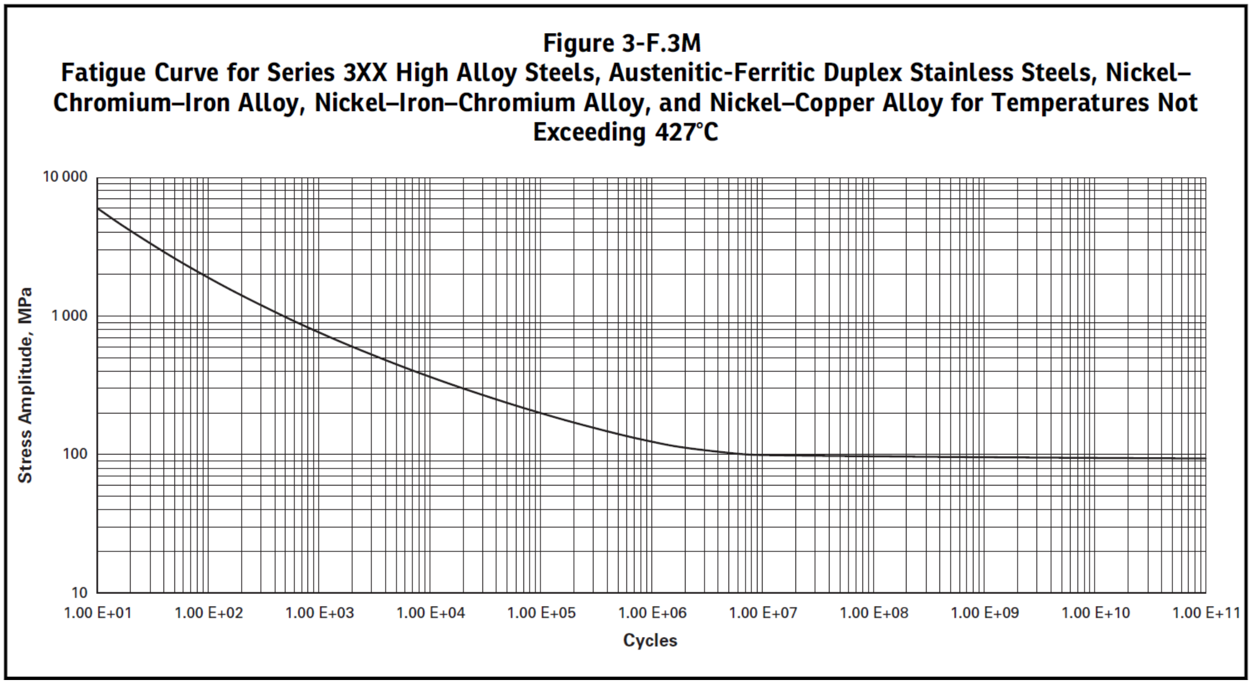

Figure 7.1 ASME BPVC Section VIII, Division 2 Fatigue Curve for 316 Stainless Steel [5]

8. CONCLUSIONS

The Moderator Reflector Assembly fasteners were evaluated to verify that they will support the expected loading on the MRA including preload, lifting, seismic, and pressure loadings. As shown in Table 8.1, the minimum safety factor to yield is 3.07 for the reflector vessel screws in the conservative calculation of the reflector vessel internal pressure causing separation of the reflector vessel and the backbone, which barely exceeds the preload applied to the reflector vessel screws. The fasteners were also evaluated for fatigue from thermal cycling and none of the fasteners are expected to have a fatigue lifetime limit.

Table 8.1 Factor Safety to Yield for MRA Fasteners for All Load Cases

	Load Case Factor of Safety to Yield			
Fastener	Preload	Lifting	Seismic	Pressure
Remote Handling Stud		10.1		
Shield Block Threaded Rods	3.08	13.9	3.95	
Shield Block Alignment Pins			8.99	
Reflector Vessel Screws	3.11	410	154	3.07
Alignment Block Screws				
Alignment Block Pins			3.32	
Seismic Block Pins			3.59	
Seismic Block Screws			38.5	
Hydrogen Vessel Pins			1020	

9. REFERENCES

[1] McManamy, "Structural Analysis of the Moderator Reflector Assembly," S03040000-DAC10013, 2026.

[2] MW Components, "Precision Disc Springs Catalog," 2026.

[3] Barrett, "Fastener Design Manual," NASA Pub. 1228, 1990.

[4] S03040000-SR0001, "System Requirements Document for Target Systems Moderator Reflector Assembly (MRA)".

[5] American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, Section VIII, Division 2, 2023.

[6] S01030100-ESH10001-R00, "STS Natural Phenomena Hazard Basis of Design," 2023.

APPENDIX A. SEISMIC LOAD DERIVATION

The seismic loads for the MRA were developed using ASCE-7-16 Chap. 13 - Seismic Requirements for Nonstructural Components (Equivalent Static Method)

Base or grade elevation = 1073.52' (Level 1 or Instrument Floor)

W_p = Component Operating Weight

a_P = Component amplification factor from Table 13.6-1 (mechanical & electrical equip.)

S_{DS} = Short period spectral acceleration

S_{DS} = 0.485 from USGS, Risk Category IV & Soil Class D at SNS

R_P = Component response modification factor from Table 13.6-1

z = Height above base where attached

h = Average Roof Height, top of level 3 (elev. 1108.0', = 34.48' above base

I_p = Importance = 1.0 (non-hazardous content), =1.5 (hazardous content)

Level	**Elevaton** (ft.)	**z** (ft.)
1	1073.52	0
2	1094	20.48
3	1108	34.48
4	1137.5	63.98
Roof	1157.67	84.15

(Note: elevations preliminary from Building Sections AR301-D, 12/20/23)

	EQ #	**Equation**
Basic Horizontal Seismic Force	13.3-1	$F_P = 0.4a_PS_{DS}I_PW_p/R_P*(1+2z/h)$
Maximum Horizontal Seismic Force	13.3-2	$F_P = 1.6S_{DS}I_PW_p$
Minimum Horizontal Seismic Force	13.3-3	$F_P = 0.3S_{DS}I_PW_p$
Vertical Seismic Force	13.3.1.2	$E_v = +/- 0.2S_{DS}W_p$

Table A.1 Derivation of Horizontal Static Force

SSC	F_p/W_p (Eq.13.3-1)	F_p/W_p max (Eq.13.3-2)	F_p/W_p min (Eq.13.3-3)	E_v (Eq.13.3.1.2)	S_{DS} (USGS)	I_p	a_P	R_P	z (ft.)	h (ft.)
Moderator Reflector Assembly (Conservative Attachment Height)	0.308	1.16	0.22	0.10	0.49	1.5	1.0	1.5	10.1	34.5
Moderator Reflector Assembly (Bottom Attachment Height)	0.246	1.16	0.22	0.10	0.49	1.5	1.0	1.5	4.6	34.5

Note: The conservative attachment height corresponds to the height of the seismic block while the bottom attachment height corresponds to the level of the alignment blocks. The conservative attachment height equivalent load will be used for all seismic calculations in this document.