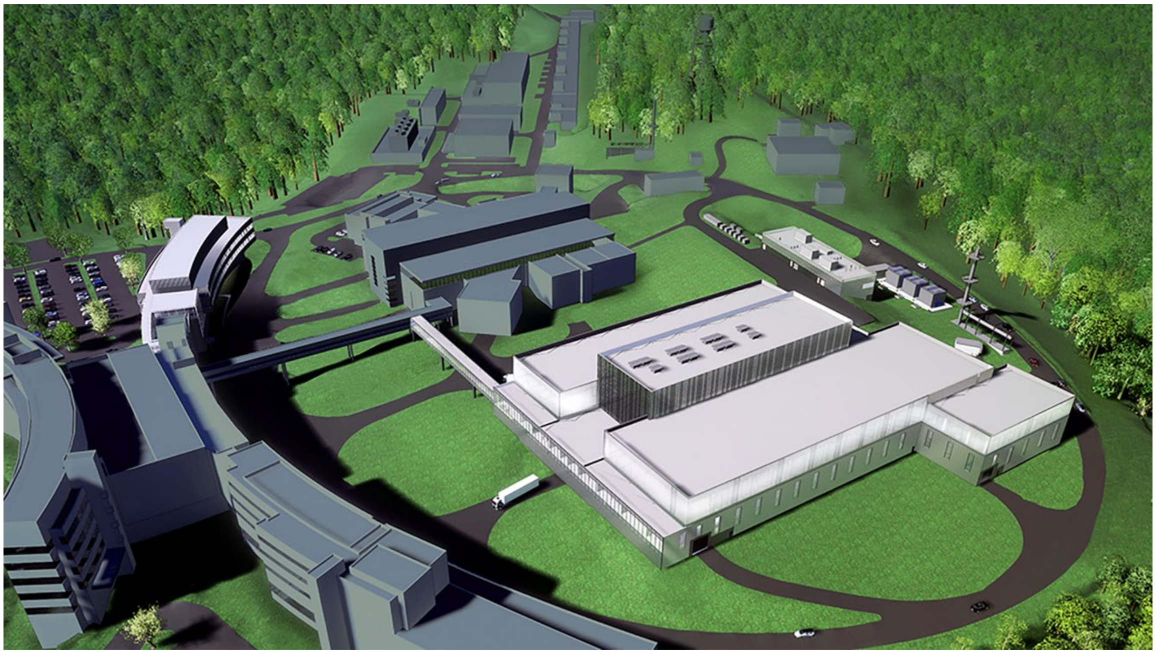
S03060000-DES10000

Second Target Station Project: Vessel Systems – Design Description



Chris Anton
Hogan Knott
Cam Eiland
Lukas Bearden
Darren Dugan
Mike Strong

April 2025

DOCUMENT AVAILABILITY

Reports produced after January 1, 1996, are generally available free via OSTI.GOV.

Website www.osti.gov

Reports produced before January 1, 1996, may be purchased by members of the public from the following source:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone 703-605-6000 (1-800-553-6847)
TDD 703-487-4639
Fax 703-605-6900
E-mail info@ntis.gov
Website http://classic.ntis.gov/

Reports are available to US Department of Energy (DOE) employees, DOE contractors, Energy Technology Data Exchange representatives, and International Nuclear Information System representatives from the following source:

Office of Scientific and Technical Information
PO Box 62
Oak Ridge, TN 37831
Telephone 865-576-8401
Fax 865-576-5728
E-mail reports@osti.gov
Website https://www.osti.gov/

S03060000-DES10000

Second Target Station Project

VESSEL SYSTEMS – DESIGN DESCRIPTION

Chris Anton
Hogan Knott
Cam Eiland
Lukas Bearden
Darren Dugan
Mike Strong

April 2025

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

Approvals

Document Title: Vessel Systems – Design Description		ISSUE DATE: April 2025
PREPARED BY Chris Anton	PROJECT Second Target Station	DOCUMENT NUMBER: S03060000-DES10000

	Signature / Date					
	Rev. 00	Date	Rev. 01	Date	Rev. 02	Date
Vessel Systems Lead Engineer	Christopher Anton	Digitally signed by Christopher Anton Date: 2025.04.11 14:50:24 -04'00'				
Interface Systems Team Leader	Mike Strong	Digitally signed by Mike Strong Date: 2025.04.11 14:53:06 -04'00'				
Target Systems Level 2 Manager	Peter Rosenblad	Digitally signed by Peter Rosenblad Date: 2025.04.14 18:05:42 -04'00'				

Revision	Description
00	Initial Release

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AIC	Accelerator Interface Components
BPVC	Boiler and Pressure Vessel Code
CAD	Computer-Aided Design
CF	Conventional Facilities
CFD	Computational Fluid Dynamics
COTS	Commercial Off The Shelf
CTE	Coefficient of Thermal Expansion
CV	Core Vessel
DAC	Design Analysis Calculation
DFMEA	Design Failure Modes and Effects Analysis
DOE	US Department of Energy
DPA	Displacements Per Atom
EOL	End of Life
ESH&Q	Environmental Safety Health and Quality
FEA	Finite Element Analysis
FEM	Finite Element Model
FTS	First Target Station
HA	Hazzard Analysis
ICS	Integrated Control System
KPP	Key Performance Parameter
LINAC	Linear Accelerator
LOF	Life of Facility
MAWP	Maximum Allowable Working Pressure
MPS	Machine Protection System
MRA	Moderator Reflector Assembly
NPH	Natural Phenomena Hazzard
ORNL	Oak Ridge National Laboratory
PB	Proton Beam
PBW	Proton Beam Window
PHAR	Preliminary Hazzard Analysis and Report
PS	Process Systems
SAD	Safety Assessment Document
SNS	Spallation Neutron Source
STS	Second Target Station
TPS	Target Protection System
TS	Target Systems
TSS	Target Station Shielding
TVP	Target Viewing Periscope
WBS	Work Breakdown Structure

SCOPE

This document provides the preliminary design description for the Vessel Systems (VS) scope within the Target Systems (TS) group of the Second Target Station (STS) project. The decomposition of requirements from the TS to VS is outlined. Additional requirements are derived from interfaces with other systems within TS as well as with other level 2 systems within the project. The design of all VS components is described. Requirements verification is discussed, and particular emphasis is placed on requirements that have yet to be verified during preliminary design. Plans for meeting all unverified requirements during final design are discussed.

1. TARGET STATION CONTEXT

The purpose of the STS Project is to build the world's brightest source of cold wavelength neutrons for cutting-edge science. To achieve this goal, a solid rotating tungsten target will receive 1.3 GeV proton pulses at a rate of 15 Hz from the existing FTS LINAC, totaling 700 KW beam power and providing neutrons via spallation of the tungsten target. Two compact liquid hydrogen moderators will be located adjacent to the tungsten target, providing cold wavelength neutrons to 18 discrete instrument beamlines. Neutron guide optics facilitate transport of cold neutrons from the moderator down the neutron beamlines to beamline instrument end stations. Samples are placed in the instrument end stations in the path of the neutron beam, where detector arrays are utilized to perform cutting-edge scientific research.

VS plays several key roles in facilitating the production of cold neutrons to the instrument end stations. The Target and MRA must be surrounded by an appropriate environment (rough vacuum or partial pressure helium) that allows for efficient transfer of the generated neutrons to the instrument beam lines. The Core Vessel (CV) in conjunction with Vacuum Systems and Process Systems (PS) provides this environment. VS is partially responsible for the alignment of numerous critical components within the monolith, including the Target, MRA, Monolith Inserts (MI) and Target Viewing Periscope (TVP). Proper alignment of these components is critical to achieving efficient neutron generation and transport. The CV and CV internal shielding also provide critical radiation shielding, protecting personnel and instrumentation both inside and outside of the target monolith.

2. VESSEL SYSTEMS SCOPE

The Vessel Systems WBS element (S.03.06) will deliver four primary subsystems:

- Core Vessel Assembly
- Core Vessel Shielding Assembly
- Nozzle Extension Assemblies
- Gamma Gate Assembly

The complete system must meet all the requirements outlined in S03060000-SRD10000, Vessel Systems Requirements (1) and derived sub-assembly requirements. Evidence and closure of the project are met by completion and passage of the verification in S03060000-TAC10000, Vessel Systems Verification Plan (2).

The scope of work associated with this WBS and its components include:

- Design Engineering
- Procurement

- Fabrication Oversight
- Subsystem Acceptance Testing
- Shipment

The scope of WBS S.03.06 ends upon receipt of all associated technical components at the STS facility but does not mark the completion of the STS capitol project. It is expected that while the VS scope may have formally ended, the project team will continue supplying technical oversight throughout installation and commissioning. The project team must document the design such that activities related to the VS but outside the formal scope of S.03.06 can be performed successfully.

WBS Scope S.03.06 does not include the following:

- System engineering and integration into Target Systems
- Installation of the VS components
- Operations and planning
- Facility testing

The following subsections describe each subsystem within Vessel Systems in greater detail.

2.1 Core Vessel assembly scope

The CV assembly consists of an upper and lower shell section joined together at the CV center split flange, as well as a top lid assembly with four access hatches. The lower CV weldment features a beltline section with water cooling that allows for accurate alignment of the neutron guide optics within the monolith. The upper CV weldment is constructed from rolled and welded shells and flanges that provide steps in the assembly to mitigate radiation streaming. The upper weldment also contains all of the utility nozzles that pass water, gasses, vacuum pumping and electrical feedthroughs from the ambient side to the controlled side of the CV. The CV lid provides landing interfaces for both the target assembly and the TVP assembly, as well as access hatches for Target segment removal, MRA removal and utility nozzle access. The exterior layout of the CV can be seen in Figure 1 below.

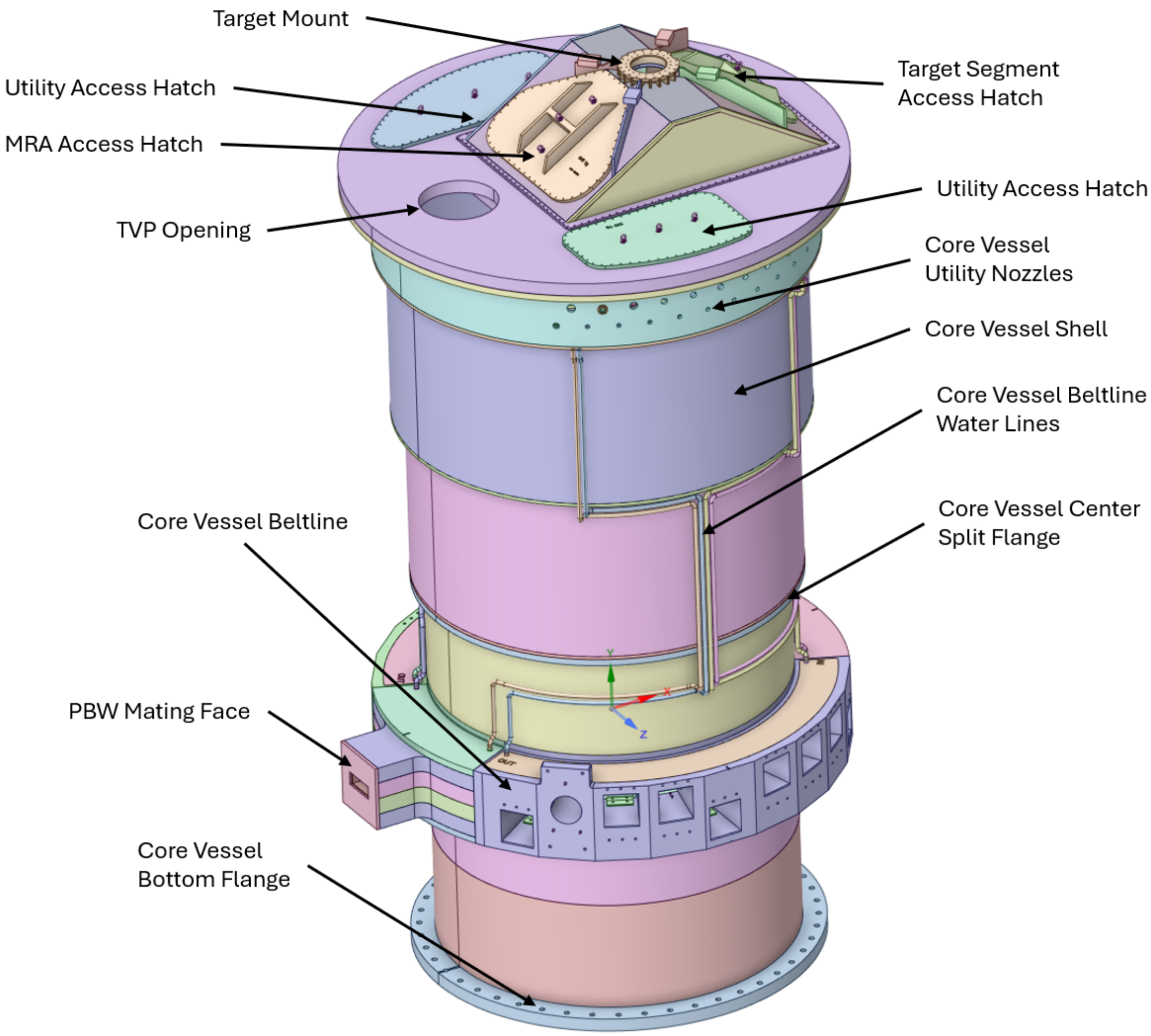


Figure 1: Basic layout of the Core Vessel assembly

2.2 CORE VESSEL SHIELDING ASSEMBLY SCOPE

The CV Shielding assembly consists of five layers of shielding that fills the majority of the CV volume. The bottom three layers of shielding are stainless steel water cooled blocks in order to cope with high levels of neutronic energy deposition. The top two layers are carbon steel uncooled shield blocks that will be nickel plated for corrosion resistance. A set of two carbon steel uncooled ring blocks wrap around the outside of layers 2 and 3. Two removable shield blocks allow access to the MRA and target segments during maintenance activities, and a third semi-permanent shield block resides downstream of the target removable block and can easily be removed in the future to accommodate potential target diagnostic equipment. Water inlet and outlet lines run from the cooled shield blocks to the utility nozzles at the top of the CV shell and will be field welded during block installation. See Figure 2 below for a detailed view of the CV Shielding assembly.

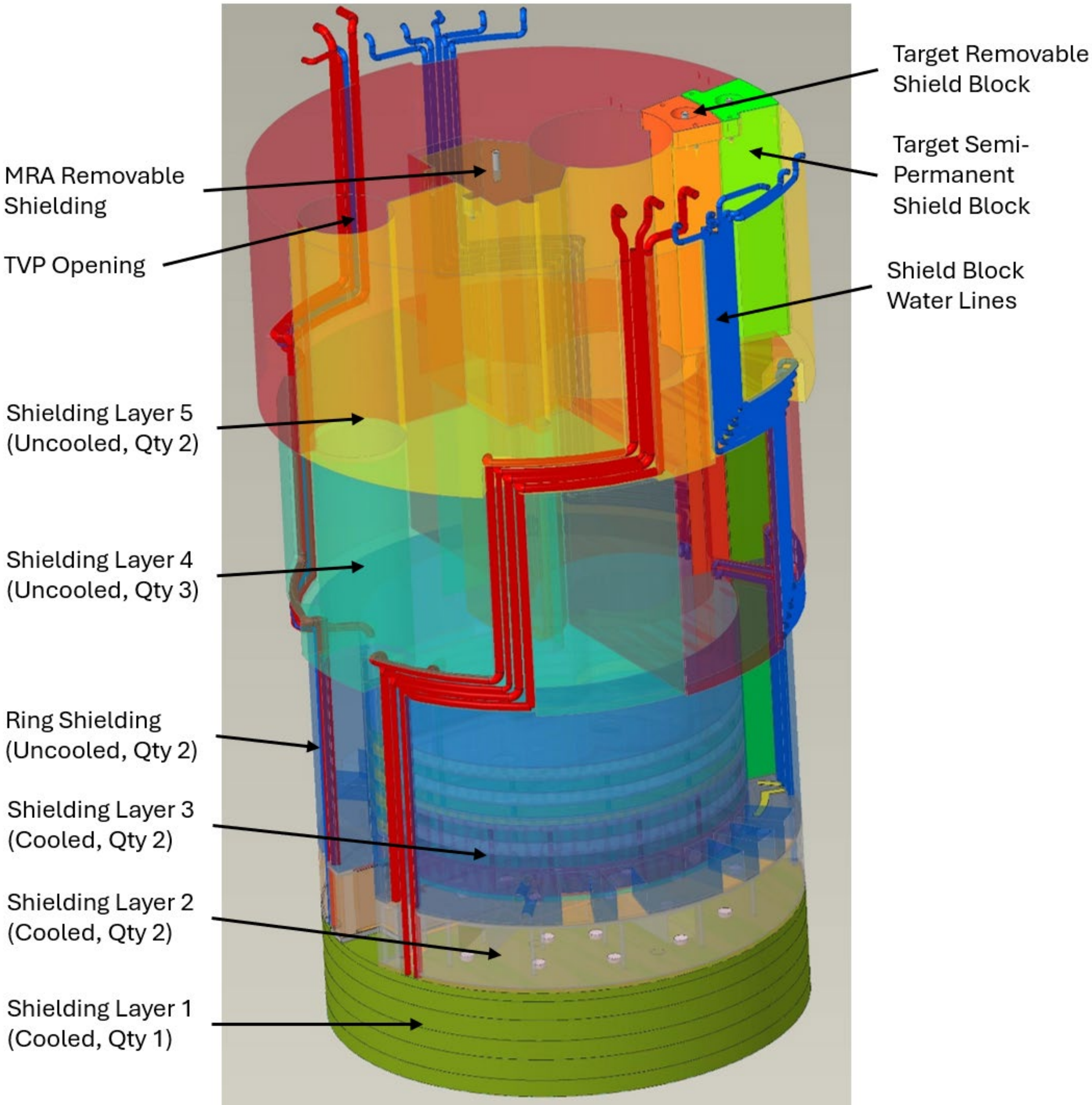


Figure 2: CAD view of the CV Shielding assembly

2.3 NOZZLE EXTENSION ASSEMBLIES

Nozzle Extension assemblies mount to the outside facets of the CV beltline and extend through both the monolith carbon steel shielding and the monolith concrete. Monolith inserts containing neutron guide optics for each beamline are inserted into the nozzle extensions by the Instrument Systems team during the facility build-out. The CV environment is contained within the nozzle extensions, and vacuum seals are made between the monolith inserts and the nozzle extensions at the downstream end of each nozzle extension. The nozzle extensions are bolted to the CV beltline and seal welded to the beltline near the inside diameter of the CV. There are 15 standard nozzle extensions, 2 dual channel nozzle extensions and 1 QIKR nozzle extension to accommodate the different monolith inserts being used by Instrument Systems. The Nozzle Extensions mounted to the CV can be seen in Figure 3 below.

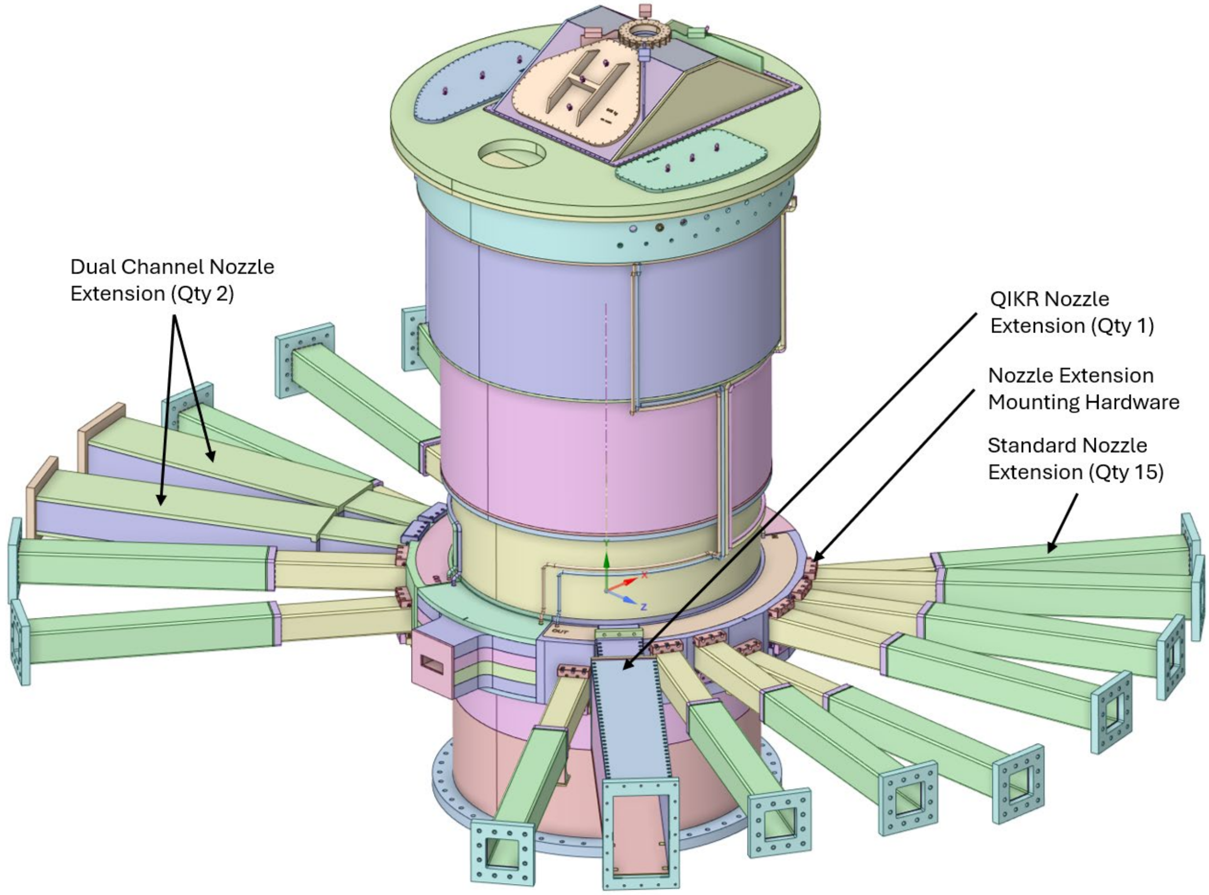


Figure 3: CAD image showing the CV with nozzle extensions attached

2.4 GAMMA GATE ASSEMBLY

In order to facilitate safe hands-on maintenance of the target assembly during target segment exchange, a gamma gate shielding system is required. The gamma gate consists of a lead filled stainless steel shield block, rail guide system and linear actuator assembly. The gamma gate needs to be actuated remotely from outside of the target drive room during target segment removal. The design and procurement of the gamma gate shield block, rails and linear actuator system are part of Vessel Systems scope of work.

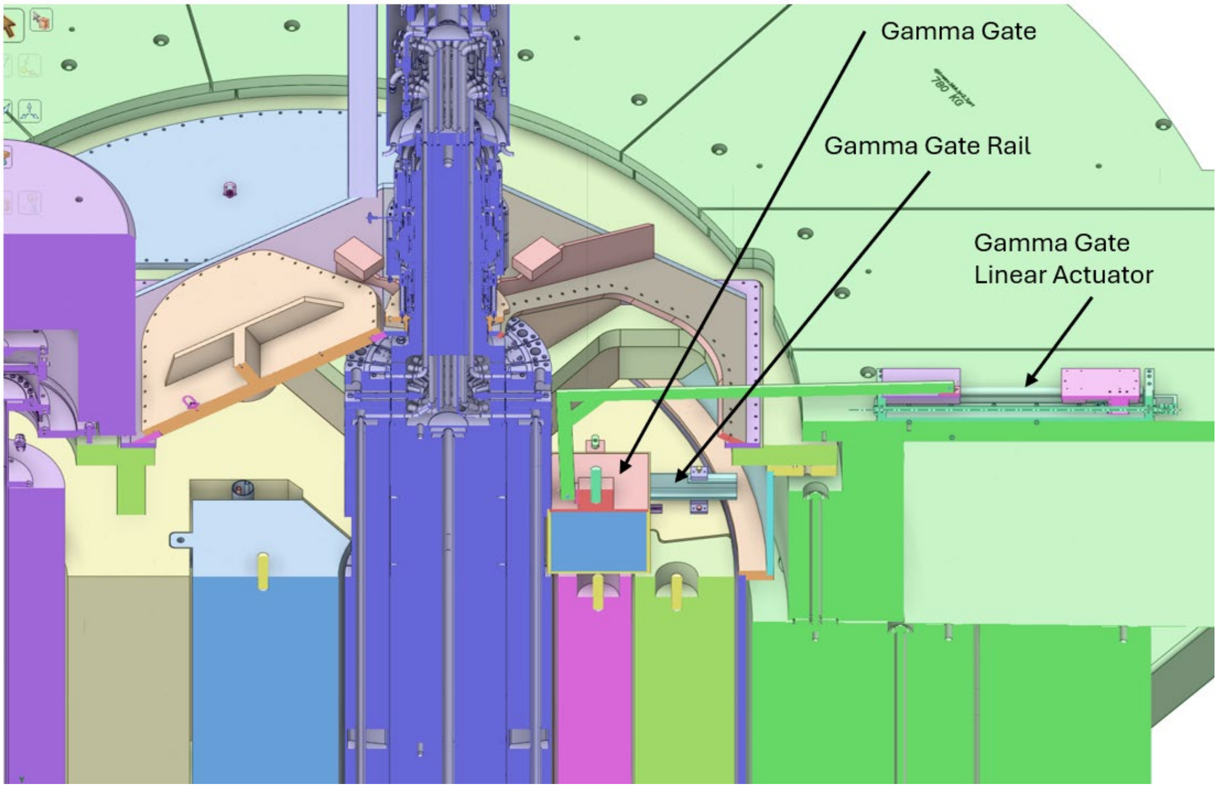


Figure 4: Cross section view showing gamma gate assembly with gamma gate in closed position inside the CV

3. INTERFACES

3.1 INSTRUMENT SYSTEMS INTERFACES

VS interfaces with the monolith inserts of Instrument Systems via the nozzle extensions, CV beltline and CV internal shielding. Alignment features located on the CV beltline as well as the downstream side of the nozzle extensions help set the location and alignment of the monolith inserts, which in turn set the final alignment of the neutron guide optics within the monolith. CV internal shielding is also designed with clearance to allow the monolith inserts to be fully installed within the monolith. Interface details are described in detail in S01020500-IS0025 (3).

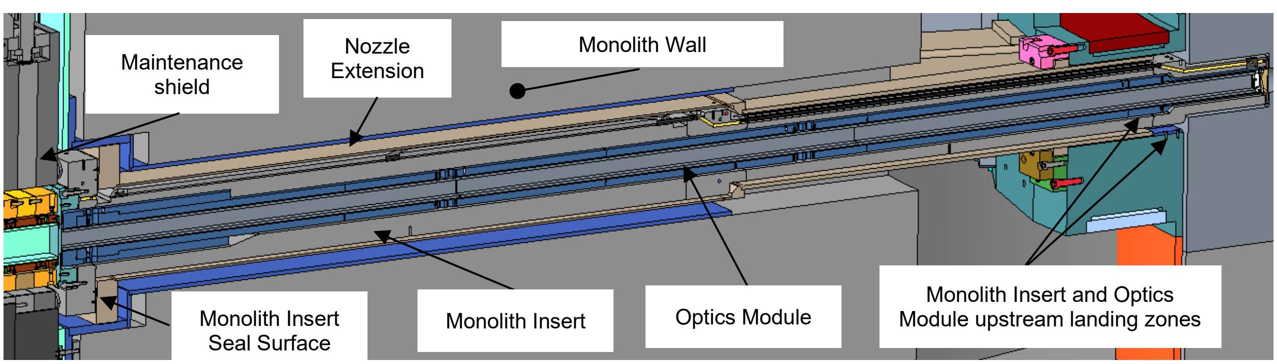


Figure 5: Cross sectional view cut along a neutron beam path through the Target Systems hardware to the inner wall of the bunker

3.2 INTEGRATED CONTROLS INTERFACES

The interface between VS and Integrated Controls centers around temperature monitoring of VS components. Within VS scope there are 5 water cooled internal shield blocks, and four quadrants of water cooled CV beltline. The temperatures of these actively cooled shield blocks will be monitored via thermocouples attached to each component. Vessel Systems is responsible for the design, procurement and installation of all thermocouples attached to its technical components, as well as all internal wiring within the CV up to hermetic electrical feedthroughs that pass the signal from the inert atmosphere inside the CV to the ambient environment of the pipe pan. Integrated Controls is responsible for procurement and installation of all signal wiring outside of the CV, as well as all temperature monitoring and control instrumentation and hardware. Interface details are described in S01020500-IST10128 (4).

3.3 TARGET SYSTEMS INTERFACES

Vessel Systems has a variety of interfaces with other technical component groups within Target Systems. In order to manage these interfaces, interface sheets have been developed between Target Systems level 3 groups. These interfaces are summarized below.

3.3.1 VS to Target Assembly

Vessel Systems and Target Assemblies share a number of mechanical and load based interfaces. The Target Assembly is mounted to a support flange on the CV lid where mechanical loads are carried and a vacuum seal is created to preserve the core vessel environment. A limiting ring mounts to the first layer of CV shielding and provides a mechanical limit to motion at the bottom of the target shaft. In a seismic event the target shaft motion must be stopped by the limiting ring to avoid contact with the MRA. The CV also plays several key roles during target segment removal and installation. Vertical removal of a target segment during a maintenance outage necessitates a target segment removable shield block and access hatch in the CV lid be provided. The profile of the permanent shielding around the target segment removable shield block act as a guide during target segment installation, and helps guarantee that each target segment is fully engaged with the target mating interface. Interface details are described in Interface Sheet S01020500-IST10209 (5).

3.3.2 VS to Cryogenic Moderator Systems Interfaces

The Cryogenic Moderator System (CMS) has a single interfacing component with VS, the cryogenic transfer line. The transfer line connects the CMS system to the MRA at an interfacing point at the top of the CV. The transfer line will penetrate the side wall of the CV just below the CV lid. The sizing and location of the CV sidewall penetration as well as the connection method between the CV sidewall and the transfer line are detailed in interface sheet S03000000-IST10010 (6).

3.3.3 VS to Moderator Reflector Assembly Interfaces

The Moderator Reflector Assembly (MRA) is housed within the CV shielding and is located around the upstream side of the target. The MRA is supported and aligned by canoe sphere kinematic mounts located on top of the first layer of CV cooled shielding. Due to the critical alignment requirements of the MRA relative to the instrument beamlines and target, stringent manufacturing and installation tolerances as well as thermal expansion limits are imposed onto the CV first layer shielding. Additional mechanical interfacing exists throughout the height of the CV shield stack to allow for vertical removal of the MRA as well as proper clearances for the MRA utility lines. VS will also design and procure utility jumper lines to connect the flanged connections at the top of the MRA utility lines to the nozzle penetrations at the side wall of the CV. Interface details are described in S03000000-IST10009 (7).

3.3.4 VS to Moderator Reflector Assembly and Target Assembly

A three-way interface between VS, MRA and Target Assembly has been generated to set a strategy for ensuring the integrity of the MRA hydrogen boundary is not damaged under any anticipated loading conditions. The primary load condition of concern occurs during a seismic event. This interface defines geometric envelopes for each interfacing system. Each system must ensure that it does not extend past these defined envelopes under any loading conditions. An accompanying interface drawing defines all relevant physical boundaries. Interface details are described in S01020500-IST10205 (8).

3.3.5 VS to AIC Interfaces

VS has interfaces with AIC's Proton Beam Window (PBW), Proton Beam Window Shielding (PBWS) and Target Viewing Periscope (TVP). The PBW separates the CV atmosphere from the Accelerator Systems atmosphere via a thin aluminum window and inflatable vacuum seals. The inflatable seals contribute to an overall leak rate within the CV. VS is also responsible for providing sizing input for the overpressure protection system (via burst disc) that must protect both the CV as well as the PBW from positive pressure induced damage. PBWS also contains an inflatable seal that interfaces directly with the CV beltline as shown in Figure 6 below.

The TVP has several mechanical interfaces within Vessel Systems. The TVP extends from above the CV lid down through the CV shielding to an elevation near the proton beam line. A flanged bellows seal seats on the CV lid to provide vacuum sealing in between the TVP and the CV. Clearance openings are provided throughout the CV shield stack to allow for installation and vertical extraction of the TVP assembly. Alignment and support of the TVP assembly is provided by a step in the CV shielding, and optical clearance is provided within the CV shielding to ensure that the TVP can properly view the nose section of the target wheel. Interface details are described in S01020500-IST10217 (9).

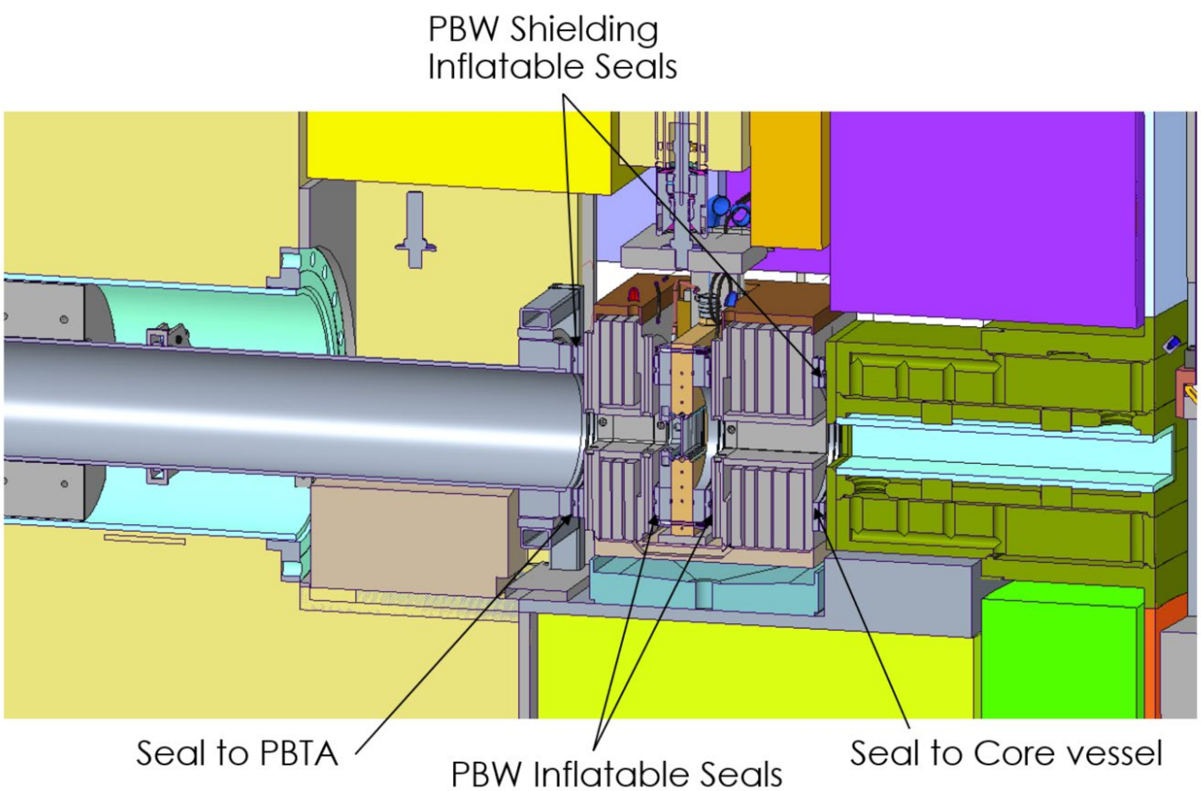


Figure 6: Cross sectional view cut down the proton beam line showing the PBW/PBWA to Vessel Systems interfacing hardware

3.3.6 VS to Process Systems Interfaces

Process Systems is responsible for providing cooling water and gasses to all of the technical components within Target Systems. Process Systems will be supplying cooling water to all cooled VS components (5x cooled shield blocks, 4x quadrants of CV beltline). VS will provide all of the necessary cooled component details to allow Process Systems to appropriately size this portion of the water system. Process Systems will also provide helium supply and return utility lines that allow for partial pressure helium operation of the CV. The top shell of the CV contains two double row arrays of utility nozzles that will be used to pass utilities from the ambient size of the CV to the inert interior of the CV. VS is responsible for the design and layout of the nozzle arrays as well as making all physical connections on the interior side of the nozzles. The current design of the utility nozzles is shown in Figure 7 below. Process Systems is responsible for field welding all utility line supplies and returns to the ambient side of the CV utility nozzles. A drain line is also present at the bottom of the CV that is a mechanical interface with the CV drain system designed and provided by Process Systems. These interfaces are formally defined in interface sheet S03000000-IST10004 (10).

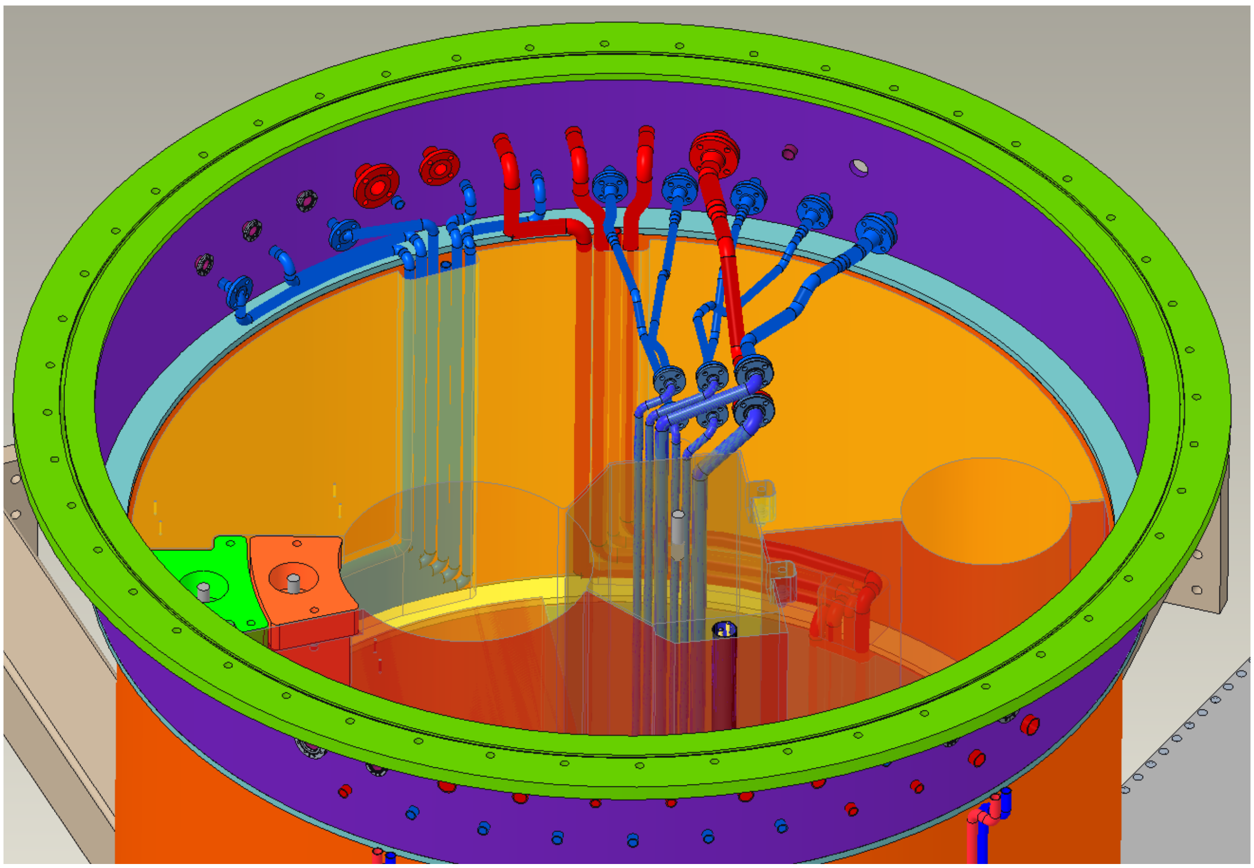


Figure 7: CAD rendering of utility nozzle connections at the top of the CV

3.3.7 VS to Remote Handling Interfaces

VS contains a number of removable components that require removal via remote handling in order to limit radiation dosage to workers. The VS components that require remote handling include the removable hatches on the CV lid (Qty 4), the target removable shield block, the MRA removable shield block, the gamma gate shield block and the gamma gate drive assembly. The control of the gamma gate actuation system is also an interface between VS and Remote Handling. Interface details are described in Interface Sheet S03000000-IST10006 (11).

3.3.8 VS to Vacuum Systems Interfaces

The CV within the VS scope is designed to operate in either rough vacuum mode or partial pressure helium mode. In either case, the CV needs to be connected to a vacuum system adequately sized to evacuate the CV in reasonable time and maintain rough vacuum under both normal operating conditions and with minor water leaks within the CV. VS will provide design inputs to the Vacuum Systems team to allow them to properly size the vacuum pumps and fore lines. VS will provide a vacuum port in the top portion of the CV shell for connecting to the vacuum system. Interface details are described in Interface Sheet S03000000-IST10008 (12).

4. REQUIREMENTS

Vessel Systems surrounds the Target Assembly and MRA, and provides a number of key features that are critical to the success of the Target System. Vessel Systems has developed a set of requirements to:

- Aid designers in providing the correct functionality
- Provide a clear definition of project status
- Clearly define successful project completion
- Promote clarity of expectations early and throughout the project lifecycle

Formal facility requirements are captured in *S01010100-SR0001, Global Requirements Document, Second Target Station* (13). The facility (level 1) requirements are decomposed into Target System (level 2) requirements, which are further decomposed into Vessel Systems (level 3) requirements that are captured in *S03060000-SRD10000 Vessel Systems Requirements* (1). Each step contains design decisions to be implemented at successive levels of detail and refinement. The explanation of design decisions between the global systems requirements and the Vessel Systems requirements is beyond the scope of this document. For further details, see the design description for the facility and the Target Systems design description. The Vessel Systems requirements are captured in a manner to ensure design success but are not an exhaustive list of all requirements. That is, many requirements are not captured due to their obvious nature or the fact that they are naturally fulfilled through the formulation of other requirements. An example of a requirement that is not captured would be "The core vessel shall be able to be manufactured". This requirement related to manufacturability is self-evident and contains several other target requirements. Therefore, the requirements presented in *S03060000-SRD0001, Vessel Systems Requirements* (1) reflect key items in the design, interfaces and understanding of the design team. The requirements are presented below with a brief explanation of their implementation.

4.1 GENERAL REQUIREMENTS

A set of requirements derived from the Target Systems requirements

4.1.1 Accept Proton Beam (CodeBeamer reference: 6121)

The Vessel and internal Shielding shall allow greater than 99.9% of the proton beam profile delivered by the Accelerator Systems to reach the Target Assembly unobstructed.

NOTE 1: Beam profile and other characteristics relevant to hardware will depend on beam area and beam position as defined in S01020500-ISXXXXX.

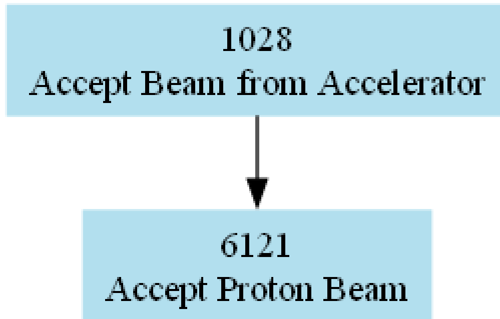


Figure 8: Requirement 6121 source and elaboration

The Core Vessel beltline and Core Vessel shielding must provide an unobstructed flight path for the proton beam to pass through in order to properly impact the target and generate neutrons. Allowing greater than 99.9% of the beam to reach the target is critical to achieving the desired brightness goals for the facility. Furthermore, direct interception of significant portions (greater than 0.1%) of the proton beam could result in localized damage to Vessel Systems life-of-facility components.

4.1.2 Radiation Shielding (CodeBeamer reference: 6130)

The Core Vessel and internal shielding shall be capable of limiting radiation exposure in areas accessible to personnel during beam-on and beam-off operations in accordance with the STS Radiation Safety Policy and Plan (14).

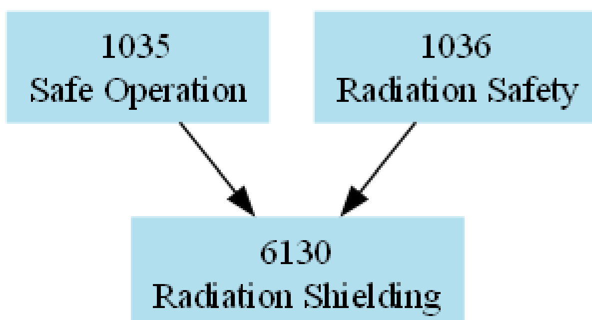


Figure 9: Requirement 6130 source and elaboration

Vessel Systems forms part of a radiation shielding strategy that limits radiation exposure to workers during facility operations. Acceptable radiation limits in different areas of the target building are described in the STS radiation safety policy and plan (14). The design of Vessel Systems components contributes significantly to the overall radiation shielding of the monolith. A variety of design aspects including shielding material selection, shielding thickness, shielding geometry and gaps between hardware impact the radiation levels seen in the target building both when the facility is active and when the facility is shut down. The overall efficacy of the radiation shielding of Vessel Systems components in combination with other monolith components will be validated through neutronics analysis.

4.1.3 Stainless Steel Temperature Limit (CodeBeamer reference: 7181)

Vessel Systems stainless steel structures should have a maximum operating temperature of 200 C.

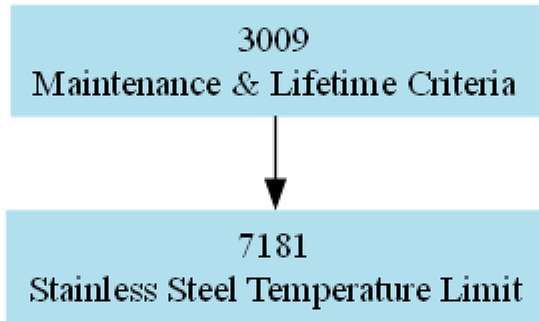


Figure 10: Requirement 7181 source and elaboration

A stainless steel maximum operating temperature was selected based on the STS materials handbook (15).

4.1.4 Carbon Steel Temperature Limit (CodeBeamer reference: 7182)

Vessel Systems nickel plated carbon steel structures should have a maximum operating temperature of 200 C.

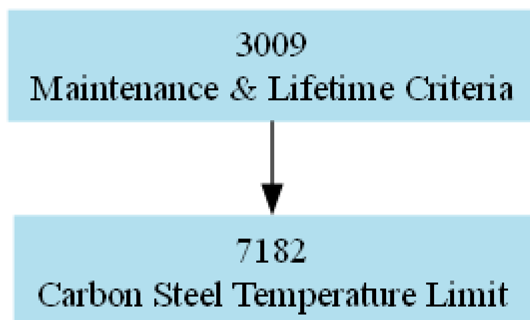


Figure 11: Requirement 7182 source and elaboration

A carbon steel maximum operating temperature was selected based on the STS materials handbook (15).

4.1.5 Lifetime (CodeBeamer reference: 7183)

All vessel systems components shall be life of the facility components having a lifetime greater than or equal to 40 years with the following exceptions:
1. Gamma Gate assembly
2. Thermocouples and associated wiring
3. Vacuum and water replaceable seals

Note: Exceptions will be governed by the maintenance and lifetime criteria for perishable components (Requirement 1.9)

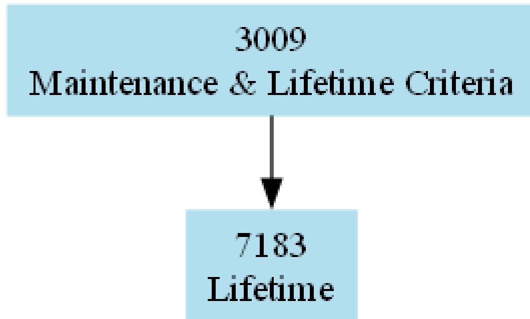


Figure 12: Requirement 7183 source and elaboration

Due to the difficulty in replacing the majority of Vessel Systems components, it is required that the majority be classified as life of the facility components. The primary driver for component lifetime within the monolith is material radiation damage as calculated by the Neutronics team. The STS materials handbook (15) is utilized to determine the maximum allowable radiation damage a material can accumulate before replacement is required. Other design considerations include robust mechanical designs that cope well with all expected loading conditions, and limiting the amount of welding for water cooled components.

4.1.6 Water Leak Rates (CodeBeamer reference: 7184)

All Vessel Systems water boundaries shall be designed to mitigate water leaks.

Note: Leak testing with water is not practical, leak rates to be verified via helium leak testing with an anticipated acceptance criteria of of 1x10^-6 mbar-l/s or less.

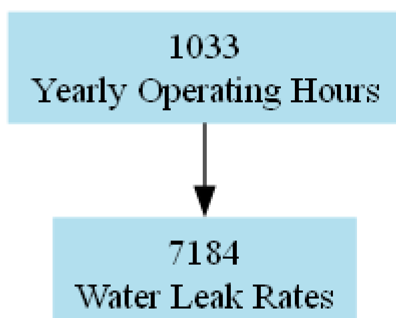


Figure 13: Requirement 7184 source and elaboration

Vessel Systems contains a number of water cooled components. Water cooling is required to dissipate heat that is generated by neutronic heating due to the spallation process. All Vessel Systems water cooled components are life of facility components, with a goal of remaining leak-free throughout the facility lifetime. Water cooled component designs will strive to reduce the chance of water leaks through intelligent engineering design. Post-fabrication testing of all water cooled components will be conducted to verify leak tight operation prior to commissioning of the Target System.

4.1.7 Pressure Bearing Component Design Criteria (CodeBeamer reference: 7185)

All Vessel Systems water cooled shielding, Core Vessel beltline and Core Vessel shall be designed per the STS Design and Fabrication of Pressure and Vacuum Systems (S01020000-PC0007 (16)*).*

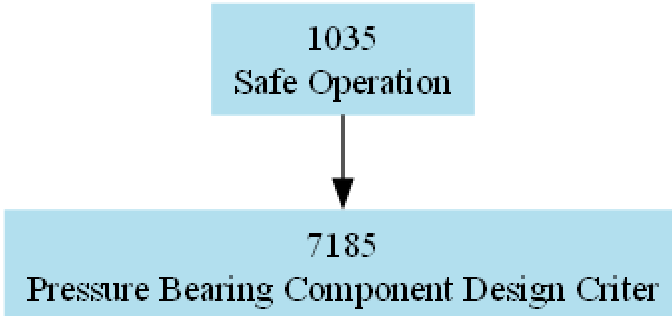


Figure 14: Requirement 7185 source and elaboration

The STS Design and Fabrication of Pressure and Vacuum Systems will be used to govern the design, analysis and fabrication of all pressure and vacuum bearing components. This includes the CV, CV beltline and all water cooled shield blocks. ASME Code stamping will not be performed on VS components.

4.1.8 Piping Design Criteria (CodeBeamer reference: 7186)

All Vessel Systems water piping shall be designed and fabricated to ASME B31.3.

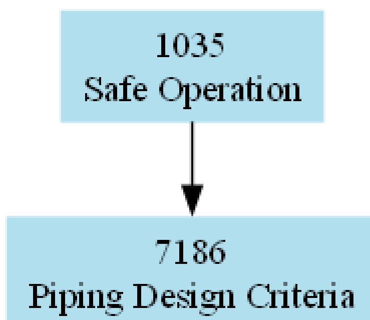


Figure 15: Requirement 7186 source and elaboration

Vessel Systems water cooled shielding and CV beltline include welded pipe spools that route water from the top of the CV to the components. These lines will be designed and fabricated per ASME B31.3.

4.1.9 Maintenance and Lifetime Criteria – Perishable Components (CodeBeamer reference: 7674)

All components shall meet one (or more) of the following criteria:

1. *Non-replaceable components shall be designed and constructed with a negligible chance of failure beyond the life of the facility.*

2. *Components that are designed for the life of the facility but have a chance of failure shall be designed and constructed to permit replacement.*
3. *Components with expected minimum lifetime of 5000 hours shall be replaceable in 1400 hours or less.*
4. *Components with expected minimum lifetime of 2500 hours shall be replaceable in 250 hours or less.*
5. *Components with expected minimum lifetime of 500 hours shall be replaceable in 72 hours or less.*
6. *Components with expected minimum lifetime of 192 hours shall be replaceable in 16 hours or less.*

Note: The criteria above give a high confidence level in meeting the availability requirement.

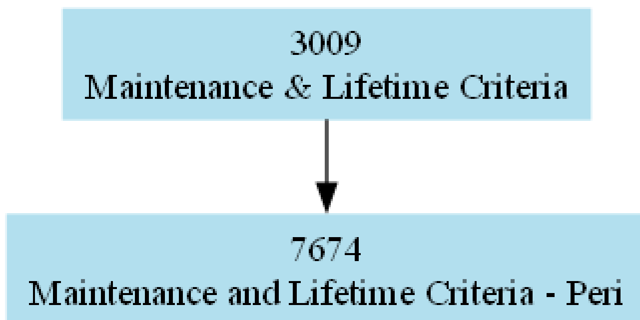


Figure 16: Requirement 7674 source and elaboration

The only perishable components within Vessel Systems are the Gamma Gate Assembly, thermocouples located throughout the CV interior, and thermocouple wiring. Failed components within the gamma gate assembly will be replaced, a process made relatively straightforward given the assembly's location at the top of the CV. Failed thermocouples and thermocouple wiring will not be replaced as they are difficult to access and are not required in order to operate the facility.

4.2 SAFETY REQUIREMENTS

Requirements derived from the PHAR (17).

4.2.1 Core Vessel Pressure Relief (CodeBeamer reference: 7047)

The Core Vessel shall maintain an internal pressure of less than +7.35 PSIG.

Note: A pressure relief system with burst disc shall be designed to ensure that + 7.35 PSIG is not exceeded.

Note: Pressure limit determined by Proton Beam Window per Interface Sheet S01020500-IST10217 (9).

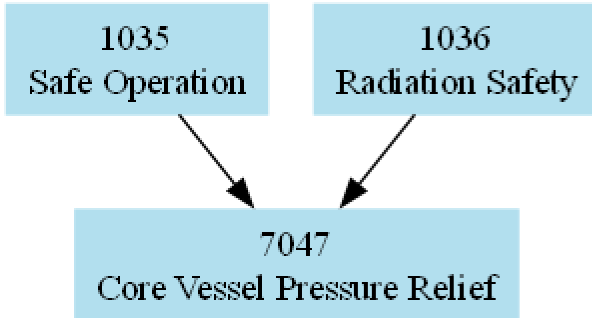


Figure 17: Requirement 7047 source and elaboration

The CV will be connected to a pressure relief system in order to protect the CV and all sealing components from over pressurization events. Key interfacing components that are vulnerable to CV overpressure includes the monolith insert sealing windows and the proton beam window.

4.2.2 Core Vessel Leak Collection (CodeBeamer reference: 7048)

The Core Vessel shall collect water leaks inside the vessel and route to a drain port near the bottom of the vessel that connects to Process Systems drain line of the same diameter.

Note: Sizing of the drain line is the responsibility of Process Systems.

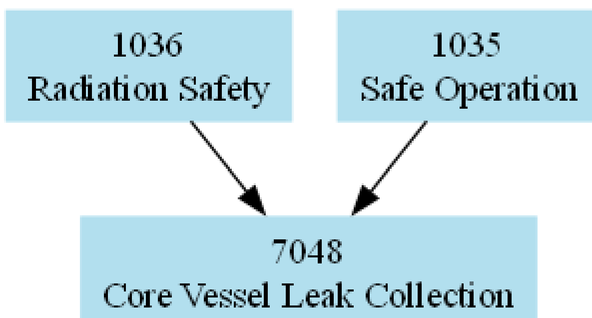


Figure 18: Requirement 7048 source and elaboration

All water that enters the CV becomes radioactive through the production of tritium in the water as well as suspended particles that can become radioactive when exposed to the spallation environment. Any water that leaks from a water cooled component inside the CV must be collected and routed to an appropriate drainage tank that can handle the activated nature of the water. It is also desirable to limit the amount of standing water in the CV in order to help maintain an appropriate spallation environment. Increasing water volume inside the CV would eventually disable the target system once the water level rises above the proton beam level.

4.2.3 Vacuum Port (CodeBeamer reference: 7049)

The Core Vessel shall have a vacuum port that connects to a vacuum system.

Note: Vacuum nozzle size may be determined in collaboration with other systems to accommodate maintenance ventilation and connection to a Hydrogen-safe release stack.

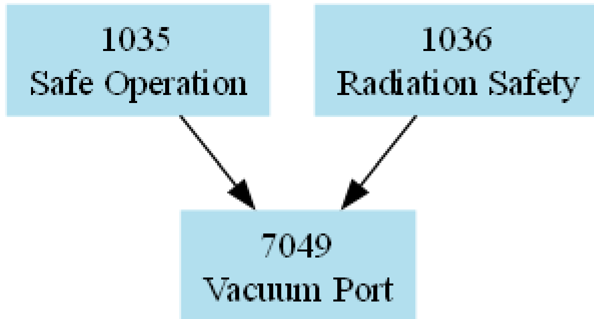


Figure 19: Requirement 7049 source and elaboration

A number of safety-related scenarios rely upon an inert environment within the CV to mitigate fire or explosions. Because generation of the inert vacuum or partial pressure helium environment within the CV is not a part of VS scope, the requirement of a physical connection to the vacuum system was specified to meet this safety requirement.

4.2.4 Core Vessel Pressure Range (CodeBeamer reference: 7052)

Core Vessel shall be designed to operate in a range of full vacuum to +15 PSIG per the STS Design and Fabrication of Pressure and Vacuum Systems (S01020000-PC0007 (16)*).*

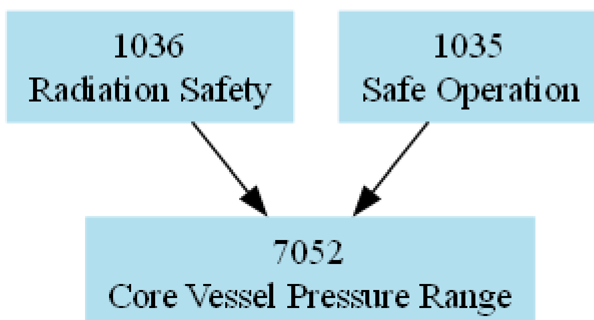


Figure 20: Requirement 7052 source and elaboration

This requirement ensures proper design of the CV to cope with the various transient and steady state pressure conditions within the CV. A pressure relief device set to 7.35 PSIG will protect more fragile components connected to the CV, while the CV will employ a more robust design to provide additional safety factor and ensure a durable design that will last the life of the facility.

4.2.5 Non-Flammable Materials (CodeBeamer reference: 7053)

Core Vessel and Core Vessel shielding components shall be made of non-flammable materials where practical.

Note: Small volumes (<0.01%) of elastomers will be used for vacuum and water seals within Vessel Systems scope.

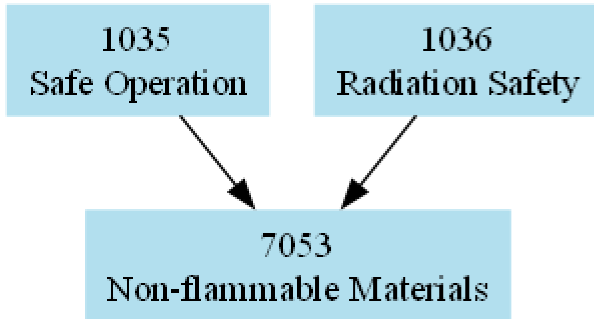


Figure 21: Requirement 7053 source and elaboration

The use of non-flammable materials within VS significantly reduces the impact of internal or external fires on the overall target system.

4.2.6 Target Temperature Limit During Facility Fire (CodeBeamer reference: 7054)

Core Vessel shielding shall keep target temperature below 800C under reasonable fire conditions.

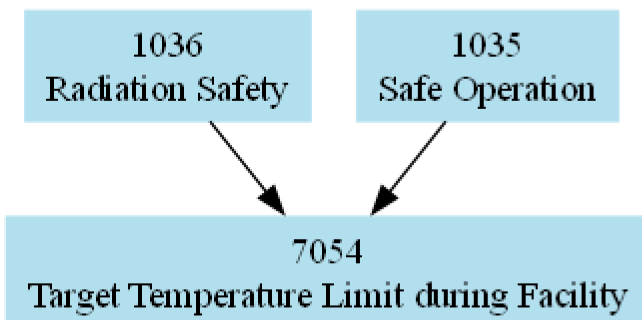


Figure 22: Requirement 7054 source and elaboration

The target must remain below 800C in order to avoid melting of the target and release of radioactive products throughout the CV. The large thermal mass of the CV and CV shielding help keep the target assembly under this temperature.

4.2.7 Impact Damage Protection (CodeBeamer reference: 7055)

The Monolith steel shielding shall protect the Target feet and Moderator Reflector Assembly from physical impact damage when the Target System is installed and in operational configuration.

Note: Monolith steel shielding does not protect Moderator Reflector Assembly or Target feet that have been removed from their home positions within the monolith.

Note: Monolith steel shielding provides less protection when removable shielding is not in place during maintenance activities.

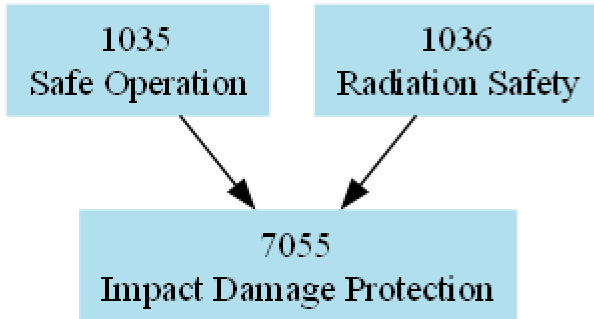


Figure 23: Requirement 7055 source and elaboration

Vessel Systems shielding provides a substantial amount of carbon and stainless steel shielding between the target feet and MRA and the exterior of the monolith. This shielding provides physical impact protection from aircraft, vehicles and tornado borne missiles that could strike the monolith. Full protection is only offered when the Target System is in operational configuration with all shielding in place. When shielding is removed for maintenance activities including Target segment or MRA changeout, the protection offered is reduced. Vessel Systems is not responsible for protecting components that have been removed from their home position within the monolith from physical impact damage.

4.2.8 Protect Cryogenic Transfer Lines (CodeBeamer reference: 7056)

Vessel Systems shall not permit the Core Vessel or shielding within the Core Vessel to cause the Moderator Reflector Assembly or cryogenic transfer lines to release Hydrogen under SDC2 seismic conditions.

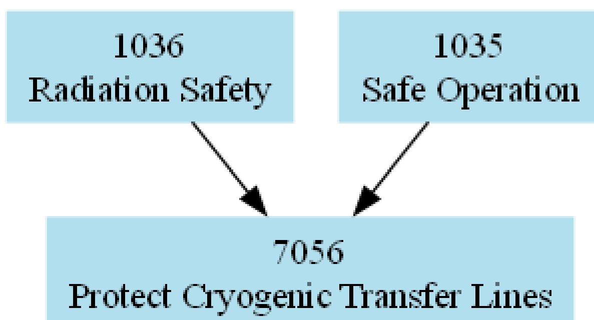


Figure 24: Requirement 7056 source and elaboration

One of the primary hazards within the monolith is a release of hydrogen into the CV due to a seismic event. Vessel Systems must help ensure that the MRA and cryogenic transfer lines will not be damaged by moving or shifting shield blocks or other hardware during a seismic event in order to prevent an unexpected release of hydrogen into the CV.

4.2.9 Core Vessel Anchoring (CodeBeamer reference: 7057)

The Core Vessel shall be anchored in such a way to limit motion of the Core Vessel base flange relative to the floor to < 0.1 mm under SDC Level 2 seismic loads.

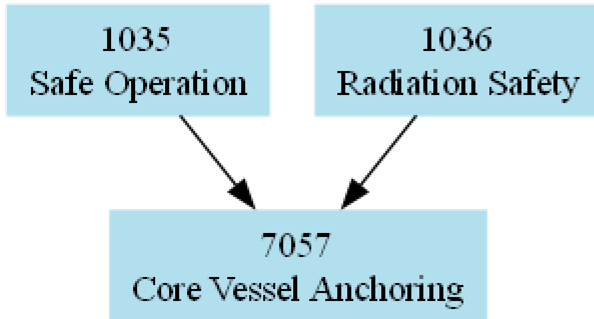


Figure 25: Requirement 7057 source and elaboration

Proper alignment of the CV and CV shielding is critical to proper operation of the target system. Instrument guide optics are aligned off of the CV, so shifts in position of the CV would result in reduced system performance. Significant shifts of the CV within the monolith also run the risk of permanent damage to the CV, CV shielding or nozzle extensions. For all of these reasons, it is critical that the design limits seismic motion of the CV base to the greatest extent possible.

4.2.10 Core Vessel Environment (CodeBeamer reference: 7058)

Core Vessel shall maintain an inert environment (≤1 torr vacuum or ≤ 700 torr helium) under normal operating conditions.

Note: The Core Vessel environment will extend to the Nozzle Extensions accommodating the Instrument Systems Monolith Inserts. Vacuum pumping and instrumentation is in the scope of Target Vacuum Systems, but Vessel Systems and interfacing components that make up the vacuum boundary must be capable of maintaining the required pressure, i.e. to hold leak rates low enough to maintain the required pressure.

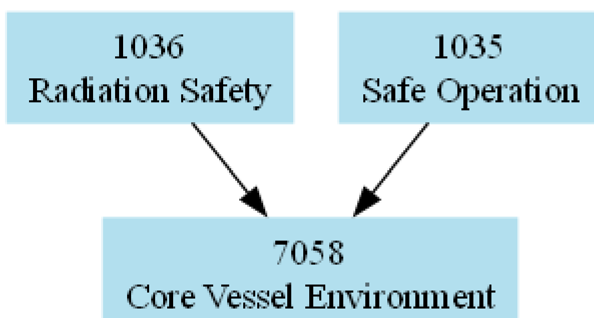


Figure 26: Requirement 7058 source and elaboration

A number of safety-related scenarios rely upon an inert environment within the CV to mitigate fire or explosions. VS components must be designed in a manor that allows for either vacuum or helium mode to be utilized within the CV to provide protection from detonations and fires within the CV.

4.2.11 Core Vessel Negative Pressure With Hatches Removed (CodeBeamer reference: 7059)

Core Vessel shall have an exhaust port that provides negative pressure when Core Vessel lid hatches are removed.

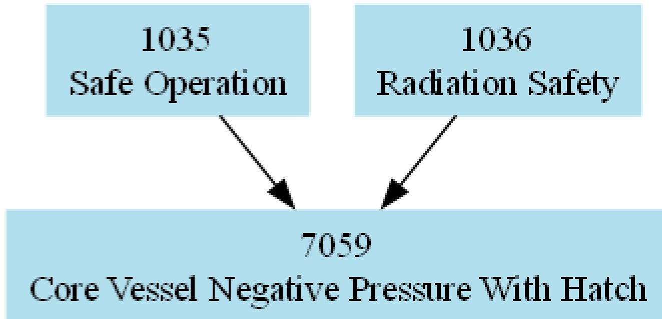


Figure 27: Requirement 7059 source and elaboration

A variety of maintenance activities will require the removal of one or more hatches from the CV lid. When these hatches are removed there is a danger of exposing workers to radioactive particulates that may reside in the CV. In order to mitigate this danger, a negative pressure will be applied to the CV interior in order to keep any loose particulate inside the CV and away from the workers.

4.2.12 Radiation Shielding Performance (CodeBeamer reference: 7060)

Vessel Systems design, along with the other Target Systems components in the Monolith and Target Drive Room, shall not prevent necessary operations in the high bay due to radiation dose.

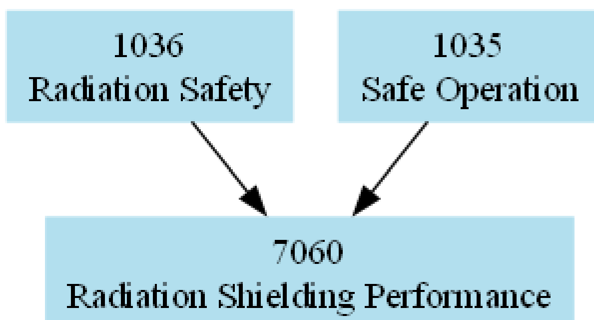


Figure 28: Requirement 7060 source and elaboration

Vessel Systems forms part of a radiation shielding strategy that limits radiation exposure to workers during facility operations. Acceptable radiation limits in the high bay are described in the STS radiation safety policy and plan (14). The design of Vessel Systems components contributes significantly to the overall radiation shielding of the monolith. A variety of design aspects including shielding material selection, shielding thickness, shielding geometry and gaps between hardware impact the radiation levels seen in the target building both when the facility is active and when the facility is shut down. The overall efficacy of the radiation shielding of Vessel Systems components in combination with other monolith components will be validated through neutronics analysis.

4.2.13 Non-LOF Water Cooled Component Connections (CodeBeamer reference: 7063)

All water-cooled components that are not considered permanent shall have flanged connections that are broken for component removal.

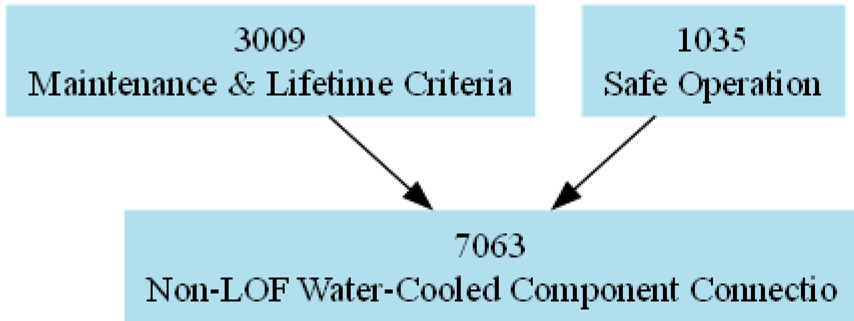


Figure 29: Requirement 7063 source and elaboration

The use of flanged connections for removable components within the CV will reduce the overall time to remove spent components and install new components, increasing the operational time of the STS. Flanged connections can be removed remotely, increasing the safety of maintenance workers.

4.2.14 Target Protection During LOCA (CodeBeamer reference: 7064)

Core Vessel shielding shall assist in maintaining < 800 C target temperatures in a loss of cooling event.

Note: The shielding acts as a thermal sink that helps maintain target temperatures of < 800 C during a loss of cooling event.

Note: LOCA to be performed by the Target Assembly team with input from Vessel Systems on shielding configuration.

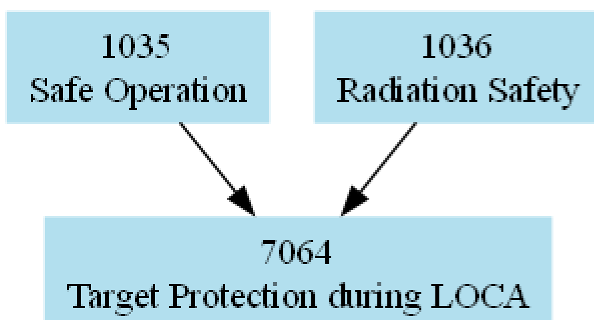


Figure 30: Requirement 7064 source and elaboration

By maintaining a low shield block temperature adjacent to the target during a loss of cooling event, the shield block acts as a heat sink that protects the target from overheating.

4.2.15 Temperature Monitoring (CodeBeamer reference: 7065)

All vessel systems water cooled components should have thermocouples that monitor component temperature.

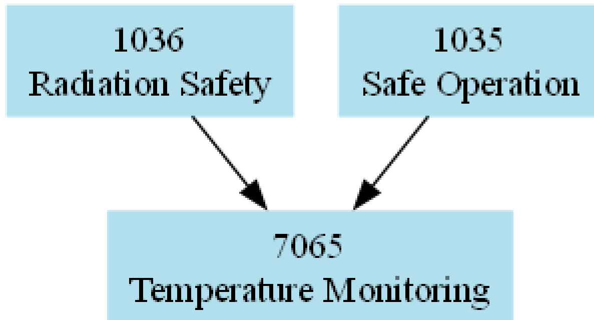


Figure 31: Requirement 7065 source and elaboration

Accurate temperature monitoring of all VS shield blocks is a goal of the design. These temperature monitors are very useful during initial commissioning of the system, and can alert operators to changes in system performance over time. Temperature monitoring can also alert operators to problems within the monolith that may justify shutting down the system to further evaluate the situation. While these temperature monitors have value to operations, they are not critical to the overall operation of the facility.

4.3 VS-TARGET ASSEMBLY INTERFACE

Requirements derived from Interface Sheet S01020500-IST10209 (5).

4.3.1 Mechanical Load Support (CodeBeamer reference: 7118)

Vessel Systems shall support the gravitational, imbalance, seismic and segment replacement loads imparted by the target assembly per Interface Sheet S01020500-IST10209 (5) *within the deflection limits specified in drawing S03000000-M8U-8800-A10001* (18) *at the physical locations specified in drawing S03020000-M8U-8800-A10000* (19).

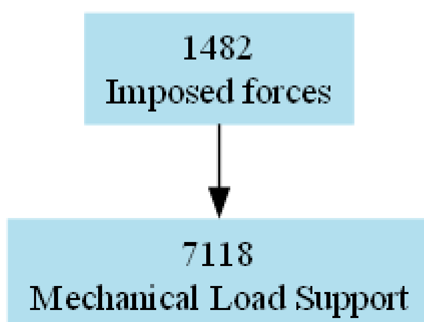


Figure 32: Requirement 7118 source and elaboration

The CV must support all of the predicted load conditions imparted by the target assembly without failure or significant deflections. Deflections in the target assembly mounting zone are particularly important in helping to ensure that the target assembly does not contact the shield stack or MRA.

4.3.2 Limiting Ring Integration (CodeBeamer reference: 7119)

Vessel Systems shall provide an interface including a mating face and tapped hole pattern to secure Target Assembly's limiting ring to the Layer 1 Core Vessel shielding. The interfacing dimensions are shown in drawing S0302000-M8U-8800-A10000 (19)*.*

Note: Currently missing from Interface Sheet S01020500-IST10209 (5)*, will be added during next revision.*

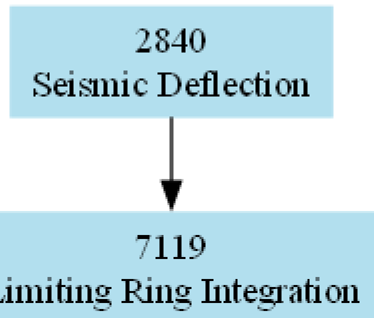


Figure 33: Requirement 7119 source and elaboration

The limiting ring resides below and around a boss at the bottom of the target shaft. The purpose of this ring is to physically limit the distance the bottom of the target shaft can travel in a seismic event. During a seismic event the target will contact the limiting ring while a physical gap is maintained between the target and the MRA, protecting the MRA hydrogen boundary.

4.3.3 Limiting Ring Mechanical Support (CodeBeamer reference: 7120)

Vessel Systems shall not allow horizontal motion of the portion of the target shaft that contacts the limiting ring in excess of xxxx under a 40 kN seismic side load imparted on the limiting ring by the target shaft.

Note: Currently missing from Interface Sheet S01020500-IST10209 (5)*, will be added during next revision.*

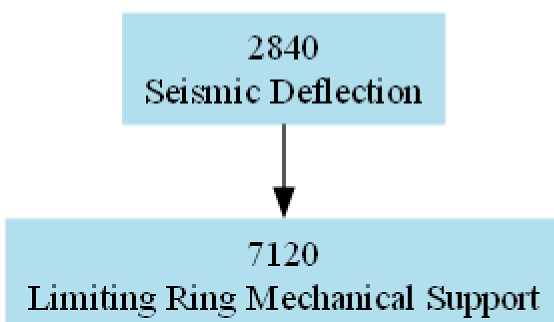


Figure 34: Requirement 7120 source and elaboration

The mounting configuration of the limiting ring must remain in place under the maximum predicted lateral seismic loads imparted by the target assembly onto the ring. If the limiting ring mounting were to fail, the target assembly would be free to contact the MRA, resulting in potential hydrogen release.

4.3.4 Target Segment Access (CodeBeamer reference: 7121)

Vessel Systems shall allow access to a single target segment within 8 hours per Interface Sheet S01020500-IST10209 (5).

NOTE 1: The clock starts when the Core Vessel is vented and stops when the Target Segment is exposed for removal.

NOTE 2: Driven by Target Segment requirement dictating time allotted for Segment replacement.

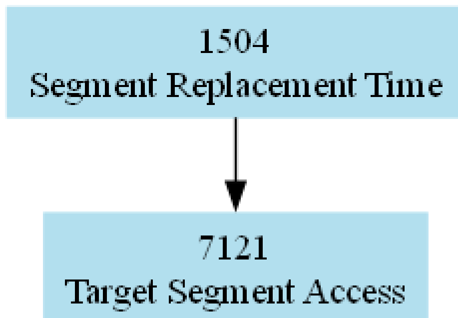


Figure 35: Requirement 7121 source and elaboration

Target segment exchange is a regular maintenance occurrence and must be accomplished with minimal downtime. Vessel Systems hardware must be configured in such a way that allows for quick access to a target segment for removal. In order to expose a target segment for removal, a single hatch is removed from the CV lid, and one uncooled CV shield block is vertically removed from the CV. Removal of these two components must be possible in a single 8 hour shift.

4.3.5 Target Segment Personnel Access (CodeBeamer reference: 7123)

Vessel Systems components shall allow space for personnel and tooling access to the target segment mounting hardware for removal, repair and reinstallation of target segments per Interface Sheet S01020500-IST10209 (5).

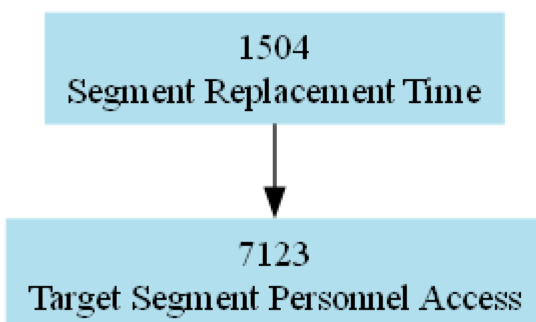


Figure 36: Requirement 7123 source and elaboration

The removal and installation of target segments is preferably accomplished via hands-on operations near the top of the target assembly. Vessel Systems design must provide sufficient access to the target shaft in this maintenance zone to allow for hands on work to be executed. This is particularly important if off-normal operations such as target segment seal surface polishing is required.

4.3.6 Target Segment Installation Guidance (CodeBeamer reference: 7124)

The Core Vessel Shielding shall provide mechanical boundaries that ensure proper engagement of the target segment to the target shaft when a target segment is installed per Interface Sheet S01020500-IST10209 (5).

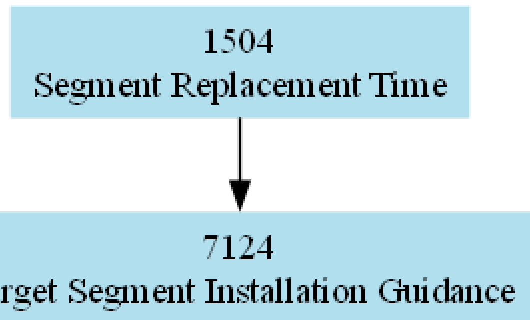


Figure 37: Requirement 7124 source and elaboration

The bottom of each target segment contains an alignment pin that engages with the bottom of the target shaft. As the target segment is lowered into position, the surrounding CV shielding acts as a guide to ensure that the target segment bottom pin engages with its mounting hole. This design ensures that if the target segment is installed to the proper height within the monolith that its engagement with the target shaft is guaranteed.

4.3.7 Shielding for Target Segment Removal and Installation (CodeBeamer reference: 7125)

Vessel Systems shall allow for hands-on maintenance at the top of the target segment with the target removable shield block removed.

Note: A gamma gate assembly is moved into place after removable shield block removal to provide radiation protection during hands-on target maintenance.

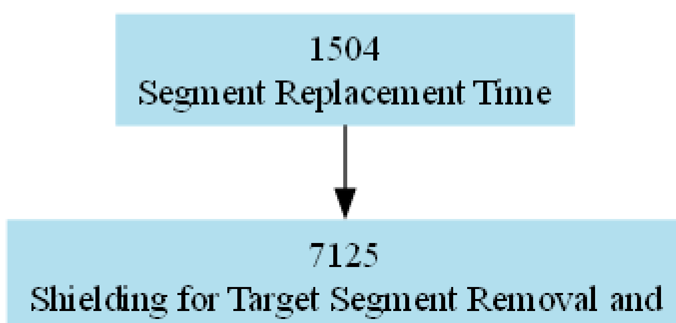


Figure 38: Requirement 7125 source and elaboration

Neutronics analysis has determined that if hands on maintenance is to be allowed during target segment removal and installation, supplemental shielding to block streaming radiation from the removed CV shielding block is required. Vessel Systems has incorporated a gamma gate assembly that can be translated horizontally via remote control during target segment removal and installation to facilitate hands on operations during target changeout.

4.3.8 Target Shaft Bottom Support (CodeBeamer reference: 7127)

Vessel Systems shall allow for the full 16,000 kg mass of the target assembly to rest on the bottom Core Vessel shield block without contacting the Moderator Reflector Assembly per Interface Sheet S01020500-IST10209 (5).

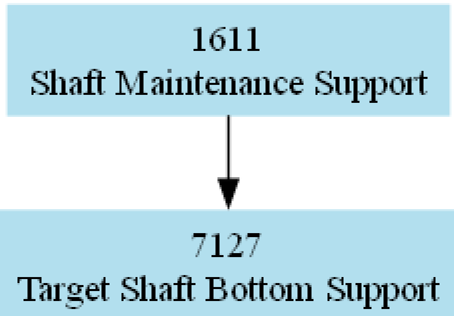


Figure 39: Requirement 7127 source and elaboration

During specific target shaft maintenance activities it is necessary to rest the full weight of the target assembly on the CV shield stack. The target shaft comes to rest on the bottom CV shield block, which must be able to support this weight without damage.

4.3.9 Target Assembly Seal (CodeBeamer reference: 7128)

Vessel Systems shall provide a seal interface for the Target Assembly per Interface Sheet S01020500-IST10209 (5) *and drawing S03020000_G8U-8800-A10000* (20).

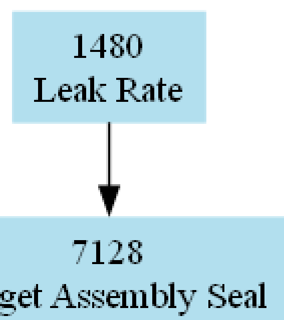


Figure 40: Requirement 7128 source and elaboration

The target assembly forms a portion of the CV vacuum boundary on the CV lid. The target assembly will be mounted to the CV via a bellows flange assembly to provide a vacuum seal.

4.4 VS-CMS INTERFACE

Requirements derived from Interface Sheet S03000000-IST10010 (6).

4.4.1 Hydrogen Transfer Line Nozzle (CodeBeamer reference: 7136)

Vessel Systems shall provide a nozzle in the side wall of the Core Vessel for the hydrogen transfer line per interface sheet S03000000-IST10010 (6).

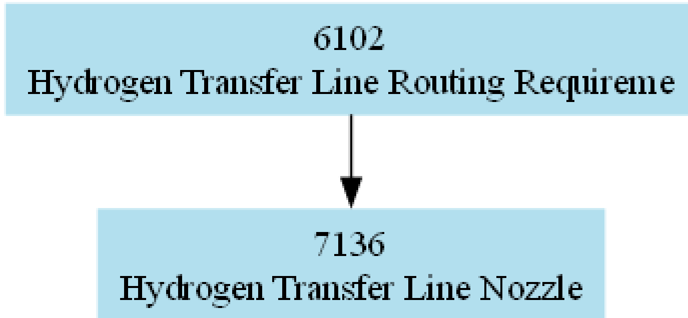


Figure 41: Requirement 7136 source and elaboration

The hydrogen transfer line must travel through the upper side wall of the CV to connect to the MRA. An oversized nozzle will be provided in the sidewall of the CV. A mating flange on the transfer line assembly will mount to this flange to provide a vacuum seal. During MRA maintenance operations the hydrogen line will be cut and moved to the side utilizing the clearance provided by the oversized nozzle in the CV wall. This allows room for MRA removal and welding fitup during MRA installation.

4.4.2 Hydrogen Transfer Line Clearance (CodeBeamer Reference: 8048)

Vessel Systems shall provide ≥ 25mm of clearance between Vessel Systems hardware and the transfer line per interface sheet S03000000-IST10010 (6).

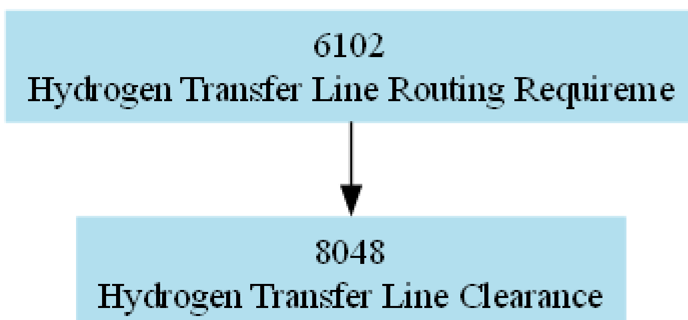


Figure 42: Requirement 8048 source and elaboration

The hydrogen transfer line must be protected from physical damage during the life of the facility in order to avoid accidental discharge of flammable hydrogen. Physical clearance of all hardware surrounding the transfer line is one way of ensuring that the line is not damaged during both normal operations as well as during a seismic event.

4.4.3 Hydrogen Transfer Line Support (CodeBeamer Reference: 8049)

Vessel Systems shall provide features in the top of the core vessel shielding stack to accommodate hydrogen transfer line supports designed and provided by Cryogenic Moderator Systems per Interface Sheet S03000000-IST10010 (6).

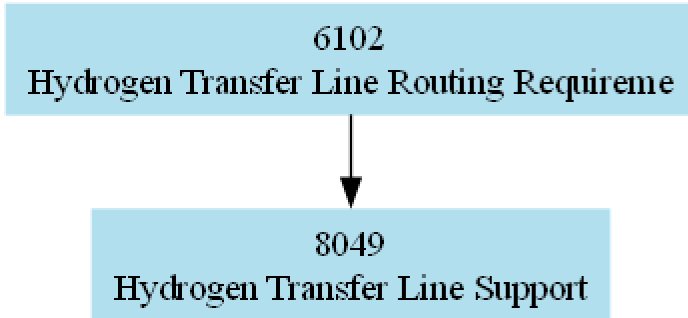


Figure 43: Requirement 8049 source and elaboration

The hydrogen transfer line requires support at regular intervals. It may be necessary to locate one of these supports inside the CV. If this is the case, VS will provide the necessary mounting features to accommodate this support. The CMS team will design and procure the support.

4.4.4 Hydrogen Transfer Line Welding Access (CodeBeamer Reference: 8050)

Vessel Systems shall provide appropriate welding access to the hydrogen transfer lines during Moderator Reflector Assembly installation via removable hatches in the Core Vessel lid and removable shielding above the transfer lines per Interface Sheet S0300000-IST10010 (6).

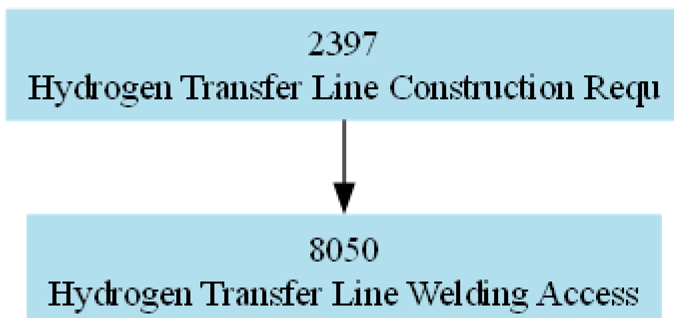


Figure 44: Requirement 8050 source and elaboration

Each time a MRA is removed and replaced it will be necessary to cut the hydrogen transfer lines from the old MRA and then field weld them to the new MRA. VS must ensure that sufficient access and physical room exists within the CV to allow for this welding to take place.

4.5 VS-MRA INTERFACE

Requirements derived from Interface Sheet S03000000-IST10009 (7).

4.5.1 MRA Cooling Water Connections (CodeBeamer reference: 7137)

Vessel Systems shall provide water supply and return lines that connect the Moderator Reflector Assembly water inlet and outlet flanges to the appropriate nozzles in the Core Vessel side wall per Interface Sheet S03000000-IST10009 (7).

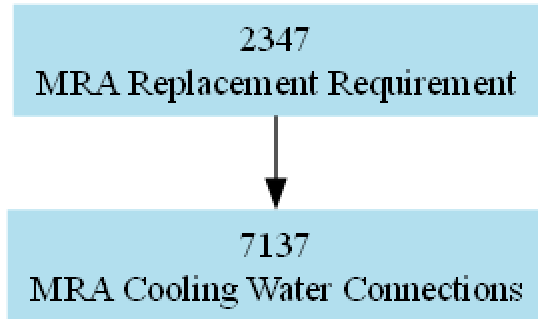


Figure 45: Requirement 7137 source and elaboration

The MRA water cooling lines travel from the MRA up to the top of the CV shielding stack where they terminate in flanged connections. Vessel Systems will design and procure custom jumper lines to connect the MRA water lines to the water nozzle flanges located at the side wall of the CV. Transitions will also be placed to reduce the diameter of the water lines from the larger lines supplied by Process Systems to the smaller MRA lines. The jumper lines will contain a flexible section that facilitates removal and installation of the MRA.

4.5.2 MRA Cooling Water Line Tie-Downs (CodeBeamer reference: 7138)

Vessel Systems will provide mounting features to accommodate Moderator Reflector Assembly water line tie-downs per Interface Sheet S03000000-IST10009 (7).

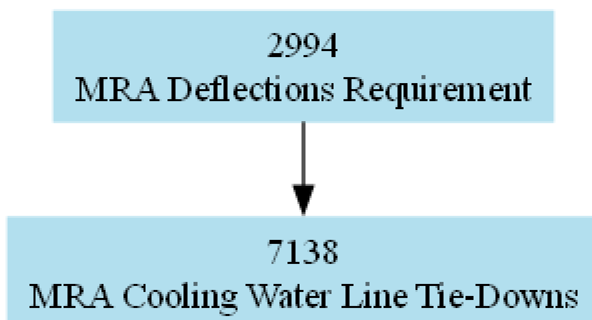


Figure 46: Requirement 7138 source and elaboration

The MRA water lines will be secured to the CV shielding using tie-down hardware provided by the MRA team. Mounting features in the CV shielding will be provided that allow for installation of these tie-downs.

4.5.3 MRA Access (CodeBeamer reference: 7139)

Vessel Systems shall allow access to the Moderator Reflector Assembly within 8 hours per Interface Sheet S03000000-IST10009 (7).

Note: The clock starts when the removal of the Moderator Reflector Assembly access hatch in the Core Vessel lid begins and stops when the Moderator Reflector Assembly is exposed for removal.

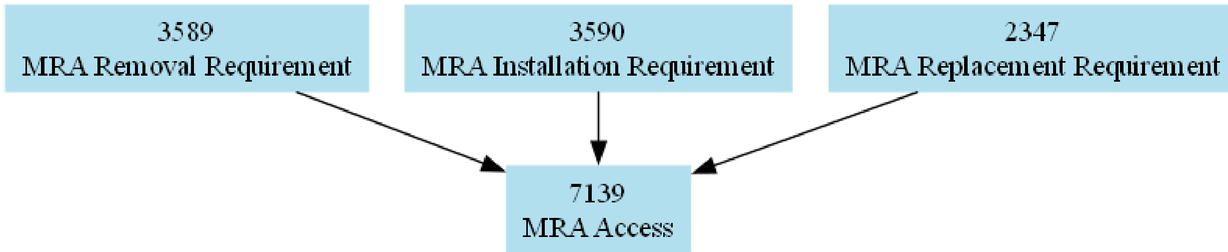


Figure 47: Requirement 7139 source and elaboration

The MRA is not a life of facility component, and will need to be changed periodically. MRA replacement is a relatively involved process that will be performed during a long outage of the STS, but where possible steps should be taken to reduce the overall time required to perform the MRA change out. In order to gain access to the MRA, the MRA access hatch on the CV lid is first removed, followed by vertical removal of the MRA removable shield block. The removal of these components is straight forward, and should be accomplished in a single 8 hour shift.

4.5.4 MRA Alignment Features (CodeBeamer reference: 7404)

Vessel Systems shall provide mounting features in the Core Vessel shielding for mounting of the Moderator Reflector Assembly canoe sphere alignment system as described in Interface Sheet S03000000-IST10009 (7).

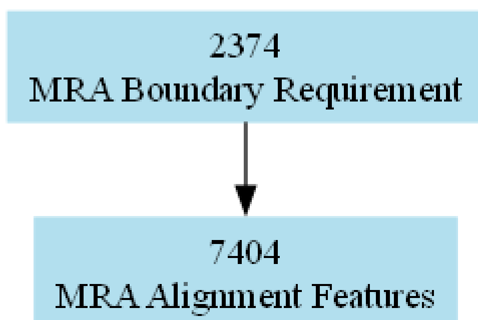


Figure 48: Requirement 7404 source and elaboration

The MRA will rest on three precision machined canoe spheres that act as kinematic mounts and mount directly to the layer 1 CV internal shielding. These canoe spheres must be accurately mounted onto the CV shielding to ensure proper alignment of the installed MRA. Drilled and tapped features in the layer 1 shield block will be machined as part of the final post-weld machining of the shield block to ensure high accuracy.

4.5.5 MRA Support (CodeBeamer reference: 7405)

Vessel Systems shall support the loads imparted by the Moderator Reflector Assembly while maintaining the alignment tolerances specified in Interface Sheet S03000000-IST10009 (7).

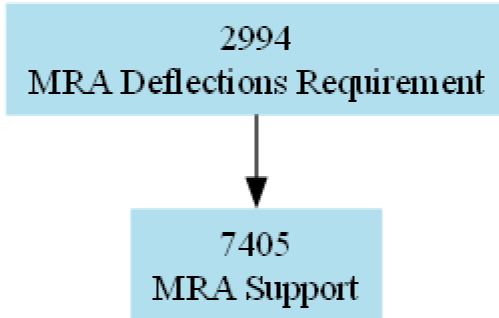


Figure 49: Requirement 7405 source and elaboration

The full weight of the MRA must be supported off of the layer 1 CV shield block. The weight is transferred through the MRA canoe sphere mounts to the shield block. Mechanical analysis of the shield block will be performed to ensure that the shield block can properly support the load without

4.6 VS-MRA-TARGET INTERFACE

Requirements derived from Interface Sheet S01020500-IST10205 (8).

4.6.1 Position and Gaps (CodeBeamer reference: 7407)

Vessel Systems shall ensure that all hardware adjacent to the Target and Moderator Reflector Assembly conforms to the positions and gaps outlined in Interface Sheet S01020500-IST10205 (8).

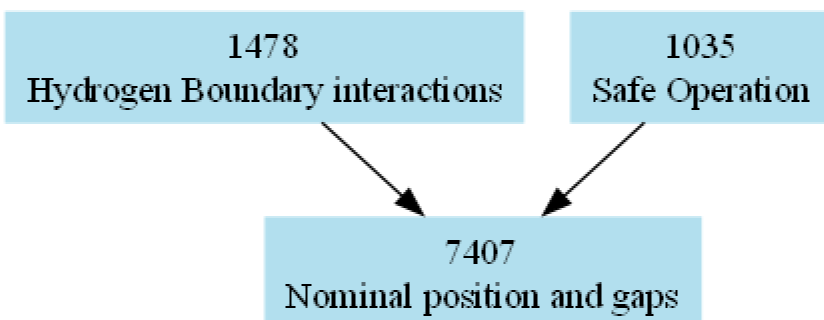


Figure 50: Requirement 7407 source and elaboration

In order to manage the gap and tolerance budget of the key components within the CV, a three way interface sheet was developed to capture the location, gaps and tolerance budgets of the Target assembly, MRA and VS components. Vessel Systems must ensure that all hardware adjacent to the MRA and Target components conform to the dimensions and tolerances laid out in the interface sheet.

4.6.2 Positional Deviations (CodeBeamer reference: 7408)

Vessel Systems shall ensure that all hardware adjacent to the Target and Moderator Reflector Assembly does not deviate beyond the Vessel Systems tolerance allotment per Interface Sheet S01020500-IST10205 (8).

Note: Anticipated deviations include manufacturing, alignment, seismic, thermal and pressure induced.

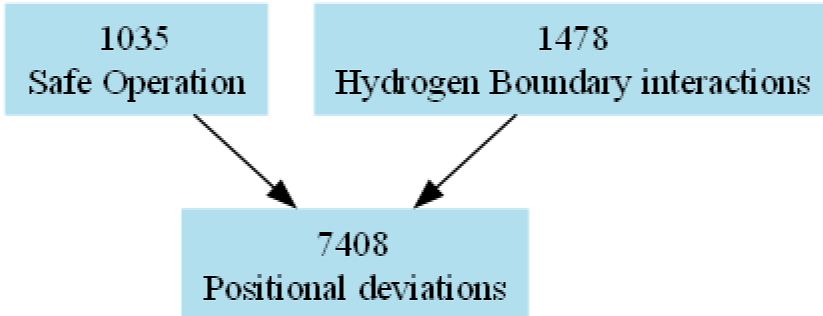


Figure 51: Requirement 7408 source and elaboration

This requirement works in tandem with the requirement above to manage the overall position of VS components in relation to Target and MRA components. This requirement manages the positional deviations from nominal in order to ensure VS components are not encroaching on Target or MRA keep-out zones.

4.7 VS-AIC INTERFACE

Requirements derived from Interface Sheet S01020500-IST10217 (9).

4.7.1 Proton Beam Window Shielding Sealing Interface (CodeBeamer reference: 7141)

Vessel Systems shall provide a sealing surface for the proton beam window shielding that is capable of achieving a <10^-4 Torr l/s leak rate.

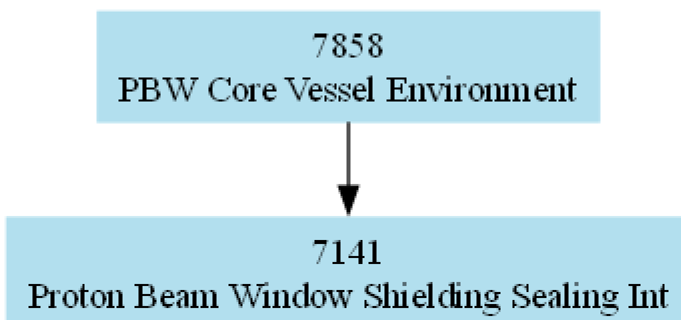


Figure 52: Requirement 7141 source and elaboration

The proton beam window shielding forms a vacuum seal with the outer face of the CV beltline to maintain the CV internal environment. The PBW shielding employs an inflatable seal to make this connection as this allows for removal and replacement of the PBW shielding in the vent of a leak or other performance problem. The CV beltline will provide a sealing surface of appropriate surface finish and flatness to accommodate the inflatable seal.

4.7.2 Target Viewing Periscope Alignment Holes (CodeBeamer reference: 7144)

Vessel Systems shall provide mounting holes in the Core Vessel Shielding for mounting of the Target Viewing Periscope canoe sphere alignment system in the locations described in Interface Sheet S01020500-IST10217 (9).

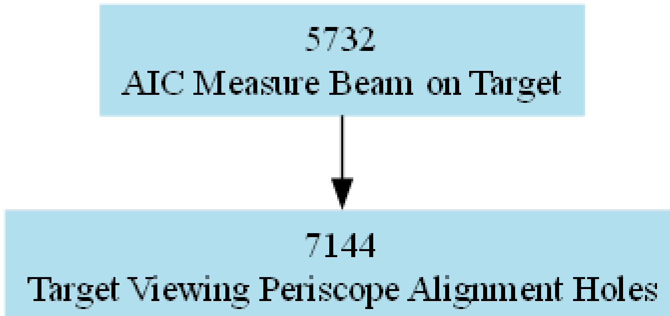


Figure 53: Requirement 7144 source and elaboration

The TVP must be accurately aligned within the CV in order to perform properly. Canoe spheres will be installed onto the CV shielding, and the TVP will land on these canoe spheres. VS will provide threaded holes as defined in the interface sheet for installation of the canoe spheres.

4.7.3 Target Viewing Periscope Support (CodeBeamer reference: 7145)

Vessel Systems shall support the loads imparted by the Target Viewing Periscope assembly while maintaining the alignment tolerances specified in Interface Sheet S01020500-IST10217 (9).

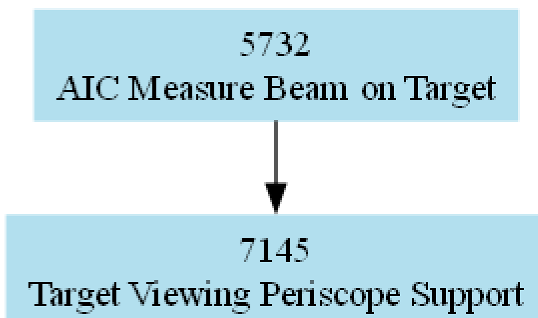


Figure 54: Requirement 7145 source and elaboration

The CV shielding will support the weight of the TVP assembly through their canoe sphere mounts. Mechanical analysis will be employed to ensure sufficient mechanical support is provided and any deviations in position due to weight are acceptable per the interface sheet.

4.7.4 Target Viewing Periscope Vacuum Flange (CodeBeamer reference: 7146)

Vessel Systems will provide a flange seal mounting interface in the Core Vessel Lid as specified in Interface Sheet S01020500-IST10217 (9).

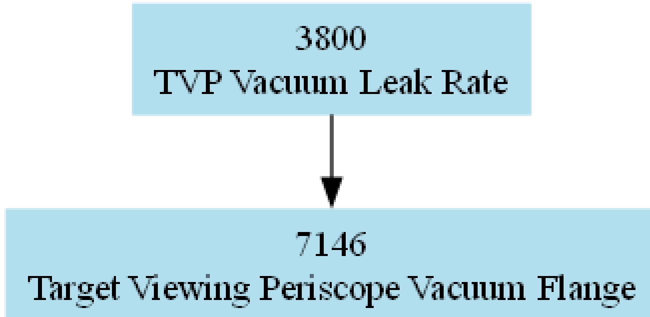


Figure 55: Requirement 7146 source and elaboration

The TVP penetrates the CV lid, and a vacuum sealing interface is required to maintain the CV internal environment. The AIC team will design and provide a vacuum flange, and the CV lid will be machined as necessary to accommodate the vacuum flange and seal.

4.7.5 Target Viewing Periscope Keep-Out Zones (CodeBeamer reference: 7147)

Vessel Systems shall provide openings in the Core Vessel Shielding per Interface Sheet S01020500-IST10217 (9).

NOTE: Decomposes from TVP requirement 5445 to ensure that the TVP can view the Target Segment without obstruction.

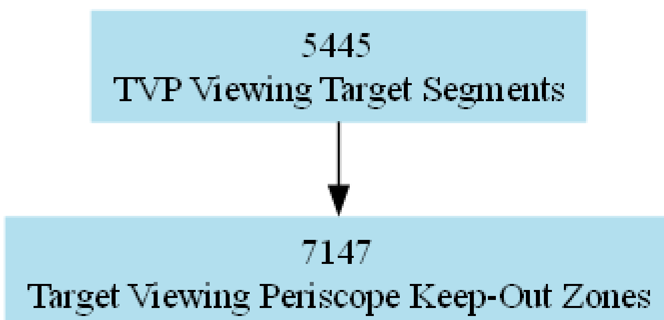


Figure 56: Requirement 7147 source and elaboration

The TVP requires a clear line of sight to the face of the target wheel impacted by the proton beam. The AIC team has defined a keep out zone that provides clear line of sight as well as appropriate clearance for the TVP mechanical components inside the CV. The CV shielding will be designed to provide the required clearance.

4.7.6 Target Viewing Periscope Doghouse Mounting (CodeBeamer reference: 7149)

Vessel Systems shall provide features in the Core Vessel lid for mounting of the Target Viewing Periscope doghouse per Interface Sheet S01020500-IST10217 (9).

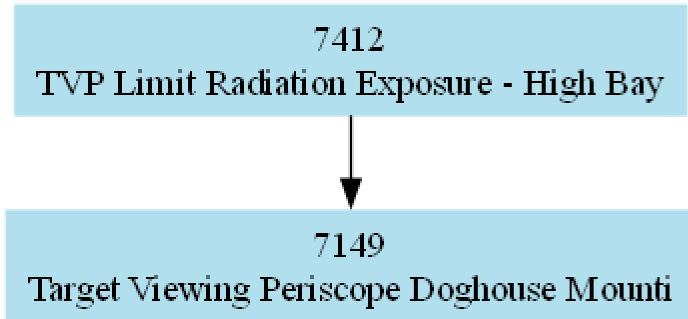


Figure 57: Requirement 7149 source and elaboration

A large shield block referred to as the TVP doghouse sits above the second mirror of the TVP above the lid of the CV to provide radiation shielding. The doghouse is mounted to the CV lid to ensure it does not shift and interfere with the TVP mirror assembly. The CV lid will provide features specified by the AIC team to allow secure mounting of the TVP doghouse to the CV lid.

4.7.7 Target Viewing Periscope 3rd Mirror Mounting (CodeBeamer reference: 7151)

Vessel Systems shall provide features in the Core Vessel lid for mounting of the Target Viewing Periscope 3rd mirror assembly per Interface Sheet S01020500-IST10217 (9).

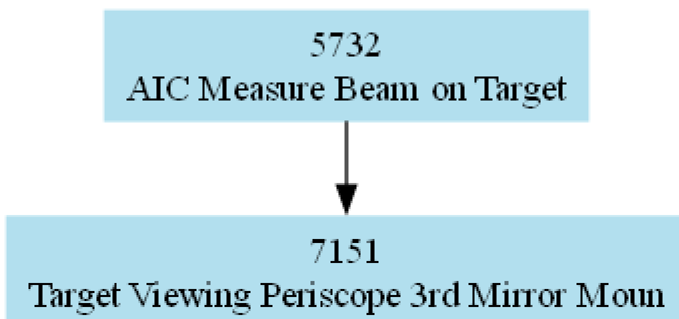


Figure 58: Requirement 7151 source and elaboration

The third mirror of the TVP assembly mounts to the CV lid. The third mirror must be accurately aligned and securely mounted for the TVP to function properly. VS shall provide mounting features specified by the AIC team to properly mount the TVP third mirror.

4.7.8 Target Viewing Periscope Position and Gaps (CodeBeamer reference: 7685)

Vessel Systems shall ensure that all hardware adjacent to the Target Viewing Periscope conforms to the positions and gaps outlined in Interface Sheet S01020500-IST10217 (9).

Note: Currently missing from Interface Sheet S01020500-IST10217 (9)*, will be added during next revision.*

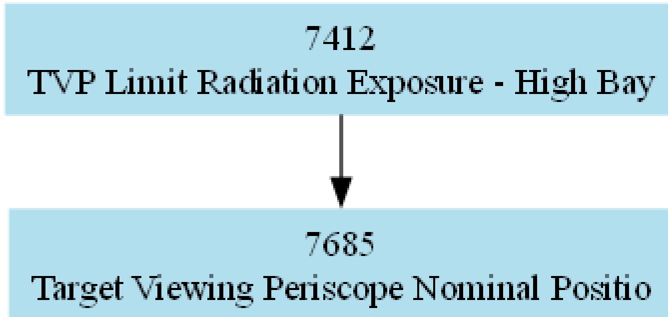


Figure 59: Requirement 7685 source and elaboration

The TVP penetrates the CV internal shielding stack down to the beamline elevation. The interface sheet and accompanying interface drawing will define the position, gaps and tolerances of the openings in the CV shielding provided for the TVP.

4.7.9 Positional Deviations (CodeBeamer reference: 7686)

Vessel Systems shall ensure that all hardware adjacent to the Target Viewing Periscope does not deviate beyond the Vessel Systems tolerance allotment per Interface Sheet S01020500-IST10217 (9).

Note: Anticipated deviations include manufacturing, alignment, seismic, thermal and pressure induced.

Note: Currently missing from Interface Sheet S01020500-IST10217, will be added during next revision.

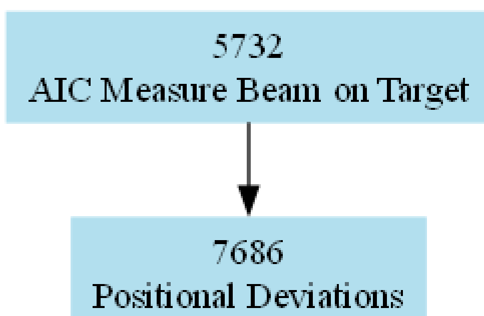


Figure 60: Requirement 7686 source and elaboration

Vessel Systems must protect the TVP from physical damage in the event of an earthquake or other off-normal event. This will be accomplished by securing the CV shield stack in such a way that block-to-block movement is minimized and the CV shielding does not encroach upon the TVP keep out zones.

4.8 VS-PROCESS SYSTEMS INTERFACE

Requirements derived from Interface Sheet S03000000-IST10004 (10).

4.8.1 Utility Nozzle Connections (CodeBeamer reference: 7155)

Vessel Systems shall provide utility nozzles in the sidewall of the Core Vessel that allow cooling water and helium gas provided by Process Systems to enter the Core Vessel. Vessel Systems shall provide the interfacing locations of all Core Vessel beltline utility waterlines. The sizes and locations of all utility nozzles and water connections are specified in Interface Sheet S03000000-IST10004 (10).

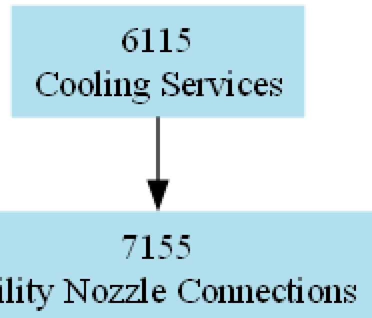


Figure 61: Requirement 7155 source and elaboration

Water and gases enter the CV via utility nozzles in the sidewall near the top of the CV. Process Systems will field weld water and gas connections to the outside nozzles in the locations specified in the Interface Sheet. Permanent cooled shielding inside the CV will be welded to the inside nozzles, while removable shielding will be connected to the water lines via bolted flanged connections.

4.8.2 Cooling Water Requirements (CodeBeamer reference: 7156)

Vessel Systems will provide the required cooling water specifications for all water cooled components within Vessel Systems scope to Process Systems per Interface S03000000-IST10004 (10).

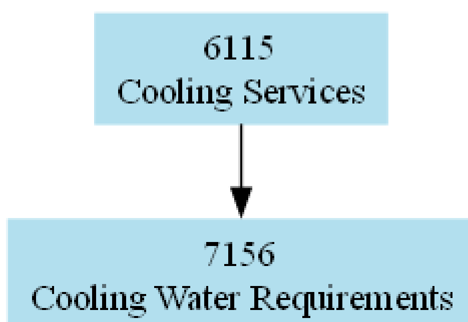


Figure 62: Requirement 7156 source and elaboration

Vessel Systems requires five cooled shield blocks as well as four water circuits to cool the CV beltline. Vessel Systems will calculate the required cooling water specifications needed for each water circuit and provide this data to Process Systems.

4.8.3 Target Water Line Support (CodeBeamer reference: 7159)

Vessel Systems will support target water line support assemblies on top of the Core Vessel lid per Interface Sheet S03000000-IST10004 (10).

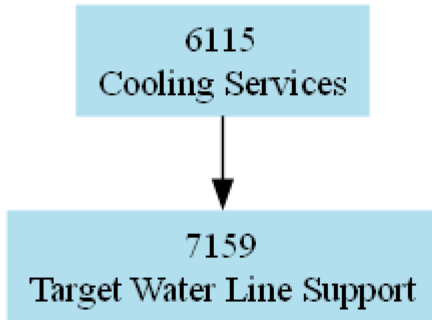


Figure 63: Requirement 7159 source and elaboration

The target assembly is supplied water via large supply and return lines that run near the roof of the target drive room. Process Systems will design pipe supports for the supply and return lines. Vessel Systems will provide the necessary mounting features in the CV lid to properly mount and secure the pipe supports.

4.8.4 Pressure Drop (CodeBeamer reference: 7187)

Vessel Systems water cooled components should have pressure drops less than 103.4 kPa (15 PSI) at 30.3 L/min (8 gpm) per cooling line.

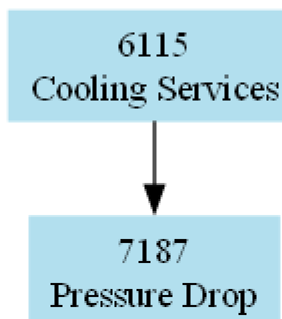


Figure 64: Requirement 7187 source and elaboration

The pressure drop in each water circuit supplied by Process Systems is a function of the internal water circuit in each shield block as well as the pipe routing within the CV. Process Systems can easily accommodate pressure drops up to 15 PSI without any modifications to the water supply system. Vessel Systems shall strive to keep all pressure drops below 15 PSI.

4.8.5 Water Boundary Pressure (CodeBeamer reference: 7188)

Vessel Systems water cooled components shall have a MAWP of 500 kPa.

Note: Pressure relief devices will be specified to ensure that the MAWP is not exceeded at the shield block locations.

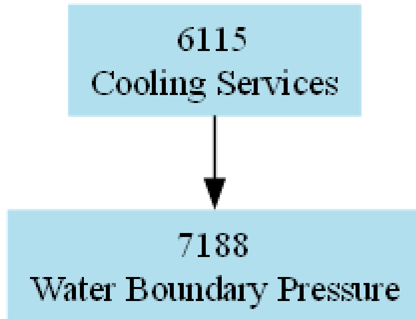


Figure 65: Requirement 7188 source and elaboration

Vessel Systems will ensure that all cooled components can be pressurized to 500 kPa without suffering pressure induced damage. Process Systems will provide a pressure relief solution that protects Vessel Systems cooled components from pressures above 500 kPa.

4.9 VS-REMOTE HANDLING INTERFACE

Requirements derived from Interface Sheet S03000000-IST10006 (11).

4.9.1 Removable Component Lifting Interfaces (CodeBeamer reference: 7162)

Vessel Systems shall provide lifting interfaces for all removable Vessel Systems components per Interface Sheet S03000000-IST10006 (11).

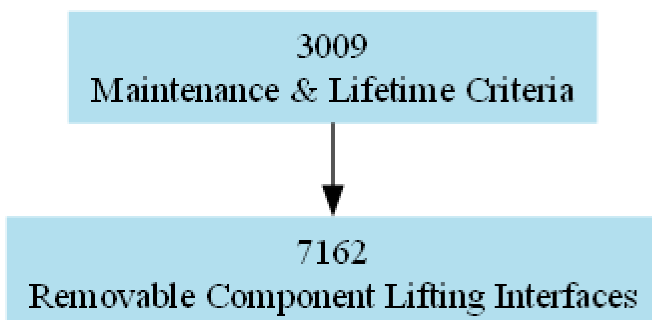


Figure 66: Requirement 7162 source and elaboration

A number of Vessel Systems components are designed to be removed to accommodate maintenance activities within the monolith. All removable components include lifting interfaces that allow removal of these components by the Remote Handling team. The method of lifting each component has been identified and the mass of removable components has been kept well below the lifting limit of the identified lifting device.

4.9.2 Gamma Gate Control (CodeBeamer reference: 7163)

Vessel Systems shall provide power and control requirements for the gamma gate linear actuator to Remote Handling per Interface Sheet S03000000-IST10006 (11).

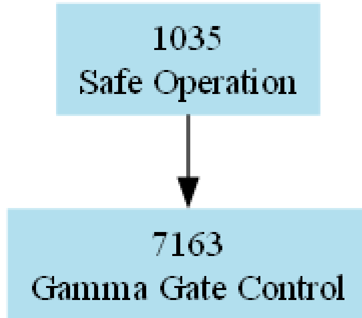


Figure 67: Requirement 7163 source and elaboration

High radiation inside the target drive room during target segment removal and installation limit personnel access inside the TDR. The gamma gate requires remote actuation during target segment removal and installation to reduce radiation levels and facilitate hands-on operations. The remote handling team already has several components within the TDR that require remote actuation. It has been decided that Remote Handling will work with the integrated controls team to manage the remote actuation portion of the gamma gate assembly.

4.10 VS-VACUUM SYSTEMS INTERFACE (CODEBEAMER REFERENCE: 7614)

Requirements derived from Interface Sheet S03000000-IST10008 (12).

4.10.1 Vacuum Pumping Performance (CodeBeamer reference: 7615)

The Core Vessel shall be capable of maintaining an operating pressure of $\leq$1 torr.

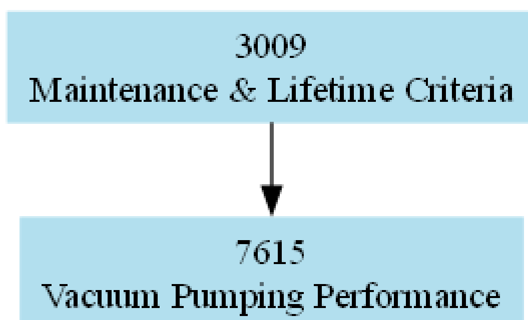


Figure 68: Requirement 7615 source and elaboration

The CV is being designed to run in rough vacuum or partial pressure helium. The design of the vessel must allow for the operation at less than or equal to 1 torr. This is accomplished through a combination of vessel design, seal design and internal component designs.

4.10.2 Operability with Water Leaks (CodeBeamer reference: 7617)

Vacuum Systems shall be able to operate with a small internal water leak per Interface Sheet S03000000-IST10008 (12).

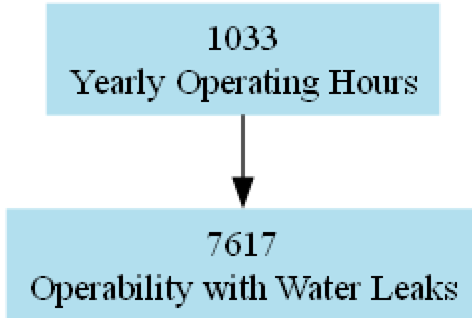


Figure 69: Requirement 7617 source and elaboration

Operational experience at FTS indicates a high likelihood of experiencing a water leak inside the CV from a water cooled component at some point. The combined designs of Vessel Systems and Vacuum Systems shall allow continued operation of the Target System in the event of a small water leak.

4.11 VS-INSTRUMENT SYSTEMS INTERFACE (CODEBEAMER REFERENCE: 7164)

Requirements derived from Interface Sheet S01020500-IST10025 [REF].

4.11.1 Monolith Insert Clearance (CodeBeamer reference: 7165)

Vessel Systems shall provide gaps between the monolith inserts and the Core Vessel technical components (nozzle extensions, Core Vessel beltline and Core Vessel internal shielding) per Interface Sheet S01020500-IST10025 (3).

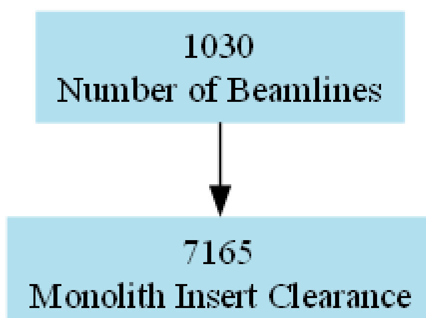


Figure 70: Requirement 7165 source and elaboration

Monolith inserts containing neutron guide optics are inserted through the CV nozzle extensions and in some cases into the CV. Vessel Systems must provide appropriate clearance around the monolith inserts such that they can be properly aligned and protected from mechanical damage. The size of the gaps in between the monolith inserts and VS hardware also has an impact on radiation streaming into the bunker and radiation induced heating of the monolith inserts, thus management of these gaps is of importance to the overall functionality of the system.

4.11.2 Monolith Insert Interfacing Component Tolerances (CodeBeamer reference: 7166)

Vessel Systems shall maintain dimensional tolerances of monolith insert interfacing components (nozzle extensions, Core Vessel beltline and Core Vessel internal shielding) per Interface Sheet S01020500-IST10025 (3).

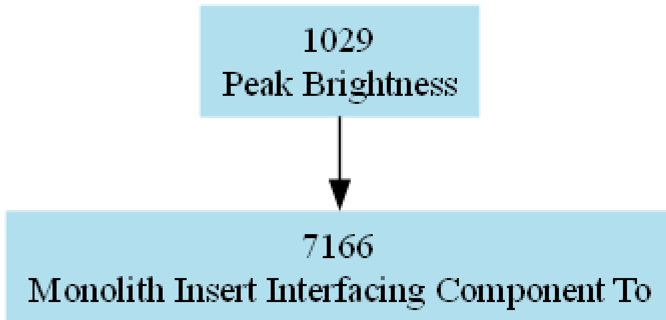


Figure 71: Requirement 7166 source and elaboration

The monolith insert for each beamline is supported off of VS hardware at both the upstream and downstream ends of the monolith insert. Proper alignment of the monolith inserts is critical to the performance of each neutron instrument. Management of the VS interface location tolerances are managed in the interface sheet.

4.11.3 Monolith Insert Sealing (CodeBeamer reference: 7167)

Vessel Systems shall provide a flanged sealing interface at the rear of each nozzle extension that corresponds to the Monolith Insert geometry per Interface Sheet S01020500-IST10025 (3).

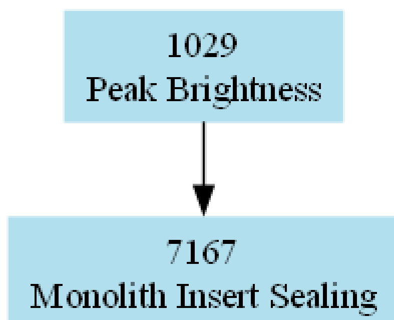


Figure 72: Requirement 7167 source and elaboration

Each monolith insert seals to the rear flange of its mating nozzle extension. Core vessel environment is carried in between the nozzle extension and monolith insert, and proper vacuum sealing is important to the overall functionality of the CV. Each monolith insert will contain a double vacuum seal, and VS will provide the appropriate sealing surface on the mating flange of the nozzle extensions per the interface sheet.

4.11.4 Monolith Insert Support (CodeBeamer reference: 7168)

Vessel Systems shall mechanically support the monolith inserts while maintaining the tolerances described in Interface Sheet S01020500-IST10025 (3).

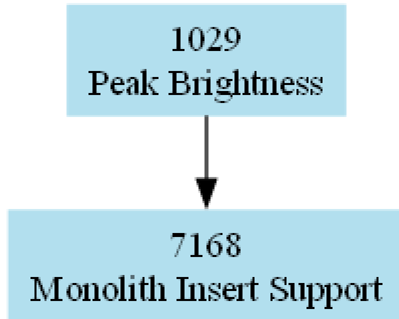


Figure 73: Requirement 7168 source and elaboration

The full weight of each monolith insert is supported by VS hardware. VS hardware must be able to accommodate the gravitational and seismic loads imparted by the monolith inserts while maintaining the tolerances specified in the interface sheet.

4.11.5 Monolith Insert Installation Support (CodeBeamer reference: 7169)

Vessel Systems shall support the Monolith Inserts during the installation process without plastic deformation per Interface Sheet S01020500-IST10025 (3).

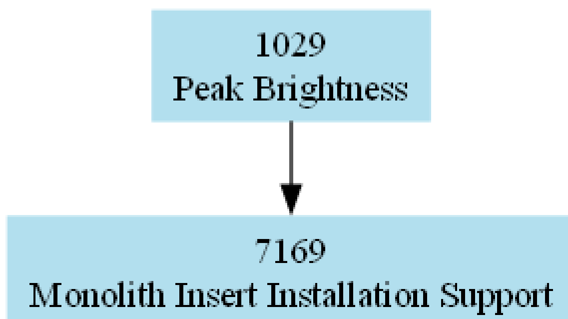


Figure 74: Requirement 7169 source and elaboration

Each monolith insert is installed radially from the instrument bunker into monolith. The monolith inserts will be installed via a cold handler that supports some of the monolith insert weight during installation. The remaining monolith insert weight is transferred to the nozzle extension via rollers integrated into the monolith insert. Vessel Systems must ensure that the monolith insert loading process does not damage the nozzle extensions via plastic deformation.

4.11.6 Neutron Flight Path to Monolith Inserts (CodeBeamer reference: 7170)

Vessel Systems shall provide clearance within the Core Vessel Shielding to ensure an unobstructed path between the monolith insert windows and the moderator per Interface Sheet S01020500-IST10025 (3).

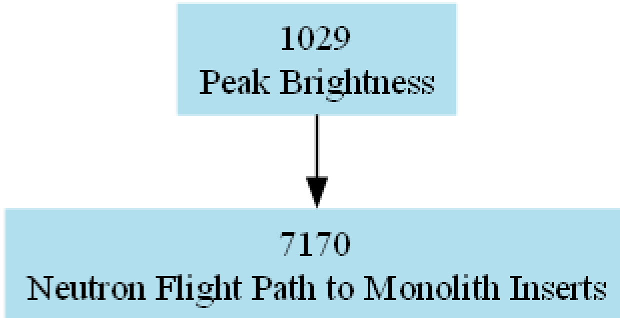


Figure 75: Requirement 7170 source and elaboration

Each monolith insert must have a clear line of sight between the start of the guide optics and the viewed face of the moderator to provide optimal neutron flux to each instrument. Vessel Systems will provide flight path holes through the CV shielding that provide this line of sight.

4.11.7 Monolith Insert Seal Leak Rate (CodeBeamer reference: 7171)

Vessel Systems shall accommodate the monolith insert rear seal leak rates specified in Interface Sheet S01020500-IST10025 (3).

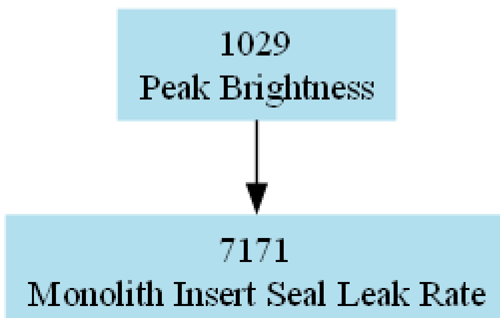


Figure 76: Requirement 7171 source and elaboration

Instrument Systems is responsible for the monolith insert seal design, and will provide an expected maximum leak rate of each monolith insert seal. Vessel Systems will use these leak rates to validate the overall CV and vacuum system design in collaboration with Vacuum Systems.

4.11.8 Monolith Insert Over Pressurization Protection (CodeBeamer reference: 7172)

Vessel Systems shall ensure that the monolith inserts are not subjected to a positive pressure greater than 7.35 PSIG per Interface Sheet S01020500-IST10025 (3).

Note: This is not currently captured in the interface sheet, but I suggested to Pete that he add it.

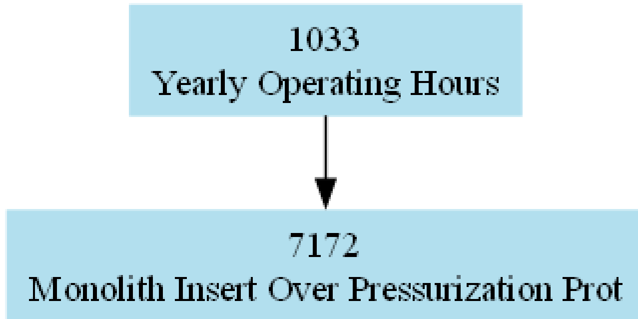


Figure 77: Requirement 7172 source and elaboration

The CV will be protected from over-pressurization via a pressure relief circuit and burst disc. The maximum internal pressure of the CV is currently being determined by the proton beam window, and is set at 7.35 PSIG. Instrument Systems must ensure that the monolith inserts are capable of seeing this positive pressure without failure of the front windows or other components within the monolith insert assemblies.

4.12 VS-INTEGRATED CONTROLS INTERFACE (CODEBEAMER REFERENCE: 7173)

Requirements derived from Interface Sheet S01020500-IST10128 (4).

4.12.1 Vessel Systems Temperature Monitoring (CodeBeamer reference: 7178)

Vessel Systems should include devices for monitoring the temperature of all cooled shield blocks as well as the cooled Core Vessel beltline per Interface Sheet S01020500-IST10128 (4).

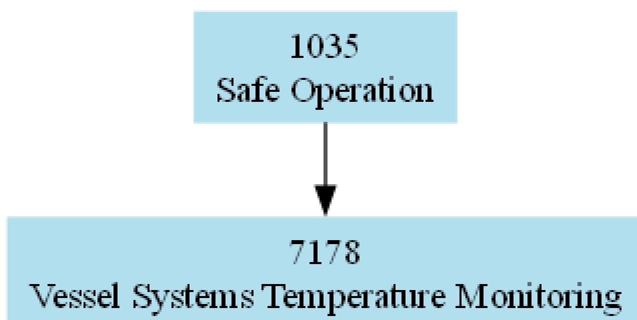


Figure 78: Requirement 7178 source and elaboration

Temperature monitoring of water cooled components is helpful during facility commissioning and during operations. Vessel Systems will incorporate thermocouples on all water cooled components to allow for temperature monitoring. These thermocouples will be wired to an electrical feedthrough at the top of the CV. These temperature monitors are intended to be informational only, and due to the difficulty of accessing them they will not be replaced if they cease to function.

4.12.2 Thermocouple Wiring (CodeBeamer reference: 7179)

Vessel Systems shall provide pin-out IDs for all temperature monitoring device connections to the hermetic feedthroughs per Interface Sheet S01020500-IST10128 (4).

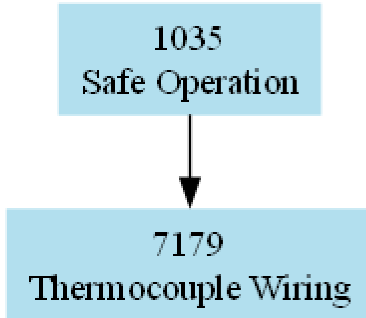


Figure 79: Requirement 7179 source and elaboration

Integrated controls is responsible for taking the thermocouple signals from the CV and routing them to monitoring hardware and eventually to the STS control room. Vessel Systems is responsible for the installation and internal wiring of the thermocouples within the CV. VS must provide pin-out details for the signal wire feedthroughs so that Integrated Controls can properly manage the signals.

4.12.3 Hermetic Electrical Feedthroughs (CodeBeamer reference: 7180)

Vessel Systems shall provide and install hermetic feedthroughs allowing thermocouple signal transfer out of the Core Vessel per Interface Sheet S01020500-IST10128 (4).

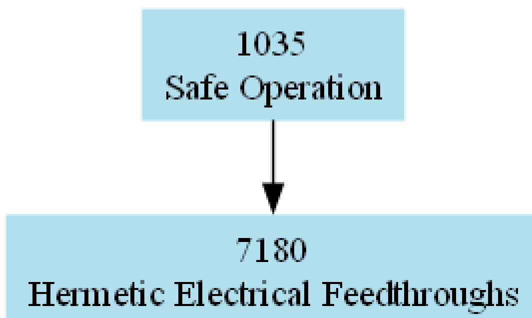


Figure 80: Requirement 7180 source and elaboration

Thermocouple signals will be passed through the side wall of the CV via hermetic feedthroughs. VS will install the hermetic feedthroughs, and provide the connection details to Integrated Controls. Integrated controls will connect to the exterior side of the hermetic feedthrough.

5. DESIGN

Vessel Systems is comprised of four subsystems; the CV assembly, the CV Shielding assembly, the Nozzle Extension assemblies, and the Gamma Gate assembly. The current configuration of these subsystems is shown in Figure 81 below.

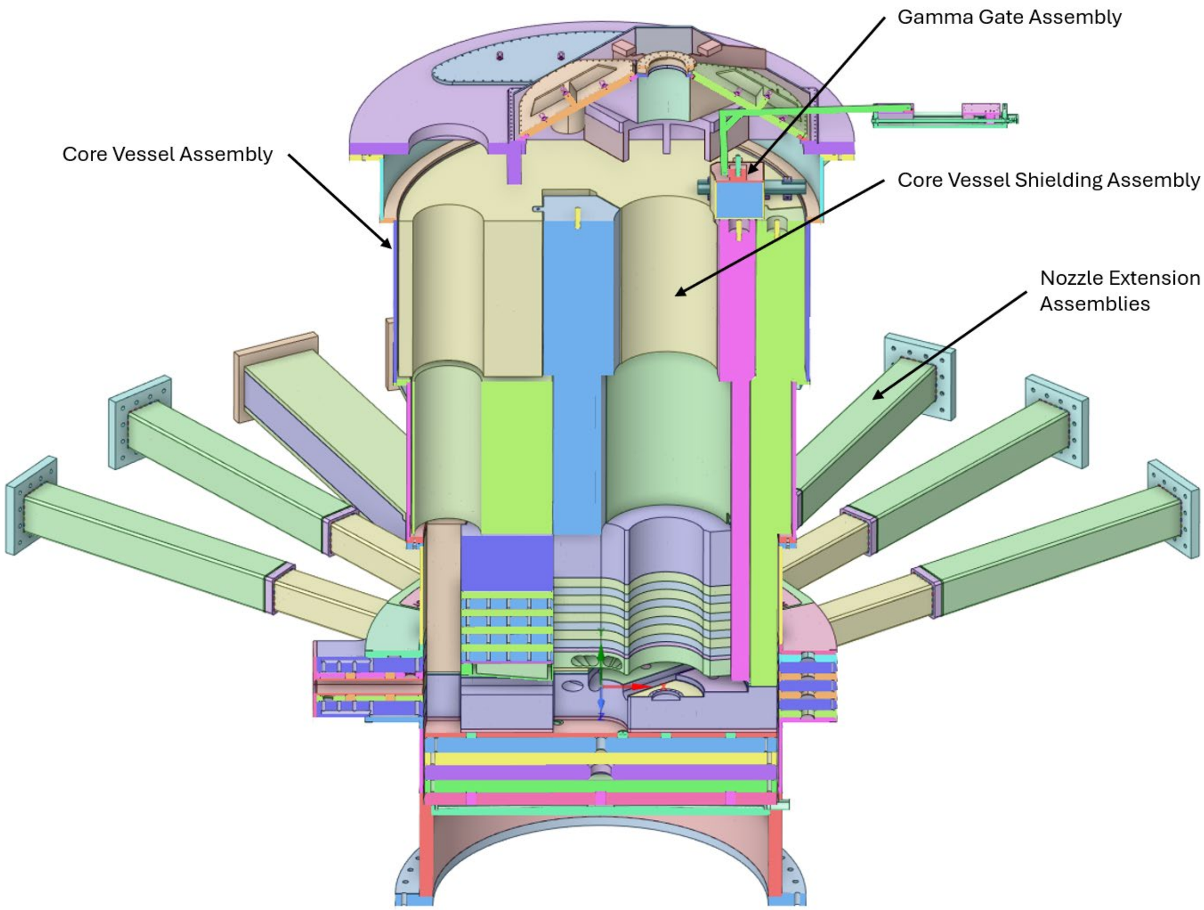


Figure 81: Cross-section view of Vessel Systems hardware

5.1 CORE VESSEL DESIGN AND ANALYSIS

The CV must provide an appropriate environment for neutron spallation to occur. In order to provide operational flexibility, the CV is being designed to operate in either a rough vacuum mode (1 mTorr) or partial pressure helium mode. Either operating mode is suitable for highly efficient neutron production, and it will be left to the operations team to decide which mode to operate in. The CV is also responsible for supporting all of the internal component mechanical loads, and providing accurate and stable landing zones for the target assembly, MRA assembly, TVP assembly and monolith insert assemblies. The CV assembly includes the CV weldment and the CV lid assembly. The general layout of the CV assembly is show in Figure 82 below.

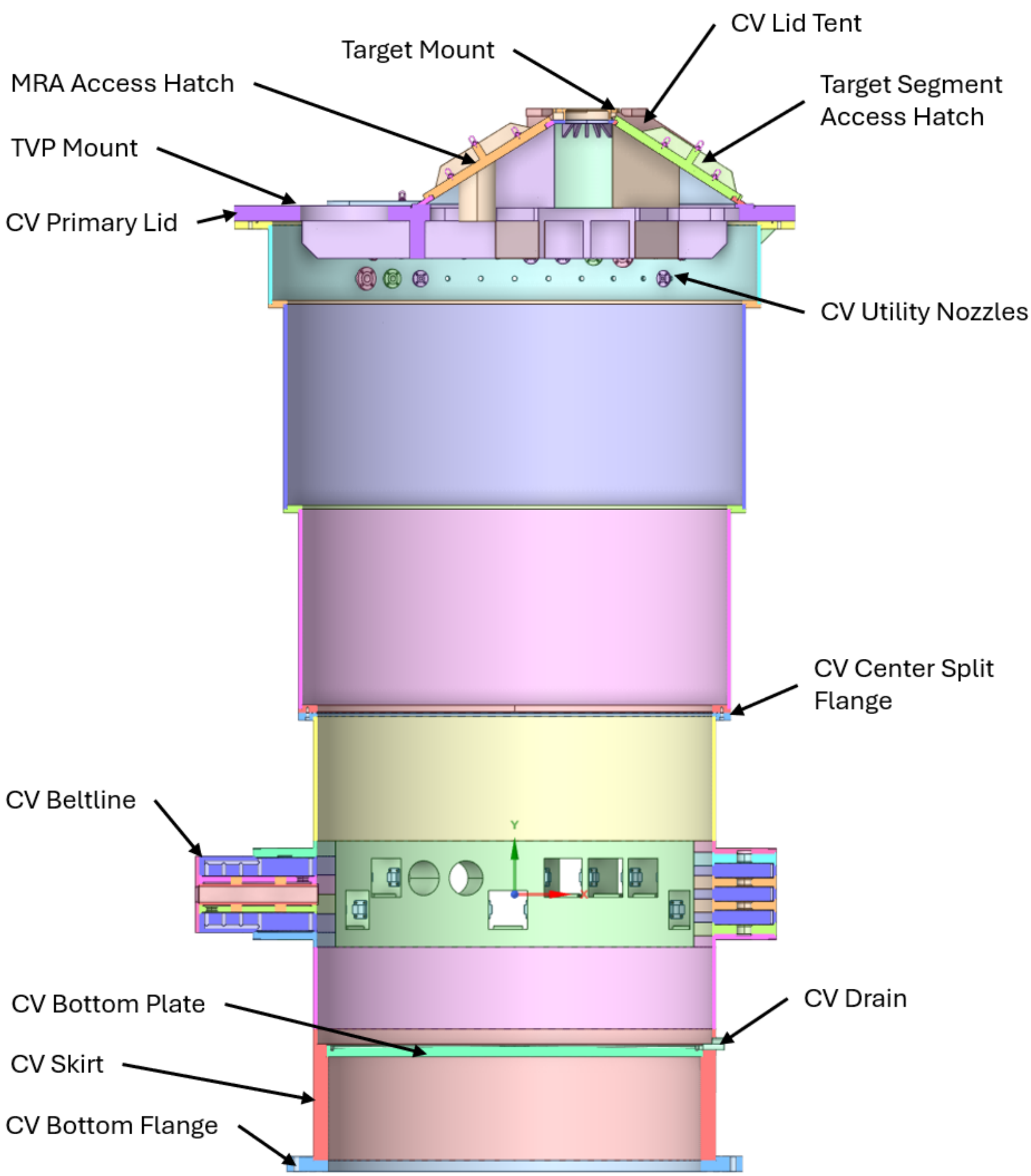


Figure 82: Cross section view showing the general layout of the Core Vessel

5.1.1 Core Vessel General Design

During conceptual design the CV was not round. It contained a protrusion in the direction upstream of the proton beam that allowed the vessel to incorporate the proton beam window within the CV (21). This design was referred to as the "keyhole" design. In the early stages of preliminary design, the PBW was moved outside of the CV, at which point a CV shape trade study was performed to determine if the CV should remain keyhole shaped or be changed to a round shape (22). The trade study found that a round CV design offered greater advantages than the keyhole design. The benefits of the round design were mostly focused on improved CV manufacturability, reliability and cost, at the expense of requiring a greater volume of CV internal shielding.

The overall shape of the CV has continued to be refined as its internal technical components have evolved. Efforts have been made to reduce the size and complexity of the CV wherever possible in order to improve its manufacturability and lower expected costs. The inside diameter of the CV has been chosen based on several key parameters. The horizontal center of the CV was set to the central location of the moderator to provide the greatest symmetry for nozzle extension and beamline integration. The lower vessel diameter of the CV has been reduced as much as possible without interfering with the TVP assembly. The overall height of the CV is driven by the CV shielding stack height. The current shield stack height was initially based on FTS shielding needs, and neutronics analysis has determined that a reduction in the shield stack height would have a detrimental effect on the high bay dose with beam on.

5.1.1.1 Core Vessel Utility Nozzle Design

The uppermost shell section of the CV resides above the CV shielding stack. This open space inside the CV is occupied by utility hard lines and jumper lines connecting all water cooled CV shielding, the cooled MRA, helium supply and return lines, and electrical cables for internal thermocouples. Structural ribs of the CV lid also protrude down into this space. A total of 44 utility nozzles are located on this uppermost shell, and provide pathways for water, helium and electrical connections to move from the pipe pan outside of the CV to the inner vacuum or helium space of the CV. Of the 44 utility nozzles, 23 feed water to cooled components, 3 are electrical feedthroughs for thermocouples, 2 are helium lines for running the CV in partial pressure helium mode, and the remaining 16 are spares. The detailed utility nozzle layout can be seen in document S03000000-IST10004 (10).

All of the water cooled CV shielding is considered permanent shielding, and will be field welded to the CV interior utility nozzles it order to minimize the number of flanged connections inside the CV. The six water cooling lines running to the MRA will be connected to flanged utility nozzles via utility jumper lines designed and procured as part of Vessel Systems scope. Each utility jumper line will contain a flexible portion to allow for easier fit up between the MRA flanged lines and the utility nozzles in the CV. The uppermost shell section will also include a large ventilation port that serves as the vacuum connection, emergency ventilation connection, and maintenance ventilation connection. The layout of the utility nozzles, hard line connections and utility jumpers can be seen in Figure 83 below.

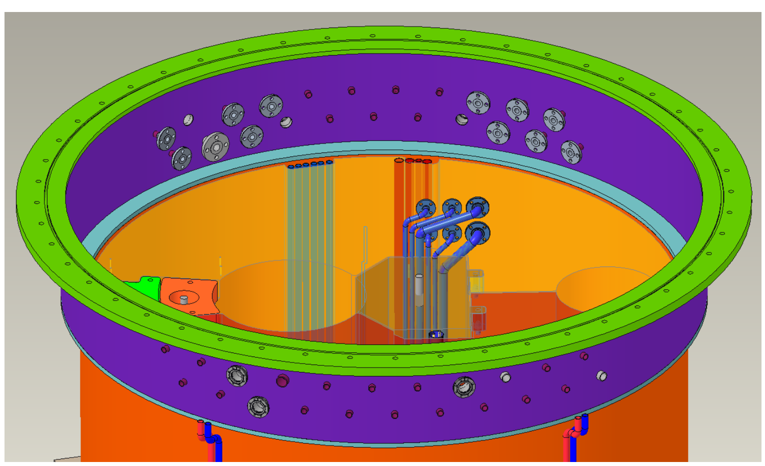


Figure 83: Placeholder figure for CV utility nozzles with jumper connections

5.1.1.2 Core Vessel Main Body Design

The main body of the CV consists of alternating shells and rings. The rings provide steps in the CV sidewalls that reduce radiation streaming from the lower portions of the CV. The rings provide two 100mm radial steps in the upper portion of the CV shell. A final 100mm radial step is found at the top of the CV that provides room for utility nozzle and flange connections at the top of the CV. The CV is split into two pieces at the lowest sidewall step location in order to allow the two CV halves to fit through the loading hatches the target and instrument building. Splitting the CV has the added benefits of improving the manufacturability of the CV and making the shipment of the CV from the vendor to ORNL more straight forward. An o-ring seal will be utilized during vendor vacuum and pressure testing. During the final installation of the CV in the monolith the two vessel halves will be bolted together without the o-ring and an interior circumferential weld will permanently vacuum seal the two halves together. The CV shell geometry can be seen in Figure 82 above.

5.1.1.3 Core Vessel Beltline Design

The CV beltline represents the most complex portion of the CV weldment. The proton beam as well as the 18 neutron beam ports all pass through the CV beltline. The Monolith Inserts containing the neutron guide optics (Instrument Systems scope, See S01020500-IS0025 (3)) pass through the beltline and are supported and aligned off of the CV beltline. Proper alignment of the guide optics relative to the moderator is critical, and because of this it is necessary to water cool the CV beltline in order to reduce thermal expansion of the lower portion of the CV.

The CV beltline is comprised of the north, south, east and west quadrants. The north and south quadrants contain the neutron guide ports that interface with the monolith inserts and nozzle extensions. The east quadrant serves as a backstop for a downstream radiation bloom from the proton beam, and the west quadrant contains the proton beam port and interfaces with the PBW shielding inflatable seal. Each quadrant is water cooled via a discrete water cooling circuit that runs up the outer wall of the CV into the pipe pan near the CV lid. A flood cooling approach is employed for all four quadrants, with the north and south quadrants designed as forged blocks with upper and lower manifolds. The East and West quadrants are currently designed using a series of stacked plates that are edge welded to contain the water cooling. These stacked plate designs will be redesigned in favor of a forged block design similar to the north and south quadrants during final design, as it is believed that this will provide a stronger and more reliable shielding design. The four beltline quadrants will be welded together, and then welded to the shell sections above and below them during CV fabrication.

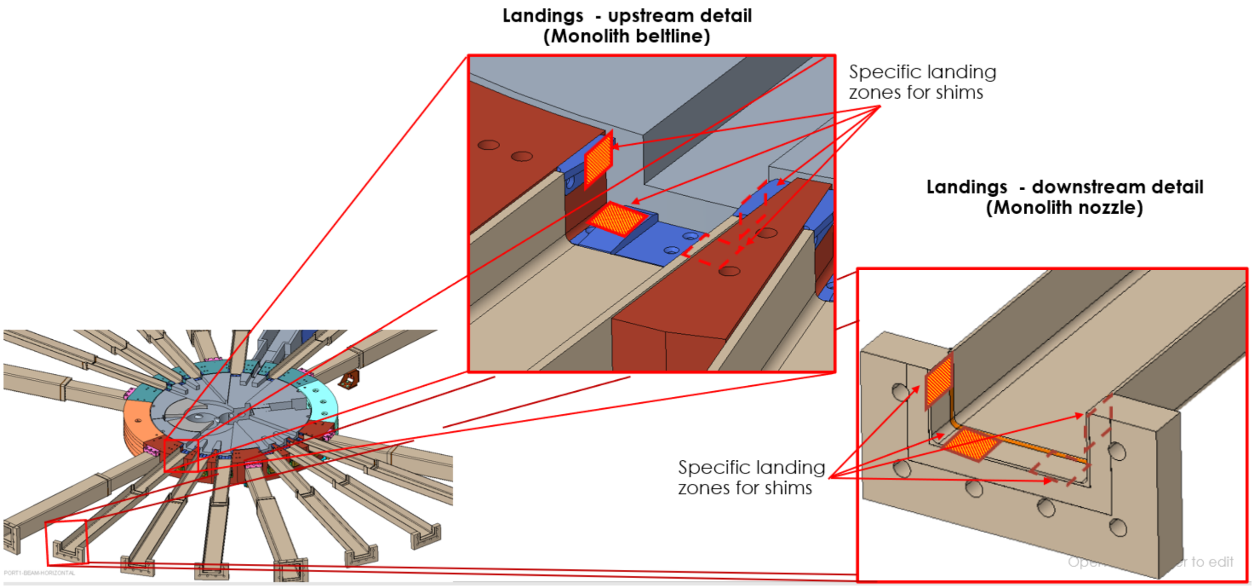


Figure 84: Views of the Vessel Systems / Instrument Systems interface between the CV beltline, nozzle extension and standard monolith inserts.

The 15 standard nozzle extensions extend into the CV beltline and are field welded to provide a vacuum seal. Inboard of these vacuum welds shim pads will be bolted in place on the bottom and sides of the beltline neutron extraction port openings. These shim pads are located such that the corresponding landing features on the Monolith Inserts will land on the shim pads, as shown in Figure 84 above. During CV installation the actual positions of these 15 ports will be determined, and the shim pads will be machined as necessary to position the Monolith Insert in their nominal positions. This allows for relaxation of the CV beltline neutron ports and provides flexibility to deal with minor manufacturing and installation errors.

5.1.1.4 Lower Core Vessel Design

The lower portion of the CV consists of the CV bottom flange, CV skirt shell, CV bottom plate and a vacuum shell section between the bottom plate and the CV beltline as seen in Figure 85 below. The CV bottom flange will bolt directly to the CV Baseplate (S.03.07 Target Station Shielding scope). The bolted flange will lock the position and alignment of the CV relative to the CV baseplate and will also secure the vessel in a seismic event. The CV skirt shell is constructed of much thicker material (100mm) than the CV shell and will vertically support the CV shielding stack on its top face. The CV bottom plate welds to the CV skirt and serves as a vacuum boundary and leak collection device. Grooves machined in the CV bottom plate route water to the CV drain port that exits the sidewall of the CV. There is a 10mm gap between the top of the CV bottom plate and the bottom of the CV shielding, and these two components are not expected to touch.

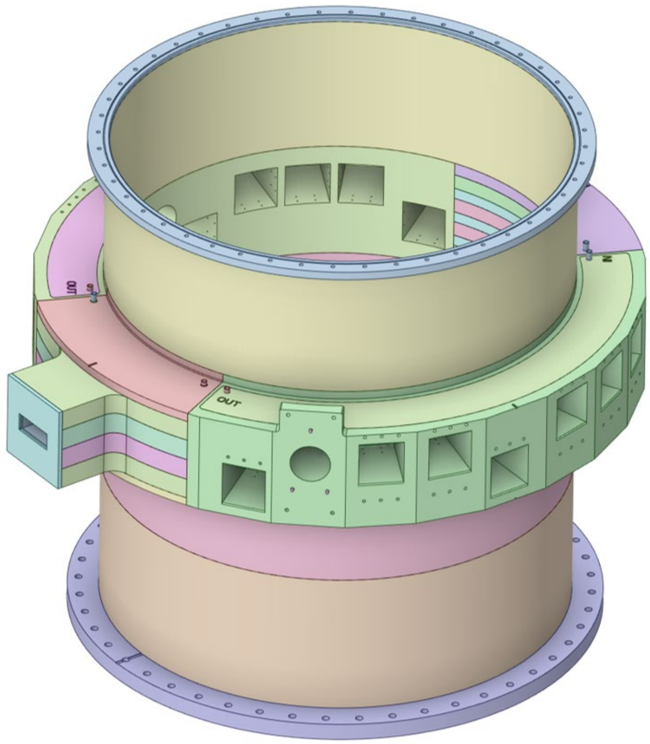


Figure 85: CAD image of lower CV weldment

5.1.2 Core Vessel Neutronics Analysis

A detailed Neutronics analysis was performed on the Core Vessel in 2023 to determine the amount of energy deposition and DPA damage that the CV experiences (23). This analysis produced point-cloud energy deposition data that was then used to perform thermal analysis of the CV. The CV design has continued to advance since this preliminary analysis was done, with most changes being minor and not expected to impact the predicted performance of the CV. One notable exception is a change to the beltline geometry where the beltline meets the PBW. A protrusion has been added to the beltline to act as a flat interfacing surface for the inflatable seal of the PBW assembly. A more recent Neutronics analysis incorporated these changes in the CV beltline into a PBW heating and DPA analysis (24). Neutronic energy deposition plots for the CV are show in Figure 86 below. A total of 1868 W of energy was predicted to be deposited into the CV by this Neutronics analysis. A new Neutronics analysis will be performed during final design once the CV geometry has fully stabilized.

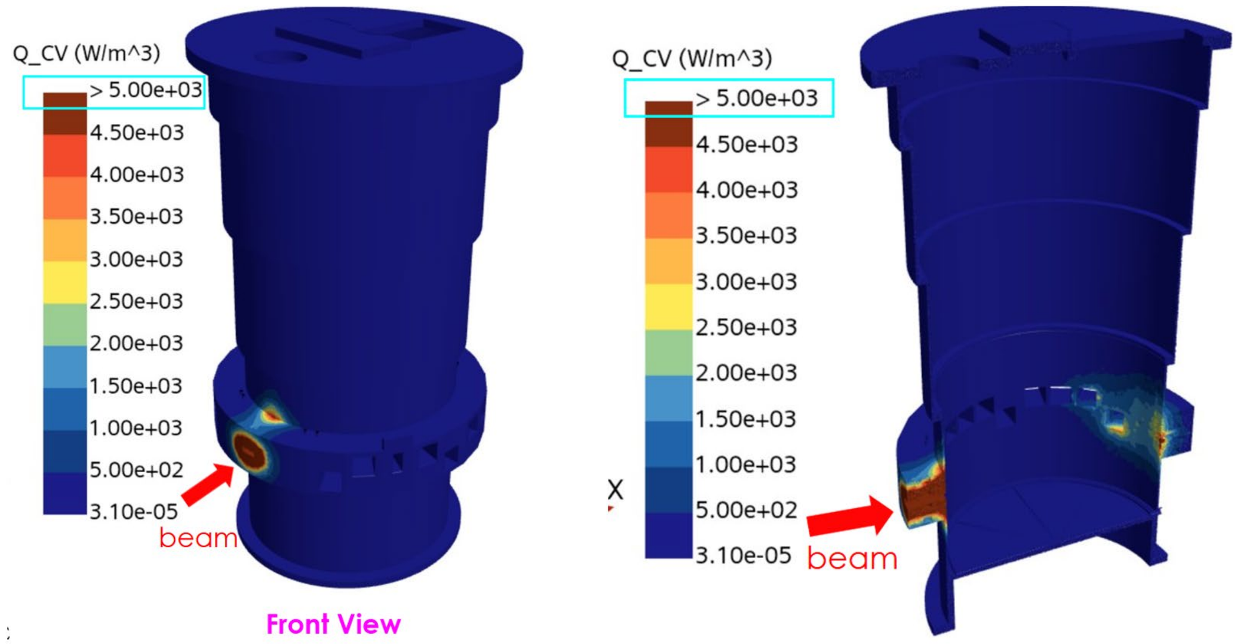


Figure 86: Neutronics point cloud energy deposition data applied to the CV geometry from late 2023.

5.1.3 Core Vessel Thermal Hydraulic Analysis

A detailed thermal hydraulic analysis was performed on the CV to determine peak stainless steel and water temperatures. The general requirement for the CV temperature is to keep the water temperature under 100C to avoid boiling of the water. However, a much better thermal profile is desired to minimize thermal expansion and stress levels within the CV (These metrics are evaluated in the structural analysis section). Computational fluid dynamics was utilized to determine the thermal performance of the CV under Neutronic heating loads. Figure 87 shows the temperature profile determined by the CFD analysis. As can be seen, the temperature profile of the CV is very well controlled around the beltline, with much of the beltline remaining near the cooling water inlet temperature of 32.2C. The peak temperature of the assembly was seen in the CV bottom plate and was 43C. A full description of the CFD analysis can be found in (25). The pressure drops in the cooling circuits were found to be well below the 10 PSI upper target. This analysis indicates that the current cooling design is performing well, and it is expected that the design changes implemented since this analysis was performed and those to be carried out during final design will not have a significant impact on the results.

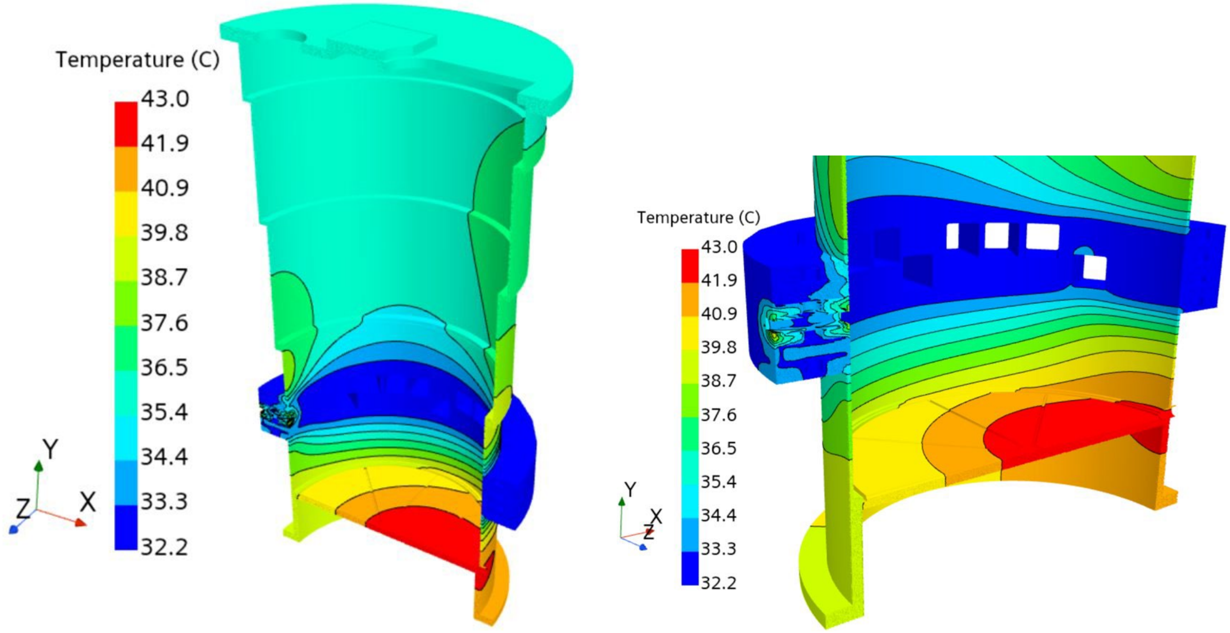


Figure 87: Results of CFD analysis of the CV Assembly

5.1.4 Core Vessel Structural Analysis

Following CFD analysis of the CV, a structural analysis was performed. Four load inputs were utilized in this analysis; thermal load based on the CFD analysis, gravity loading including CV shielding and the target assembly, pressure loading of the cooling circuits as well as the vacuum load on the CV when under full vacuum, and seismic loading. A static structural analysis was performed using Finite Element Analysis (FEA) to determine the stress levels of the CV assembly. Per ASME code the maximum allowable stress is 137 MPa. The FEA analysis showed localized stresses at single point sharp corners in the CV lid of 228 MPa, which exceeds the limit. Fillets will be added in these high stress areas and the mesh will be refined during a follow-up analysis. All other areas of the CV showed stress levels below 100 MPa, indicating that the current design is generally robust. A full summary of the FEA and results are presented in (26).

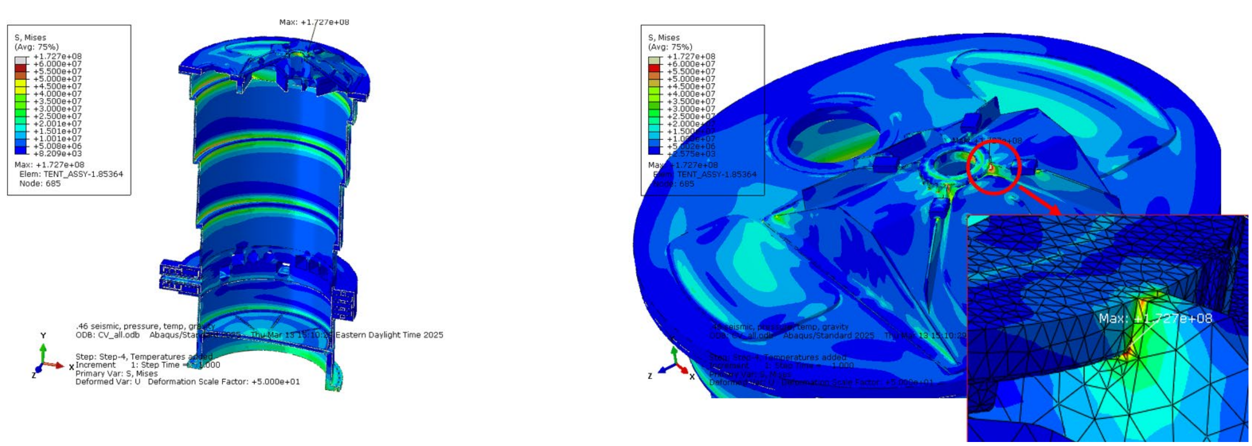


Figure 88: Von-Mises stress results of static structural FEA of the CV under combined operational and seismic loading

FEA of the same model was also utilized to determine the deflection profile of the CV. Understanding how much thermal expansion to expect in the CV weldment is critical in understanding how the target assembly will move relative to the MRA. The Target assembly is supported off of the top of the CV lid, therefore any thermal expansion experienced by the CV will be transferred to the Target assembly. Maximum deflections at the top of the CV are roughly 0.60 mm, with larger deflections observed in the target assembly. The results of this analysis are summarized in Figure 89 below and are fully detailed in (26).

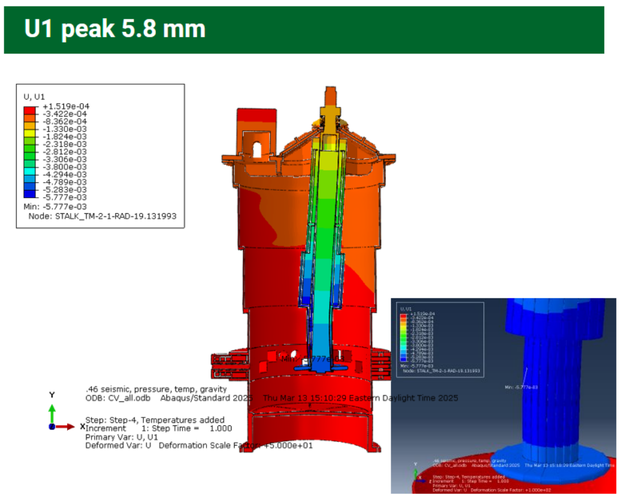


Figure 89: FEA analysis results of total CV deformation resulting from thermal, gravity, pressure and seismic loads

In the current design of the CV, the entire internal shielding stack rests on a relatively small area around the inside diameter of the CV. A structural analysis of this region of the CV was performed to determine if this design was acceptable from a stress and deflection standpoint. In this analysis, the full gravity load of the internal shielding stack and any supported technical components was applied to the bottom shield block that interfaces with the thick CV bottom skirt. Peak stresses were shown to be 25 MPa due to gravity loading only. When the vacuum load was applied to the CV, stress concentrations at the bottom of the CV bottom plate drainage groove were shown to be ~70 MPa, which can be seen in Figure 90 below. In both cases these stresses are well below the maximum allowable stress of 137 MPa per ASME Section VIII.

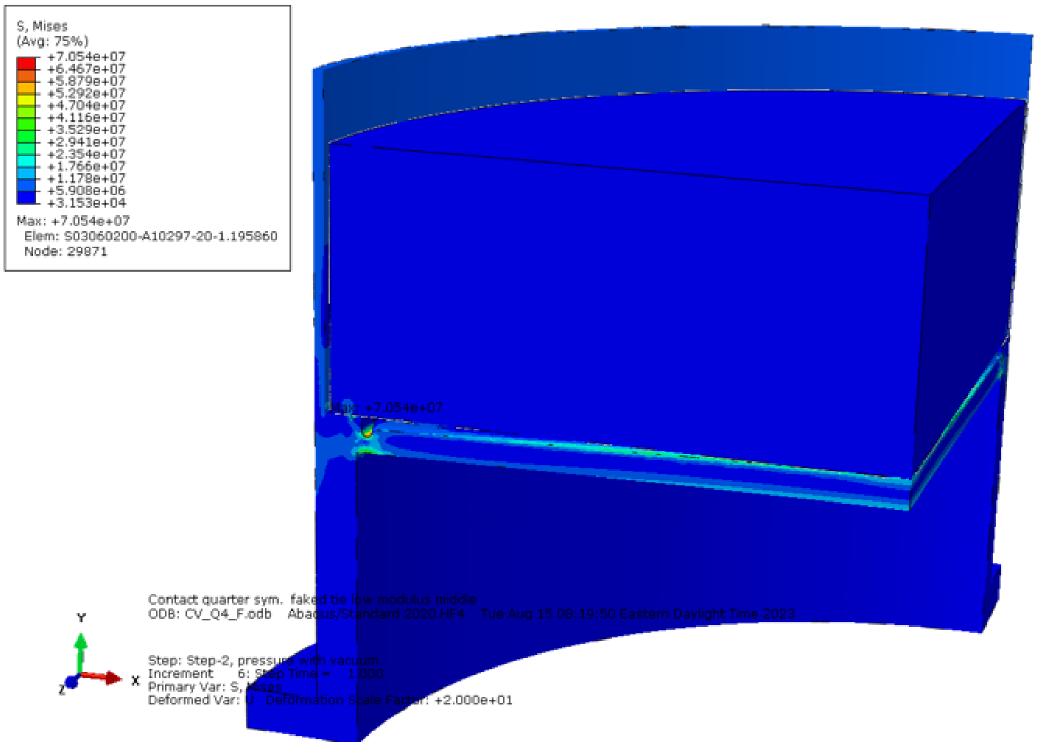


Figure 90: FEA results showing the stress profile of the CV where the CV shielding is supported

5.1.5 Core Vessel Manufacturing

The CV will be constructed from 316/316L stainless steel due to its excellent corrosion resistance and proven performance in high radiation environments. The main CV body is made from a variety of ring plates and rolled-and-welded shells. The beltline of the CV will be made from four water cooled quadrants that will be welded together to form the complete beltline section. The current beltline design consists of north and south forged sections with plenum covers. The east and west quadrants are currently a laminated plate design, however these quadrants will be redesigned in final design to incorporate a forged design. It has been found that forged cooled block design offers strength advantages under water pressure without sacrificing cooling performance. This added strength should improve the safety margin in the design and result in a more reliable CV design. The Vessel Systems manufacturing and fabrication strategy details all steps necessary to fabricate the Core Vessel assembly (27).

While not an explicit requirement of the CV, manufacturability of the CV was a key goal of the preliminary design. The CV is a large and complex weldment with challenging design requirements and a long lead time to fabricate. In order to optimize the manufacturability of the CV, an R&D manufacturing study was conducted. Two manufacturing firms capable of fabricating the CV were contracted to study the preliminary vessel design and provide feedback to improve manufacturability. The manufacturing firms also provided budgetary pricing based on the presented designs. The results of the manufacturing study are highlighted in (28). The resulting feedback from the manufacturing firms were incorporated into the CV design, and subsequent design changes have further sought to improve manufacturability where possible. Notable manufacturing improvements to the CV design include reducing both the height and outside diameter of the CV beltline, and replacing ramped landing zones in the beltline weldment with bolted landing pad inserts, allowing for tolerance relaxation in the neutron port regions of the CV beltline.

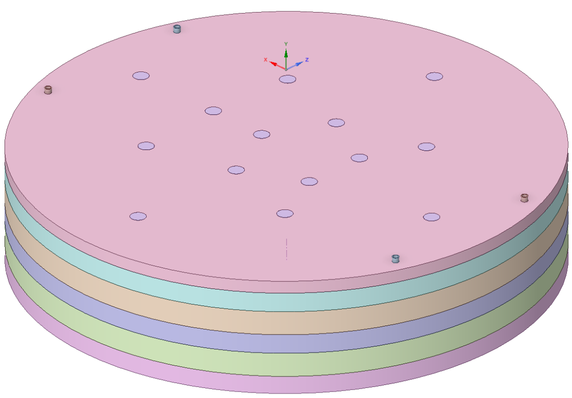
5.2 CORE VESSEL SHIELDING DESIGN AND ANALYSIS

The CV shielding has undergone a number of redesign efforts throughout preliminary design. Because the CV shielding must conform to the profile of all internal components within the CV as well as to the ID of the CV itself, any time a physical changes is made to the Target, MRA, TVP or CV the shielding models must be adjusted. In recent months the technical component designs have began to stabilize, allowing the CV shielding geometry to also stabilize.

A total of five layers of shielding reside within the CV. Nominal gaps of 10mm are maintained between individual shielding blocks and any adjacent component. Care has been taken in the design to place these gaps in such a way that gaps to not align unnecessarily and cause radiation streaming issues moving vertically up the CV. Piping galleries are formed in the shield stack to allow utility lines to travel throughout the shield stack.

5.2.1 Layer 1 Cooled Shield Block Design

CV Shielding layer 1 is comprised of a single puck shaped shield block with active water cooling. The remaining shielding blocks rest on this single layer 1 block, which is in turn supported on the rim of the CV skirt. The MRA is directly supported off of this shield block, thus thermal expansion and pressure induced shield block deflections need to be well managed. Water cooling is provided to the shield block via two 1'' SCH40 inlet pipes and two 1'' SCH40 outlet pipes. This shield block utilizes a flood cooled laminated plate design, where individual plates are layered and edge welded to create the complete shield block. A water plenum exists where each set of plates meet, and feeds alternating central and perimeter holes in order to cool the shield block. Columns are located between the thin top plate and the thicker plate second from the top to reduce plate deflection and stress due to water pressure. Figure 91 shows the laminated design on the left, and the water cooling passages on the right.



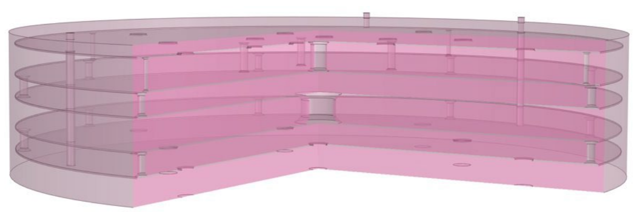


Figure 91: CAD renderings of Shield Block #1

5.2.1.1 Layer 1 Cooled Shield Block Neutronic Analysis

A detailed Neutronics analysis was performed on the Core Vessel Shielding in 2023 in order to determine the amount of energy deposition and DPA damage that the CV experiences (23). This analysis produced point-cloud energy deposition data that was then used to perform thermal analysis of the CV Shielding. Figure 92 shows the Neutronics energy deposition data applied to Shield Block #1, with a total energy deposition of 12.56 kw predicted. A new Neutronics analysis will be performed during final design once the CV Shielding geometry has fully stabilized.

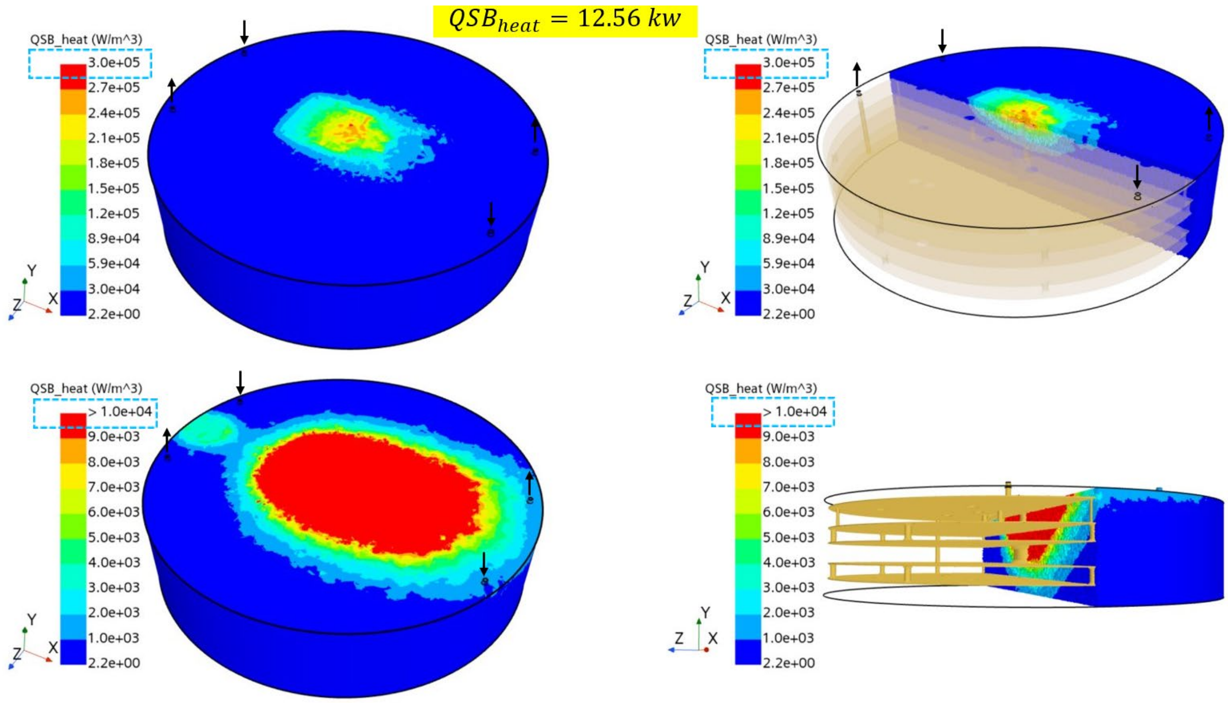


Figure 92: Neutronics point cloud energy deposition data applied to the CV Shield Block #1 geometry from late 2023.

5.2.1.2 Layer 1 Cooled Shield Block Thermal Hydraulic Analysis

A detailed thermal hydraulic analysis was performed on the CV Shield Block #1 to determine peak stainless steel and water temperatures. The general requirement for the shield block temperature is to keep the water temperature under 100C to avoid boiling of the water. However, a much better thermal profile is desired to minimize thermal expansion and stress levels within CV Shield Block #1 (These metrics are evaluated in the structural analysis section). Computational fluid dynamics was utilized to determine the thermal performance of the shield block under the Neutronic heating loads described above.

Figure 93 shows the temperature profile of both the stainless steel and the water determined by the CFD analysis. The peak stainless steel temperature was shown to be 71.4 C, while the peak water temperature was 66.1 C. These results meet the baseline requirements for temperature and were acceptable to move forward into structural analysis. The pressure drops in the cooling circuits were found to be well below the 10 PSI upper target. A full description of the CFD analysis can be found in (29).

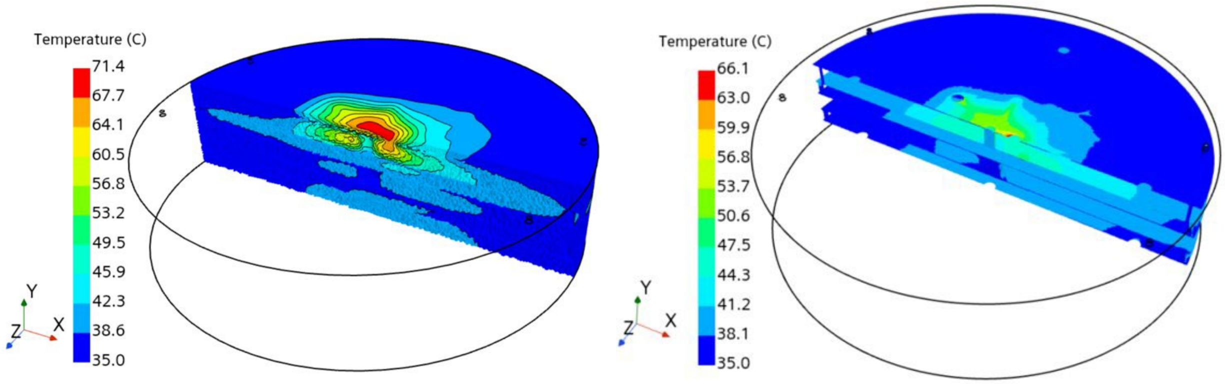


Figure 93: Results from CFD analysis of Shield Block #1 showing stainless steel temperature (left) and water temperature (right)

5.2.1.3 Layer 1 Cooled Shield Block Structural Analysis

Following CFD analysis of CV Shield Block #1, a structural analysis was performed. Three load inputs were utilized in this analysis; thermal load based on the CFD analysis, gravity loading, and pressure loading of the cooling circuits. A static structural analysis was performed using Finite Element Analysis (FEA) in ANSYS Mechanical to determine the stress levels of the shield block. Per ASME code the maximum allowable stress is 137 MPa. Figure 94 shows the resulting stress profile of the shield block. High stresses nearing 500 MPa are observed in the columns that are utilized in the design to tie the laminated shielding layers together. A number of refinements have been made to the existing design in order to mitigate these high localized stresses, but thus stress levels remain unacceptably high. Work is currently underway to design and analyze a forged shield block with thru holes and plenums that is expected to eliminate the high stresses observed in the laminated shield block design. A full summary of the FEA and results are presented in (29).

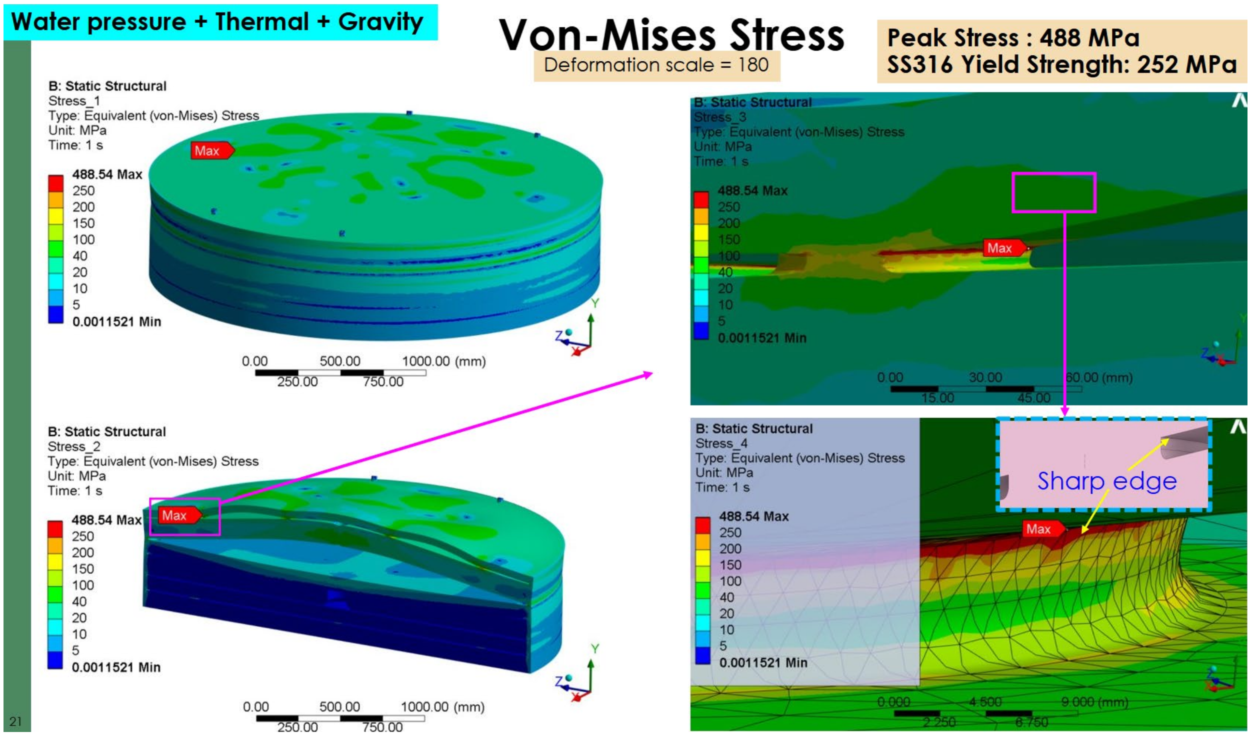


Figure 94: Von-Mises stress results of static structural FEA of CV Shield Block #1 under thermal, gravity and pressure loading

FEA of the same model was also utilized to determine the deflection profile of CV Shield Block #1. The maximum deformation of just over 1 mm was observed in the region directly below the MRA supports. We wish to improve this deflection figure as it will have a negative impact on MRA alignment. The new forged block design is expected to significantly reduce this deflection. The results of this analysis are summarized in Figure 95 below and fully detailed in (29).

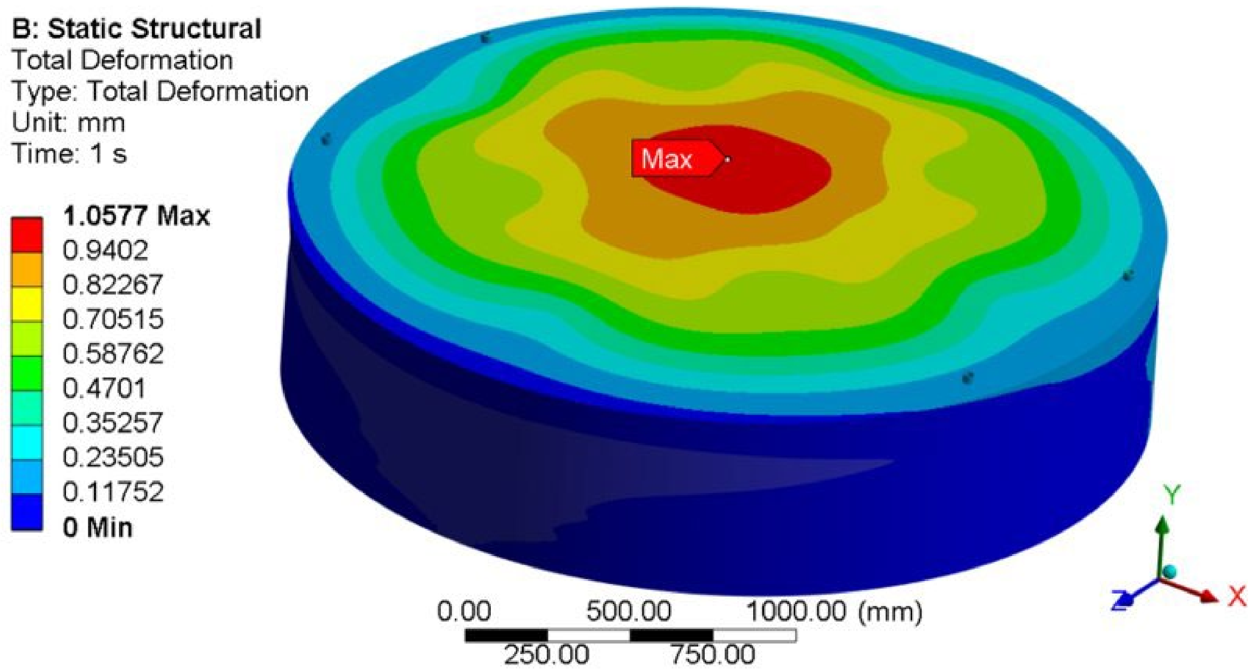


Figure 95: FEA analysis results of total CV Shield Block #1 deformation resulting from thermal, gravity and pressure loads

5.2.2 Layer 2 Cooled Shield Block Design

Layer 2 of the CV shielding consists of two shield blocks with a split line along the proton beam direction. These shield blocks contain neutron paths for the six lower beamlines, as well as a cutout for the MRA and Target. Due to their close proximity to the target and MRA, this shield block sees higher neutronics energy deposition than Layer 1 shielding. The two shield blocks are almost perfectly symmetrical, and analysis efforts during preliminary design have focused on Shield Block #3. Thermal and structural analysis is expected to be nearly identical between the two shield blocks.

Shield Block #3 consists of a main forging of 316/316L stainless steel that makes up the majority of the shield block. Large arrays of 8mm holes are gun drilled into the forging to creating cooling paths. Plenums connect small arrays of holes to allow for controlled parallel flow. Each layer 2 shield block is connected to three 1’’ SCH40 supply lines and a single 1.5’’ SCH40 return line. Three large radial holes pass through each block to allow neutrons from the MRA to reach the guide optics residing near the outside diameter of the shield block. The profile of the shield block provide clearance for the target wheel, MRA and proton beam. CAD renderings of Shield Block #3 are shown in Figure 96 below.

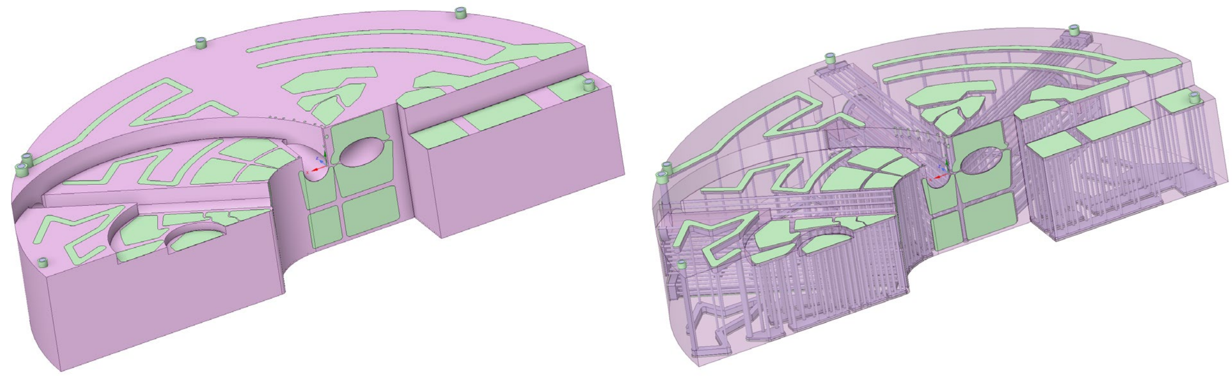


Figure 96: CAD model views of Shield Block #3 in solid form (left) and transparent form (right) showing the water circuits

5.2.2.1 Layer 2 Cooled Shield Block Neutronic Analysis

A detailed Neutronics analysis was performed on the Core Vessel Shielding in 2023 in order to determine the amount of energy deposition and DPA damage that the CV experiences (23). This analysis produced point-cloud energy deposition data that was then used to perform thermal analysis of the CV Shielding. Figure 97 shows the Neutronics energy deposition data applied to Shield Block #3, with a total energy deposition of 24.08 kW predicted. A new Neutronics analysis will be performed during final design once the CV Shielding geometry has fully stabilized.

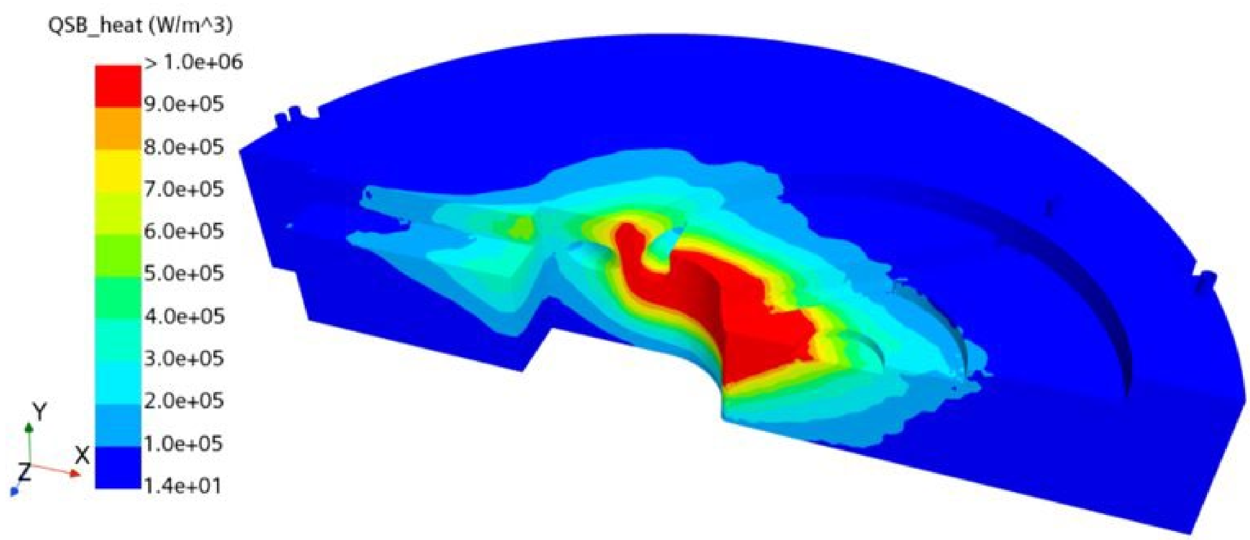


Figure 97: Neutronics point cloud energy deposition data applied to the CV Shield Block #3 geometry.

5.2.2.2 Layer 2 Cooled Shield Block Thermal Hydraulic Analysis

A detailed thermal hydraulic analysis was performed on the CV Shield Block #3 to determine peak stainless steel and water temperatures. The general requirement for the shield block temperature is to keep the water temperature under 100C to avoid boiling of the water. Computational fluid dynamics was utilized to determine the thermal performance of the shield block under the Neutronic heating loads described above.

Figure 98 shows the temperature profile of both the stainless steel and the water determined by the CFD analysis. The peak stainless steel temperature was shown to be 53.2 C, while the peak water temperature was 40.0 C. These results meet the baseline requirements for temperature and were acceptable to move forward into structural analysis. The pressure drops in the cooling circuits were found to be between 9-12 PSI. This pressure drop is higher than our target pressure of 10PSI for two out of the three circuits. Revisions to the flow path will be investigated as a method for reducing pressure drop while maintaining cooling performance. These thermal results are a significant improvement over previous designs including a stacked plate concept and a forged concepts with cooling slots instead of small holes. A full description of the CFD analysis can be found in (30).

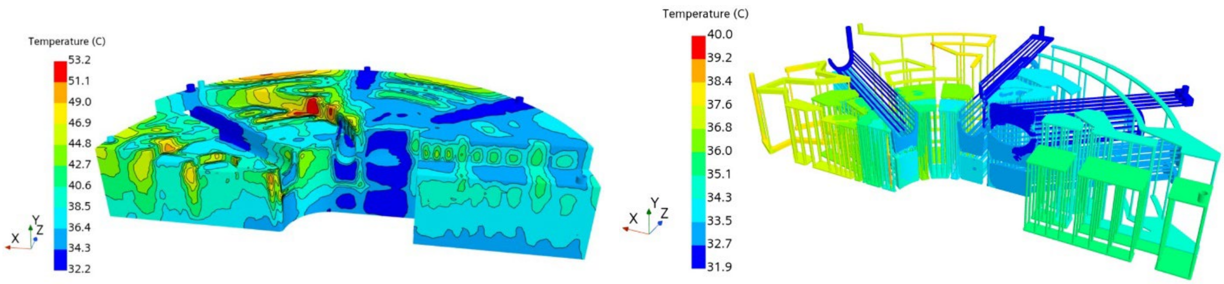


Figure 98: Results from CFD analysis of Shield Block #3 showing stainless steel temperature (left) and water temperature (right)

5.2.2.3 Layer 2 Cooled Shield Block Structural Analysis

Following CFD analysis of CV Shield Block #3, a structural analysis was performed. Three load inputs were utilized in this analysis; thermal load based on the CFD analysis, gravity loading, and pressure loading of the cooling circuits. A static structural analysis was performed using Finite Element Analysis (FEA) in ANSYS Mechanical to determine the stress levels of the shield block. Per ASME code the maximum allowable stress is 137 MPa. Figure 99 shows the resulting stress profile of the shield block. High stresses over 500 MPa are observed around several water plenum covers as well as at a sharp transition around the target wheel cutout. However, the majority of the shield block shows stresses below 80 MPa. Minor adjustments to the shield block and cover geometry will be made based on these results to mitigate these localized stresses. A full summary of the FEA and results are presented in (30).

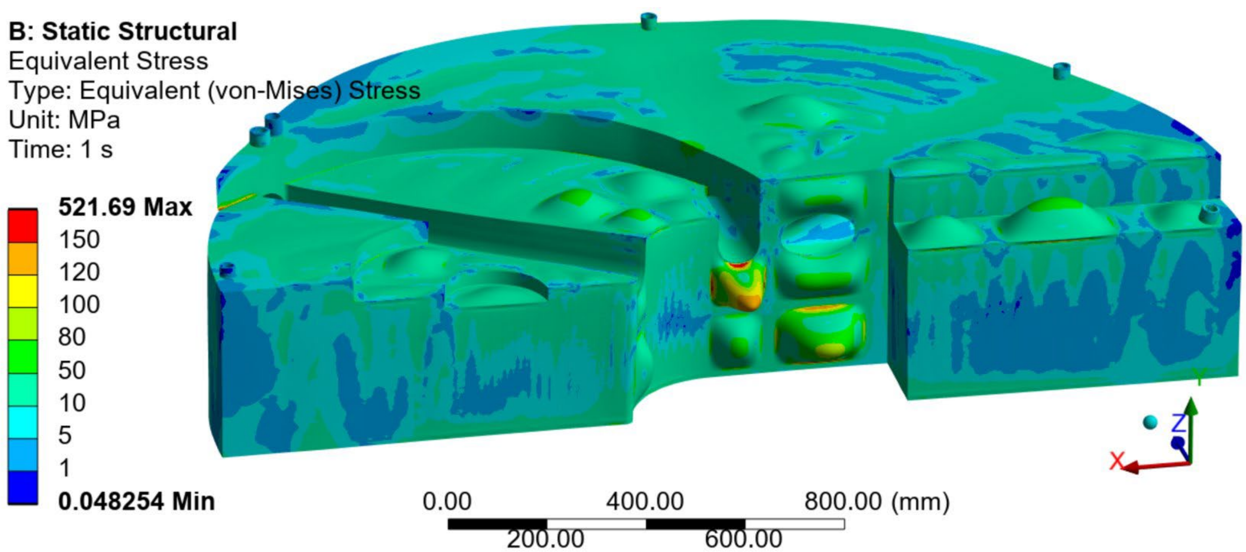


Figure 99: Von-Mises stress results of static structural FEA of CV Shield Block #3 under thermal, gravity and pressure loading

FEA of the same model was also utilized to determine the deflection profile of CV Shield Block #3. The maximum deformation of just over 0.276 mm was observed in one of the water plenum covers. While this amount of deflection is not problematic in this area, high stress levels around this cover will require minor redesign. It is anticipated that in addressing the stress concentrations this deflection will also be reduced. Overall deflection in the main body of the shield block was quite reasonable at <0.2 mm. The results of this analysis are summarized in Figure 100 below and fully detailed in (30).

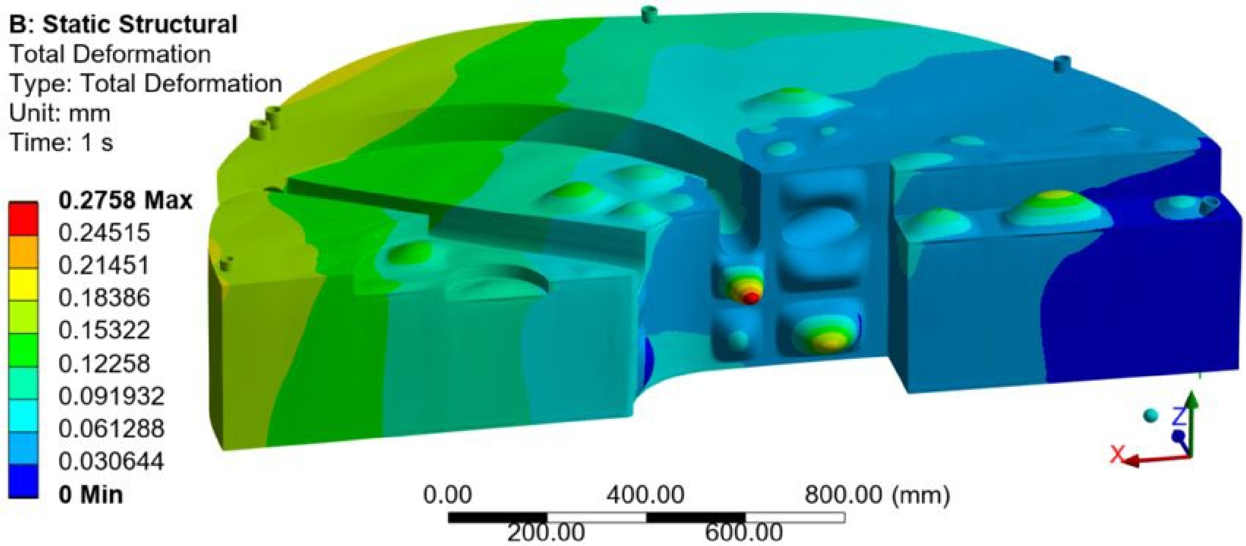


Figure 100: FEA analysis results of total CV Shield Block #3 deformation resulting from thermal, gravity and pressure loads

5.2.3 Layer 3 Cooled Shield Block Design

Layer 3 of the CV shielding consists of two shield blocks with a split line along the proton beam direction. These shield blocks contain neutron paths for the twelve upper beamlines, as well as a cutout for the Target and proton beam. The two shield blocks are almost perfectly symmetrical, and analysis efforts during preliminary design have focused on Shield Block #5. Thermal and structural analysis is expected to be nearly identical between the two shield blocks.

Shield Block #5 consists of a main forging of 316/316L stainless steel that makes up the majority of the water cooled portion of the shield block. The current design utilizes deep slots and large vertical holes to route water to the hot regions of the cooled shield block. Plenum plates at the top and bottom route the water to the slots and large vertical holes. An uncooled carbon steel section of the shield block assembly sits on top of the water cooled section, and will be secured in place with tie rods bolted to the cooled block section (Not shown in current design). Each layer 3 shield block is connected to two 1'' SCH40 supply lines and a single 1.5'' SCH40 return line. Six large radial holes pass through each block to allow neutrons from the MRA to reach the guide optics residing near the outside diameter of the shield block. The profile of the shield block provide clearance for the target wheel and proton beam. CAD renderings of Shield Block #3 are shown in Figure 101 below.

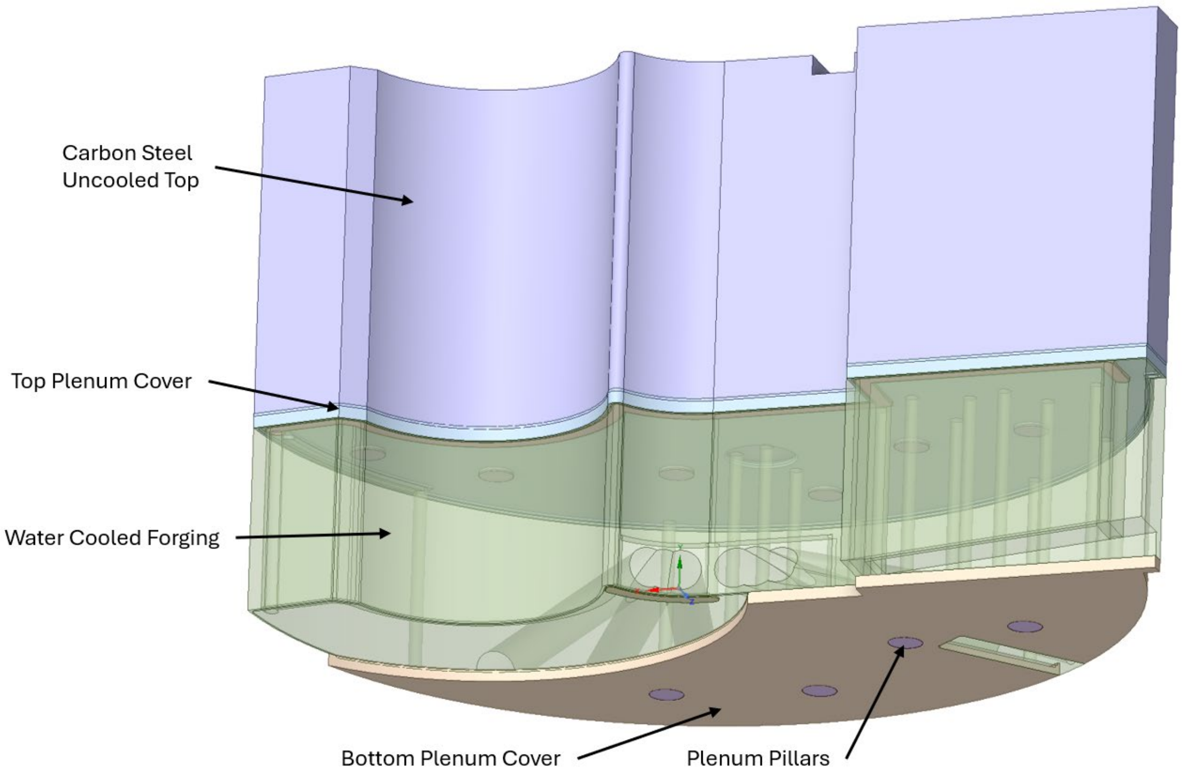


Figure 101: CAD model views of Shield Block #5

5.2.3.1 Layer 3 Cooled Shield Block Recent Changes and Future Efforts

The Layer 3 shield blocks have undergone significant recent changes in order to adapt to target design changes throughout 2024. Preliminary thermal and mechanical analyses were carried out in 2023, however the changes to the shielding design has rendered those analyses obsolete due to significant block shape changes. Significant recent changes include transitioning from a three block design to a two block design, reducing the outside diameter of the cooled shield block and replacing this portion of shielding with an uncooled outer ring, and significantly reducing the height of the water cooled block based on the findings of the MRA upper cooled shielding. This height reduction is reflected in the large carbon steel top portion of the current layer 3 shield design. Analysis efforts have focused on the more challenging layer 2 shielding, as the cooling solutions from these blocks will significantly influence the approach taken in the Layer 3 shield blocks. Based on the promising recent results of the gun drilled cooling approach employed on the layer 2 shield blocks, the layer 3 shielding will be redesigned to utilize this approach. Redesign of Shield Block #5 is already underway, and analysis is expected to commence at the beginning of final design.

5.2.4 Uncooled Permanent Core Vessel Shielding

Permanent uncooled CV shielding includes the two outer shield rings at layers 2 and 3 of the shield stack, as well as shielding layers 4 and 5. The uncooled outer ring of shielding was a recent change to the shield stack made to facilitate removal of a fully assembled target assembly. This would only be necessary in an off-normal condition where target rotation was not possible and removal of the entire target shaft with all target feet installed was required. In this event, the outer ring shielding can be removed, which allows the cooled shield blocks to be shifted towards the CV sidewall in order to clear the target shaft, then vertically removed.

All permanent shield blocks will be constructed of low-cost off-spec carbon steel similar to that used in the FTS. After fabrication the shield blocks will be nickel plated to improve their corrosion resistance. Carbon steel offers significant cost savings over stainless steel, and also has a significantly higher thermal conductivity which helps the uncooled shield blocks maintain reasonable temperatures.

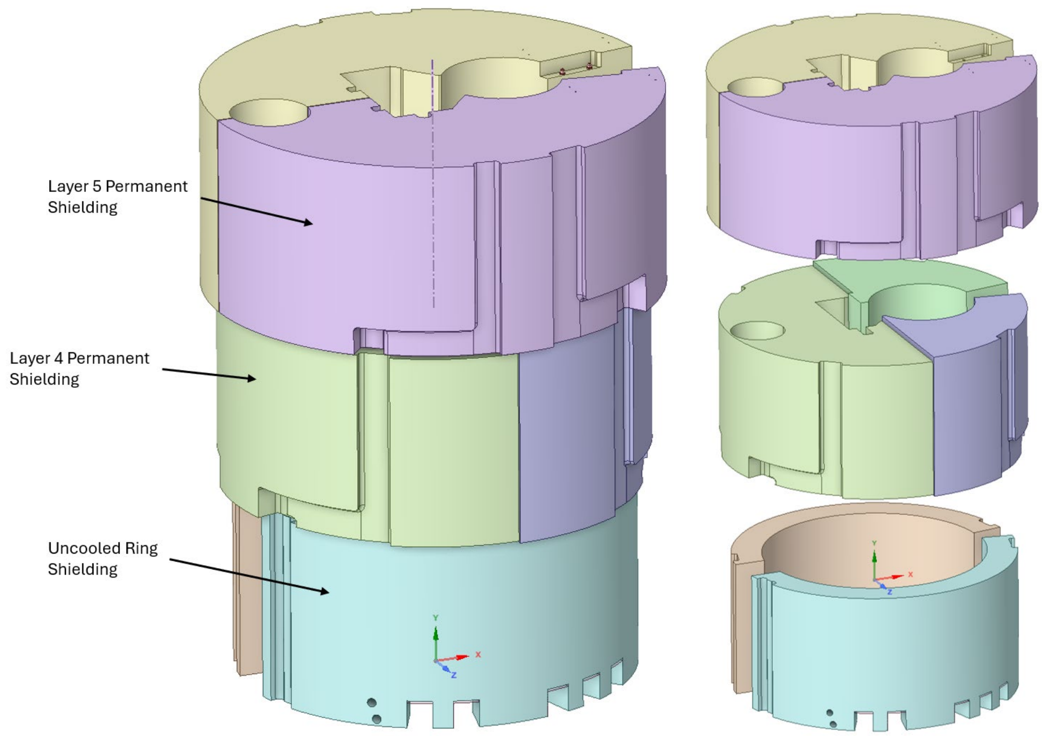


Figure 102: CAD renderings of the uncooled permanent shielding

5.2.4.1 Uncooled Shielding Analysis

A thermal and mechanical analysis of the uncooled ring shielding was recently performed in order to determine if this was an acceptable solution. Each half of the outer ring is broken up into two separate blocks. This allows removal of the upper block section without needing to remove the monolith inserts that reside inside the square cutouts in the ring shielding. Neutronics heating was applied to the ring shielding, and the resulting temperature rise and stresses were determined via FEA. Thermal contact resistance was taken into account, as was the temperature of Shield Block #1 in the region in which the ring shielding was resting. A peak stress of just over 120 MPa was observed in the sharp corners of the monolith insert square ports, with the majority of the shield blocks well below 100 MPa. A maximum deflection of just over 0.8 mm was observed due to thermal effects. A peak temperature of just below 70 C was observed. Based on these results, utilizing uncooled shielding in this region of the CV is acceptable. A summary of results is shown in Figure 103 and Figure 104 below, and are described in detail in (31).

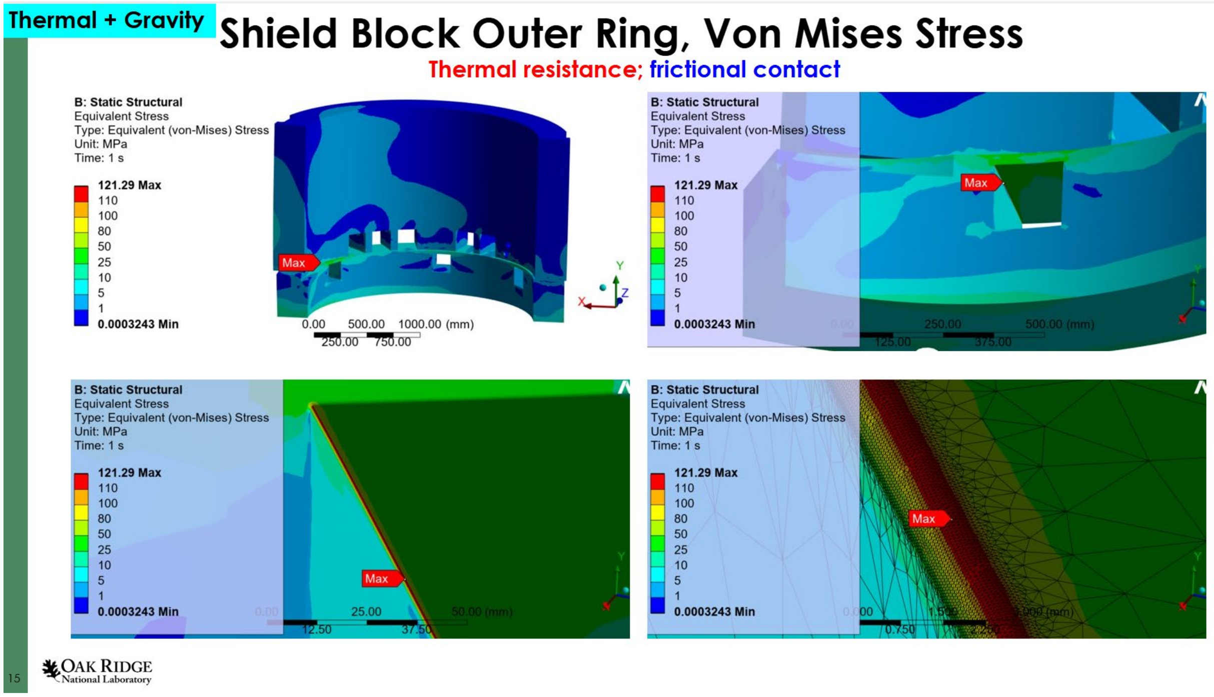


Figure 103: Ring Shielding FEA stress analysis including thermal and gravity effects

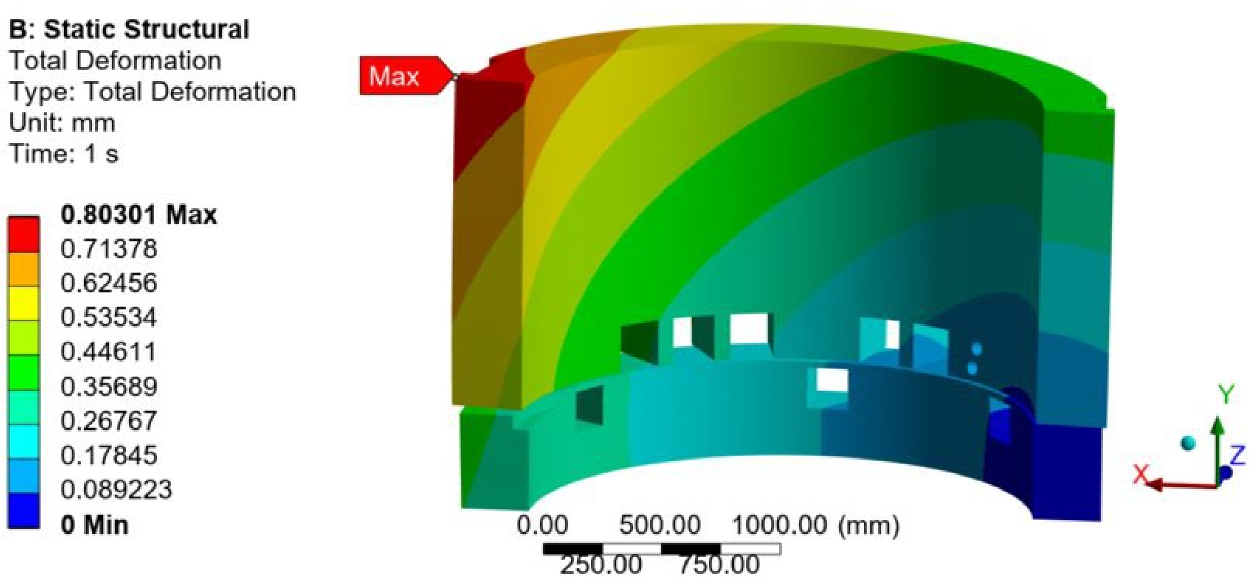


Figure 104: Ring Shielding FEA deformation analysis including thermal and gravity effects

Thermal analysis of the entire permanent uncooled shielding stack was performed to understand how heat flows out of the uncooled shielding and into the cooled shielding. Thermal contact resistance between mating surfaces of the uncooled shielding was applied to model the thermal circuit. At surfaces mating with cooled shielding, a constant temperature boundary condition was applied. The effects of free convective cooling from non-mating surfaces of the shielding were assumed to be zero due to the rough vacuum environment of the core vessel. Neutronics heating was applied to the uncooled shielding assembly and the result temperature rise was determined via FEA. A summary of results is shown in Figure 105, and are described in detail in (32).

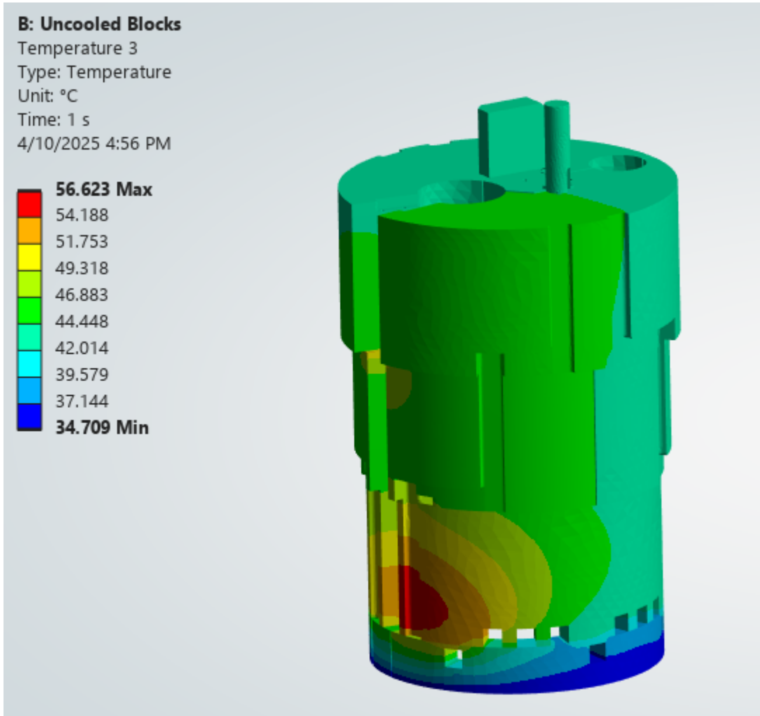


Figure 105:Premenant Uncooled Vessel Shielding Thermal Results

5.2.5 Uncooled Removable Core Vessel Shielding Analysis

There are currently three removable CV shielding blocks, two that allow access to the target segments and one that allows access to the MRA. These shield blocks are supported at their intermediate steps, and are aligned via pins in the permanent shielding that extend through holes in the removable shielding. Each shield block will have a zip lift stud that interfaces with remote handling lifting fixtures to allow for remote removal and installation of these shield blocks. Only the smaller of the target removable shield blocks needs to be removed to facilitate target segment removal and installation. The second removable shield block will not be removed under normal operations but may be removed to provide space for target diagnostics that may be designed and implemented later. The layout of the removable shield blocks is shown in Figure 106 below.

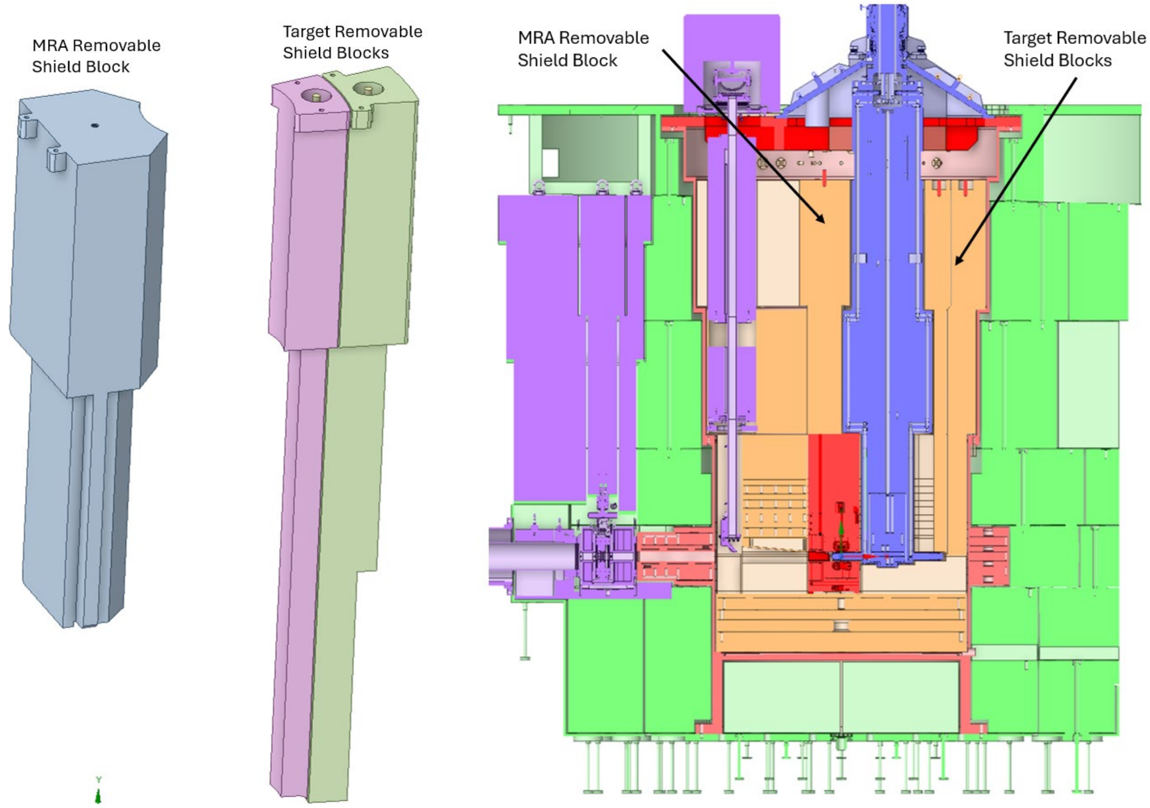


Figure 106: CAD images of the removable shield blocks in isolation (left) and in the monolith assembly (Right)

5.2.5.1 Target Removable Shield Block Analysis

Initial designs of the target removable shield block were not split into two blocks, but rather were a single block that was removed in order to exchange a target segment. This block was also assumed to require water cooling, however analysis of surrounding shield blocks indicated that active cooling might not be necessary. To determine if an uncooled shield block design would be acceptable, a steady state thermal analysis was performed. Peak block temperatures near the target foot were found to reach just under 108 C, with stress levels around 54 MPa and deflections of less than 0.002 mm. These results indicated that this shield block does not require water cooling, which removes cost and complexity from this shield block and also makes it possible to split the block into two separate shield blocks. Recent incorporation of the CV Gamma Gate required splitting of this block into two separate blocks. Splitting up this shield block allows for vertical targe segment removal while leaving as much shielding as possible in place to reduce radiation dose rates during maintenance activities. An initial thermal analysis of the split block design shows a significant increase in the smaller upstream shield block as it absorbs the majority of the neutron energy. A further design effort will be undertaken during final design to improve the passive cooling of this shield block. A summary of results is shown in Figure 107 below and are described in detail in (32).

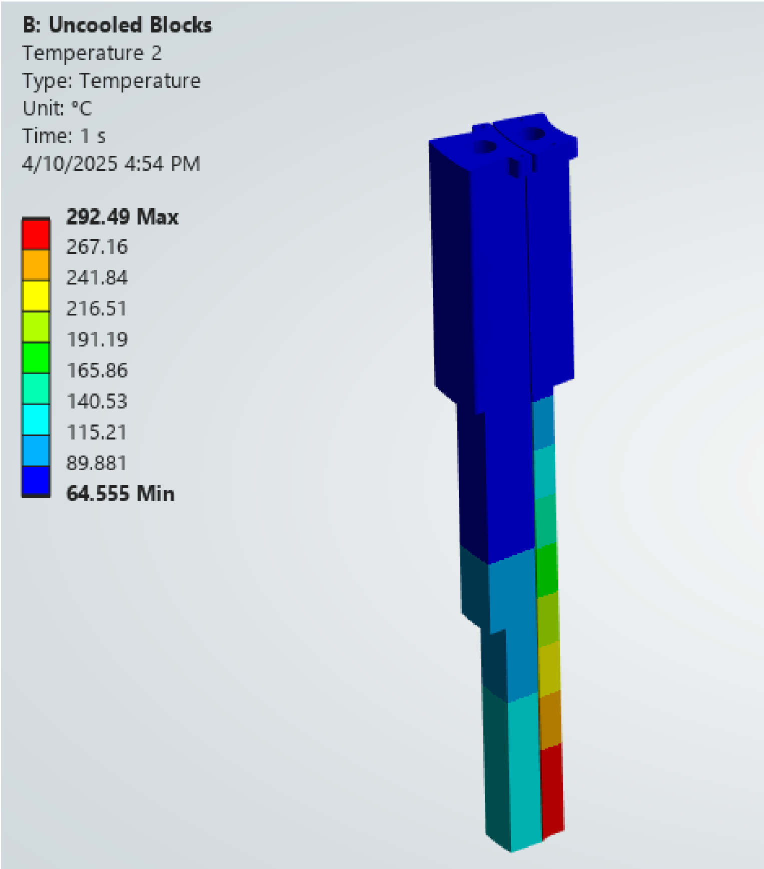


Figure 107: Thermal results from FEA analysis of target removable shield blocks

5.2.6 Core Vessel Shielding Manufacturing

The cooled CV shielding will be constructed from 316/316L stainless steel due to its excellent corrosion resistance and proven performance in high radiation environments. All three layers of cooled shielding will be constructed from larger forgings with gun drilled cooling hole arrays and machined water plenums capped with welded covers. It has been found that forged cooled block design offers strength advantages under water pressure without sacrificing cooling performance. This added strength should improve the safety margin in the design and result in a more reliable CV shielding design. Uncooled CV shielding will be constructed from carbon steel with a nickel plating added for corrosion protection. The Vessel Systems manufacturing and fabrication strategy details all steps necessary to fabricate the CV Shielding (27).

5.3 NOZZLE EXTENSION ASSEMBLY DESIGN AND ANALYSIS

The Nozzle Extension assemblies mount to the faceted outside faces of the CV beltline and extend radially outward through the target station shielding and monolith concrete to the outside face of the monolith. There are three types of nozzle extensions that correspond to the three types of monolith inserts designed by Instrument Systems. The nozzle extensions are seal welded to the CV beltline to provide a vacuum seal, and the core vessel environment is maintained inside the nozzle extensions up to vacuum seals on the outboard flanges of the nozzle extensions where they mate with the monolith inserts. Each nozzle extension type is unique in design, and the details of each are described in this section.

5.3.1 Standard Nozzle Extension Assembly General Design

The standard nozzle extension serve both the standard length and extra length monolith inserts, and there are 15 total in the current design. Standard length inserts are utilized on all standard inserts looking at the upper moderator, as well as the two downstream inserts looking at the lower moderator. The monolith insert profiles are identical through the nozzle extension, allowing a single design to be utilized. The latest design of the standard nozzle extension utilizes commercial off the shelf (COTS) stainless steel square tubing for the main body, with machined transition and rear flanges and mounting bars to attach to the CV beltline. Earlier versions of the nozzle extension were constructed of welded plates, and changing to the square tubing allows for significant cost savings. The nozzle extension is welded together to provide a vacuum tight seal, as the CV environment is carried through the inside of the nozzle extensions.

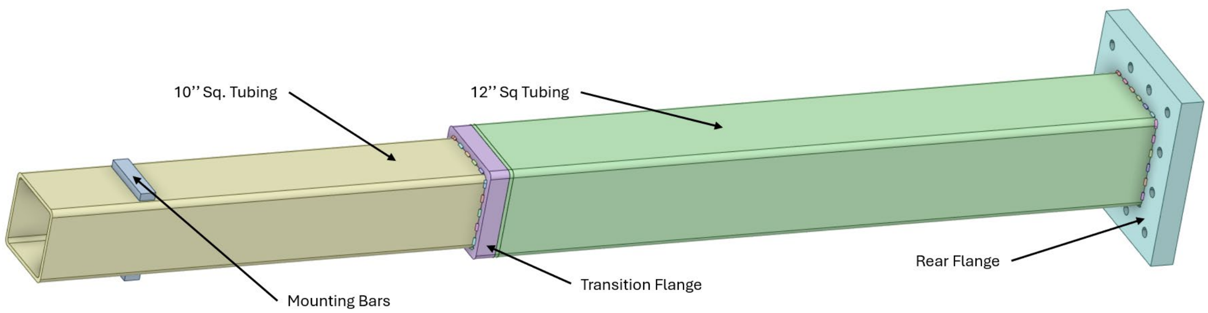


Figure 108: Standard nozzle extension geometry and part layout

The standard nozzle extension is attached to the CV via two mounting bars. The mounting bars to not extend past the larger 12'' square tubing outer profile in order to minimize the gaps between the nozzle extensions and the monolith ports cast into the monolith concrete. Machined brackets mounted to the CV beltline align the bracket and secure it to the CV beltline. The upper brackets are shared between upper and lower moderator nozzles, but the bottom brackets are different due to the beltline geometry. The rear flange of each nozzle extension is supported horizontally and vertically via jacking screws mounted to the bunker side of the monolith port weldments. The nozzle extensions are not constrained axially in order to allow for small amounts of thermal deflection to take place without inducing high stress levels in the nozzle extensions. The front of each nozzle extension is seal welded to the CV beltline to provide a vacuum seal and preserve the CV environment.

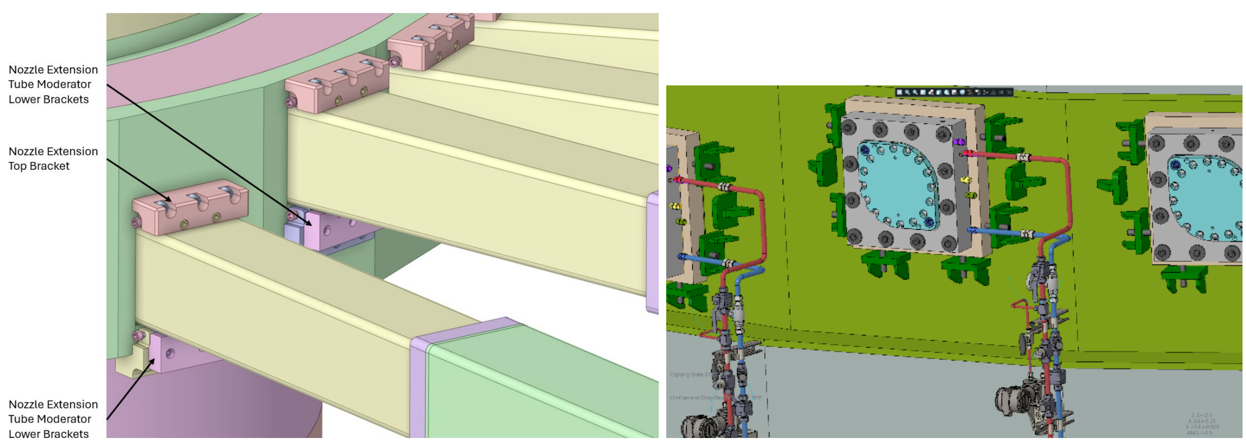


Figure 109: Standard nozzle extension attachment details to the beltline (left) and rear flange support (right)

5.3.1.1 Standard Nozzle Extension Assembly Thermal Analysis

Neutronics energy deposition was obtained and applied to the standard nozzle extension geometry in a steady state thermal analysis (33). Beamlines 10 and 11 were analyzed as they have the highest energy deposition to cope with. Two different contact conditions were considered; a conservative adiabatic contact condition case where the nozzle extension connection to the water cooled beltline was not considered, and a front contact model where the welded connection to the beltline was considered. A summary of the analysis results is shown in Table 1 below, with a 10-15 degree decrease in nozzle extension temperatures shown when the more realistic front cooled boundary condition is applied. Overall, the nozzle extension temperature is well controlled.

Table 1: Summary of results from a detailed thermal analysis of monolith inserts and nozzle extensions from beamlines ST10 and ST11

		Monolith Insert ST10 (normal heating)		Monolith Insert ST11 (bounding case)	
		Adiabatic Condition	Front Cooled	Adiabatic Condition	Front Cooled
Material	**Component**	**Peak Temperature (°C)**	**Peak Temperature (°C)**	**Peak Temperature (°C)**	**Peak Temperature (°C)**
Al6061	**Upstream & Downstream Windows, and Guide Substrate**	**38.7**	**38.6**	**48.2**	**48.2**
Cu	Downstream Seal, Rollers, and Shims	37.5	36.7	39.6	39.6
Float Glass	Guide Substrate	35.4	35.3	35.8	35.8
Macor	**Guide Shield**	41.2	41.2	**68.6**	**68.5**
SS304	Optics Module	40.6	40.6	62.4	62.4
SS304l	Monolith Insert	37.5	37.5	48.6	48.6
SS316l	**Nozzle Extension**, Seals, and Rollers	**52.7**	**42.2**	**60.7**	**46.6**
He	Helium	41.2	41.2	68.4	68.4
H_2O	Water	36.0	36.0	40.4	40.4

5.3.1.2 Standard Nozzle Extension Assembly Structural Analysis

A detailed structural analysis was performed on the standard nozzle extension assembly using FEA (34). The nozzle extension experiences gravitational and vacuum loading during normal operation, and both loads were considered in this analysis. Both upper and lower nozzle extension configurations with their associated brackets and bolts were analyzed. The monolith inserts reside inside the nozzle extensions, and these masses were also considered in this analysis. During normal operational conditions the nozzle extension stresses were found to be acceptable at below 100 MPa, with resulting deflections well below 1mm. Elevated stresses were seen in the nozzle extension bolts, indicating the need for high strength bolts in the final design. The nozzle extension brackets saw the highest stress levels on the nozzle extension, and the front seal welds were very well protected and did not show significant stresses. Protecting the front seal welds is critical to ensuring that the nozzle extensions will not leak due to failed seal welds during operation. Figure 110 shows stress analysis results from the FEA of the lower nozzle extension. Seismic loading was not considered for the standard nozzle extensions and will be addressed during final design.

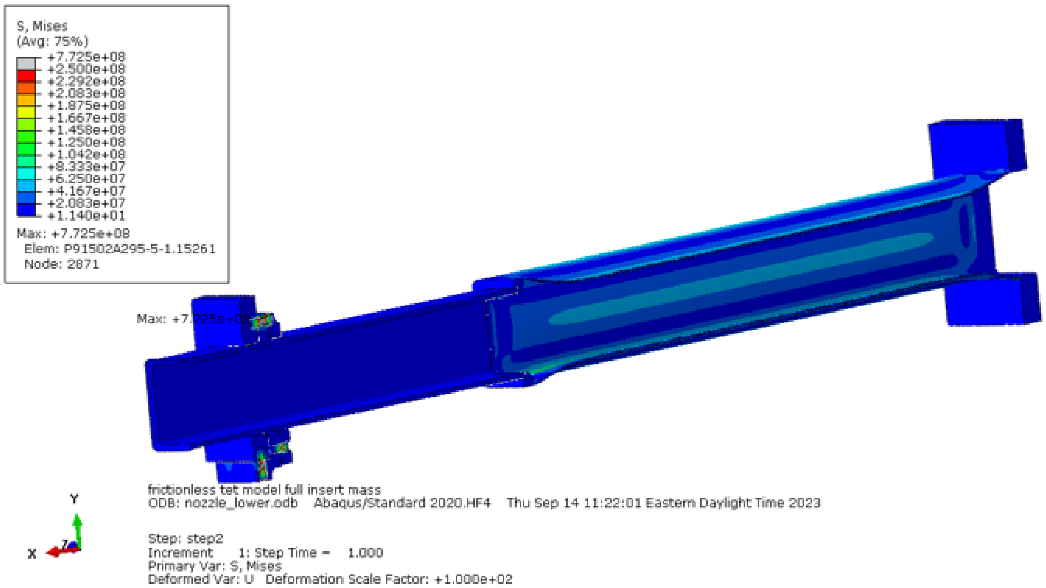


Figure 110: FEA results of the standard nozzle extension (lower position) under vacuum and gravity loads

Several off-normal loading conditions that represent possible loading conditions seen during nozzle extension and monolith insert installation were also analyzed. A scenario where the nozzle extension was not supported on the downstream side was considered. In this scenario the mass of the nozzle extension acts as a cantilever load, inducing high stresses in the nozzle extension mounting bars. Peak stresses of 234 MPa were observed near the fillet welds of the mounting brackets, indicating that plastic deformation would occur due to this loading condition. Nozzle extensions are never expected to be left unsupported in this way, and this analysis underlines the importance of ensuring that the downstream flanges of the nozzle extensions are supported during the installation process.

The second off-normal case considered the impact of monolith insert installation on the nozzle extensions. During monolith insert installation, rollers on the monolith inserts will engage with the bottom walls of the nozzle extensions, resulting in transient mechanical loads as the monolith inserts are installed. In a very conservative loading condition where the full monolith insert mass is exerted on the thinnest portion of the nozzle extension bottom wall a stress slightly yield was observed along with a localized deflection of 0.6 mm. It is expected that the actual maximum loading in this zone would be less than ½ of the simulated loads. Additional analysis will be performed during final design that will apply a more realistic load to this zone to better understand the impact of monolith insert loading on the nozzle extensions.

5.3.2 QIKR Nozzle Extension Assembly General Design

The QIKR nozzle extension serves a unique dual channel beamline. The two neutron beams for this beamline diverge both horizontally and vertically as they travel through the monolith, resulting in a monolith insert that is considerably taller and wider than the standard monolith insert. Another key difference of the QIKR monolith insert is that it does not extend into the CV like the standard monolith inserts but instead ends just outside of the CV beltline. The QIKR nozzle is also much larger in cross section than the standard nozzle extension and cannot be made from commercially available stainless steel tubing as the proper size does not exist. The QIKR nozzle extension walls must also be significantly thicker than a standard nozzle extension as roughly half the weight of the QIKR monolith insert and optics module is supported off the bottom of the nozzle extension.

The QIKR nozzle extension employs what is referred to as a bolted and welded design. Flat plates are machined to form two boxed sections. These boxed sections are bolted together with stainless steel screws to carry the majority of the mechanical loads and then seal welded in order to form a vacuum tight interior. Bolting the boxed sections together allows for smaller welds to be employed, which should reduce overall weld distortion. The boxed sections will then be welded to the front, rear and transition flanges as well as the round front nose section. Figure 111 shows the general design of the QIKR Nozzle Extension.

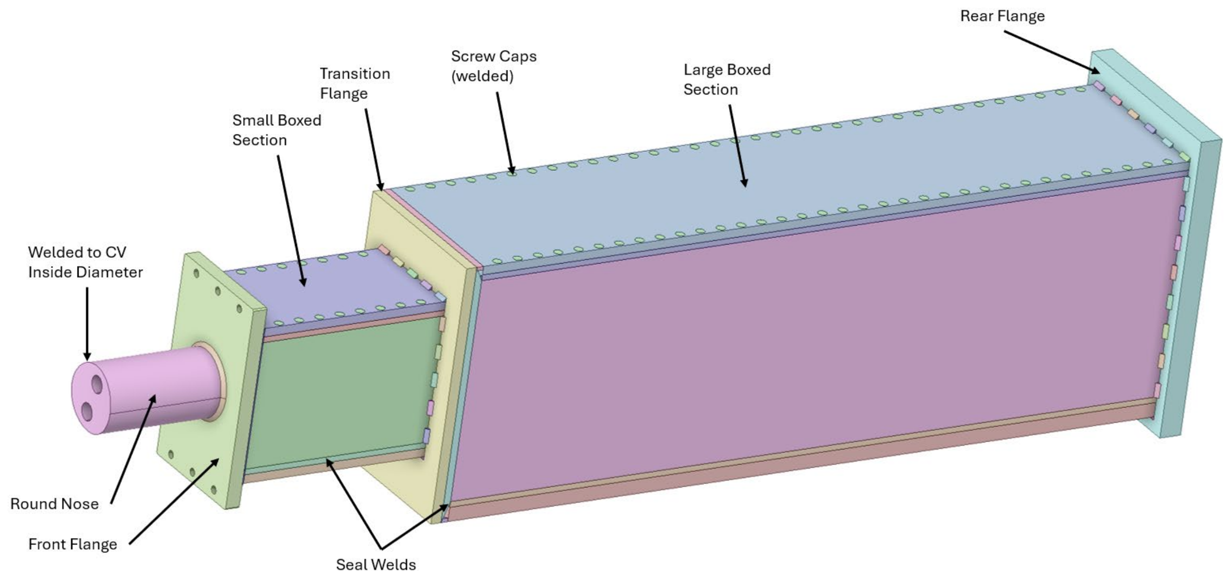


Figure 111: CAD model of QIKR Nozzle Extension

Because the QIKR nozzle extension does not extend to the beltline, it is not necessary to provide a large opening like is done with the standard nozzle extensions. In order to reduce heat load on the QIKR monolith insert, a stainless steel nose section will be inserted into the CV beltline and welded to the inside diameter of the CV. This nose section is solid except for the two diverging round holes cut along the neutron flight path from the moderator to the QIKR monolith insert windows. This solid nose will intercept stray radiation and provide radiation and thermal shielding to the monolith insert. As with the standard nozzle extensions, there is a step in the QIKR nozzle extension to reduce streaming into the instrument bunker. Unlike the standard nozzle extensions, the QIKR nozzle utilizes a large front flange that is bolted directly to the CV beltline. Figure 112 shows the beltline connection details of the QIKR Nozzle Extension.

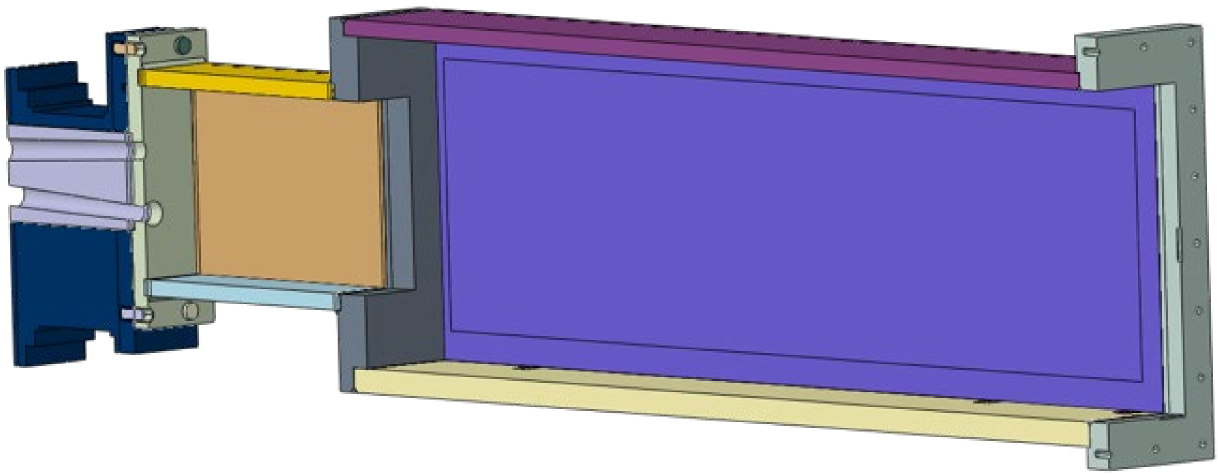


Figure 112: Half symmetry Abaqus model of the QIKR nozzle extension showing beltline mounting details to the left

5.3.2.1 QIKR Nozzle Extension Assembly Thermal Analysis

Neutronics energy deposition was obtained and applied to the QIKR nozzle extension geometry in a steady state thermal analysis (33). A front contact model was considered where the welded connection to the beltline was set to the CV beltline temperature. The temperature of the CV beltline is well controlled via water cooling and acts as a heat sink for the nozzle extension. As can be seen in Figure 113 below the QIKR nozzle temperature is very well controlled, with a peak temperature of 36.8 degrees C at the rear flange.

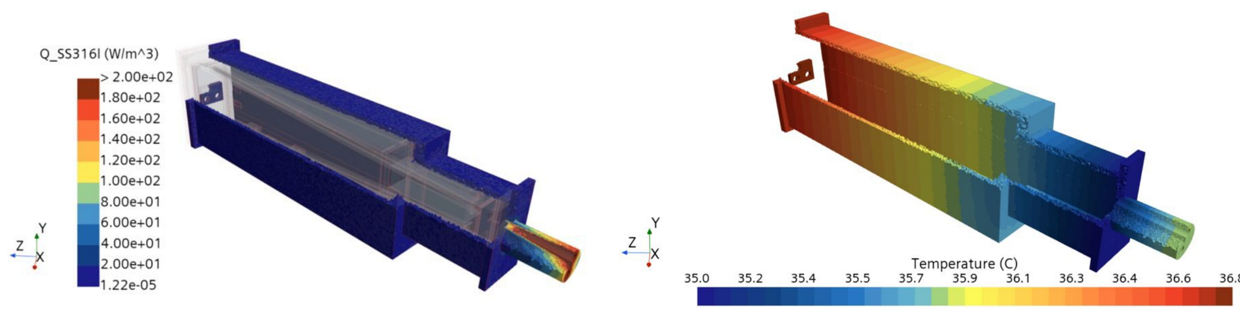


Figure 113: Neutronic energy deposition (left) and temperature profile (right) of the CV QIKR Nozzle Extension

5.3.2.2 QIKR Nozzle Extension Assembly Structural Analysis

A detailed structural analysis was performed on the QIKR nozzle extension assembly using FEA (35). The nozzle extension experiences gravitational and vacuum loading during normal operation, and both loads were considered in this analysis. The QIKR monolith insert resides inside the nozzle extension, and all of its weight is supported by three sets of rollers. The monolith insert is installed using a cold handler designed by Instrument Systems that supports the monolith insert from the rear flange during installation. The rollers assist in this radial insertion, and once fully inserted support the weight of the insert.

Based on preliminary structural analysis results, several improvements to the QIKR nozzle extension were implemented. The bolt sizes used to secure the front flange to the CV beltline were increased to deal with bolting stresses. Two Inconel pins were added to the front flange and CV beltline with Inconel sleeves installed in the beltline to support the substantial vertical load of the nozzle and monolith insert. The thickness of the rear box section bottom plate was increased from 40mm to 60mm to reduce deflections induced by the monolith insert loads. Finally, 10mm thick Inconel inserts were added to the rear box section bottom plate to deal with high contact stresses between the wheels of the monolith insert and the nozzle extension.

After implementing these improvements the nozzle extension stresses were found to be acceptable at below 100 MPa, with resulting deflections well below 1mm. Seal weld stresses were shown to be below 100 MPa, and the maximum bolting stress in the nozzle extension body bolts were under 50 MPa. Elevated but acceptable stresses were seen in the nozzle extension Inconel pins in the beltline and landing pads. Nozzle extension deflections under full operational loads were also very well managed at under 0.2 mm. Seismic loading was also evaluated in this analysis, with results not adding significant stress or deflections when compared to normal operating conditions. Figure 114 shows stress analysis results from the FEA of the QIKR nozzle extension.

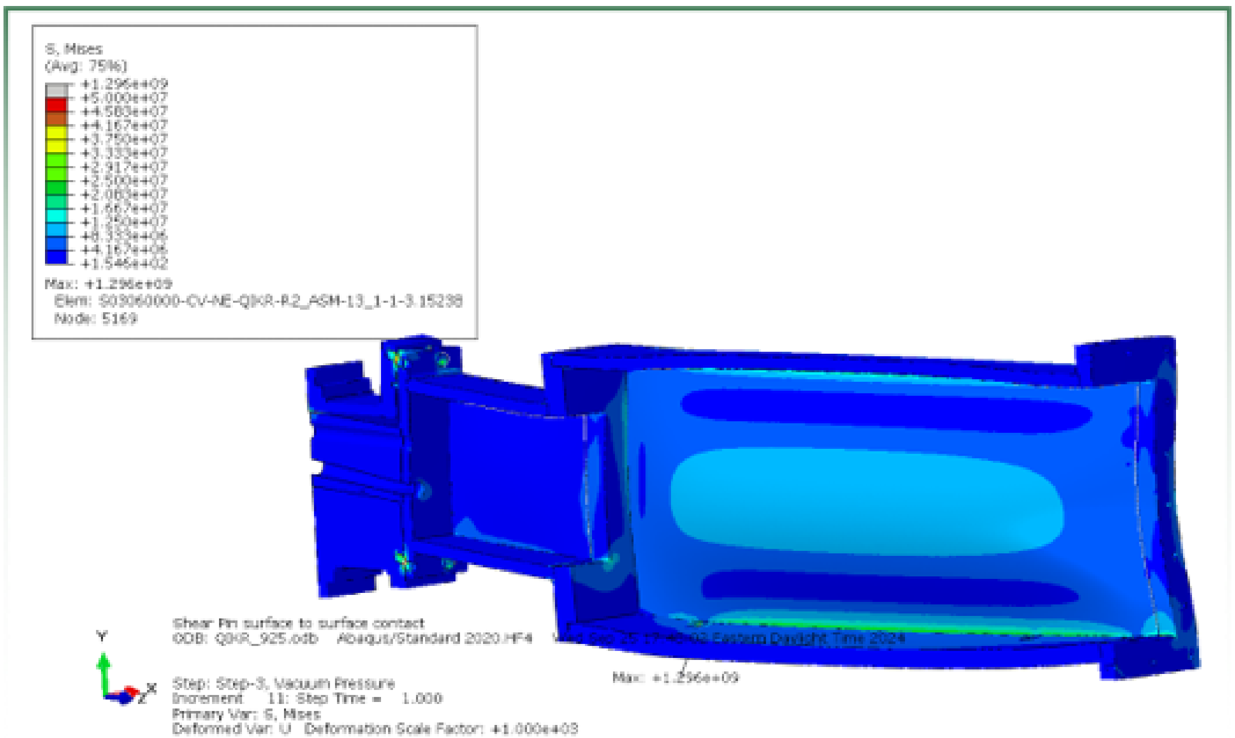


Figure 114: QIKR nozzle FEA stress analysis results

5.3.3 Dual Channel Nozzle Extension Assembly General Design

The STS project utilizes two dual-channel beamlines on ST15 and ST16. The beamlines diverge horizontally as they move outward from the MRA and require non-standard monolith inserts. These beamlines include dual-channel monolith inserts that are the height of a standard monolith insert and the width of the QIKR monolith insert. The dual channel inserts do not extend to the CV beltline and are supported by the nozzle extension on rollers like QIKR. Commercial off the shelf stainless steel tubing is not available in the required cross sectional profile to fit the dual channel monolith inserts and support their weight, so a similar design to QIKR will be utilized.

The dual channel nozzle extensions will also utilize a bolted and welded design. Flat plates are machined to form two boxed sections. These boxed sections are bolted together with stainless steel screws to carry the majority of the mechanical loads and then seal welded in order to form a vacuum tight interior. Bolting the boxed sections together allows for smaller welds to be employed, which should reduce overall weld distortion. The boxed sections will then be welded to the front, rear and transition flanges as well as the round front nose section. Figure 115 shows the general design of the dual channel Nozzle Extension. Note that the current CAD design has not yet been updated to include the transition flange seen in QIKR. This change was made during QIKR analysis in order to improve manufacturability and reduce cost of the insert and will be applied to the dual channel nozzle extensions during final design.

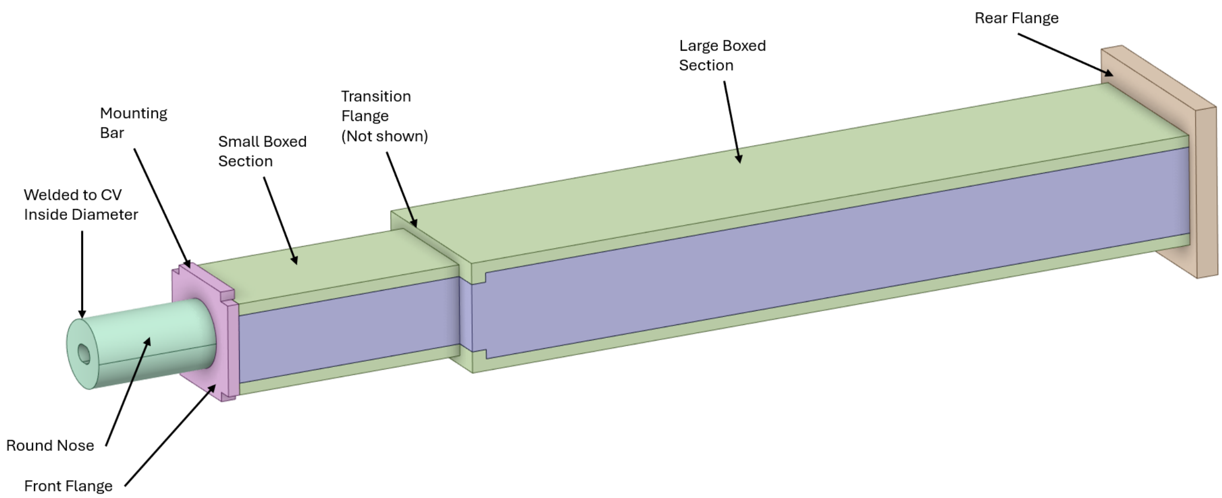


Figure 115: CAD model of Dual Channel Nozzle Extension

Because the dual channel nozzle extensions do not extend to the beltline, it is not necessary to provide a large opening like is done with the standard nozzle extensions. In order to reduce heat load on the dual channel monolith inserts, a stainless steel nose section will be inserted into the CV beltline and welded to the inside diameter of the CV. This nose section is solid except for the two diverging round holes cut along the neutron flight path from the moderator to the dual channel monolith insert windows. This solid nose will intercept stray radiation and provide radiation and thermal shielding to the monolith insert. As with the standard nozzle extensions, there is a step in the dual channel nozzle extension to reduce streaming into the instrument bunker. Because the dual channel nozzle extension is standard height with a small vertical streaming step, there is not room for a large flange to bolt the nozzle extension to the CV beltline like is done for QIKR. A mounting bar mounting arrangement similar to the standard nozzle extensions will be used for the dual channel nozzle extension mounting. Figure 116 shows the beltline connection details of the dual channel nozzle extension.

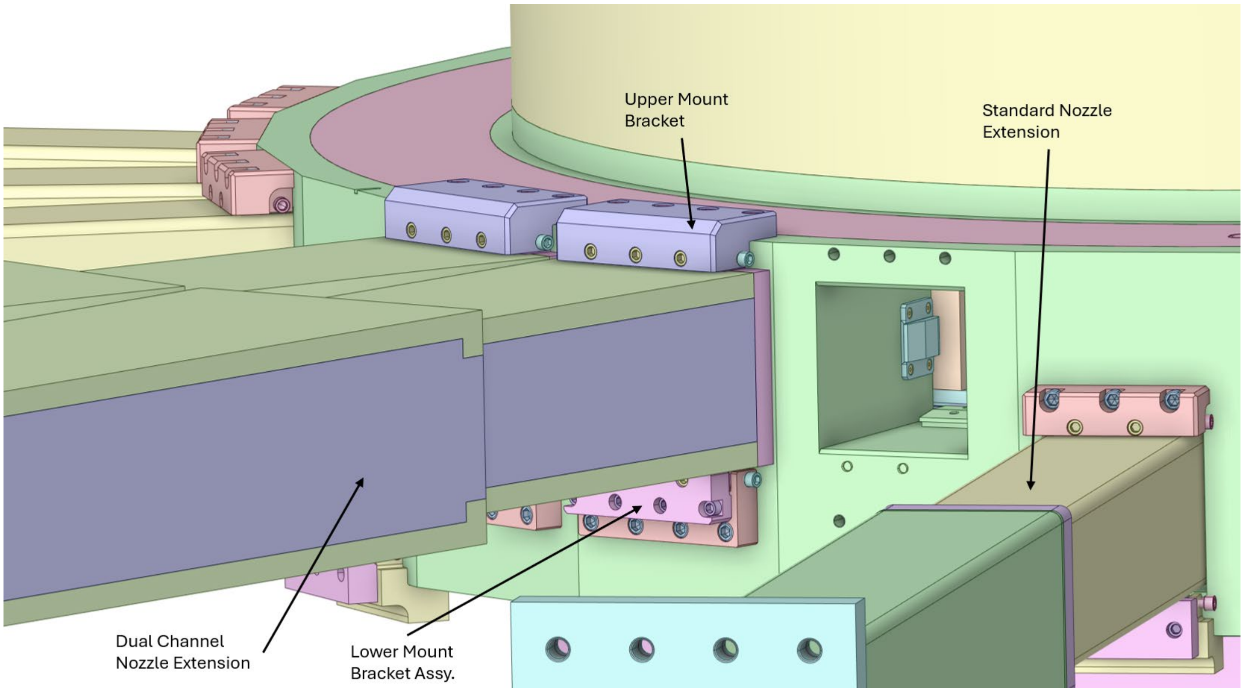


Figure 116: Dual Channel Nozzle Extension beltline mounting details

5.3.3.1 Dual Channel Nozzle Extension Assembly Thermal Analysis

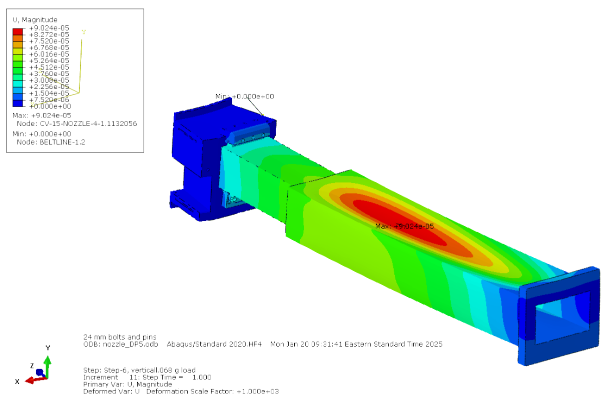
A detailed thermal analysis of the dual channel nozzle extensions has not yet been conducted. The dual channel nozzle extensions are very similar to the QIKR nozzle extension, which showed very minor temperature increase due to neutronic heating. A similar result is anticipated for the dual channel nozzle extension, and will be confirmed during final design.

5.3.3.2 Dual Channel Nozzle Extension Assembly Structural Analysis

A detailed mechanical analysis of the dual channel insert will be conducted during final design. The design of the dual channel nozzle extension is very similar to the QIKR nozzle extension with the exception of the height difference and the nozzle mounting to the CV. Because the dual channel monolith inserts are lighter in weight than the QIKR monolith insert, do we not anticipate any issues with stress or deflection of the dual channel nozzle extension body. A detailed structural analysis was performed on the dual channel nozzle extension mounting to the CV using FEA (36). The nozzle extension experiences gravitational and vacuum loading during normal operation, and both loads were considered in this analysis. The dual channel monolith insert resides inside the nozzle extension, and all of its weight is supported by three sets of rollers. The monolith insert is installed using a cold handler designed by Instrument Systems that supports the monolith insert from the rear flange during installation. The rollers assist in this radial insertion, and once fully inserted support the weight of the insert.

Based on preliminary structural analysis results, several improvements to the dual channel nozzle extension were implemented. The bolt sizes used to secure the front flange to the CV beltline were increased to deal with bolting stresses. It was found that elevated deflection and stress were seen in the lower mounting bracket, and the height of the bracket was increased to reduce the bending moment on the bracket and improve the stress distribution. All of the improvements applied to the QIKR nozzle extension (Inconel pins and pads, ect.) were applied to the dual channel design.

After implementing these improvements, the nozzle extension stresses were found to be acceptable at below 100 MPa, with resulting deflections well below 1mm. Seal weld stresses were shown to be below 100 MPa, and the maximum bolting stress in the nozzle extension body bolts were under 50 MPa. Elevated but acceptable stresses were seen in the nozzle extension Inconel pins in the beltline and landing pads. Nozzle extension deflections under full operational loads were also very well managed at under 0.2 mm. Seismic loading was also evaluated in this analysis, with results not adding significant stress or deflections when compared to normal operating conditions. Figure 117 shows stress analysis results from the FEA of the QIKR nozzle extension.



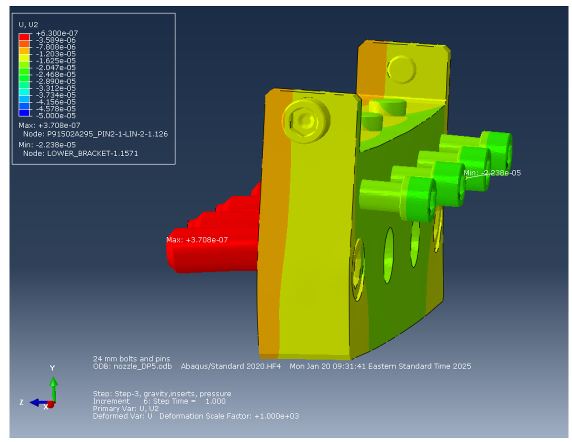


Figure 117: Deflection profile of the Dual Channel Nozzle Extension (left) and peak stress in the lower bracket bolts (right)

5.3.4 Nozzle Extension Assembly Manufacturing

The standard nozzle extensions will be constructed from 304/304L stainless steel square tubing and plate due to its excellent corrosion resistance and proven performance in high radiation environments. The use of COTS stainless steel square tubing provides a significant cost savings over the bolted and welded design of the original standard nozzle extensions. The front mounting bars, central transition flange and rear flange will be machined from 304/304L stainless steel plate. The components will be welded together to create a finished Nozzle Extension. The Vessel Systems manufacturing and fabrication strategy details all steps necessary to fabricate the Nozzle Extensions (27).

Fabrication of the standard nozzle extensions is challenging due to the tight profile tolerance required. Monolith inserts must be closely fit to the inside profile of the nozzle extensions to minimize radiation streaming into the instrument bunker. Because of the uncertainty associated with the manufacturing of the standard nozzle extension, a prototype nozzle extension was manufactured as a research and development manufacturing study. A full sized nozzle extension was produced by Keller Technology Corporation. The primary concern was the ability to hold manufacturing tolerances through the welding process. Keller verified that the weld distortions seen during manufacturing would allow for our design to be produced with the desired profile tolerance. Unfortunately, a machining error during final machining damaged the nozzle extension and resulted in a prototype nozzle extension that did not meet our specifications. However, the manufacturing study did validate the overall weld design was sound, increasing confidence that the manufacturing of the standard nozzle extensions will be successfully carried out during the procurement phase of the project.

Figure 118: Prototype Nozzle Extension during fabrication at Keller Technology Corporation

As was described above, the QIKR and dual channel nozzle extension designs differ significantly from the standard nozzle extensions. These nozzle extensions will be constructed entirely from machined plates. The two box sections of the nozzle extensions will be bolted together prior to welding to reduce the depth of weld penetration required to be mechanically sound. This reduction in weld volume should reduce the amount of weld distortion seen during fabrication of the nozzle extensions. Because of the shape of the nozzle extensions, post-weld machining of the nozzle extension interior is not practical. This means that weld distortions must be well managed to maintain the desired profile tolerances. These larger nozzle extensions are expected to be more costly and challenging to build than the standard nozzle extensions due to the physical layout required, and care was taken in the design to reduce cost and complexity wherever possible while maintaining the design intent of the nozzle extensions.

5.4 GAMMA GATE ASSEMBLY DESIGN AND ANALYSIS

5.4.1 Gamma Gate Assembly General Design

The Gamma Gate consists of a 0.5-inch-thick vessel constructed of 316 stainless steel filled with 30 cm of lead to attenuate gamma rays streaming through the gap in the vessel shielding created when the Target Removable Shield Block is removed during target segment removal. The gamma gate is mounted on a set of linear rails made of stainless steel to enable the gamma gate to actuate into position over the gap in shielding. Motion of the gamma gate is enabled by a linkage to a lead screw linear actuator that is mounted external to the core vessel environment and is driven by a stepper motor. Design considerations have included the addition of a stud to enable lifting the gamma out of the vessel using the zip lift in the event of required maintenance or troubleshooting. A pair of plunger latches have been included in the assembly to prevent motion of the gamma gate when it is not in use.

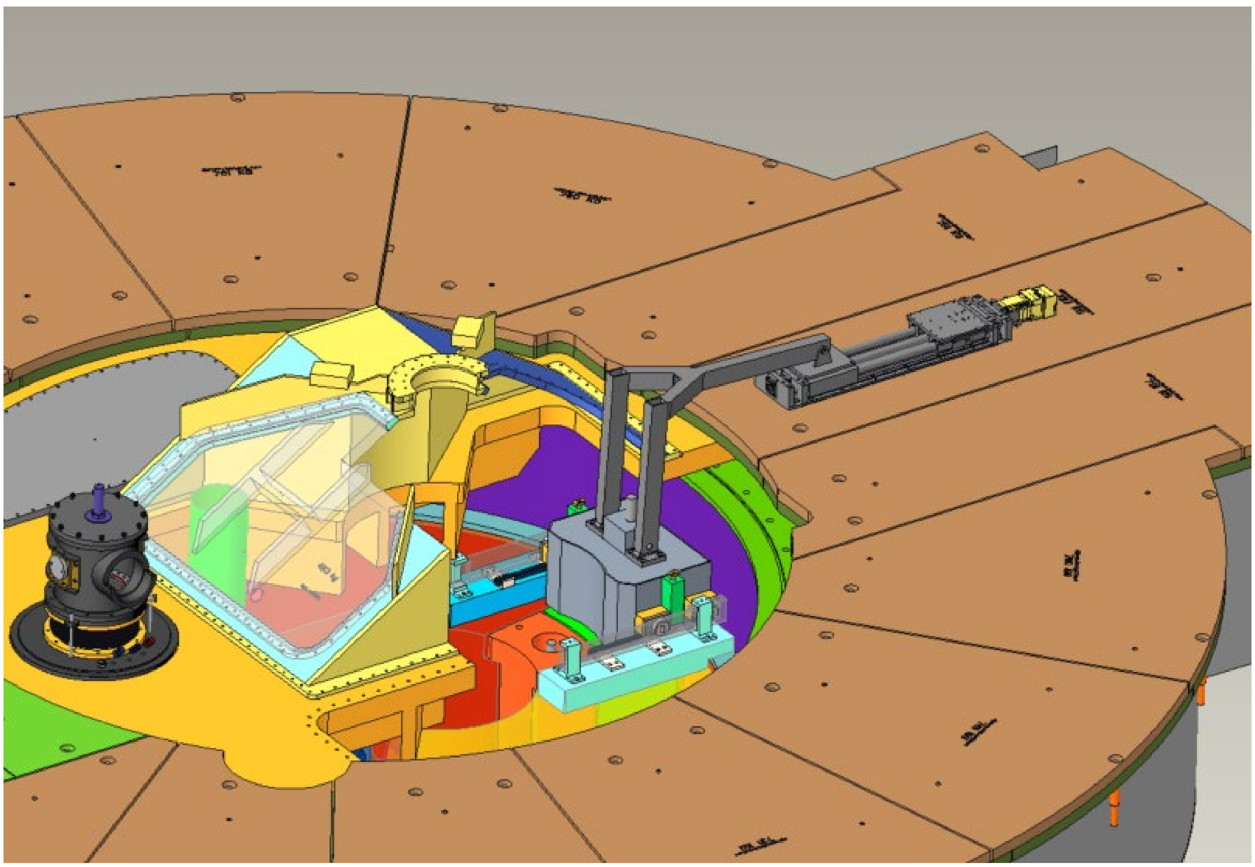


Figure 119: Position on the Gamma Gate in the Core Vessel

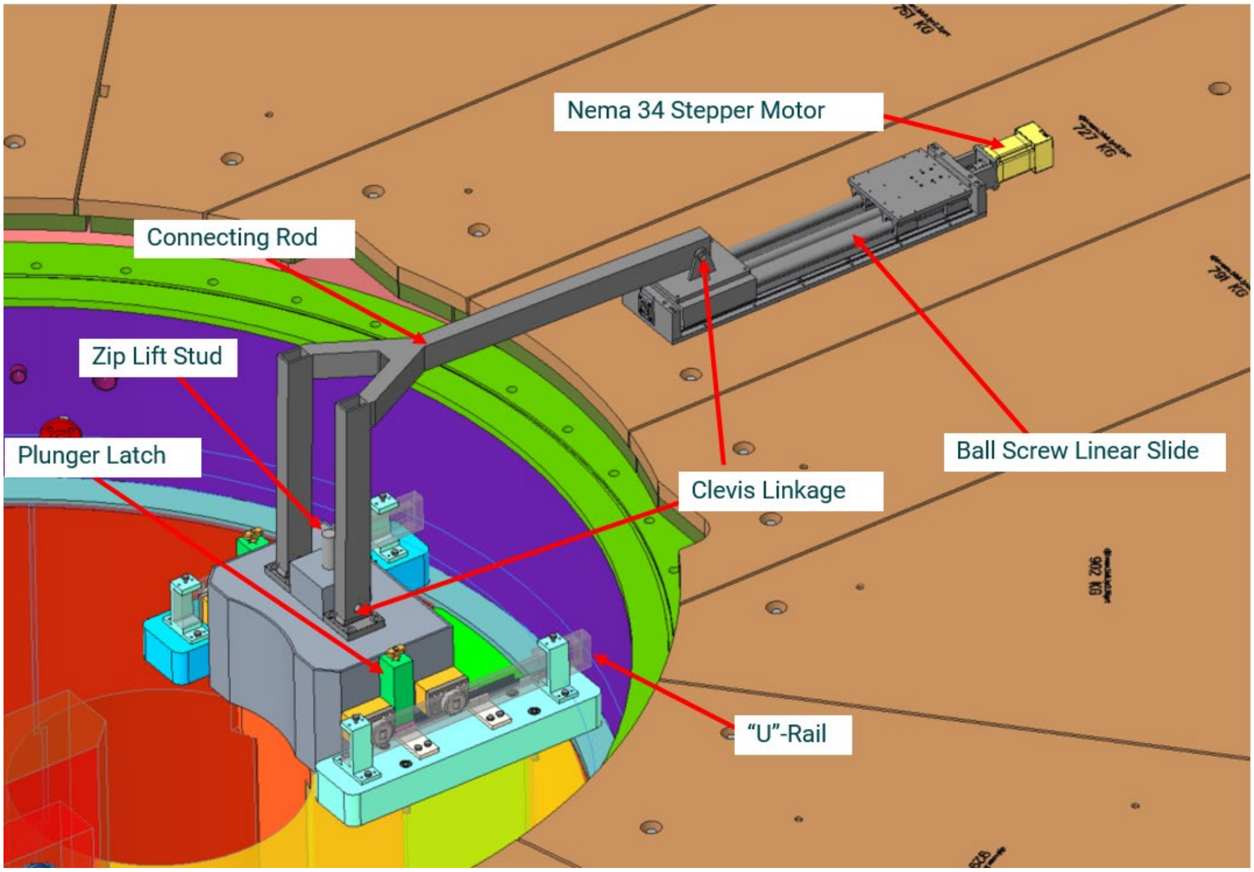


Figure 120: Gamma Gate Component Definition

5.4.2 Gamma Gate Assembly Thermal Analysis

Due to the low levels of radiation present at the top of the vessel shielding, the Gamma Gate will experience minimal heat deposition during operation of the Second Target Station.

5.4.3 Gamma Gate Assembly Structural Analysis

Structural calculations were performed on the Gamma Gate assembly to ensure that the rail system would be able to support the weight of the lead filled vessel. A load of 10 kilonewtons was applied to the center of a single stainless-steel rail to simulate the entire weight of the gamma gate resting on a single rail. A peak stress of 93.4 MPa and a maximum deformation of 0.6 mm was observed in this scenario. These results provide confirmation that the set of two rails will be able to sufficiently support the weight of the gamma gate during operation.

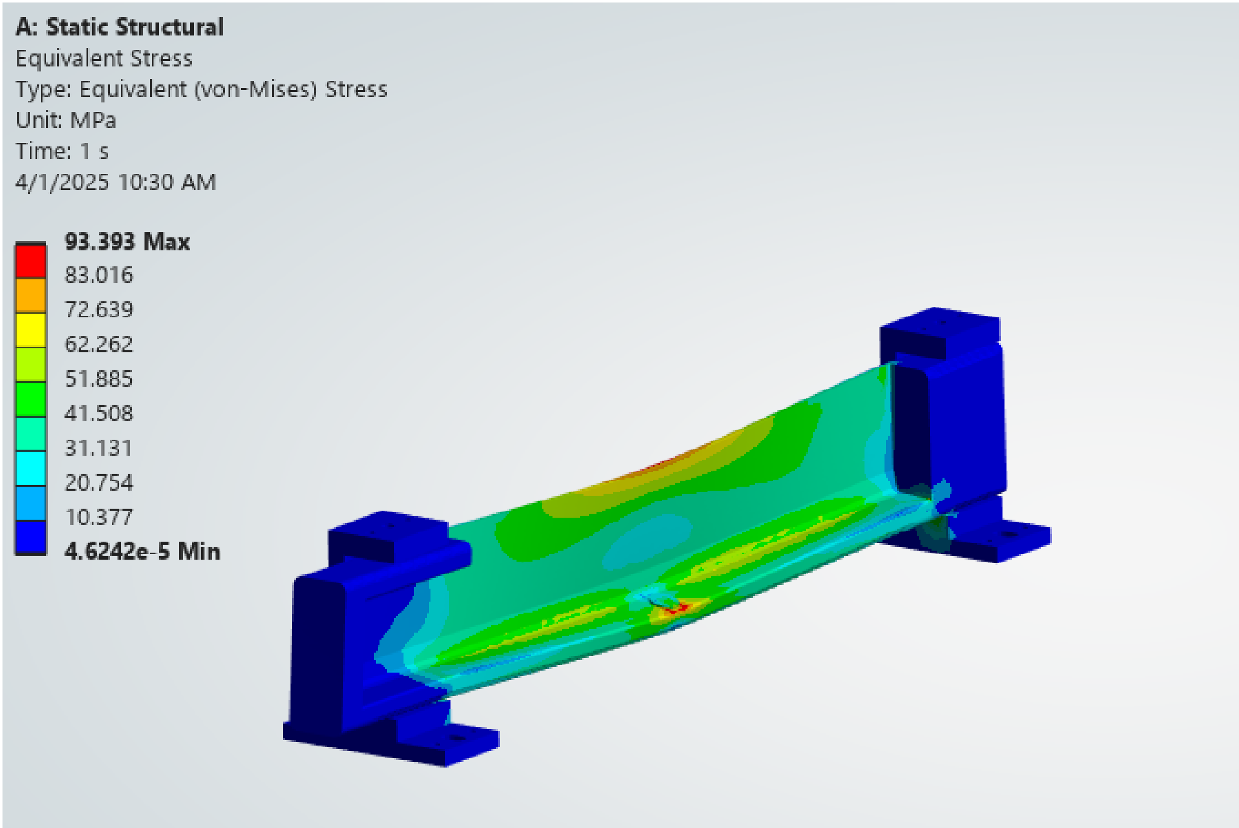


Figure 121: Stress Structural Results of the Gamma Gate rail system

Structural calculations were performed on the linkage arm to ensure that the correct gage of rectangular tubing was used in the design of the linkage arm. A load of 1000 newtons was applied at the connecting interface of the linkage arm to the gamma gate to simulate a coefficient of static friction of 0.1 present between the gamma gate bearings and the linear rail. A coefficient of static friction of 0.1 represents a conservative assumption of static friction between the gamma gate bearing and the linear rail. A peak stress of 28.5 MPa and a maximum deformation of 2.8 mm was observed in the linkage arm in this scenario. These results provide confirmation that the linkage arm will be able to support the load necessary to actuate the Gamma Gate assembly.

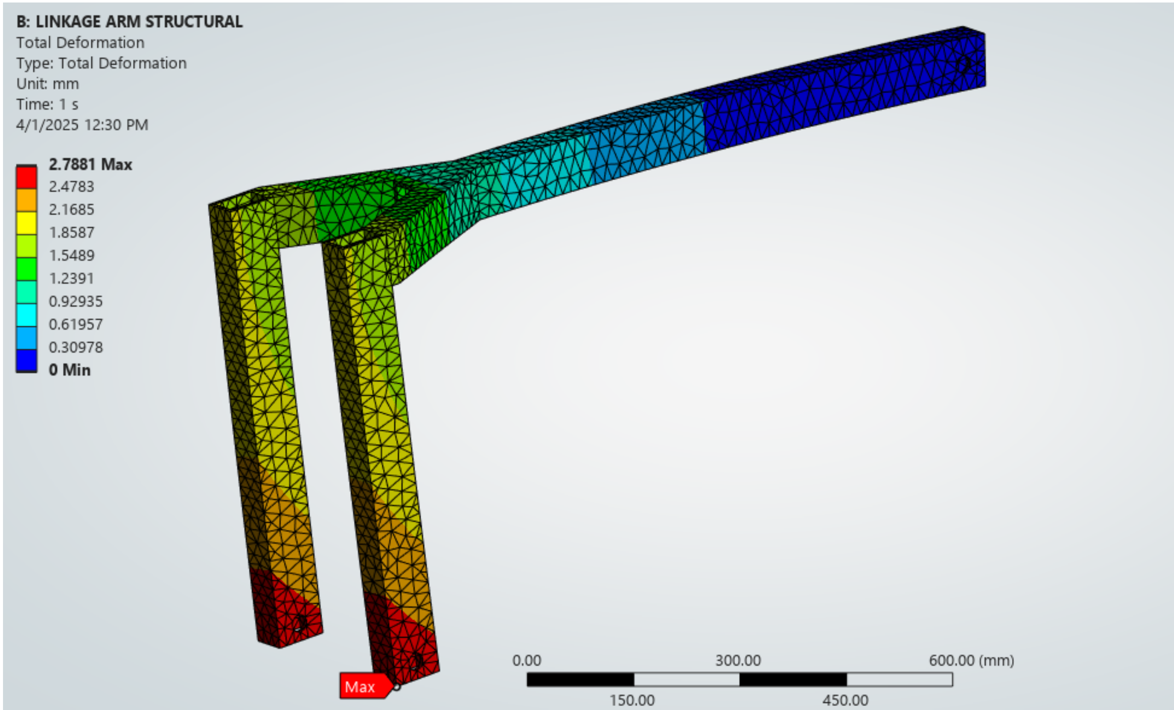


Figure 122: Linkage Arm Total Deformation Results

Structural calculations were performed on the latch assembly to ensure that the latch was sufficiently strong to prevent motion of the gamma gate during target segment maintenance or in a seismic event. A load of 5 kN was applied to the latch pin to simulate the load the latch pin experiences due to acceleration of the gamma gate during a seismic event. A peak stress of 106 MPa and a maximum deformation of 0.005 mm was observed in the latch pin in this scenario. These results provide confirmation that the latch pin will be able to prevent motion of the gamma gate during a seismic event. Additional details of the gamma gate mechanical analysis can be found in (37).

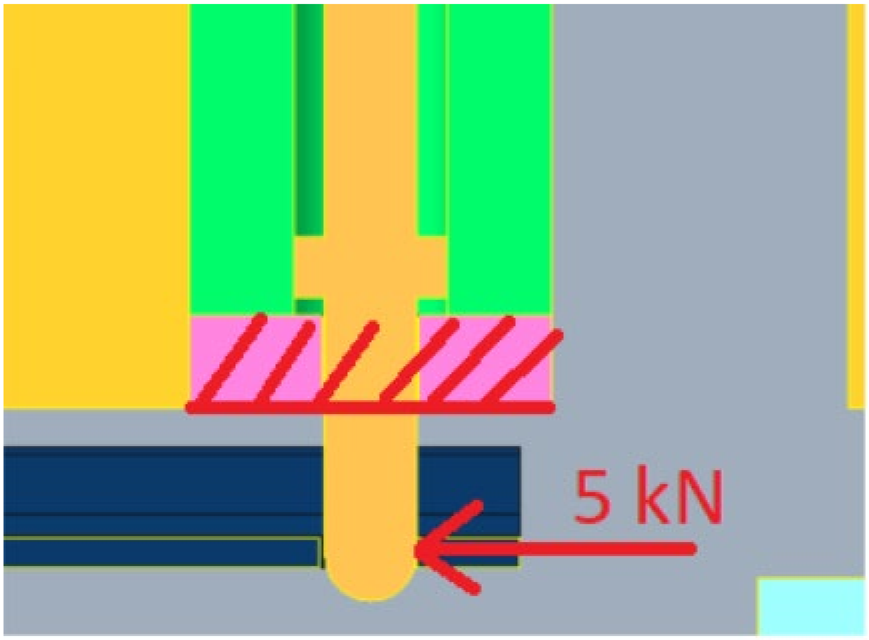


Figure 123: Latch Pin Free Body Diagram

5.4.4 Gamma Gate Assembly Manufacturing

The vessel of the Gamma Gate will be constructed from 316/316L stainless steel due to its excellent corrosion resistance and proven performance in high radiation environments. The vessel will be filled with lead to serve as the primary blocker of gamma radiation streaming through the gap in the vessel shielding created when the Target Removable Shield Block is removed. The lead will be added to the vessel by utilizing a lead pour and fill service. The Gamma Gate will have linear roller bearings bolted to its sides to enable the Gamma to actuate. The linear roller bearing selected for this application are the HVB-055 axial roller bearings from PBC Linear. These bearings were selected due to their ability to support the load of the gamma gate. These roller bearings will be lubricated with RG-42R-1 grease from Moresco. This grease has been chosen due to its proven performance in high radiation and vacuum environments. The roller bearings will ride on a set of "U-channel" rails. The actuation of the gamma will be enabled by a lead screw linear actuator. The lead screw linear actuator chosen for this application is the 2N34BE-16S3-036.000-AB7R from PBC Linear. The lead screw linear actuator is compatible with a Nema 34B stepper motor. The Vessel Systems manufacturing and fabrication strategy details all steps necessary to fabricate the Gamma Gate (27).

5.5 VESSEL SYSTEMS REMOTE HANDLING

All removable VS components were designed to allow for remote handling removal and reinstallation after operation of the STS. The target and MRA removable shield blocks include zip lift studs over the centers of gravity of each block for hands free attachment and release from the overhead crane. The removable hatches in the CV lid include swivel hoist rings and are sized to be lifted either by the high bay crane or the 1 ton Jib crane located inside the target drive room. Additional details can be found in Interface Sheet S03000000-IST10006 (11).

5.6 VESSEL SYSTEMS INSTALLATION

Installation of the Vessel Systems components into the monolith is intertwined with the installation of other Target Systems components. Installation of the CV occurs relatively early in the construction of the monolith structure, following installation of some of the lower Target Station Shielding components. The CV is installed in two pieces and then field welded together. The nozzle extensions are installed radially from the instrument bunker after a lower portion of the target station bulk shielding is installed. Core Vessel shielding is installed in sequence with the target shaft. Each water cooled shield block is field welded to utility nozzles at the top of the CV prior to installation of the next layer of shielding. Care must be taken to install and test components in the proper order to ensure proper installation is achieved. Installation details are described in greater detail in the Vessel Systems installation plan (38).

6. REFERENCES

Ref	Document Title	Document Number
(1)	Vessel Systems Requirements	S03060000-SRD10000
(2)	Vessel Systems Verification Plan	S03060000-TAC10000
(3)	Interface Sheet for S.03.06 Vessel Systems and S.03.07 Target Station Shielding to S.04.03 Bunker	S01020500-IS0025
(4)	Interface Sheet for Vessel Systems and Vessel Systems I&C	S01020500-IST10128
(5)	IS – Target Assembly – Core Vessel	S01020500-IST10209
(6)	Interface Sheet for Cryogenic Moderator System and Vessel Systems	S03000000-IST10010
(7)	Interface Sheet – Vessel Systems (S.03.06) to Moderator Reflector Assembly (S.03.04)	S03000000-IST10009
(8)	Interface Sheet for Target Assembly, Moderator Reflector Assembly, and Vessel Systems	S01020500-IST10205
(9)	Interface Sheet for Core Vessel, Target Station Shielding and Accelerator Interface Components	S01020500-IST10217
(10)	Interface Sheet – Vessel Systems (S.03.06) to Process Systems (S.03.09)	S03000000-IST10004
(11)	Interface Sheet – Vessel Systems (S.03.06) to Remote Handling (S.03.10)	S03000000-IST10006
(12)	Interface Sheet – Vessel Systems (S.03.06) to Vacuum Systems (S.03.11)	S03000000-IST10008
(13)	Global Requirements Document, Second Target Station	S01010100-SR0001
(14)	STS Radiation Safety Policy and Plan	S01030100-PN0001
(15)	Materials Handbook: Second Target Station Project	S03010300-TDO10000
(16)	STS Design and Fabrication of Pressure and Vacuum Systems	S01020000-PC0007
(17)	STS Preliminary Hazzard Analysis Report	S01030000-ES0002
(18)	Target-MRA-Vessel Systems Interface Drawing	S03000000-M8U-8800-A10001
(19)	Target-MRA-Vessel Systems Interface Drawing	S03020000-M8U-8800-A10000

(20)	Target Systems, Assembly Drawing	S03020000_G8U-8800-A10000
(21)	Second Target Station Conceptual Design Report Volume 1	S01010000-TR0001
(22)	Vessel Systems Shape Trade Study	S03060000-TR0001
(23)	Core Vessel Shielding Preliminary Design Neutronics Analysis	CV_Neutronics_Heating_PDR
(24)	Neutronics Analysis of Heating and DPA of the Proton Beam Window and Core Vessel Nozzle of the Second Target Station	S03120100-TRT10016
(25)	Vessel Systems - Core Vessel Thermal Hydraulic Analysis	S03060000-DAC10000
(26)	Vessel Systems - Core Vessel Structural Analysis	S03060000-DAC10001
(27)	Vessel Systems Manufacturing and Fabrication Strategy	S03060000-MFP10001
(28)	Vessel Systems - Manufacturing Study	S03060000-TRT10001
(29)	Vessel Systems - Cooled Shield Block #1 Thermal and Structural Analysis	S03060000-DAC10002
(30)	Vessel Systems - Cooled Shield Block #3 Thermal and Structural Analysis	S03060000-DAC10003
(31)	Vessel Systems - Uncooled Ring Shield Block Thermal Analysis	S03060000-DAC10004
(32)	Vessel Systems - Uncooled Shield Stack Thermal Analysis	S03060000-DAC10005
(33)	Vessel Systems - Standard Nozzle Extension Thermal Analysis	S03060000-DAC10006
(34)	Vessel Systems - Standard Nozzle Extension Structural Analysis	S03060000-DAC10007
(35)	Vessel Systems - QIKR Nozzle Extension Structural Analysis	S03060000-DAC10008
(36)	Vessel Systems - Dual Channel Nozzle Extension Structural Analysis	S03060000-DAC10009
(37)	Vessel Systems - Gamma Gate Structural Analysis	S03060000-DAC10010
(38)	Vessel Systems - Installation Plan	S03060000-TDO10000