AA4 - Accident Analysis Report - Public:
Leakage from target cooling circuit into monolith

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<thead>
<tr>
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<th>Role/Title</th>
</tr>
</thead>
<tbody>
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</tbody>
</table>
EXECUTIVE SUMMARY

In the event analysed in this report, the proton beam is off and the target helium cooling system is operating normally when the target vessel ruptures, causing the cooling helium to leak out into the monolith. The target rupture may also damage the water premoderators in case there is major break of the wheel, causing water to flow onto the wheel and into the monolith. In the unmitigated scenario, the increased pressure inside the monolith leads to loss of monolith confinement and a release of radioactive material to the surrounding areas and consequently to the public. The target vessel rupture will not damage the water moderators in case there is only a smaller leak, and in this case, only helium and particulates leak out.

The doses presented in this report are only for when there is no beam hitting the target wheel, and the doses are only with respect to the public. A rupture of the target wheel during beam on target is covered by AA3 – Accident Analysis Report – Public: loss of target wheel cooling during beam on target (ESS-0051595).

UNMITIGATED CONSEQUENCES

The material released consists of helium together with particulates previously trapped in the loop filters and possibly water from the water moderator system.

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass Damaged</th>
<th>Airborne Release Fraction</th>
<th>Release time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium coolant</td>
<td>30 kg</td>
<td>1</td>
<td>10 s</td>
</tr>
<tr>
<td>Filter particulates</td>
<td>10 g</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Moderator coolant</td>
<td>700 kg</td>
<td>1</td>
<td>389 h</td>
</tr>
</tbody>
</table>

The unmitigated dose consequence for the wheel rupture is as follows:

- Public from an emission at 10 m = 0.11 mSv.

The event class is H3, the dose limit for the public representative person for an H3 event is 1.0 mSv. The dose to the public is below the limit for H3 but above the limit for H2 and thus tolerable.
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1. SCOPE

This document describes the investigation and analysis of radiological consequences for Accident Analysis #4 - Public: “Leakage from Target Cooling circuit into monolith” along with related calculations during normal operation when the proton beam is not hitting the target wheel. This accident analysis collects results from other accident analyses, namely AA3 and AA10. This analysis is part of the overall radiological hazard analysis for the Target Wheel and Helium System 10.


1.1. System description

1.1.1. Target wheel and cooling systems

The target wheel is essential to the fundamental purpose of the ESS facility in that it is the source of the neutrons produced during the spallation process as a result of the interaction with the 2 GeV 5 MW proton beam generated by the ESS linear accelerator.

The wheel and shaft systems are contained within the target monolith, which is located in the target building at the end of the accelerator-to-target (A2T) area (see Figure 1). The wheel is a disk composed of 36 sectors of tungsten blocks contained within a steel shroud and cooled by flowing helium (see Figure 2). It is located deep within the target monolith (see Figure 3) at the base of a 5 m long shaft that positions the wheel at the level of the incoming proton beam.

Figure 1  Cross section of the target station building showing the location of target systems
During normal operations, the wheel rotates around a vertical axis at a rate of 23 rpm to bring consecutive sectors into alignment with the impact of the proton beam to optimize neutron production. The flowing helium cools the spallation material. The rotation of the wheel is timed with the arrival of the proton beam such that the beam interacts with each sector once every 2.6 seconds.

**Figure 2** Principal helium gas coolant flow path through target wheel [3]

**Figure 3** Cross section of the Target Monolith showing the target wheel at the level of the incoming proton and outgoing neutron beamlines. The moderator/reflectors plug, proton beam window plug, beam instrumentation plug, and target monitoring plug are also shown contained within the monolith.
1.1.2. Target Monolith system

The target monolith contains all the subsystems needed to produce the spectra of neutrons required by the ESS neutron science instruments. These include the target wheel, the liquid hydrogen moderators, the water pre-moderators, the water-cooled beryllium reflectors, and the neutron beam guides that lead out of the monolith toward each instrument. It also contains proton beam instrumentation, target wheel instrumentation, the proton beam window (PBW) and shielding blocks. Figure 3 shows an overview of the monolith and the systems contained within it.

1.1.3. Primary cooling circuit, system 1010.

System 1010 is the main target cooling system, shown in Figure 4. The helium flow enters and leaves the target wheel via shut-off valves YSV-01 and YSV-02 at the top of the shaft. The heat is removed from the system by heat exchangers W01, W02 and W03 connected to the intermediate cooling circuits. Particles released are captured in 2 sets of filters, after the blower F01 and after the outlet from the target F02.

1.2. Safety Functions – Operational group

See Appendix A for the list of safety functions and associated safety-related SSCs within the Operational Group relevant to this analysis.

2. ISSUING ORGANISATION

Monolith Systems (WP4), Target Division.
3. **ACCIDENT SCENARIO OVERVIEW**

In the event under evaluation, the target vessel ruptures during normal operation when the proton beam is not hitting the target wheel, causing a release of the cooling helium and particulates that had been trapped in the cooling system filters from the target vessel into the monolith. The increasing pressure in the monolith vessel will cause a breach, creating a release path out of the monolith. All possible leak paths are evaluated to determine the potential dose to the public. The rupture of the target vessel is also postulated to damage the water moderator [9], causing contaminated water to flow into the monolith vessel and onto the wheel.

In this analysis, consequences of a target vessel rupture due to the following Postulated Initiating Events (PIEs) are evaluated: mechanical or operational failure as the result of for example fatigue, cracks or vibrations. The effects of other possible initiators for the rupture of the vessel during beam ON are evaluated in other accident analysis reports, including AA3 – Accident Analysis Report – Public: loss of target wheel cooling during beam on target (ESS-0051595), AA2 – Accident Analysis Report: Proton Beam events on Target and Proton Beam Window (ESS-0063901) and AA1 – Accident Analysis Report – Public: Target wheel rotation stop during beam on Target (ESS-0050081).

3.1. **Assumptions**

The list of assumptions applied to this analysis is given in Table 1.

<table>
<thead>
<tr>
<th>ID</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>There is no proton beam hitting the target wheel.</td>
</tr>
<tr>
<td>A2</td>
<td>The helium cooling system [5] is pressurised to 11 bar(a).</td>
</tr>
<tr>
<td>A3</td>
<td>The inventory in the helium is considered to be that for normal operation [10].</td>
</tr>
<tr>
<td>A4</td>
<td>When considering the helium and particulates, the event takes place after 5 years of operation. This is the design lifetime of the target wheel, and with a full power beam of 5MW this means the highest contamination level in the helium cooling system.</td>
</tr>
<tr>
<td>A5</td>
<td>When considering the water inventory in the premoderators, the event takes place after 40 years of operation using the same water.</td>
</tr>
<tr>
<td>A6</td>
<td>Due to difficulties to define the ratio of the radiological inventory that goes through each leak path, the inventory involved is conservatively assumed to go through each one of them independently.</td>
</tr>
</tbody>
</table>
Table 1  Assumptions

<table>
<thead>
<tr>
<th>ID</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>A7</td>
<td>No filtration in the HVAC is applied prior to emission.</td>
</tr>
<tr>
<td>A8</td>
<td>For the purposes of calculating the movement of the air with the evaporated material through building D02 to the emission point it is assumed that the air is saturated with contaminated water (RH=100%) at a temperature of 20°C thus containing 17.2 g of water/m3.</td>
</tr>
</tbody>
</table>

3.1.1. Operational mode

The event under study is assumed to begin during a normal operational mode of the target wheel and helium cooling systems. However, there is no beam hitting the target wheel during this event, so the event can happen directly after the beam shuts off or at a much later state when all water cooling systems, target, moderator, reflector, shielding and plugs have cooled down. For accidents while the beam is hitting the target wheel, see AA3 – Accident Analysis Report – Public: loss of target wheel cooling during beam on target (ESS-0051595).

3.1.2. Size of crack in wheel

For the analysis in this report, we assume that there is a severe rupture of the target wheel vessel, but the hole could also be of a much smaller size. With a smaller hole in the wheel, the consequence can be that we reach an equilibrium state in both the monolith vessel and in the primary cooling system (1010). This equilibrium is reached because the vacuum pumps in the monolith vessel keep extracting the helium and the pressure control & helium storage system (1011) keeps putting fresh helium into system 1010. The pressure in 1010 will decrease to a steady level which then reduces the cooling effect on the target wheel. If the proton beam is on, the wheel may then become too hot. This event is covered by AA3 – Accident Analysis Report – Public: loss of target wheel cooling during beam on target (ESS-0051595). If the pressure in 1010 stays at a level high enough that the wheel does not become too hot, the event is then not initially covered by AA3. However, eventually the helium storage 1011 will run out of helium and cause the loss of cooling, and the event is thereby covered by AA3.

The scenario with a small crack in the wheel will not have a radiological release larger than for the case with a severe rupture of the target wheel, since the radiological inventory is the same and the release is just slower. Therefore, in this report, only the scenario when there is a major rupture of the wheel is analysed.

3.2. Role of Operational Group systems

3.2.1. Monolith atmosphere

The monolith atmosphere is assumed to be rough vacuum with a pressure of about 1 mbar(a). This design requires a PBW to separate the monolith rough vacuum from the
high vacuum required within the accelerator beam pipe. The PBW is therefore also assumed to be in place.

3.2.2. Monolith vessel

The monolith vessel itself (not including the NBWs and the PBW) is assumed to be intact during this whole event.

3.2.3. Monolith pressure relief system

The monolith pressure relief system is present, possibly (depending on the scenario) guiding the inventory to an emission height of 30 m.

3.2.4. Off-gas system

There is an off-gas system possibly (depending on the scenario) connected to the vacuum pumps, guiding the inventory to the stack and further out to an emission height of 45 m. The filters in the off-gas system are not included.

3.2.5. Primary cooling system 1010

The helium cooling system is pressurised to 11 bar(a) and operational.

3.2.6. Wheel, drive and shaft

The target shaft and drive are intact during this event, but a major rupture of the wheel vessel is postulated, which is also the initiating failure for this accident analysis. The target wheel is assumed to be rotating.

3.2.7. Monolith rough vacuum system 1027

There are one, two or three vacuum pumps operating. The capacity of these pumps is maximum 600 g/hour each [17]. For the scenarios where the inventory flows out through this path, all three pumps are conservatively assumed to operate at their maximum capacity, extracting a total of 1800 g/hour.

3.2.8. HVAC system

This system has no impact on the course of events itself, but rather on the leak through the monolith into the target building or the leak through the accelerator tunnel into the klystron gallery, and the subsequent release to the environment.

3.2.9. Accelerator

There is no proton beam on target. The beam pipe is intact and protected by the proton beam window.

As will be described below, the proton beam window may break as a result of the blast when helium is released. In this case, the pressure from the helium expansion will damage the beam pipe and lead to a release of radioactivity out through the accelerator tunnel, further into the klystron gallery, and out at an emission height of 10 m.
4. **UNMITIGATED ACCIDENT SCENARIO ANALYSIS**

4.1. **Dependencies**

The list of dependencies applied to this analysis is given in Table 2.

**Table 2  Dependencies**

<table>
<thead>
<tr>
<th>ID</th>
<th>Description of Dependency</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Since there are no automatic or manual actions to stop the water evaporation/boiling-off, all spill water evaporates/boils-off before the event ends.</td>
</tr>
<tr>
<td>D2</td>
<td>For the purposes of calculating the movement of evaporated/boiled-off material through building D02, the HVAC is assumed to be OFF and the leak rate out of a room is assumed to be 0.2 room volumes/hour. This is based on that the required room leak rate shall be ( \leq 0.2 \text{ vol/h} @ \text{the normal operating pressure} ) [24].</td>
</tr>
</tbody>
</table>

4.2. **Scenario development**

A. There is no proton beam hitting the target wheel.
B. The helium cooling system is running normally.
C. The target vessel ruptures due to a mechanical or operational failure, e.g. fatigue, crack, vibrations, etc.
D. Helium and particulates previously trapped in the loop filters of the helium cooling system leak into the monolith vessel. The monolith pressure starts to increase.
E. As a consequence of the wheel rupture, the water premoderators may also be damaged, causing water to flow out into the monolith and onto the target wheel shroud.
F. If the monolith vacuum integrity is still intact and water is flowing out from the premoderators, a portion of the water flashes until the water vapour pressure at 50°C has been reached in the monolith vessel. This development depends on the leak rate for the helium in comparison with the leak rate for the water. If the monolith vessel is already pressurised and the water leaks out, there will be no water flashing. Instead the water will begin to evaporate in a fairly rapid rate since the atmosphere is dry, however not as fast as if it would flash in case of vacuum. Due to this uncertainty, it is conservatively assumed that the water flashes in all scenarios that contain water.
G. The pressure increase creates leak paths out of the monolith vessel. At this point, the accident is developed in four different scenarios. In summary, helium, particulates, and possibly water start to flow through one of the following paths[8]:
a. Scenario 1 - LP-101b - The Proton Beam Window (PBW) bursts due to the increased pressure and the leakage flows out through the beam pipe and into the accelerator tunnel, and further into the klystron galleries with an emission point at the height of 10 m. This is an event with no break of the premoderators, hence no released water (some water will still leak into the monolith vessel but not being released, see 6.3 for more details).

b. Scenario 2 - LP-102 – The helium, particulates, and water are pumped through the vacuum pumps of the monolith vessel into the triangular room and further into the high bay, with an emission point at the height of 20 m. This is an event including a break of the premoderators.

c. Scenario 3 - LP-104 – The rupture disc on top of the monolith vessel bursts and the leakage flows directly through the pressure relief system to an emission point at the height of 30 m. This is an event including a break of the premoderators. After the rupture disc bursts, the inside of the monolith vessel is exposed to the outside environment and there will be no fast evaporation of water due to the vacuum pumps since these will not be able to cause any low pressure and they will just circulate the air in the top of the monolith vessel.

d. Scenario 4 - LP-104 – The helium, particulates, and water move through the vacuum pumps of the monolith vessel into the off-gas system. The emission point is at the height of 45 m. This is an event including a break of the premoderators.

H. The monolith pressure starts to decrease as the helium flows out.

I. The pressure inside the monolith vessel stabilizes and the remaining helium, particulates, and water vapour start to slowly leak out of the monolith.

J. Neither the shroud nor the tungsten is hot; therefore, no steam interacts with the tungsten in the wheel.

K. No tungsten is vaporised as it is below the oxidation temperature.

The timeline for this event is shown in Figure 5.

![Figure 5](image-url) **Unmitigated event timeline.** Steps 1-4 happen very close together and changes in the timing on these steps in the sequence do not change the overall outcome; therefore, they are all stated to occur at t=0 seconds.
4.3. Event categorisation

Initiating events considered in this analysis and the probabilities for events to occur are shown in Table 3. The structural verification of the target wheel is performed in accordance with the RCC-MRx code, taking radiation damage mechanism into account [2]. For this reason, a rupture of the target wheel vessel is not expected to occur during the lifetime of ESS and the event class for this is H3. The H1 to H5 ranking refers to the occurrence intervals described in the ESS General Safety Objectives [25].

Table 3 Probability of occurrence for different postulated initiating events

<table>
<thead>
<tr>
<th>Postulated Initiating Event</th>
<th>Occurrence probability [y-1]</th>
<th>Event class</th>
<th>Reference for the occurrence probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target wheel vessel rupture due to a mechanical or operational failure e.g. fatigue, crack, brittle behaviour, vibrations.</td>
<td>$10^3 &gt; F \geq 10^4$</td>
<td>H3</td>
<td>Unanticipated event</td>
</tr>
<tr>
<td>Water premoderator rupture due to target wheel vessel rupture</td>
<td>$10^2 &gt; F \geq 10^4$</td>
<td>H3</td>
<td>Unanticipated event</td>
</tr>
</tbody>
</table>

4.4. Radiological consequences

4.4.1. Inventory

The source term for this event is calculated using (1) the total cooling helium inventory, (2) particulates captured in the helium loop filters, (3) part of the inventory of the premoderator water cooling loop.

The radiological release is regarded as consisting of two parts: an immediate release directly following the rupture of the target shroud and a longer-perspective release during 389 hours for Scenario 2 and 4.

The unmitigated Material at Risk (MAR) for this event contains the following:

- The total cooling helium inventory [10] of approximately 30 kg
- Particulates (10 g) captured in the helium cooling loop filters after one year of ESS full power operation [18]
- Part of the inventory of the water moderators cooling loop. The primary cooling system for the moderators 1041 and the primary cooling system for the PBW 1070 share the same cooling water, therefore the activation from 1070 [20] must be added to that of 1041 [12]. The total MAR for these systems is 1640 kg.

4.4.2. Release fraction from source – airborne release fraction (ARF)

Calculation of the inner source term applies the definition of damage ratio (DR) according to [11]. The Airborne Release Fraction (ARF), as defined in the glossary, is also applied for each material. These fractions are described for each inventory below:
• Helium: The release fraction of helium from the target cooling system is assumed to be 100%, and the entire inventory is released. Therefore, DR = 1 and $\text{ARF}_{\text{gases}} = 1$.

• Particulates: It is postulated that 1% of the particulates in the helium cooling system filters is released [13]. Here, DR=1 (all 10 g of the captured particulates are affected) and $\text{ARF}_{\text{other}} = 0.01$ for aerosols in the filters (since only 1% is released).

• Moderator water: In the event of a break in the water premoderator system inside of the monolith, it is postulated that 700 kg of the total 1640 kg of water in the system leaks out into the monolith vessel [16]. However, only 3.4 kg of water flashes (81 g/m$^3$ · 42 m$^3$ (free volume of monolith vessel) = 3.4 kg), the rest is pooled at the bottom of the vessel. The rest of the water, 696.6 kg, evaporates due to the vacuum pumps during 389 hours for Scenarios 2 and 4. It is assumed that all three vacuum pumps work at their maximum capacity of 600 g/hour of vapour [17], giving this longer perspective release time of 389 h (700 kg / (0.6 kg/h · 3) ≈ 389 h). Here, DR=0.0021 (3.4 kg / 1640 kg ≈ 0.0021) or DR=0.43 (700 kg / 1640 kg ≈ 0.43) depending on the scenario, and $\text{ARF}_{\text{gases}}=1$, $\text{ARF}_{\text{volatiles (incl C)}}=1$ and $\text{ARF}_{\text{other}}=0$.

Table 4 below summarizes the inventory, release fractions, and the resulting inner source term for all four scenarios.

<table>
<thead>
<tr>
<th>Material</th>
<th>MAR</th>
<th>DR</th>
<th>ARF</th>
<th>$\text{ST}_{\text{inner}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>30 kg</td>
<td>1</td>
<td>1</td>
<td>30 kg</td>
</tr>
<tr>
<td>Particulates</td>
<td>10 g</td>
<td>1</td>
<td>0.01</td>
<td>0.1 g</td>
</tr>
<tr>
<td>Water 1)</td>
<td>1640 kg</td>
<td>0.43</td>
<td>$\text{ARF}_{\text{gases}}=1$</td>
<td>700 kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\text{ARF}_{\text{volatiles (incl C)}}=1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\text{ARF}_{\text{other}}=0$</td>
<td></td>
</tr>
<tr>
<td>Water 2)</td>
<td>1640 kg</td>
<td>0.0021</td>
<td>$\text{ARF}_{\text{gases}}=1$</td>
<td>3.4 kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\text{ARF}_{\text{volatiles (incl C)}}=1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\text{ARF}_{\text{other}}=0$</td>
<td></td>
</tr>
</tbody>
</table>

1) Relevant for Scenario 2 and 4
2) Relevant for Scenario 3

4.4.3. Leaks and transport to points of emission

The possible leak paths [8] for the inventory out of the monolith must all be considered. From the monolith vessel, the release can take several different leak paths, including to the instrument hall via the bunker, to the high bay via the bunker and instrument hall, to the high bay via the connection cell, out of the building via the HVAC from the connection.
cell, or to the accelerator tunnel. The release could also go directly out of the monolith via the pressure relief system. These paths are summarized in Figure 6 and addressed separately below.

![Figure 6 Sketch of some possible leak paths from the monolith vessel. This picture is a general one for all accident analyses involving the monolith vessel [8].](image)

Three of the possible leak paths from the monolith vessel are all identified as a possible worst case leak path, where LP-104 is used for both Scenario 3 and 4 in this accident analysis. The points of emission to the surroundings are at four different heights. The leak paths and emission points are summarized as follows:

- Through the broken PBW into accelerator beam pipe – into accelerator tunnel – emission at 10 m (assuming HVAC not operational in accelerator tunnel)
- Through the vacuum pumps into the triangular room – into high bay – emission at 20 m
- Through the burst disc at the top of the monolith into the pressure relief system – emission at 30 m
- Through the vacuum pumps into the off-gas system – emission at 45 m

A conservative approach is taken during the analysis, in that it is assumed that the entire inventory produced by the accident is released via each of the chosen paths. An overview of the monolith and its surroundings is shown in Figure 7, and each leak path is examined more closely below.
Figure 7  General layout of the monolith and the surroundings

Release to the accelerator tunnel

Scenario 1 (LP-101b) to the accelerator tunnel is via the beam pipe through the broken PBW with an emission point at 10 m. The first part of the path is shown in Figure 8.

Release through PBW towards accelerator tunnel

Figure 8  Release path to the accelerator

Release to the high bay via the triangular room

Scenario 2 (LP-102) to the high bay is via the vacuum pumps into the triangular room, with an emission point at 20 m. The paths and transports are shown above in Figure 6.

Release through the monolith pressure relief system

Scenario 3 (LP-104) is via the rupture disc at the top of the monolith vessel and out through the monolith pressure relief system, with an emission point at 30 m. The paths and transports are shown above in Figure 6.
Release through the off-gas system

Scenario 4 (LP-104) is through the vacuum pumps and out via the off-gas system to the stack, with an emission point at 45 m.

Details of the scenarios for the unmitigated event are given in Table 5.

Table 5  Leak paths for unmitigated event

<table>
<thead>
<tr>
<th>Scenario Path ID</th>
<th>STinner</th>
<th>Volume</th>
<th>Flow rate (m³/s)</th>
<th>Volume</th>
<th>Flow rate (m³/s)</th>
<th>Volume</th>
<th>Flow rate (m³/s)</th>
<th>Emission point</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 LP-101b</td>
<td>30 kg Helium 0.1 g Particulates Monolith 42 m³</td>
<td>18 ¹)</td>
<td>Accelerator Tunnel 1827 m³</td>
<td>1.5 ²)</td>
<td>Klystron Gallery 3136 m³</td>
<td>4.67 ³)</td>
<td>10 m</td>
<td></td>
</tr>
<tr>
<td>2 LP-102</td>
<td>30 kg Helium 0.1 g Particulates Monolith 42 m³</td>
<td>18 for helium and particulates¹, 0.030 for water vapour⁴</td>
<td>Triangular room 813 m³</td>
<td>18 ¹)</td>
<td>High bay 40701 m³</td>
<td>2.261 ³)</td>
<td>20 m</td>
<td></td>
</tr>
<tr>
<td>3 LP-104</td>
<td>30 kg Helium 0.1 g Particulates 3.4 kg water Monolith 42 m³</td>
<td>18 ¹)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>30 m</td>
<td></td>
</tr>
<tr>
<td>4 LP-104</td>
<td>30 kg Helium 0.1 g Particulates 700 kg water Monolith 42 m³</td>
<td>18 for helium and particulates¹, 0.030 for water vapour⁴</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>45 m</td>
<td></td>
</tr>
</tbody>
</table>

1) All is assumed to have been released within 10 seconds.
2) The stubs connecting the Tunnel with the Galley will have a combined leak tightness better than 1.5 m³/s [21].
3) The flow rate out from the Gallery building is stated in the specifications for the component “AHS05-TE001” in a plan drawing for the Gallery [22]. The specifications for AHS05-TE001 can be seen in the component list [23]. The flow rate 4.67 m³/s was used in the dose calculations but the flow rate that is stated in [23] is actually 4.76 m³/s. The impact of this deviation is discussed further in chapter 6.6.
4) Flow rate is calculated from the three vacuum pumps capacity with minimum ballast gas [17]. The helium is conservatively not being accounted for in this calculated flow rate (to maximize the water vapour flow).
5) Flow rate is estimated to 20% of the room volume per hour.
4.4.4. **Spreading to public**

The point of emission from the accelerator tunnel to the public is from the building at 10 m for Scenario 1. The other three scenarios have points of emission at the heights of 20, 30 or 45 m.

4.4.5. **Dose to public – representative person**

For the purpose of the radiation hazard analysis, the public is represented by a representative person located just outside of the site boundary.

It is not obvious which of the four scenarios that cause the highest dose to the public. Therefore, the dose was calculated for all of these scenarios. The final doses can be seen in Table 6 below.

The dose to public for Scenario 1 was extracted from the dose calculations for AA3 [15], since LP-101b is also included in AA3 with the same flows and inventory for the helium and the filter particulates as in this AA4. For comparison, see sheet “AA03_100s_LP-153_1 M Public” in [15] (here LP-101b is the same as LP-153).

The dose calculations performed for AA4 includes Scenario 2, 3 and 4 [14]. However, at the time of these calculations the amount of water that leaks into the monolith was estimated to be 370 kg. This estimation was later increased due to changes in the design of the moderator water cooling system 1041, and the current estimated amount is therefore 700 kg [16]. The dose contribution from the water is calculated separately from the dose contribution that the helium and the particulates have. Therefore, the dose to public from the 700 kg of water can be extracted from the dose calculations performed for AA10 [19], since part of this accident analysis share the same moderator water amount, flows and leak paths as Scenario 2 and 4 in this AA4. For comparison, see Table 10 in [16] where Case 1 is used for Scenario 4, and Case 5 is used for Scenario 2.
Table 6  Dose to public for all scenarios

<table>
<thead>
<tr>
<th>Scenario Path ID</th>
<th>Event class</th>
<th>Release height</th>
<th>Dose from water [mSv]</th>
<th>Dose from helium + particulates [mSv]</th>
<th>Total dose to public [mSv]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 LP-101b</td>
<td>H3</td>
<td>10 m</td>
<td>N/A</td>
<td>0.108 [15]</td>
<td>0.108</td>
</tr>
<tr>
<td>2 LP-102</td>
<td>H3</td>
<td>20 m</td>
<td>0.0260 [19]</td>
<td>0.0273 [14]</td>
<td>0.053</td>
</tr>
<tr>
<td>3 LP-104</td>
<td>H3</td>
<td>30 m</td>
<td>Calculated together¹</td>
<td>0.064 [14]</td>
<td></td>
</tr>
<tr>
<td>4 LP-104</td>
<td>H3</td>
<td>45 m</td>
<td>0.00381 [19]</td>
<td>0.0212 [14]</td>
<td>0.025</td>
</tr>
</tbody>
</table>

¹) The dose to public from the flashed water is included in the dose calculations for the helium and the filter particulates, hence no separate dose results for the water.

The resulting maximum dose is 0.11 mSv.

The nuclides that are the primary contributors to the unmitigated dose to the public representative person for Scenario 1 (the worst case) are shown in Table 7. All nuclides that contribute to 91% of the effective dose are listed. This table can be extracted from the document ‘AA03_100s_LP-153_All Publ Mit - Dose dominating nuclides_a003_190207.xlsx’ in [26] by adding together the relevant lists of the 50 most dominating nuclides.

Table 7  Nuclides dominating the total effective unmitigated dose for the scenario that results in the highest dose (Scenario 1) [26]

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Effective dose [mSv]</th>
<th>% of total dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gd-148</td>
<td>2.09E-02</td>
<td>19.31%</td>
</tr>
<tr>
<td>Eu-154</td>
<td>1.48E-02</td>
<td>13.71%</td>
</tr>
<tr>
<td>Eu-146</td>
<td>1.44E-02</td>
<td>13.29%</td>
</tr>
<tr>
<td>Eu-147</td>
<td>1.14E-02</td>
<td>10.50%</td>
</tr>
<tr>
<td>Eu-148</td>
<td>1.08E-02</td>
<td>10.02%</td>
</tr>
<tr>
<td>Eu-145</td>
<td>8.03E-03</td>
<td>7.43%</td>
</tr>
</tbody>
</table>
4.5. Risk assessment

In consideration of the accident probabilities of Section 4.3 and the radiological consequences of Section 4.4 it is possible to elaborate the risk ranking of the accident in accordance with the Target Station Radiological Hazard Analysis [11].

The calculated worst effective dose to the public for each PIE for the unmitigated scenarios of this accident are listed in Table 8 below [14],[15],[16].

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Effective dose [mSv]</th>
<th>% of total dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y-88</td>
<td>5.18E-03</td>
<td>4.79%</td>
</tr>
<tr>
<td>Eu-149</td>
<td>4.02E-03</td>
<td>3.71%</td>
</tr>
<tr>
<td>Eu-156</td>
<td>3.41E-03</td>
<td>3.15%</td>
</tr>
<tr>
<td>H-3</td>
<td>2.80E-03</td>
<td>2.59%</td>
</tr>
<tr>
<td>Eu-152</td>
<td>2.67E-03</td>
<td>2.47%</td>
</tr>
<tr>
<td>Sum</td>
<td>9.84E-02</td>
<td>90.98%</td>
</tr>
</tbody>
</table>

Table 8 Risk ranking of unmitigated accident – Dose to public

<table>
<thead>
<tr>
<th>Postulated Initiating Event</th>
<th>Event class</th>
<th>Radiological Consequences</th>
<th>Risk Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical or operational failure (e.g. fatigue, crack, vibrations)</td>
<td>H3</td>
<td>Emission at 10 m (Scenario 1) 0.11 mSv</td>
<td>TOLERABLE</td>
</tr>
<tr>
<td>Water premoderator rupture due to target wheel vessel rupture</td>
<td>H3</td>
<td>Emission at 30 m (Scenario 3) 0.06 mSv</td>
<td>ACCEPTABLE</td>
</tr>
</tbody>
</table>

The Risk Ranking, based on event class and dose calculations for the unmitigated accident, gives a tolerable risk ranking for one of the postulated initiating events and an acceptable risk ranking for the other postulated initiating event. The tolerable result means that the regulatory requirements are met but additional measures should be considered, see next section.
5. MITIGATED ACCIDENT SCENARIO ANALYSIS

Due to the results of the unmitigated scenario analysis, no Safety Group functions are required for this event.

However, since the risk ranking is ‘tolerable’ for one PIE in the unmitigated event, further mitigating or precautionary functions should be considered.

The ‘tolerable’ risk ranking is due to Scenario 1 where the leak path is through the broken PBW into the accelerator tunnel and further out through the stubs and up into the klystron gallery and finally to an emission point at the height of 10 m. In this scenario, one of the assumptions is that the HVAC is not operational in the accelerator tunnel. However, it is very unlikely that the HVAC would be malfunctioning at the same time as the target wheel would break. If the HVAC is operational it will guide the helium and the particulates out through the off-gas system and further on to the stack, where it will be released at the height of 45 m. If this would be the case, the dose to the public for Scenario 1 would then be less than 0.025 mSv as it is for Scenario 4. This can be stated due to that in Scenario 4 there is also water being released and the vacuum pumps will pump out the materials much faster than the HVAC would be able to do.

5.1. Safety functions – Safety group

There are no safety functions required for this accident scenario.

6. ASSESSMENT OF UNCERTAINTY IN ANALYSIS

Conservative assumptions and uncertainties in the analysis are listed below. Some of the conservative assumptions and uncertainties are described in more detail in the related paragraphs.

- Conservative assumptions
  - Dose to public is calculated independently for each leak path.
  - Severe rupture of the target wheel (see 6.1 below)
  - The event is assumed to take place after 5 years of operation with a full power beam, which means the highest contamination level in the helium cooling system (see 6.2 below)
  - The water inventory is maximized by assuming 40 years of operation with the same water (see 6.2 below)
  - No filtration in any leak path is applied, including for material which is emitted via the stack (see 6.7.4 and 6.7.8 below)
  - Water inventory applied to the analysis is based on the inventory present when the beam is on and does not include any reduction due to decay time without beam.

- Uncertainties
  - Water from the PBW cooling system in Scenario 1 (see 6.3 below)
Uncertainty in the amount of particulates (10 g) captured in the helium loop filters after 1 year of operation (see 6.4 below).

Uncertainty in the postulated 1 % for the number of particulates that is released from the helium loop filters at the time of the accident. The assumed amount of released particulates contribute to maximum 10 % of the total dose to the public (see 6.4 below).

Uncertainty in the water inventory. However, corrosion products in the water has no effect on the dose to the public, since these are not airborne (see Table 13 in [16]).

Uncertainty in the amount of spill water. The dose to the public from the water is linear dependent of the amount that is being released with a 1:1 ratio (assuming a constant flow). For example, if the spill water amount increase with 25%, the dose to public will also increase with 25%, see Table 13 in [16].

Uncertainty in the estimated flows and leak rates. For the water inventory, the estimated emission duration has a fairly big impact on the dose to the public. If the emission duration increases by 25% the dose to the public would decrease by 10%, and if the emission duration decreases by 25% the dose to the public would increase by 15%, see Table 13 in [16].

- Possible ways of reducing the uncertainties
  - Measure the number of particulates in the filters after facility is operational. This will be conducted (see 6.4 below)
  - Monitoring or sampling the water periodically.

6.1. Size of crack in wheel

A scenario with a small crack in the wheel will not have a radiological release larger than for a case with a severe rupture of the target wheel, since the radiological inventory is the same and the release is just slower. Therefore, in this report, only the scenario when there is a major rupture of the wheel is analyzed.

6.2. Beam power

The inventories used in this analysis for the helium and the particulates assume 5 years of full power beam on target (the helium loop filters are however replaced before reaching at total of 10g of particulates, which is roughly every year). For the water inventory, a full power beam during 40 years is assumed (since the water in this system is not scheduled to be replaced during the lifetime of the facility). If the accelerator provides a lower beam power, the impact and also the activity level in the target station would be lower, resulting in a lower dose to the public in case of an accident.

Running ESS with a beam power lower than 5 MW would also enable target systems (e.g. the wheel) to operate for a longer period of time before they need to be replaced.
6.3. Water from the PBW in Scenario 1

In Scenario 1, the assumption is that no water is being released from the premoderators since these do not break. However, the PBW will break and this window is actually cooled with the same water as the premoderators. After the initial helium has been released, the same amount (700 kg), will slowly pour out into the beam pipe and down onto the monolith vessel floor. This water is cold (room temperature) and it will take a long time before this water has been evaporated and possible transported somewhere else. Due to the complex leak path (LP-101b) through the beam pipe, into the accelerator tunnel, up through the stubs, into the Klystron Gallery and out at 10 m, this water will also condensate on the walls along the way. The water in Scenario 1 is therefore assumed to not being released to the public and is therefore not included in the overall analysis.

On the other hand, one can imagine that the vacuum pumps will then pump out this water eventually and that this amount should then be included in the resulting dose to the public. However, in order for the vacuum pumps to create this lower pressure (that speeds up the evaporation as in Scenario 2 and 4), the monolith vessel has to be tight, which is not the case for Scenario 1. The vacuum pumps will then simply circulate the air above where the water is located (at the bottom of the monolith vessel). If we still consider that this water will eventually evaporate and leave the building, it will likely go out this way through the vacuum pumps and further on to the stack (LP-102 or LP-104).

So, disregarding the fact that the water will take a very long time to evaporate (and that it will also condensate along the way) and assuming that it goes out the same way as in Scenario 2 or 4, the resulting dose to the public from this water would be 0.0260 mSv (for LP-102) or 0.00381 mSv (for LP-104) as stated in Table 6. Adding 0.0260 mSv to the dose for Scenario 1 would then result in a total maximum dose to the public of 0.066 mSv instead of the calculated 0.040 mSv.

6.4. Amount of filter particulates

Calculations have shown that roughly 10 g of particulates will be collected in the helium loop filters after 1 year of full beam power operation [18]. However, continuous measurements will be conducted on these filter units. The level of radioactivity just outside the filters will be measured as well as the pressure drop for the components. If the value of 10 g is about to be exceeded, the filters will be replaced.

An assumption has been made that 1% of the filter particulates in the helium cooling system is being released in all AA4 scenarios. When only looking at the dose due to the public from the primary cooling system (that is the helium and the filter particulates), the contribution to the dose from the filter particulates are about 10% of the total dose (the rest comes from the helium). This means that if the assumption would have been that 2% of the filter particulates are being released instead of the previous 1% in Scenario 1, the total dose to the public would be 0.044 mSv instead of 0.040 mSv (that is 10% higher). If we increase the value by one order of magnitude, changing from 1% to 10%, the total dose to the public would be 0.076 mSv, which is less than double the original dose and...
the value is still below the acceptable limit of an H2 event (which is 0.1 mSv). For the other three scenarios, the sensitivity of this assumption is lower due to that these scenarios also contain water that contributes to the dose.

6.5. **Structural verification of the target wheel**

The structural verification of the target wheel is done in accordance with the RCC-MRx code, taking radiation damage mechanism into account [2]. For this reason, a rupture of the target wheel vessel is not expected to occur during the lifetime of ESS and the event class for this is H3. It should also be noted that material data for proton irradiated steel is limited, and the damage on the wheel vessel is instead estimated using data for neutron irradiated steel. One might argue that this uncertainty would increase the probability of a wheel rupture, but this uncertainty has been accounted for in the design by introducing extra margins to account for the proton irradiation.

6.6. **Incorrect flow rate used for the dose calculations**

The flow rate out from the Gallery building that was used in the dose calculation [15], for Scenario 1, was 4.67 m$^3$/s. However, this number is slightly wrong since the value given in the component list [23] (for component AHS05-TE001) is in fact 4.76 m$^3$/s. There is a 2% difference between these values, and the difference in terms of the resulting dose to the public is less than these 2%. This statement is based on the sensitivity study that was conducted for AA10 [16], where a 25% decrease of emission duration leads to a 15% increase of dose to the public.

6.7. **Impact of Operational Group systems**

The Impact of Operational Group systems study is aimed at determining what radiological consequence (negative/negligible/positive/none) to the public a safety related system has if it is not functioning as assumed.

6.7.1. **Monolith atmosphere**

A monolith atmosphere with a higher pressure than rough vacuum would not increase the dose to the public. An effect would be that no water flashes and it starts to evaporate instead, causing a slower release of water vapour which would decrease the dose to the public.

6.7.2. **Monolith vessel**

If the monolith vessel does not stay intact, this would lead to a dispersion of the inventories into adjacent volumes in the facility. The inventory would then be more diluted before it is released outside of the buildings, and the release height would be at 20 m as in Scenario 2. A monolith vessel that does not hold its integrity would therefore not increase the dose to the public.
6.7.3. Monolith pressure relief system

The function of this system is to keep the pressure in the monolith vessel below the design pressure. If this system fails (e.g. the burst disc does not break) this could lead to a failure of the monolith vessel. However, this does not cause any increase of dose to the public.

6.7.4. Off-gas system

It is assumed for this accident that there are no filters in the off-gas system. There will be no fast flows in this system leading to a release of particulates from the filters themselves. Hence, if the existing filtration is applied, the dose to the public would not increase.

6.7.5. Primary cooling system 1010

It is assumed that the helium cooling system is in operation and running normally. If the primary cooling system is not operational and the pressure inside is therefore lower, this would decrease the dose to the public. The decrease is due to the smaller amount of helium combined with less force available from the outflowing helium to release the particulates from the loop filters.

The helium purification system is also assumed to be operational. If this system is not functional for some time, the inventory will be higher than that for normal operation. The helium purification system and inventory will therefore be measured.

6.7.6. Wheel, drive and shaft

A major rupture of the wheel is postulated for this event, and if the wheel would not rupture, this would not cause any release at all.

If the shaft would fail, this could lead to the release of helium and particulates above the shielding blocks inside the monolith vessel. However, the dose to the public would not increase.

If the wheel is not rotating during this event, there is a lower risk of breaking the premoderators. As such, without the water system involved in the event, the dose to the public would decrease. So, if the wheel is not rotating, the dose to the public would not increase, while the beam is not hitting the target wheel.

6.7.7. Monolith rough vacuum system 1027

It is assumed that there are three vacuum pumps operating at their maximum capacity. If there are fewer pumps or if the pumps are turned off in case of an accident, then the dose to public would decrease since the release would then be much slower.
6.7.8. **HVAC system**

No filtration in the target HVAC is applied prior to emission. There will be no fast flows in this system leading to a release of particulates from the filters themselves. Hence, if the existing filtration is applied, the dose to the public would not increase.

The HVAC in the tunnel is assumed to be turned off during this event. This is the worst case, as the dose to the public would decrease if the HVAC system was operational and guiding the release through the stack and out at an emission height of 45 m.

6.7.9. **Accelerator**

It is assumed that there is no beam on target for this event. If there is a beam on target and the wheel ruptures, the dose to public would increase, see AA3 – *Accident Analysis Report – Public: loss of target wheel cooling during beam on target* (ESS-0051595).

7. **ASSESSMENT OF IMPACT DUE TO SINGLE AND MULTIPLE FAILURES IN THE SAFETY GROUP**

No mitigations are implemented to reduce the risk and/or the dose consequences to the public, hence single and multiple failures are not applicable.

8. **SUMMARY**

The accident scenario studied shows that a leakage from the target cooling circuit into the monolith, leading to depressurisation of the helium cooling system, would lead to radiological consequences to the public that are tolerable at the event probability. Therefore, it is not necessary to implement mitigating measures to reduce the risk and/or the dose consequences.
9. **GLOSSARY**

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational group</td>
<td>A specific composition of the structures, systems and components, including manual measures, required to perform all the safety tasks necessary to manage a specific event or a specific circumstance so that this does not lead to increased radiation levels, as well as limiting the dispersion of radioactive substances within the facility and enabling the facility to return to normal operations.</td>
</tr>
<tr>
<td>Safety function</td>
<td>A function that is of importance to the safety of a facility.</td>
</tr>
<tr>
<td>Safety group</td>
<td>A specific composition of the structures, systems and components, including manual measures, required to perform all the safety tasks necessary to handle a specific event or a specific circumstance so that the consequences, in the form of increased levels of radiation or dispersion of radioactive substances, are minimised, and extensive damage on radiation sources counteracted.</td>
</tr>
<tr>
<td>MAR</td>
<td>Material At Risk; The material containing the inventory that is at risk in the analysed scenario, e.g. the wheel tungsten, the reflector beryllium or the cooling fluid in a system</td>
</tr>
<tr>
<td>DR</td>
<td>Damage Ratio; the fraction of the MAR that may be released in the analysed scenario</td>
</tr>
<tr>
<td>ARF</td>
<td>Airborne Release Fraction; The fraction of the MAR*DR that is airborne in the analysed scenario and is thus possible to transport from the inner point of release</td>
</tr>
<tr>
<td>ST&lt;sub&gt;inner&lt;/sub&gt;</td>
<td>Inner Source Term = MAR * DR * ARF; The amount of material containing radioactive inventory that is airborne at the inner point of release, typically at an opening of the vessel or pipe</td>
</tr>
<tr>
<td>RF</td>
<td>Respirable Fraction; The fraction of the airborne particle that can reach into the lungs (detailed in the dose calculation report by Spanier)</td>
</tr>
<tr>
<td>LPF</td>
<td>Leak Path Factor; The fraction of the inner source term that reaches the outer point of release (modelled in the dose calculation report by Spanier, using the flow rates and volumes given in this report)</td>
</tr>
<tr>
<td>ST</td>
<td>Outer Source Term = ST&lt;sub&gt;inner&lt;/sub&gt; * RF * LPF; The amount of material containing radioactive inventory that is airborne at the outer point of release, typically at the top of the stack or at an opening in the building</td>
</tr>
<tr>
<td>SSC</td>
<td>A general term that covers all parts of the facility, except human factors, and it stands for “Structures, Systems and Components”</td>
</tr>
<tr>
<td>Defence in depth (DID)</td>
<td>The implementation of several successive technical, organisational and administrative measures to prevent the occurrence and development of events and circumstances, and to maintain the effectiveness of the barriers placed between a radiation source and employees, the general public and the environment.</td>
</tr>
</tbody>
</table>
10. REFERENCES

[1] Hazard Analysis - Target Wheel and Helium Cooling system (ESS-0037525 rev 2)
[2] System Description Document- Requirements Target Wheel, Drive and Shaft (ESS-0020435 rev 4)
[3] System Description Document- Solution Target Wheel, Drive and Shaft (ESS-0026412 rev 1)
[6] SDD-req - 1067 - Covers, Penetrations and Monolith Vessel and 1076 Proton Beam Window Port Block & Vessel (ESS-0040693 rev 5)
[8] Leak paths for Target Accident Analyses (ESS-0088177 rev 2)
[10] Target He inventory for normal operations (ESS-0045261 rev 1)
[12] Inventory in the moderator water loop after 40years (ESS-0185862 rev 2)
[14] Calculation of dose to the public for AA04 (ESS-0085822 rev 2)
[15] Calculation of dose to the public for AA03 (ESS-0085821 rev 4)
[18] Report – Radionuclides content in Target cooling systems (ESS-0105244 rev 1)
[19] Calculation of dose to the public for AA10 (ESS-0241704 rev 1)
[20] Inventory in the Proton Beam Window water loop after 40years (ESS-0185865 rev 2)
[22] V02-57---1-G02110121.pdf (ESS-0029803 rev 3)
[23] V02-DL-DEDGGDGO2-Component list G02.xls (ESS-0029794 rev 3)
[24] Target Station Logistics (ESS-0011043 rev 5)
[26] Calculation files for AA03 for the public (ESS-0093006 rev 4)
The analysis is now divided into two documents, one addressing the dose to the public and one addressing the dose to the workers. The $S_{\text{Inner}}$ for the moderator water has increased from 70 kg to 700 kg. The monolith pressure relief system has been included. Only the case when the proton beam is not hitting the target wheel is now considered in this accident analysis. The resulting dose to public is lower, meaning no mitigations are required. A sensitivity study has been included (chapter 6) together with the impact of the operational group systems.

<table>
<thead>
<tr>
<th>Revision</th>
<th>Reason for and description of change</th>
<th>Author</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>First issue</td>
<td>Arezou Firouzi</td>
<td>2015-11-19</td>
</tr>
<tr>
<td>2</td>
<td>Second issue</td>
<td>Arezou Firouzi</td>
<td>2017-02-10</td>
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<td>3</td>
<td>The analysis is now divided into two documents, one addressing the dose to the public and one addressing the dose to the workers. The $S_{\text{Inner}}$ for the moderator water has increased from 70 kg to 700 kg. The monolith pressure relief system has been included. Only the case when the proton beam is not hitting the target wheel is now considered in this accident analysis. The resulting dose to public is lower, meaning no mitigations are required. A sensitivity study has been included (chapter 6) together with the impact of the operational group systems.</td>
<td>Emil Lundh</td>
<td>2019-03-22</td>
</tr>
</tbody>
</table>
APPENDIX A

Table 9  Safety functions – Safety-related SSCs

<table>
<thead>
<tr>
<th>Safety Function</th>
<th>SSC Description</th>
<th>Defence in depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confine helium</td>
<td>Target shroud</td>
<td>L1</td>
</tr>
<tr>
<td>Confine helium</td>
<td>Primary cooling system pipes and components</td>
<td>L1</td>
</tr>
<tr>
<td>Limit inventory</td>
<td>Helium purification system</td>
<td>L1</td>
</tr>
<tr>
<td>Limit inventory</td>
<td>Radiation monitoring in helium cooling system loop and filters</td>
<td>L1</td>
</tr>
<tr>
<td>Limit inventory</td>
<td>Radiation monitoring in helium cooling system loop and filters and act if limit is exceeded</td>
<td>L2</td>
</tr>
<tr>
<td>Wheel cooling</td>
<td>Process control system for helium cooling system functional</td>
<td>L1</td>
</tr>
<tr>
<td>Wheel cooling</td>
<td>Helium flowing and cooling as designed, monitor process variables (temperature, flow, pressure), turn off beam if exceed limits</td>
<td>L1, L2</td>
</tr>
<tr>
<td>Wheel cooling</td>
<td>Pressure relief valve in helium cooling system 1010 bleeds off into off-gas extraction system</td>
<td>L2</td>
</tr>
<tr>
<td>Wheel cooling</td>
<td>Internal helium cooling channels and inner rotational seal</td>
<td>L1</td>
</tr>
<tr>
<td>Wheel rotates</td>
<td>Drive motor functional including shaft</td>
<td>L1</td>
</tr>
<tr>
<td>Wheel rotates</td>
<td>Process control system for wheel drive functional</td>
<td>L1</td>
</tr>
<tr>
<td>Wheel rotates</td>
<td>Wheel rotates as designed, detect lost synchronisation and stop beam</td>
<td>L2</td>
</tr>
<tr>
<td>Wheel rotates</td>
<td>Wheel rotates as designed, detect low speed and turn off beam</td>
<td>L2</td>
</tr>
<tr>
<td>Confine monolith atmosphere to limit contamination production</td>
<td>Monolith vessel, PBW, NBWs</td>
<td>L1</td>
</tr>
</tbody>
</table>

Note: Defence in Depth (DiD) – L1, L2, L3, L4 or L5