S03040000-DES10000-R01

SECOND TARGET STATION (STS) PROJECT

Moderator Reflector Assembly Design Description

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July 2026

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Prepared by
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00	Initial Release
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CONTENTS

1. PURPOSE

This document describes the design of the Second Target Station (STS) Moderator Reflector Assembly (MRA). The requirement decomposition from Target Systems level to the MRA is described. The MRA design is described, along with how it meets its requirements. Requirements verification, and specifically requirements which have yet to be evaluated or are not met by the preliminary design, is discussed. Finally, plans for meeting these unverified requirements during final design are outlined.

2. REQUIREMENTS DECOMPOSITION

The following list of Target Systems Requirements [1] decompose to the MRA Requirements [2]. Most of the requirements decompose in a straightforward way; however, the following sections offer additional explanations where warranted and a basis for how requirements were derived. MRA requirements have also been linked to the relevant requirements of the STS Hazard Analysis Report (HAR) [3]

Table 2.1 Relevant Target Systems Requirements to the Moderator Reflector Assembly Requirements.

<table>
<tr><td>[S03-1028]</td><td>The Target Systems shall accept a pulsed proton beam of 700 kW, 1.3 GeV, 15 Hz from Accelerator Systems.</td></tr>
<tr><td>[S.03-1029]</td><td>The Target Systems shall convert the proton beam pulses into cold neutron pulses using high-brightness moderators that will meet or exceed the peak brightness of $2x10^{14}n/cm^2/sr/Å/s$ at the neutron wavelength 5Å.</td></tr>
<tr><td>[S.03-1030]</td><td>The Target Systems shall distribute neutrons to 22 beamlines.</td></tr>
<tr><td>[S.03-1031]</td><td>The Target Systems design shall consider instrument background.</td></tr>
<tr><td>[S.03-1032]</td><td>The Target Systems design shall allow for a lifetime of forty years of operation.
Note: Components of the Target Systems that are not expected to be operational for the specified lifetime must be identified by the design.</td></tr>
<tr><td>[S.03-1033]</td><td>The Target Systems design shall allow for greater than five thousand hours of proton beam on target per year with accommodation for maintenance intervals in accordance with the STS operating schedule.</td></tr>
<tr><td>[S.03-1034]</td><td>The Target Systems design shall allow for greater than 95% availability.</td></tr>
<tr><td>[S.03-3009]</td><td>Components shall meet one of the following criteria:
<table>
<tr><th>Reliability and Maintainability Group</th><th>Replacement Time (Beam on-off)</th><th>Minimum Life-time*</th><th>Failure Indication</th></tr>
<tr><td>Life of Facility</td><td>N/A</td><td>40 yrs</td><td>Not anticipated</td></tr>
<tr><td>Group A (long outage, predictable failures)</td><td>1400 hours</td><td>5,000 hrs</td><td>predictable and with diagnostic warning</td></tr>
<tr><td>Group B (Long outage replacement, anticipated failures with significant consequences)</td><td>250 hrs**</td><td>2,500 hrs***</td><td>Less predictable, un-reliable diagnostics</td></tr>
<tr><td>Group C (Short Outage replacement)</td><td>72 hrs</td><td>500 hrs</td><td>N/A</td></tr>
<tr><td>Group D (tuning outages)</td><td>16 hrs</td><td>192 hrs</td><td>N/A</td></tr>
</table></td></tr>
<tr><td>[S.03-1035]</td><td>The Target Systems design shall allow safe operation.</td></tr>
<tr><td>[S.03-1036]</td><td>The Target Systems design shall prevent release of contamination and limit exposure ALARA in accordance with the STS Radiation Safety Policy and Plan.</td></tr>
<tr><td>[S.03-1037]</td><td>The Target Systems design shall include a replacement scheme and disposal path for all perishable components.</td></tr>
<tr><td>[S.03-1041]</td><td>The Target Systems shall provide the means to measure proton beam position and profile delivered by the Accelerator Systems.</td></tr>
<tr><td>[S.03-1042]</td><td>The Target Systems design shall provide for monitoring and operation and will accommodate timing triggers provided via the SNS control system.</td></tr>
<tr><td>[S.03-1478]</td><td>Components shall not damage (inadvertent contact) the hydrogen boundaries, regardless of load combination. Note: This requirement specifically includes seismic loads.</td></tr>
</table>

The MRA also has interfaces with other STS systems, both inside and outside of Target Systems, which also decompose to requirements as described in the following sections. These interfaces are documented in interface sheets for the MRA-Instrument Systems Interface [4], MRA-CMS Interface [5], MRA-Process Systems Interface [6], MRA-AIC Interface [7], MRA-Vessel Systems Interface [8], , MRA-Target Assembly Interface [9], and MRA Remote Handling Interface [10] and MRA-MRA Instrumentation and Controls [11].

2.1 MRA NEUTRON BRIGHTNESS REQUIREMENTS

Table 2.2 MRA-Instrument Systems Interface Derived Requirements

Summary	Description	Decomposed From	Item ID
MRA Neutron Brightness Requirement	The MRA shall deliver 18 neutron beams with the characteristics and locations described in the MRA-Instrument Systems Interface Sheet, S01020500-IS0023. The peak brightness of all neutron beams shall be greater than 2x10^14n/cm^2/sr/Å/s at the neutron wavelength 5Å.	[S.03-1029] - Peak Brightness,[S.03-1030] - Number of Beamlines,[S.03-1031] - Consider Background Effects	2887
MRA Moderator Hydrogen Density Requirement	The hydrogen in both moderators shall have a minimum average density of 72.0 kg/m^3.	[S.03.04-2887] - MRA Neutron Brightness Requirement	2888
MRA Moderator Hydrogen Maximum Temperature Requirement	The hydrogen temperature shall at no point in the moderators exceed 32 K.	[S.03.04-2887] - MRA Neutron Brightness Requirement	2889
MRA Moderator Alignment Requirement	The MRA shall position the moderator viewed faces within +/- 1 mm of their ideal locations during installation.	[S.03.04-2887] - MRA Neutron Brightness Requirement	2323
MRA Moderator Operational Displacement Requirement	The MRA moderators shall have a displacement of 0.3 mm or less relative to the MRA mounting points from installation to 700 kW operation.	[S.03.04-2887] - MRA Neutron Brightness Requirement	2892

Note –requirements with white backgrounds are primary MRA requirements and requirements with grey backgrounds are derived from the above white requirement

The MRA neutron brightness requirement decomposes 3 target systems requirements: peak brightness, number of beamlines, and consider background effects. The requirement is decomposed directly from the STS project Key Performance Parameters for facility neutron performance. It should be noted that the MRA does not achieve this requirement alone, but in coordination with the Target Assembly, Accelerator Systems, and other surround structures. The MRA-Instrument Systems Interface Sheet [4] is an agreement with instrument systems that the neutron beams described in the interface sheet are optimized for meeting instrument performance requirements. Therefore, the MRA geometry that produces the desired neutron beams is the basis for MRA design. The interface also details the moderator viewed face geometry and locations, beamline angles, and guide entrance locations and sizes. Additional requirements on hydrogen state in the moderators and moderator location tolerances are decomposed to ensure that neutron performance is not significantly degraded by the engineering of the MRA. Note – these additional decomposed requirements are not a part of the interface sheet but are decomposed within the MRA to provide the required neutronic performance.

2.2 MRA PROTON BEAM PORT REQUIREMENT

Table 2.3 Proton Beam Port Size Requirement

Summary	Description	Decomposed From	Item ID
MRA Proton Beam Port Size Requirement	The MRA proton beam port shall be 262.8 mm wide by 80.8 mm tall or greater in order to allow for >99.9% of the nominal proton beam profile to pass through to the target.	[S.03-1028] - Accept Beam from Accelerator	2321

The MRA proton beam port was sized to allow >99.9% of the nominal proton beam to pass through the aperture to the target. The sizing of the port is quite conservative due to the uncertainties with the distribution of protons in the outside edges of the beam profile.

2.3 MRA TEMPERATURE REQUIREMENT

Table 2.4 MRA Temperature Requirement Derived Requirements

Summary	Description	Decomposed From	Item ID
MRA Temperature Requirement	The MRA shall be capable of maintaining temperature of the assembly such that structural integrity is unaffected at 700 kW beam power.	[S.03-1028] - Accept Beam from Accelerator	2324
MRA Aluminum Temperature Requirement	The MRA aluminum 6061-T6 structures shall have a maximum operating temperature of 100 C.	[S.03.04-2324] - MRA Temperature Requirement	2325
MRA Stainless Steel Temperature Requirement	The MRA stainless steel structures shall have a maximum operating temperature of 200 C.	[S.03.04-2324] - MRA Temperature Requirement	2326
MRA Beryllium Temperature Requirement	The MRA beryllium shall have a maximum operating temperature of 100 C.	[S.03.04-2324] - MRA Temperature Requirement	2327
MRA Water Temperature Requirement	The MRA cooling water shall have a maximum temperature of 100 C.	[S.03.04-2324] - MRA Temperature Requirement	2328

The MRA temperature requirement ensures that the energy deposition from the proton beam does raise the MRA material temperatures to a point where the materials are degraded and cannot serve their intended function. These temperatures were chosen quite conservatively, especially for stainless steel and beryllium, and could be revisited in future MRA designs. The aluminum temperature was set at 100 C as a conservative basis preventing overaging of the aluminum 6061-T6 and associated loss of the T6 condition properties, but could potentially be relaxed to 120 C. The water temperature requirement was set at 100 C to prevent boiling of water and associated uncertainties but could be relaxed as the water in the MRA is pressurized and has a higher boiling point. The stainless steel and beryllium temperatures were set as goals for minimizing thermal deflection of the MRA but their values due not have a precise origin.

2.4 MRA TEMPERATURE MONITORING REQUIREMENT

Table 2.5 MRA Temperature Monitoring Requirement

Summary	Description	Decomposed From	Item ID
MRA Temperature Monitoring Requirement	The MRA shall include thermocouples for monitoring the temperature of the MRA through the integrated control system per S01020500-IST10126.	[S.03-1042] - Accommodate timing & monitoring	2336

The MRA temperature monitoring requirement specifies thermocouples for monitoring the MRA temperature. No process control is planned for these thermocouples and they will be used for general temperature monitoring and confirmation of MRA analysis. As they are not used for control, complete coverage of MRA structures is not expected and inclusion should not significantly complicate design.

2.5 MRA LIFETIME REQUIREMENT

Table 2.6 MRA Lifetime Requirement Derived Requirements

Summary	Description	Decomposed From	Item ID
MRA Lifetime Requirement	The MRA design shall allow for a lifetime of at least 5 years of operation.	[S.03-1032] - Operational Life	2337
MRA Material Lifetime Requirement	The MRA materials shall allow for a lifetime of at least 5 years.	[S.03.04-2337] - MRA Lifetime Requirement	2338
MRA Cyclic Loading Requirement	The MRA shall be designed for a lifetime of 5 years (25000 hours of 700 kW beam power operation) or more with respect to cyclic loading. The hydrogen boundaries are expected to experience 50 full pressure cycles during commissioning and 10 full pressure cycles per year during operation. Hydrogen pressure is expected to fluctuate 2 bar or less during beam trips and ramps. The water boundaries are expected to experience 20 pump start cycles during commissioning and 4 pump start cycles per year during operation. A pump start cycle is expected to produce an MRA water pressure change of 1 bar or less. No full pressure cycles are expected for the water boundaries. 10000 beam trips are expected to occur each year.	[S.03.04-2337] - MRA Lifetime Requirement	2339

The MRA lifetime requirement is decomposed from the Target Systems Operational Life requirement. Due to the proximity to the target and associated radiation damage rate, the MRA will not be a life of the facility component. A minimum lifetime of 5 years was selected as the MRA is complicated, expensive component with complicated replacement activities which are undesirable to repeat on a shorter interval. In practice, the MRA lifetime should be limited by the radiation damage to the MRA materials to maximize MRA usage. The cyclic loading requirements are imposed by outside systems: Cryogenic Moderator Systems, Process Systems, and Accelerator Systems. The number of cycles imposed by these systems are predicted using conservative estimates from existing facilities and actual STS system performance should be monitored to ensure the predictions are appropriate.

2.6 MRA AVAILABILITY REQUIREMENT

Table 2.7 MRA Availability Requirement Derived Requirements

Summary	Description	Decomposed From	Item ID
MRA Availability Requirement	The MRA design shall allow for greater than 95% availability for greater than 5000 hours of proton beam on target per year with accommodation for maintenance intervals in accordance with the STS operating schedule.	[S.03-1033] - Yearly Operating Hours,[S.03-1034] - Availability,[S.03-3009] - Maintenance & Lifetime Criteria	2344
MRA Maintenance Requirement	The MRA shall be designed to require no maintenance during its lifetime.	[S.03.04-2344] - MRA Availability Requirement	2345
MRA Joining Requirement	The MRA design shall use all welded construction (including friction welds and explosion bonds) on all pressure boundaries.	[S.03.04-2344] - MRA Availability Requirement	2346
MRA Replacement Requirement	The MRA shall be capable of being replaced in a 1400 hour maintenance outage.	[S.03.04-2344] - MRA Availability Requirement	2347

The MRA Availability Requirement is decomposed from Target Systems Yearly Operating Hours, Availability, and Maintenance & Lifetime Criteria Requirements. The Maintenance & Lifetime Criteria Requirement sets maintenance outage length based on predictability and frequency of failure. The MRA is categorized as Group A component which sets the maintenance outage duration of 1400 hours in the MRA Replacement Requirement. Note, this requirement is that the MRA design shall allow the capability; however, STS operations will be responsible for planning outages and may choose a more conservative outage length based on staffing and risk tolerance. The MRA Joining Requirement specifies all welded construction to minimize unexpected leaks and ensure the highest availability for the MRA, as repair is not feasible. Future MRA designs could consider relaxing this requirement to allow high reliability, all metal mechanical seals if design simplification is shown to outweigh potential risk.

2.7 MRA LEAK RATE REQUIREMENT

Table 2.8 MRA Leak Rate Requirement Derived Requirements

Summary	Description	Decomposed From	Item ID
MRA Leak Rate Requirement	The MRA shall maintain leak rates less than what would cause degradation of the core vessel environment or the insulating vacuum surrounding the hydrogen boundary.	[S.03-1034] - Availability	10927
MRA Hydrogen Leak Rate Requirement	All MRA hydrogen boundaries shall have a leak rate of 1 x 10 ^ -9 mbar-l/s or less.	[S.03.04-10927] - MRA Leak Rate Requirement	2351
MRA Water Leak Rate Requirement	All MRA water boundaries shall have a leak rate of 1 x 10 ^ -6 mbar-l/s or less.	[S.03.04-10927] - MRA Leak Rate Requirement	2350
MRA Vacuum Leak Rate Requirement	All MRA vacuum boundaries shall have a leak rate of 1 x 10 ^ -9 mbar-l/s or less.	[S.03.04-10927] - MRA Leak Rate Requirement	2352

The MRA Leak Rate Requirement is decomposed from the Target Systems Availability Requirement as MRA leaks could require replacement of the MRA, potentially compromising STS availability. The MRA Hydrogen and Vacuum Leak Rate Requirements are set to 1 x 10 ^ -9 mbar-l/s or less as these boundaries are critical to the successful operation of the Cryogenic Moderator System and this limit represents the upper end of general purpose helium leak testing equipment. The MRA Water Leak Rate Requirement is set to 1 x 10 ^ -6 mbar-l/s or less as this is several orders of magnitude greater than a leak that would allow liquid water into the core vessel, giving high confidence that the MRA water boundary will remain leak tight.

2.8 MRA STRUCTURAL INTEGRITY REQUIREMENT

Table 2.9 MRA Structural Integrity Requirement Derived Requirements

Summary	Description	Decomposed From	HAR Links	Item ID
MRA Structural Integrity Requirement	The MRA shall maintain structural integrity under all expected loading conditions.	[S.03-1034] – Availability,[S.03-1035] - Safe Operation		2348
MRA Hydrogen Transfer Line Requirement	The MRA hydrogen transfer lines shall be designed and fabricated to 2019 ASME B31.12. Applied seismic loads shall be derived from the NPH BOD.	[S.03.04-2348] - MRA Structural Integrity Requirement	[CDF-9951] - credited DF28,[CDF-9941] - credited DF18,[CAIC-10066] - DF Critical to Event Evaluations 37	2349
MRA Water Piping Requirement	The MRA water piping shall be designed and fabricated to 2020 ASME B31.3. Applied seismic loads shall be derived from the NPH BOD.	[S.03.04-2348] - MRA Structural Integrity Requirement		2353
MRA Hydrogen Vessel Requirement	The MRA hydrogen vessels shall be designed to the intent of the 2023 ASME BPVC. Applied seismic loads shall be derived from the NPH BOD.	[S.03.04-2348] - MRA Structural Integrity Requirement	[CDF-9941] - credited DF18,[CAIC-10066] - DF Critical to Event Evaluations 37	2354
MRA Vacuum Vessel Requirement	The MRA vacuum vessels shall be designed to the intent of the 2023 ASME BPVC. Applied seismic loads shall be derived from the NPH BOD.	[S.03.04-2348] - MRA Structural Integrity Requirement		2893
MRA Reflector Vessel Requirement	The MRA reflector vessels shall be designed to the intent of the 2023 ASME BPVC. Applied seismic loads shall be derived from the NPH BOD.	[S.03.04-2348] - MRA Structural Integrity Requirement		2355
MRA Backbone Requirement	The MRA Backbone shall be designed to the intent of the 2023 ASME BPVC. Applied seismic loads shall be derived from the NPH BOD.	[S.03.04-2348] - MRA Structural Integrity Requirement		10921
MRA Fastener Requirement	The fasteners employed within the MRA shall have a factor of safety of 3 or greater against yielding for all expected loading conditions including lifting and seismic. Applied seismic loads shall be derived from the NPH BOD.	[S.03.04-2348] - MRA Structural Integrity Requirement		11057

The MRA Structural Integrity Requirement is decomposed from the Target Systems Availability Requirement and Safe Operations Requirement, as a structural failure could impact both availability and facility safety. In order to ensure structural integrity with high certainty, the MRA components are designed to the intent of the 2023 ASME BPVC while the hydrogen transfer line is designed to 2019 ASME B31.12 and the water piping is designed to 2020 ASME B31.3. Note that the versions of these codes are consistent with the STS Code of Record Document [12]. As the MRA fasteners are not involved in pressure boundaries, design to the BPVC was not appropriate. Instead, designing to prevent any material yielding was chosen to ensure that alignment between MRA components is maintained. Note that the hydrogen vessel and hydrogen transfer line requirements are linked to credited HAR requirements, as discussed in Section 2.17. For the hydrogen vessel, the HAR [3] does not specify design to the intent of the ASME BPVC, but states, "Moderator and Hydrogen transfer line designed to meet design basis seismic loads." The MRA design has chosen to meet this HAR requirement by specifying design to the intent of the ASME BPVC, which includes guidance on how to apply seismic loads derived from the STS Natural Phenomena Hazard Basis of Design [13]. The Hydrogen System is a high energy system, as defined in Second Target Station (STS) Project Design and Fabrication of Pressure and Vacuum Systems [14]. The hydrogen vessels will follow the referenced ORNL SBMS Equivalent Protection Exhibit. Note that the required Pressure System Hazard Analysis will be developed within the CMS scope, as the CMS provides the pressurization and over pressure protection to the hydrogen vessels.

2.9 MRA-CMS INTERFACE REQUIREMENTS

Table 2.10 MRA-CMS Interface Derived Requirements

Summary	Description	Decomposed From	HAR Links	Item ID
MRA-CMS Interface Requirements	Requirements derived from the MRA-CMS Interface Sheet, S01020500-IST10148	[S.03-1029] - Peak Brightness,[S.03-1035] - Safe Operation		2320
MRA Hydrogen Loop Pressure Drop Requirement	The MRA hydrogen loop pressure drop shall be less than 0.15 bar @ 0.5 l/s and 20 K.	[S.03.04-2320] - MRA-CMS Interface Requirements		2356
MRA Hydrogen Boundary Pressure Requirement	The MRA hydrogen boundary MAWP shall be 19 bara.	[S.03.04-2320] - MRA-CMS Interface Requirements		2357
MRA Vacuum Boundary Pressure Requirement	The MRA vacuum boundary MAWP shall be 2 bara.	[S.03.04-2320] - MRA-CMS Interface Requirements		2358
MRA Vacuum Space Requirement	The MRA vacuum space shall be designed to provide insulating vacuum surrounding all MRA hydrogen boundaries. The vacuum space shall be designed for vacuum service.	[S.03.04-2320] - MRA-CMS Interface Requirements	[CAIC-10078] - DF Critical to Event Evaluations 49	2359
MRA Vacuum Venting Requirement	The MRA vacuum space shall be designed to support venting of hydrogen leaks without exceeding the MAWP.	[S.03.04-2320] - MRA-CMS Interface Requirements	[CAIC-10079] - DF Critical to Event Evaluations 50	3591
MRA Hydrogen Venting Requirement	The MRA hydrogen lines shall be designed to support venting of hydrogen after loss of transfer line vacuum without exceeding the MAWP.	[S.03.04-2320] - MRA-CMS Interface Requirements		3592

The MRA-CMS Interface Requirements are decomposed from the MRA-CMS Interface Sheet [5] and support Target Systems Peak Brightness and Safe Operation Requirements. The CMS supplies the liquid hydrogen that is critical to the MRA meeting Peak Brightness requirements at the specified flowrate, pressure, and temperature. The CMS also provides overpressure protection and venting for the hydrogen system and vacuum for the MRA vacuum boundary. The MRA Hydrogen Loop Pressure Drop Requirement sets the maximum pressure drop from the MRA portion of the hydrogen that the CMS must design around. The Hydrogen and Vacuum Pressure Requirements set the MAWPs to be used in structural integrity verifications and are provided by pressure relief devices in the CMS. The MRA Vacuum Space Requirement specifies that all hydrogen boundaries must be vacuum insulated to minimize static heat loads to the CMS. The Vacuum and Hydrogen Venting Requirements incorporate the MRA portions of the vacuum and hydrogen boundaries into CMS venting requirements. The verification of these venting requirements will be performed within CMS scope. Note that the Vacuum Space and Venting Requirements are linked to HAR critical design features, as discussed in Section 2.17.

2.10 MRA-PROCESS SYSTEM INTERFACE REQUIREMENTS

Table 2.11 MRA Process System Interface Derived Requirements

Summary	Description	Decomposed From	Item ID
MRA-Process Systems Interface Requirements	Requirements derived from the MRA-Process Systems Interface Sheet, S01020500-IST10186	[S.03-1028] - Accept Beam from Accelerator	2360
MRA Water Boundary Pressure Requirement	The MRA water boundaries shall have a MAWP of 5 bara.	[S.03.04-2360] - MRA-Process Systems Interface Requirements	2361
MRA Upper Premoderator Pressure Drop Requirement	The MRA upper premoderator water loop shall have a pressure drop of less than 15 psi at 7.5 gpm and 32.2 C inlet temperature	[S.03.04-2360] - MRA-Process Systems Interface Requirements	2362
MRA Lower Premoderator Pressure Drop Requirement	The MRA lower premoderator water loop shall have a pressure drop of less than 15 psi at 7.5 gpm and 32.2 C inlet temperature	[S.03.04-2360] - MRA-Process Systems Interface Requirements	2363
MRA Upper Reflector Pressure Drop Requirement	The MRA upper reflector water loop shall have a pressure drop of less than 15 psi at 7.5 gpm and 32.2 C inlet temperature	[S.03.04-2360] - MRA-Process Systems Interface Requirements	2364
MRA Lower Reflector Pressure Drop Requirement	The MRA lower reflector water loop shall have a pressure drop of less than 15 psi at 7.5 gpm and 32.2 C inlet temperature	[S.03.04-2360] - MRA-Process Systems Interface Requirements	2365
MRA Backbone Pressure Drop Requirement	The MRA backbone water loop shall have a pressure drop of less than 15 psi at 15 gpm and 32.2 C inlet temperature	[S.03.04-2360] - MRA-Process Systems Interface Requirements	2366

The MRA-Process Systems Interface Requirements are decomposed from the MRA-Process Systems Interface Sheet [6] and support Target Systems Accept Beam from Accelerator Requirement. Process Systems provides the cooling water for the MRA at the specified temperatures and flowrates. The Water Boundary Pressure Requirement sets the MAWP for water boundary structural integrity design and is included as Process Systems provided the pressure relief for the water system. The Pressure Drop Requirements set the pressure drop for each MRA water loop which can be accommodated by the process systems design, in addition to the definition of the flowrate and inlet temperature.

2.11 MRA-AIC INTERFACE REQUIREMENT

Table 2.12 MRA-AIC Interface Requirement

Summary	Description	Decomposed From	Item ID
MRA-AIC Interface Requirement	The MRA design shall provide a clear path through the MRA for the optical path from the TVP mirror to the target assembly face as shown in S03050230_L-M8U-8800-A001-SKEL.PRT as specified in the MRA-AIC Interface Sheet, S03000000-IST10000.	[S.03-1041] - Measure beam profile & position	2371

The MRA-AIC Interface Requirement is decomposed from the MRA-AIC Interface Sheet [7] and supports Target Systems Measure Beam Profile & Position Requirement, and ensures that the optical path from the TVP mirror to the target assembly face is unobstructed by the MRA.

2.12 MRA-TARGET ASSEMBLY-CORE VESSEL CLEARANCE REQUIREMENTS

Table 2.13 MRA-Target Assembly-Core Vessel Clearance Requirements Derived Requirements

Summary	Description	Decomposed From	HAR Links	Item ID
MRA-Target Assembly-Core Vessel Clearance Requirements	The MRA shall not contact the target assembly and shall not contact the core vessel shielding, except for the alignment features and the seismic restraint, by meeting the requirements of the MRA-Target Assembly-Core Vessel Clearance Budget Document.	[S.03-1035] - Safe Operation,[S.03-1034] - Availability	[CDF-9931] - credited DF8	2373
MRA Boundary Requirement	The MRA nominal boundary shall match the boundary defined in the MRA-Target Assembly-Core Vessel Clearance Budget Document.	[S.03.04-2373] - MRA-Target Assembly-Core Vessel Clearance Requirements,[S.03-1478] - Hydrogen Boundary interactions	[CDF-9931] - credited DF8	2374
MRA Profile Tolerance Requirement	The MRA shall have an overall profile tolerance of +/- 1mm to the ideal boundary after installation.	[S.03-1478] - Hydrogen Boundary interactions,[S.03.04-2373] - MRA-Target Assembly-Core Vessel Clearance Requirements	[CDF-9931] - credited DF8	2995
MRA Deflections Requirement	The MRA outside surfaces shall not deflect more than +/- 1.5mm from their installed locations under any expected loading conditions.	[S.03-1478] - Hydrogen Boundary interactions,[S.03.04-2373] - MRA-Target Assembly-Core Vessel Clearance Requirements	[CDF-9931] - credited DF8	2994

The MRA-Target Assembly-Core Vessel Clearance Requirements are decomposed from Target Systems Safe Operation and Availability Requirements and ensure that the MRA does not contact the Target Assembly and Core Vessel Shielding except for alignment and seismic restraint features. The derived requirements set the MRA nominal boundary, the MRA installed profile tolerance to the boundary, and the MRA deflection requirements as defined in the MRA-Target Assembly-Core Vessel Clearance Budget [15]. Note that the Clearance Requirement and all derived requirements are linked to HAR critical design features, as discussed in Section 2.17.

2.13 MRA SHIELDING REQUIREMENT

Table 2.14 MRA Shielding Requirement

Summary	Description	Decomposed From	Item ID
MRA Shielding Requirement	The MRA design shall support the Target Systems Monolith meeting the Target Systems Radiation Shielding Requirement. Note: The MRA design must be carefully coordinated with surrounding structures to minimize the impact of streaming gaps.	[S.03-1036] - Radiation Safety	3593

The MRA Shielding Requirement is decomposed from the Target Systems Radiation Safety Requirement. Although the MRA design must support this requirement, it cannot be met by the MRA alone but instead must be met by the Target Systems as a whole by careful coordination of materials, gaps, and utility routing to minimize radiation streaming and meet radiation safety requirements.

2.14 MRA REMOTE HANDLING REQUIREMENT

Table 2.15 MRA-Remote Handling Requirement Derived Requirements

Summary	Description	Decomposed From	Item ID
MRA Remote Handling Requirement	The MRA design shall include features to allow for remote handling and replacement	[S.03-1037] - Replacement and Disposal Path	2329
MRA Lifting Stud Requirement	The MRA shall include a 1.5"-8 UN threaded stud located over the assembly CG.	[S.03.04-2329] - MRA Remote Handling Requirement	2330
MRA Pipe Cutting Requirement	The MRA piping shall be designed for cutting above the upper shield block.	[S.03.04-2329] - MRA Remote Handling Requirement	2331
MRA Blowdown Requirement	The MRA shall be capable of blowdown of water passages such that the subsequent water level is at or below the top of the MRA shield block.	[S.03.04-2329] - MRA Remote Handling Requirement	3588
MRA Removal Requirement	The MRA shall be capable of vertical removal from core vessel after the removal of 3 target segments.	[S.03.04-2329] - MRA Remote Handling Requirement	3589
MRA Installation Requirement	The MRA shall be capable of vertical installation after the removal of 3 target segments.	[S.03.04-2329] - MRA Remote Handling Requirement	3590
MRA Utilities Dose Rate Requirement	The dose rates at 30 cm from the MRA hydrogen transfer line connection and water line connections shall be 100 mrem/hour or less after MRA operation and decay time of 8 hours to allow for hands on replacement of these connections with the target station in nominal operating configuration with the exception of the removal of the Core Vessel MRA hatch.	[S.03.04-2329] - MRA Remote Handling Requirement	10944

The MRA Remote Handling Requirement is decomposed from the Target Systems Replacement and Disposal Requirement. The MRA-Remote Handling Interface Sheet [10] describes MRA requirements to facilitate MRA replacement and disposal. The MRA Piping Requirement ensures feasibility of cutting of MRA upper piping so that the MRA can fit into a reasonable handling cask for transport to the service cell. This requires that the piping arrangement should be designed for cutting and that the radiological conditions in the target drive room are acceptable for performing the cutting operation. Additionally, the MRA blowdown requirement ensures the capability of the blowing water out of the MRA to below the level of the piping cuts prior to cutting. The MRA Removal and Installation Requirements ensure capability for vertical installation and removal through the void opened by the removal of 3 target segments. The MRA must also fit through the vessel systems structures and remote handling hatches above to allow for vertical removal and installation. The MRA Utilities Dose Rate Requirement ensures that hands on maintenance is possible for the MRA water flange connection and MRA transfer line welded connection as these are not designed to be remote handling tasks.

2.15 MRA DISPOSAL REQUIREMENT

Table 2.16 MRA Disposal Requirement Derived Requirements

Summary	Description	Decomposed From	Item ID
MRA Disposal Requirement	The MRA shall be capable of shipping to and disposal at a waste facility at the end of life.	[S.03-1037] - Replacement and Disposal Path	2332
MRA Size Requirement	The MRA shall fit within a liner designed to fit in the TN-RAM shipping cask after removal of piping above the upper shield block.	[S.03.04-2332] - MRA Disposal Requirement	2333
MRA Mass Requirement	The mass of the MRA shall be less than 2400 kg after removal of piping above the upper shield block and subsequent drying of water passages.	[S.03.04-2332] - MRA Disposal Requirement	2334
MRA Shipping Requirement	The MRA shall meet the radiological requirements for shipping in the TN-RAM cask after operation of 6 years and decay time of 2 years or less.	[S.03.04-2332] - MRA Disposal Requirement	2335
MRA Disposal Classification Requirement	The MRA shall meet the waste acceptance criteria for Nevada National Security Site after operation of 6 years and decay time of 2 years or less.	[S.03.04-2332] - MRA Disposal Requirement	2322

The MRA Disposal Requirement is decomposed from the Target Systems Replacement and Disposal Path Requirement. The MRA Disposal Requirement ensures that a feasible path to shipping to and disposal at a waste facility exists for the MRA at the end of its life. Note that this requirement does not dictate that the identified waste transportation and disposal solution will be used at the end of MRA but instead ensures that feasible solutions exist. The derived requirements assume the TN-RAM shipping cask as the shipping solution and Nevada National Security Site as the disposal solution. Other pathways which were not evaluated may be available.

2.16 MRA ASSEMBLY STRUCTURE REQUIREMENT

Table 2.17 MRA Assembly Structure Requirement

Summary	Description	Decomposed From	HAR Links	Item ID
MRA Assembly Structure Requirement	The hydrogen vessels shall be located within the vacuum vessels, which are located in the central region of the reflector vessels and surrounded by premoderator water and beryllium, providing 2 layers of aluminum and the beryllium reflector around each hydrogen vessel to prevent potential contact.	[S.03-1035] - Safe Operation	[CAIC-10082] - DF Critical to Event Evaluations 53	10931

The MRA Assembly Structure Requirement is decomposed from the Target Systems Safe Operations Requirement and is also a critical design feature in the HAR, as discussed in section 2.17.

2.17 MRA REQUIREMENTS FROM THE HAZARD ANALYSIS

Table 2.18 MRA Hazard Analysis Report Linked Requirements

Summary	Description	Decomposed From	HAR Links	Item ID
MRA Hydrogen Transfer Line Requirement	The MRA hydrogen transfer lines shall be designed and fabricated to 2019 ASME B31.12. Applied seismic loads shall be derived from the NPH BOD.	[S.03.04-2348] - MRA Structural Integrity Requirement	[CDF-9951] - credited DF28, [CDF-9941] - credited DF18, [CAIC-10066] - DF Critical to Event Evaluations 37	2349
MRA Hydrogen Vessel Requirement	The MRA hydrogen vessels shall be designed to the intent of the 2023 ASME BPVC. Applied seismic loads shall be derived from the NPH BOD.	[S.03.04-2348] - MRA Structural Integrity Requirement	[CDF-9941] - credited DF18,[CAIC-10066] - DF Critical to Event Evaluations 37	2354
MRA Vacuum Space Requirement	The MRA vacuum space shall be designed to provide insulating vacuum surrounding all MRA hydrogen boundaries. The vacuum space shall be designed for vacuum service.	[S.03.04-2320] - MRA-CMS Interface Requirements	[CAIC-10078] - DF Critical to Event Evaluations 49	2359
MRA Vacuum Venting Requirement	The MRA vacuum space shall be designed to support venting of hydrogen leaks without exceeding the MAWP.	[S.03.04-2320] - MRA-CMS Interface Requirements	[CAIC-10079] - DF Critical to Event Evaluations 50	3591
MRA-Target Assembly-Core Vessel Clearance Requirements	The MRA shall not contact the target assembly and shall not contact the core vessel shielding, except for the alignment features and the seismic restraint, by meeting the requirements of the MRA-Target Assembly-Core Vessel Clearance Budget Document.	[S.03-1035] - Safe Operation,[S.03-1034] – Availability,[S.03-1478] - Hydrogen Boundary interactions	[CDF-9931] - credited DF8	2373
MRA Boundary Requirement	The MRA nominal boundary shall match the boundary defined in the MRA-Target Assembly-Core Vessel Clearance Budget Document.	[S.03.04-2373] - MRA-Target Assembly-Core Vessel Clearance Requirements,[S.03-1478] - Hydrogen Boundary interactions	[CDF-9931] - credited DF8	2374
MRA Profile Tolerance Requirement	The MRA shall have an overall profile tolerance of +/- 1mm to the ideal boundary after installation.	[S.03-1478] - Hydrogen Boundary interactions,[S.03.04-2373] - MRA-Target Assembly-Core Vessel Clearance Requirements	[CDF-9931] - credited DF8	2995
MRA Deflections Requirement	The MRA outside surfaces shall not deflect more than +/- 1.5mm from their installed locations under any expected loading conditions.	[S.03-1478] - Hydrogen Boundary interactions,[S.03.04-2373] - MRA-Target Assembly-Core Vessel Clearance Requirements	[CDF-9931] - credited DF8	2994
MRA Assembly Structure Requirement	The hydrogen vessels shall be located within the vacuum vessels, which are located in the central region of the reflector vessels and surrounded by premoderator water and beryllium, providing 2 layers of aluminum and the beryllium reflector around each hydrogen vessel to prevent potential contact.	[S.03-1035] - Safe Operation	[CAIC-10082] - DF Critical to Event Evaluations 53	10931

Table 2.19 Hazard Analysis Report Requirements Relevant to the MRA

Summary	Description	Item ID
credited DF8	Large components are structurally anchored and building structures seismically qualified to prevent collapse, protect evacuation paths, and protect applicable confinement of hazardous material.	9931
credited DF18	Moderator and Hydrogen transfer line designed to meet design basis seismic loads.	9941
credited DF28	Hydrogen transfer lines shall be designed and constructed in accordance with the applicable portions of ASME B31.12 and shall remain capable of performing their intended safety function following a design basis seismic event.	9951
DF Critical to Event Evaluations 37	Moderator and Hydrogen transfer line designed to meet design basis seismic loads.	10066
DF Critical to Event Evaluations 49	A vacuum layer surrounds the hydrogen vessel and serves as insulation between the cold hydrogen (20 degrees K) and the pre-moderator/reflector (Loop 2) water.	10078
DF Critical to Event Evaluations 50	Vacuum vessel is designed to contain a moderator vessel failure and hydrogen release.	10079
DF Critical to Event Evaluations 53	Hydrogen vessels are buried in the reflector with two layers of aluminum and the beryllium reflector preventing any contact.	10082

The MRA must meet the requirements imposed by the STS Project Hazard Analysis Report [3] for safe operation of the STS facility. Note, many of these MRA requirements are decomposed from other Target Systems requirements, in addition to the Safe Operations requirements. Where MRA requirements are meeting requirements from the HAR, they are noted in the HAR link column, compiled in Table 2.18. The HAR requirements relevant to the MRA are listed in Table 2.19. The requirements for the MRA from the HAR all relate to preventing release of hydrogen by designing pressure boundaries to ASME BPVC and ASME B31.12 for all expected loading scenarios, including seismic. Note that the MRA-CMS Interface Sheet [5] transfers the scope for performing B31.12 hydrogen piping analysis and all venting analyses to the Cryogenic Moderator System, where the majority of the hydrogen piping resides.

The HAR also includes a requirement that seismic loads on surrounding components shall not cause interaction with the hydrogen boundary that could cause a release of hydrogen. Rather than attempt to define uncertain interactions, target systems will prevent contact between the MRA and surrounding structures as described in Target Systems requirement 1478. This requirement decomposes to the MRA as a nominal boundary and an allowable deviation from the boundary under all loading scenarios.

3. MRA DESIGN

3.1 OVERVIEW

In the STS design, a pulsed proton beam is converted to pulsed high brightness cold neutron beams optimized for neutron scattering experiments. The Target Systems group is responsible for designing a Target Assembly to produce neutrons from the pulsed proton beam and a Moderator Reflector Assembly to convert the neutrons emitted from the target to cold neutron beams useful for neutron scattering experiments on the instruments designed by Instrument Systems group.

During conceptual design [16], a rotating solid tungsten target was chosen as the target concept for the STS. In order to produce the required neutron performance, two compact liquid hydrogen moderators are located adjacent to the target: a cylinder directly above and a triangular arrangement of three tubes directly below, as shown in **Figure** 3.1 and the MRA drawing [17]. The moderators are surrounded by light water premoderators and beryllium reflectors within the reflector vessels in order to improve neutron performance. Note that the neutronic performance of the MRA is almost entirely based on the structures within the reflector vessels and the coupling of the reflector vessels to the Target Assembly.

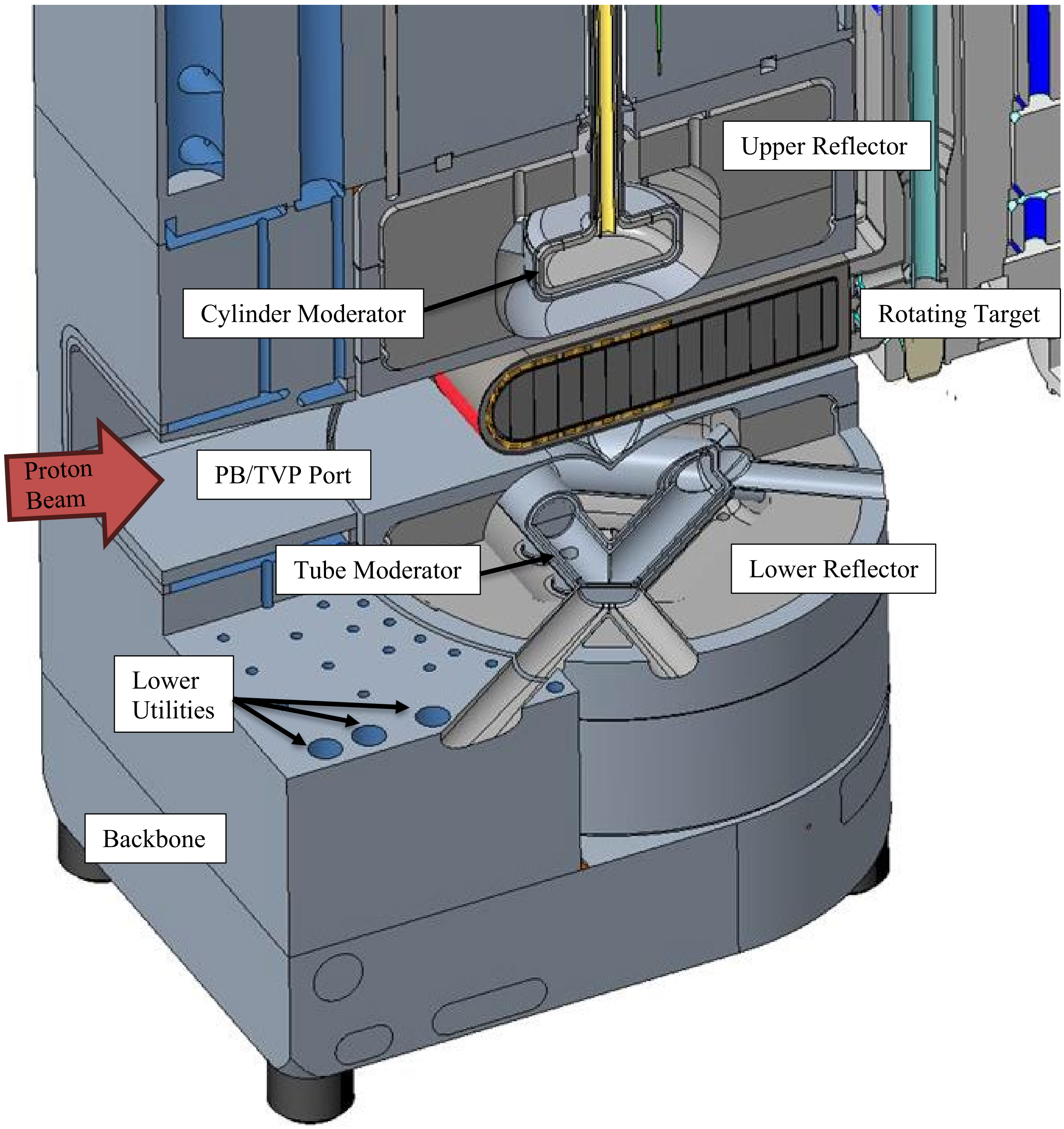


Figure 3.1 Moderator Reflector Assembly and Target Assembly Layout.

During conceptual design, many concepts were examined for the construction and cooling of the reflector vessel. Brazing cooling structures to the beryllium was considered but dismissed due to risk compared to flood cooling. Early concepts also considered heavy water cooling of the reflectors; however, this requires an extra aluminum wall separating the light water premoderator zones from the heavy water reflector cooling, adding complexity and increasing distance between the reflectors and the moderators. Early conceptual simulations showed that removing the extra separating wall offset the effect of switching from heavy water to light water cooling around the reflector. Therefore, the simpler solution was chosen and both the premoderator and reflector cooling is light water. This has an additional advantage of simplifying Process Systems by removing the heavy water cooling loop.

The other structures in the MRA are for supporting and aligning the reflector vessels as well as providing shielding. The geometry of the rotating target requires the reflector vessels be supported on the upstream end, relative to the proton beam. This C-shaped support structure, called the backbone, must have a proton beam port large enough to allow the proton beam to pass through to the target without significant interaction. The upper side of the proton beam port is also enlarged to allow the Target Viewing Periscope (TVP) a full view of the proton beam incident on the target face. The backbone is just wide enough to allow utilities (hydrogen and water) for the lower moderator and reflector vessel to pass on either side of the proton beam port. The backbone is a water cooled stainless steel structure which is designed to minimize thermal deflections of the moderators from neutronic heating. A shield block has been added above the upper backbone to reduce dose rates during MRA remote handling pipe cutting activities in preparation for removal of the MRA from the core vessel. In order to provide precise location of the moderators, the backbone is supported by quasi kinematic mounts and is precisely cooled in order to limit thermal displacement of the moderators. The quasi kinematic mounts consist of 3 alignment blocks with flats on the bottom to support the MRA mass and slots aligned to the moderator centers which interface to MRA alignment pins in the core vessel shielding. This quasi kinematic mounting scheme was chosen over the alternative canoe spheres in v-blocks, which are fully kinematic, because of the decoupling of horizontal and vertical misalignment and ease of alignment verification with dimensional inspection of the alignment blocks. A seismic block has been added to the top of the MRA shield block, which interfaces to a pin in the core vessel shielding, to restrain tipping of the MRA during a seismic event. The MRA water piping and hydrogen transfer line extend from the top of the backbone to above the core vessel shielding where they connect to their interfacing systems, each jogging 2 times to reduce radiation streaming. Thermocouples are included for monitoring MRA temperature although they are located in or above the upper backbone to reduce installation complication and risk.

The materials of construction for the reflector vessels were chosen to maximize neutron performance. Aluminum was chosen as the structural material for the hydrogen vessels, vacuum vessels and reflector vessels due to its low neutron scattering cross section. Al 6061-T6 was selected due to its radiation damage resistance, excellent cryogenic properties, high strength, high thermal conductivity, and corrosion resistance. This alloy has a long history of success in analogous applications at SNS and HFIR [18]. Although other aluminum alloys could be suitable and would provide more straightforward welding, namely Al 5083-0, Al 6061-T6 was selected as the low risk choice in this critical application. Beryllium was chosen as the reflector material based on maximizing neutron performance. In conceptual design, other reflector materials were investigated; however, no alternatives approached the performance of beryllium. While beryllium is expensive, produces hazardous dust when machined, and is extremely brittle, it does present some engineering advantages such as high thermal conductivity and low coefficient of thermal expansion. 316L stainless steel was chosen for the backbone material due to its long history of use in radiation environments, general corrosion resistance, high weldability, and shielding properties. The MRA shield block is made from carbon steel due to its high thermal conductivity relative to austenitic stainless steels so that the shield block can be contact cooled from the backbone below it, simplifying MRA design. Carbon steel also activates less than stainless steels during neutron irradiation, lowering dose rates above the MRA during MRA removal activities.

The number of moderators, number of beamlines, and angular orientation of the beamlines to be included in the STS design were determined during the conceptual design phase of the project [16] while the characteristics of those neutron beams such as the size of the viewed area of the moderator [19], the maximum acceptance aperture of the guide entrance, the distance of the guide entrance from the viewed face of the moderator, and the desired neutron beam characteristics have been determined by the Instrument Systems group in collaboration with the Target Systems group during early preliminary design. After preliminary design, the STS project reduced the number of beamports from 22 to 18 to give each instrument a larger angular segment but later added 2 dual beamports which accommodate 2 beamlines each. These changes have been documented in the latest MRA-Instrument Systems Interface Sheet [4] and have been incorporated into the MRA final design.

During conceptual design, the MRA was simplified to ease manufacturing difficulty while still maintaining the desired cryogenic hydrogen vessel, vacuum vessel, light water premoderator and beryllium reflector topologies. The helium layer which existed around the SNS first target station moderators was eliminated to ease manufacturing and increase neutronic performance, resulting in the vacuum vessels being integrated into the reflector vessels, and was justified in [20]. The premoderator vessels were eliminated as the beryllium could be used to define the premoderator boundary while the light water premoderator was used to remove heat from the beryllium. This elimination removed the option of using heavy water as a coolant for the reflector and instead light water will be used; however, because of the relatively low power of STS and the compact size of the reflectors, cooling can be accomplished from the premoderator zone and the outer surfaces of the reflector which minimizes the neutronic performance penalty from light water reflector cooling. The described topology was analyzed with varying hydrogen and beryllium sizes to create curves for hydrogen vessel, vacuum vessel, and reflector vessel wall thicknesses as described in [21]. These wall thickness curves were then used in the MRA neutronics optimization to add feedback from engineering reality to the neutronics optimization.

3.2 MRA NEUTRONICS OPTIMIZATION

Early in preliminary design, the Neutronics Team completed a moderator optimization which determined optimal MRA configurations for peak brightness, time-average brightness, and a middle configuration between the two for each moderator, as shown in Table 3.1 and Table 3.2 [22]. Source files for all configurations for both moderators were supplied to the Instrument Systems group for further evaluation. After detailed analysis on representative instruments, the Instrument Systems group decided that the middle configuration resulted in the best instrument performance for both the upper, cylinder moderator and lower, tube moderator [23].

Table 3.1 Preliminary Cylinder Moderator Optimal Parameters

Optimized for	Para-H Radius (mm)	Lower Premod. (mm)	Radial Premod. (mm)	Top Premod. (mm)	Be Radius (mm)	Offset[1] (mm)
Peak	40	27.5	20	20	162.5	87
Mid	**50**	**30**	**29**	**29**	**172.5**	**87**
Tave	62	30	33	33	182.5	87

[1]Offset is the distance from the front edge of tungsten to the vertical axis of the cylindrical moderator.

Table 3.2 Preliminary Tube Moderator Optimal Parameters

Optimized for	Para-H Tube Diameter (mm)	Para-H Tube length[1] (mm)	Premod. Thickness (mm)	Be Radius (mm)	Offset[2] (mm)
Peak	30	125	25	182.5	87
Mid	**30**	**170**	**27.5**	**182.5**	**87**
Tave	30	210	27.5	182.5	87

[1]The length of the tube perpendicular to the proton beam
[2]Offset is the distance from the front edge of the tungsten to the point defined by the intersection of angular bisectors of the tube moderator.

Early in final design, the Neutronics Team completed an additional moderator optimization with the most recent Target Assembly design, which had changed significantly since the previous optimization, and additional degrees of freedom in the tube premoderator geometry [24]. The final optimization resulted in the same optimal parameters as the preliminary optimization for the cylinder moderator and tube hydrogen vessel with slight changes to the tube premoderator geometry to take advantage of the additional degrees of freedom. The final moderator parameters are shown in Table 3.3. This additional optimization round also showed that while target assembly does impact the neutron beam performance, the optimal moderator design is insensitive to the target assembly design. So, if target design changes in the future, the optimal moderator design is not expected to change.

Table 3.3 Final Moderator Optimization Selected Parameters

Moderator	H_2 Tube Length / Cylinder Radius (mm)	Light Water Premoderator				Beryllium Radius (mm)
		Top Thickness (mm)	Bottom Thickness (mm)	Center Thickness (mm)	Side Thickness (mm)	
Tube	170	26.5	30	20	30	172.5
Cylinder	50	29	30		29	172.5

3.3 FINAL MRA MODEL

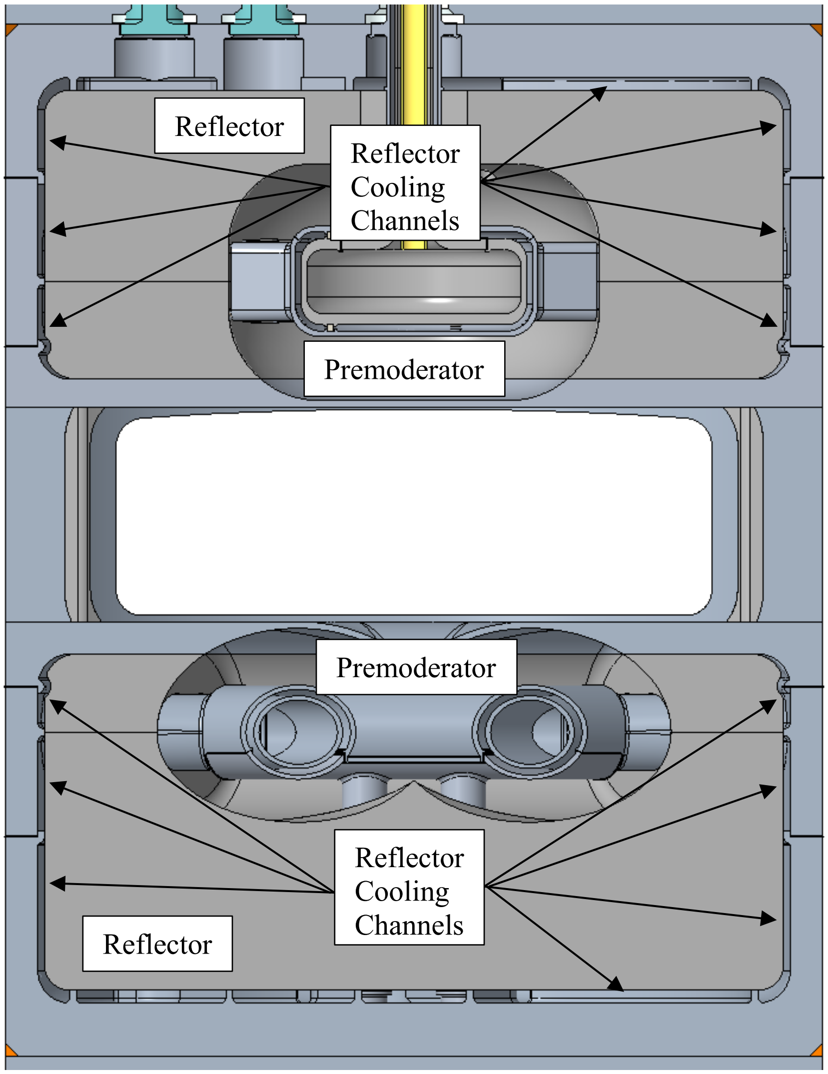
The moderator configurations optimized by the neutronics team and chosen by the instrument systems team serve as the basis for the MRA design. Additional details, such as the bump outs in the neutron extraction port to allow extraction of the QIKR neutron beams at angles offset from horizontal were added to the model, as they were not included in the optimizations for simplicity. Even though the wall thickness curves used in the moderator optimization predicted the required wall thicknesses, these wall thicknesses were reoptimized for the final configuration based on internal pressure loadings to create the Final MRA CAD Model [25].

The water cooling flow patterns for the MRA were also developed in preliminary design and refined as part of the Final MRA Model. Both beryllium reflectors and reflector vessels are cooled by light water in the premoderators and on the outside edges of the reflectors, except on the target side of the reflectors, which are fed by 2 water supplies per reflector vessel, as shown in Figure 3.2. The premoderator zones have entry jets and exits located to promote constant flow without large recirculation zones. The reflector cooling channels on the outside of the reflectors direct flow to the target side outside edge of the vessels before splitting and making 3 circumferential half sweeps on the way back to the opposite side of the reflector. The water in the reflector vessels joins together in both reflectors just before exiting on the flat sides opposite the target.

After exiting the lower reflector vessel, the water then travels through the lower backbone in an array of long drilled holes from the downstream proton beam end back towards the middle backbone, as shown in Figure 3.3. After exiting the upper reflector vessel, the water travels in a pipe to the top side of the upper backbone, where flows through an array of long drilled holes in the top half of the upper backbone from the downstream proton beam end back towards the middle backbone. An independent backbone cooling line feeds water to the top reflector side of the middle backbone which then travels down through an array of holes, around the proton beam port, and then through a lower array of holes to the bottom of the middle backbone. The flow then moves away from the reflectors and reverses course through additional arrays of holes and around the proton beam part to the top of the middle backbone. The middle backbone flow then enter the upper backbone, where it travels in an array of holes in the downstream proton beam direction before reversing direction and entering another ray of holes in the opposite direction. The flow from all of the cooling water joins in passages in the upper backbone and exits into a return pipe at the top of the upper backbone. This pipe, along with all 5 MRA water supplies, are routed in chases and passages through the MRA shield block. All the water pipes jog into a chase where they are aligned in a row at the top of the MRA shield block. This row of water pipes takes one additional jog about halfway to the top of the core vessel shielding. Above the core vessel shielding the water lines are connected at flanges to flexible jumpers supplied by vessel systems which route water to and from the Target Process Systems.

The transfer line routing patterns were developed during preliminary design. Early in preliminary design, the CMS was envisioned as two independent hydrogen loops feeding the moderators independently. Maturing of the CMS design resulted in a switch to a single hydrogen loop with the moderators being supplied in series, simplifying and increasing robustness of CMS design and reducing the hydrogen inventory. The main advantage for the MRA of this change is reduction to a single transfer line, giving a little extra space for the crowded utility routing. The disadvantage is that both hydrogen vessels are now on the same loop, so any failure will remove the option of continuing operation with a single moderator. This small disadvantage simply does not outweigh the large advantages of overall simplification.

Therefore, the hydrogen now enters the MRA in a single transfer line from the CMS transfer line, as shown in Figure 3.4. Above the upper backbone plate, the hydrogen supply is routed to the upper moderator. The return from the upper moderator is an annular channel around the supply, which is broken off at a Y above the upper backbone plate. The return is then routed back towards and through the middle backbone to reach the lower moderator. The lower moderator return is then routed back to and through the middle backbone and back into the return of the transfer line. The transfer line makes two jogs, one at the top of the backbone shield block, and one half way from there to the top of the core vessel shielding. The hydrogen boundary is surrounded by an uninterrupted, all welded, vacuum boundary, which is connected to and supplied vacuum by the CMS transfer line vacuum space.



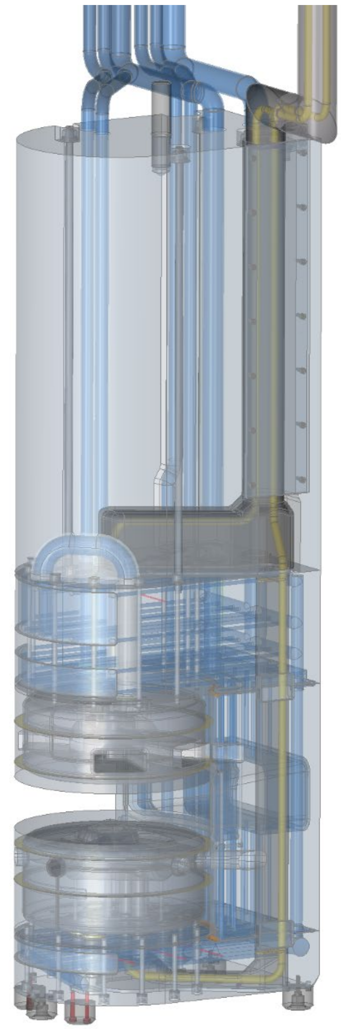


Figure 3.2 Reflector Vessel (left)

Figure 3.3 Backbone Cooling Scheme (right).

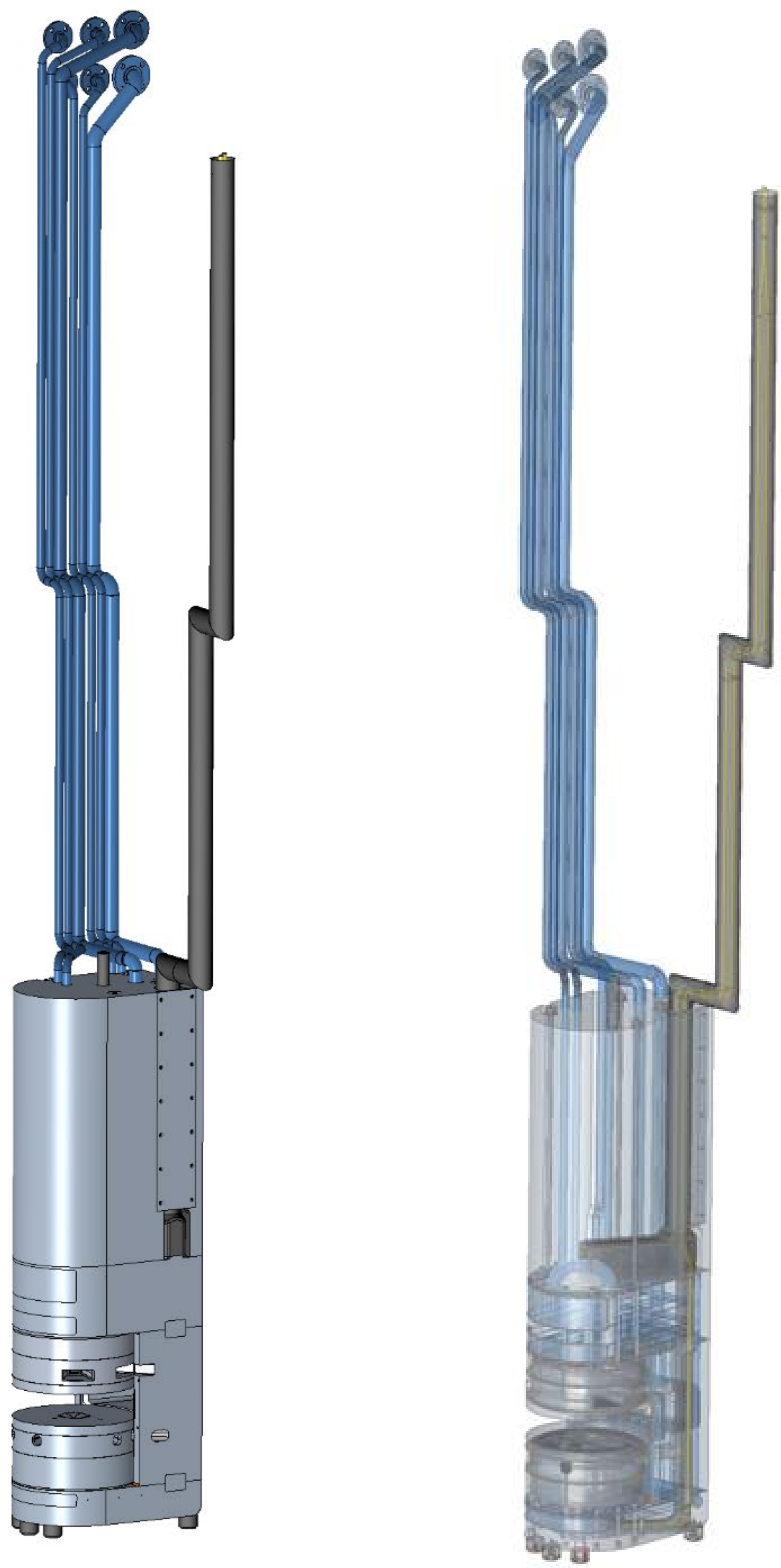


Figure 3.4 Preliminary MRA Utility Routing – chases around the upper utility lines are formed by the Vessel Systems shielding.

3.4 NEUTRONICS ANALYSIS

The first step to take with the final MRA model was to confirm that the performance predicted by the optimization was not degraded by the additional engineering details. The neutronics analysis [26] of the final MRA model confirmed no degradation of performance from additional detail, meeting the neutron brightness KPP with healthy margin of 24% for the cylinder moderator and 50% for the tube moderator, as shown in Figure 3.5.

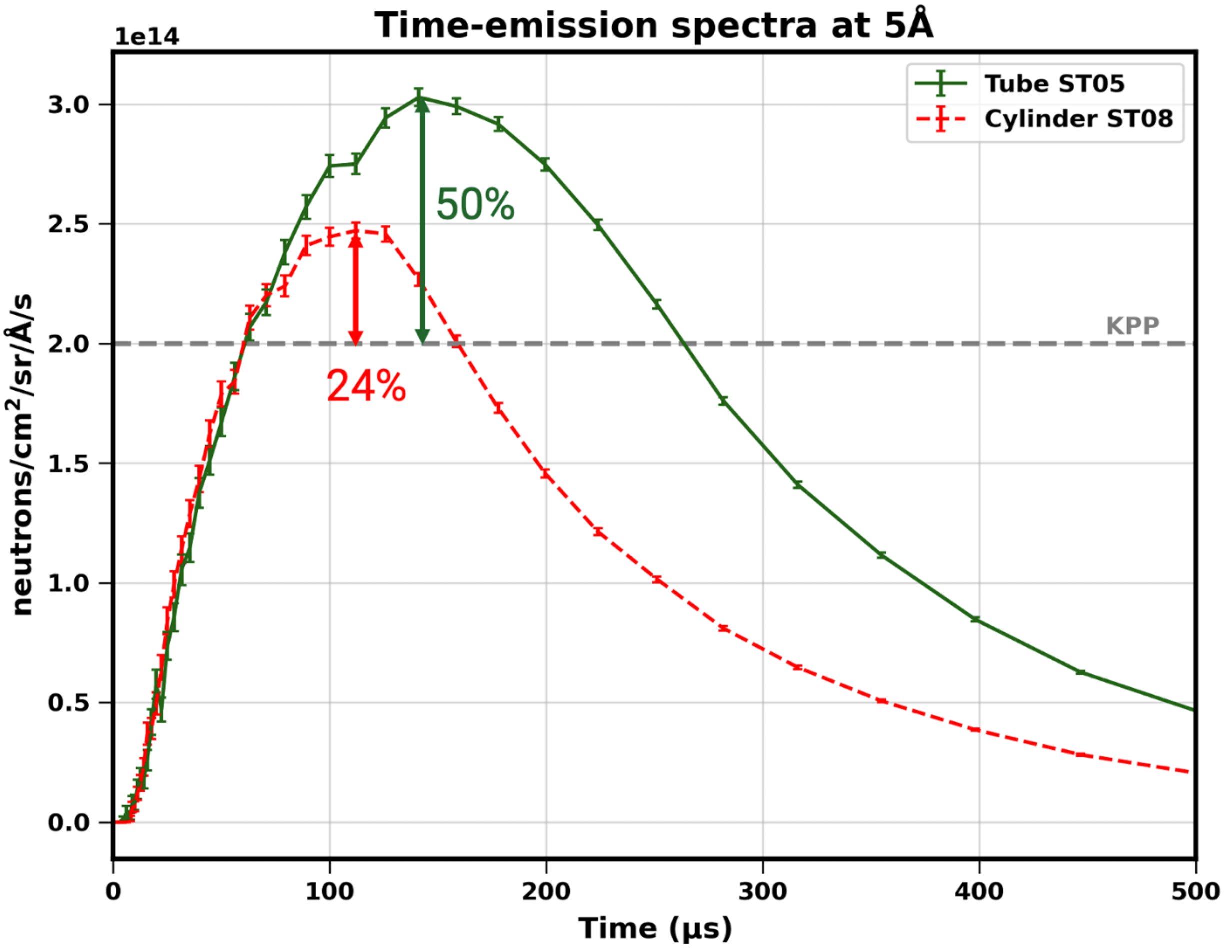


Figure 3.5 Time-emission Spectra for the Tube and Cylinder Moderators relative to the STS KPP.

Once the neutronic performance was confirmed, the neutronics analysis continued to provide energy deposition data for the MRA. Detailed data was provided for all MRA structures. This energy deposition data was used to provide heat loads for the MRA interfaces with the CMS [5] and Process Systems [6].

3.5 THERMAL HYDRAULIC ANALYSIS

This data was also used as input for thermal hydraulic analyses for the hydrogen vessels and associated piping as well as the rest of the MRA structures which are water cooled. The MRA thermal hydraulic analysis provided verification of all temperature and pressure drop requirements [27]. Additionally, hydrogen state requirements for density and temperature in the moderators were confirmed ensuring expected neutronic performance.

3.6 HYDROGEN BOUNDARY STATIC HEAT LOAD ANALYSIS

The static heat load from the warm MRA structures to the hydrogen boundary, which operates at cryogenic temperatures, was analyzed [28]. As the hydrogen boundary operates within continuous vacuum insulation, convection heat transfer is negligible while radiation to all surfaces and conduction through the hydrogen vessel and hydrogen tubing supports were considered. The resulting heat load was 77 W for beam off conditions and 96 W for beam on condition. The difference is caused by increased warm MRA structure temperatures when the beam is on. These heat loads are reported in the MRA-CMS Interface Sheet for use in CMS design.

3.7 LOSS OF COOLING ANALYSIS

While the MRA does not produce enough decay heat to be concerned about overheating in loss of cooling scenarios, it does feature cryogenic temperatures in close proximity to water cooled structures, which could pose a risk of freezing water if water flow is lost while hydrogen flow is maintained [29]. Using the hydrogen boundary static heat loads previously analyzed, the minimum time to initiation of freezing of water within the MRA was estimated to be 33 hours. This is considered sufficient time to evaluate troubleshoot the loss of cooling condition and potentially vent the hydrogen system if water flow is not restored with significant margin to freezing.

3.8 STRUCTURAL ANALYSIS

The temperature profiles from the thermal hydraulic analyses described in section 3.5 were used as input to structural analyses for the reflector vessel and the backbone [30]. Note that because the coefficient of thermal expansion of aluminum is nearly 0 at 20K, no thermal stress analysis was performed for the hydrogen vessels, and their structural analysis only considered internal pressure [31]. Structural analysis of the reflector vessels and backbone considered deadweight, fastener preload, internal pressure, thermal stress, and seismic loading. The internal pressures used for the structural analyses were the maximum allowable working pressures defined in the interfaces with CMS [5] and Process Systems [6] – 2 bar for vacuum boundaries, 19 bar for hydrogen boundaries, and 5 bar for water boundaries. These structural analyses demonstrated that the hydrogen, vacuum, and reflector vessels and the backbone were designed to the intent of the 2023 ASME BPVC. Cyclic loading was considered in these analyses and the minimum lifetime against fatigue was shown to be 20 years in the vacuum tube connecting the upper reflector vessel and backbone. The MRA structural analysis also provided verification that the moderator displacement limit was not exceeded [30]. The MRA moderator displacement was also combined with MRA tolerances and Core Vessel displacements in the Moderator Deflection and Tolerance Analysis [32] which determined the worst case moderator alignment for subsequent neutronics analysis. The deflections of the MRA seismic block were used in the MRA Seismic Block Deflection Analysis to ensure the block and mating pin do not interact except during a seismic event [33]. The MRA boundary deflection limits were shown to be met for all outside MRA surfaces with the largest deflections of slightly over 1 mm seen in the flat reflector vessel walls facing the target. The MRA fasteners which hold the MRA shield block and reflector vessels to the backbone, the alignment blocks and seismic block to the MRA, and the threaded rod for lifting were analyzed and shown to meet the requirement of no yielding with a factor of safety of 3 or greater for all loading conditions, including seismic and lifting [34].

3.9 PIPING ANALYSIS

Piping analysis for both the MRA water piping and MRA hydrogen transfer line will be completed within the CMS scope [5]. This analysis has yet to be completed but will be completed before the Procurement Readiness Review. This analysis is not expected to impact the piping design but is expected to add pipe supports to the MRA.

3.10 ADDITIONAL NEUTRONICS ANALYSES

Additional neutronics analyses were performed to confirm other MRA requirements [26]. A worst case alignment analysis was performed proving acceptable neutronic performance. The worst case alignment is described in the Moderator Deflection and Tolerance Analysis [32]. A material damage rate analysis was performed, revealing an expected MRA lifetime of 6.5 years, limited by dpa damage. A streaming analysis was performed for the target monolith shielding, revealing significant streaming from the MRA hydrogen transfer line chase and MRA water piping chase, requiring the addition of small core vessel shield blocks over the tops of the chases [35]. An activation analysis was performed to determine the dose rates in the target drive room once the Vessel Systems MRA Shield Block is removed to allow access to the MRA after 6 years of operation [36]. The dose rates in the target drive room were evaluated to be acceptable for pipe cutting with long handled tools and other planned activities [37]. Finally, the MRA radionuclide inventory after 6 years of operation was evaluated at several decay time lengths [38] in order to support evaluation of MRA shipping and disposal requirements.

3.11 MRA SHIPPING AND DISPOSAL

The most problematic aspect of the activated MRA for shipping is the neutron production caused by the beryllium reflectors. The most problematic aspect of the activated MRA for disposal are the transuranic isotopes produced from uranium impurities in the beryllium reflectors. The predicted MRA nuclide inventory was determined to exceed the classification requirements for Class C waste, indicating that the activated MRA would be limited to potential disposal at the Nevada National Security Site. Confirmation of acceptance of the activated MRA radionuclide inventory at the Nevada National Security Site is ongoing. The activated MRA evaluation against radiological requirements for shipment in the TN-RAM shipping cask is still ongoing as well. The MRA design was confirmed to meet the size and weight limits for the TN-RAM cask [37].

3.12 INSTALLATION

The installation of the MRA is straightforward other than the final preparation of the initial assembly to meet alignment requirements based on the as installed mounting interface which is described in the MRA Installation Plan [39].

3.13 REMOTE HANDLING

The MRA was designed to allow for remote handling and replacement following operation, and has been evaluated in [37]. A threaded lifting stud was included over the center of gravity of the MRA with its piping fully intact to allow for remote installation and replacement. The MRA piping was designed to allow for cutting above the upper shield block with a hydraulic shear. The pipes were spaced to allow access for cutting and to the lifting stud as they run across the backbone shield, although the pipes must be cut sequentially to allow access. Neutronics analysis indicated that dose rates for performing this operation are acceptable due to the shielding from the MRA shield block. The water pipes must be capable of blowdown prior to cutting the piping in order to prevent spilling activated water into the core vessel. Blowdown has yet to be evaluated but will be completed prior to the Procurement Readiness

Review. Finally the MRA allows for vertical removal and installation after the removal of 3 target segments. The void in the target must be rotated under the MRA to prepare for removal. The MRA water piping and hydrogen transfer line have been designed to fit through the MRA access port in the Core Vessel Lid. The estimated time for replacement of an MRA is less 1400 hours, including the removal and replacement of the target segments that allow for MRA removal.

3.14 AVAILABILITY

The MRA was designed for high availability. Because of the radiological conditions after operation, any maintenance below the top of the core vessel shielding is not possible. Therefore, the MRA will be designed to require no maintenance (no moving parts, no seals requiring replacement) and instead use all welded connections (including friction welds or explosion bonds for dissimilar metals) on all pressure boundaries.

3.15 MANUFACTURABILITY

While not an explicit requirement of the MRA, manufacturability was a key goal of the MRA design. Similar components at other neutron scattering facilities are extremely complex, risky, and expensive to fabricate, so every opportunity to simplify the MRA was taken. The MRA Fabrication Plan details all the steps necessary to fabricate an MRA [40]. The MRA Acquisition Strategy details the timeline and procurement strategy for the MRA [41]. In general, the following goals were used to guide improved manufacturability – reduce the number of pressure boundaries, reduce the number and complexity of welds, especially in aluminum, and reduce risky steps which offer limited recovery from options.

The most complex manufacturing involved in the MRA fabrication is the moderator fabrication. In order to reduce risk around moderator fabrication, prototypes of both the cylinder and tube moderator were manufactured during preliminary design. Both prototypes were successful in proving the planned moderator manufacturing strategy [42] [43] and in demonstrating the tolerances used in the Moderator Deflection and Tolerance Analysis. The prototypes also provided weld shrinkage data that has been applied to the final moderator designs.

4. REQUIREMENTS VERIFICATION

The MRA Requirements Verification Plan [44] summarizes the status of requirements verification at the end of final design, as well as verifications planned throughout the rest of the MRA project. Throughout Section 3, requirements which have yet to be verified were noted. These outstanding requirements are listed in table 4.1, with yellow indicating not verified. Most MRA requirements that have yet to be verified are work that is planned within the CMS scope but also include the MRA Blowdown, MRA Shipping, and MRA Disposal Classification requirements. Verification of these requirements will be completed prior to the MRA procurement readiness review.

The MRA Requirements Verification Plan reveals the importance of dimensional inspections, material test reports, and pressure and leak tests during the MRA fabrication process. These are the only requirements verification for nearly all MRA requirements from analysis and supporting drawings until operations when the neutronic performance of the MRA can be verified through testing.

Table 4.1 MRA Outstanding Requirements at the Final Design Review.

Requirement		Verification		
Summary	**Description**	**FDR**	**PRR**	**FAT**
MRA Structural Integrity Requirement	The MRA shall maintain structural integrity under all expected loading conditions.	Derived Requirement Verification	Derived Requirement Verification	Derived Requirement Verification
MRA Hydrogen Transfer Line Requirement	The MRA hydrogen transfer lines shall be designed and fabricated to 2019 ASME B31.12. Applied seismic loads shall be derived from the NPH BOD.		Analysis	Test
			Piping Analysis, Drawings	Pressure Test
MRA Water Piping Requirement	The MRA water piping shall be designed and fabricated to 2020 ASME B31.3. Applied seismic loads shall be derived from the NPH BOD.		Analysis	Test
			Piping Analysis, Drawings	Pressure Test
MRA-CMS Interface Requirements	Requirements derived from the MRA-CMS Interface Sheet, S01020500-IST10148	Derived Requirement Verification	Derived Requirement Verification	Derived Requirement Verification
MRA Vacuum Venting Requirement	The MRA vacuum space shall be designed to support venting of hydrogen leaks without exceeding the MAWP.		Analysis	Inspection
			CMS Venting Analysis, Drawings	Dim. Insp.
MRA Hydrogen Venting Requirement	The MRA hydrogen lines shall be designed to support venting of hydrogen after loss of transfer line vacuum without exceeding the MAWP.		Analysis	Inspection
			CMS Venting Analysis, Drawings	Dim. Insp.
MRA Remote Handling Requirement	The MRA design shall include features to allow for remote handling and replacement	Derived Requirement Verification	Derived Requirement Verification	Derived Requirement Verification
MRA Blowdown Requirement	The MRA shall be capable of blowdown of water passages such that the subsequent water level is at or below the top of the MRA shield block.		Analysis	Inspection
			Analysis, Drawings	Dim. Insp.
MRA Disposal Requirement	The MRA shall be capable of shipping to and disposal at a waste facility at the end of life.	Derived Requirement Verification	Derived Requirement Verification	Derived Requirement Verification
MRA Shipping Requirement	The MRA shall meet the radiological requirements for shipping in the TN-RAM cask after operation of 6 years and decay time of 2 years or less.		Analysis	Inspection
			Shipping Evaluation, Drawings	Dim. Insp. and MTRs
MRA Disposal Classification Requirement	The MRA shall meet the waste acceptance criteria for Nevada National Security Site after operation of 6 years and decay time of 2 years or less.		Analysis	Inspection
			Disposal Evaluation, Drawings	Dim. Insp. and MTRs

5. PREPERATION FOR PROCUREMENT READINESS

After the final design phase, the MRA design with be prepared for procurement, beginning with completing verification of outstanding requirements. Additional analyses are planned to be performed within the Cryogenic Moderator System design including certification of the hydrogen transfer line design to ASME B31.12, water piping to ASME B31.3, and venting analyses of hydrogen through the hydrogen transfer line and insulating vacuum space, as agreed to in [5]. The results of these analyses are not expected to alter the design of the MRA with the exception of the addition of pipe supports as required by the piping analyses. The MRA Blowdown Analysis and Shipping and Disposal Classification Evaluations will also be completed.

The other component of preparation for procurement readiness is completion of the procurement package. Currently, the lower reflector drawing package has been prepared and has been through checking. The upper reflector vessel package has been drafted and is in internal review. The MRA water piping and transfer line drawing packages have been drafted and internally reviewed. The backbone and MRA integration drawing packages have not been started. The equipment specifications to support the procurement package have been drafted but have not been reviewed. These drawing packages and equipment specifications will be completed promptly following the final design review. A procurement readiness review will follow, confirming completion of the procurement package so that the MRA procurement can begin as planned in the project schedule.

6. CONCLUSIONS

The final design of the Moderator Reflector Assembly has been presented. Requirements and their decomposition from Target Systems requirements have been discussed. The final MRA design has been shown to meet nearly all of the MRA requirements, and requirements which have not been verified have been clearly identified. Importantly, the MRA design exceeds the KPP for required neutron beam brightness, which is critical to the success of the STS project. Plans for preparation for procurement readiness have been outlined to complete requirement verification and finalize the procurement package.

7. REFERENCES

[1] "System Requirements Document for Target Systems," S03000000-SR0001.

[2] "System Requirements Document for Target Systems Moderator Reflector Assembly," S03040000-SR0001.

[3] "STS Project Hazard Analysis Report," S01030000-ESH10002.

[4] "MRA-Instrument Systems Interface Sheet," S01020500-IS0023.

[5] "MRA-CMS Interface Sheet," S01020500-IST10148.

[6] "MRA-Process Systems Interface Sheet," S01020500-IST10186.

[7] "MRA-Accelerator Interface Components Interface Sheet," S03000000-IST10000.

[8] "MRA-Vessel Systems Interface Sheet," S03000000-IST10009.

[9] "MRA-Target Assembly Interface Sheet," S01020500-IST10207.

[10] "MRA-Remote Handling Interface Sheet," S03000000-IST10016.

[11] "MRA-MRA I&C Interface Sheet," S01020500-IST10126.

[12] "Second Target Station Project Code of Record," S01020500-COR10000.

[13] "STS Natural Phenomena Hazard Basis of Design," S01030100-ESH10001.

[14] "Second Target Station (STS) Project Design and Fabrication of Pressure and Vacuum Systems," S01020000-PC0007.

[15] "Target Error Budget," S03000000-CAC10000.

[16] "Second Target Station Conceptual Design Report," S01010000-TR0001.

[17] "Moderator Reflector Assembly Drawing," 0000064880.

[18] Farrell, "Materials Selction for the HFIR Cold Neutron Source," ORNL/TM-99-208.

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[21] "MRA Thickness vs. Size Curves," S03040000-TR0001.

[22] "Preliminary Moderator Optimization Report," S03040000-TRT10001.

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[28] "Moderator Reflector Assembly Hydrogen Static Heat Load Analysis," S03040000-DAC10015.

[29] "Moderator Reflector Assembly Loss of Cooling Analysis," S03040000-DAC10016.

[30] "Structural Analysis of the Moderator Reflector Assembly," S03040000-DAC10013.

[31] "Structural Analysis of the Moderator Reflector Assembly Hydrogen Vessels," S03040000-DAC10012.

[32] "MRA Moderator Deflection and Tolerance Analysis," S03040000-DAC10017.

[33] "MRA Seismic Block Deflection Analysis," S03040000-DAC10018.
[34] "Moderator Reflector Assembly Fastener Analysis," S03040000-DAC10014.
[35] "Target Drive Room Beam On Dose Rates," S03120100-TRT10017.
[36] "Target and MRA Maintenance Dose Rates," S03120100-TRT10015.
[37] "MRA FDR - Remote Handling Overview," S03100500-TDO10001.
[38] "Target and MRA Radionuclide Inventory and Decay Heat," S03120100-TRT10026.
[39] "MRA Installation Plan," S03040000-TDO10000.
[40] "MRA Fabrication Plan," S03040000-MFP10000.
[41] "MRA Aquisition Strategy," S03040000-MFP10001.
[42] "Cylinder Moderator Prototype Manufacturing Report," S07030200-TRT10000.
[43] "Tube Moderator Prototype Report," S07030200-TRT10007.
[44] "MRA System Verification Plan," S03040000-SRD10000.