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AA3 – AA5- Accident analysis report- global bypass and local blocking of target wheel

	Name	Role/Title
Owner	Kristoffer Sjögreen	Work Unit Leader Target Wheel, Drive and Shaft
Reviewer	Ulf Oden	Lead Engineer – Target Systems
	Per Persson	Radioactive Waste Group Leader – ESH
	Jan Espen Presteng	Safety Engineer - Target
	Linda Coney	Group Leader – Target safety and controls
Approver	Eric Pitcher	Head of Target Division

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1. SCOPE

The purpose of this document is to describe the investigation and analysis of radiological consequences for Accident Analysis #5: Consequences of possible events causing local blocking or internal bypass in Target Wheel. This analysis is part of the overall radiological hazard analysis for the Target Wheel and Helium System [1].

In the following section, brief descriptions of the Target wheel and helium cooling systems are given. A comprehensive description can be found in the Target Wheel, Drive and Shaft System Description Document- Requirements[2] and Solution[3] documents, and in the Helium Cooling Description Document – Requirements[4] and Solution[5] documents.

1.1. System description – Target wheel and helium 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.

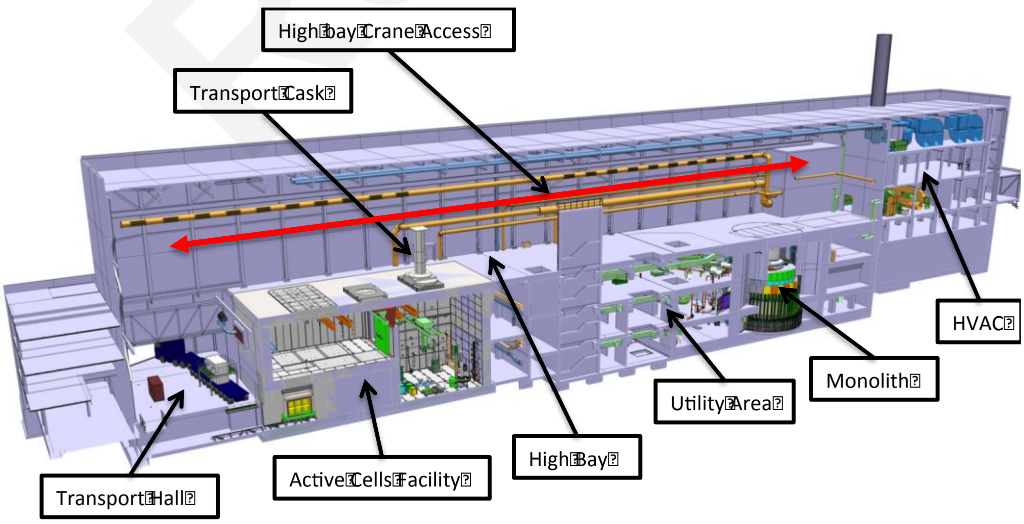

Figure 1 – Target building - Monolith area containing target wheel shown on right

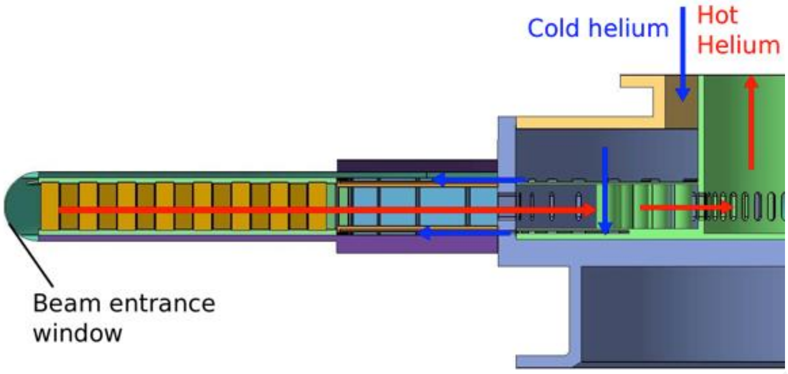

Figure 2 – Principal helium gas coolant flow path through target wheel

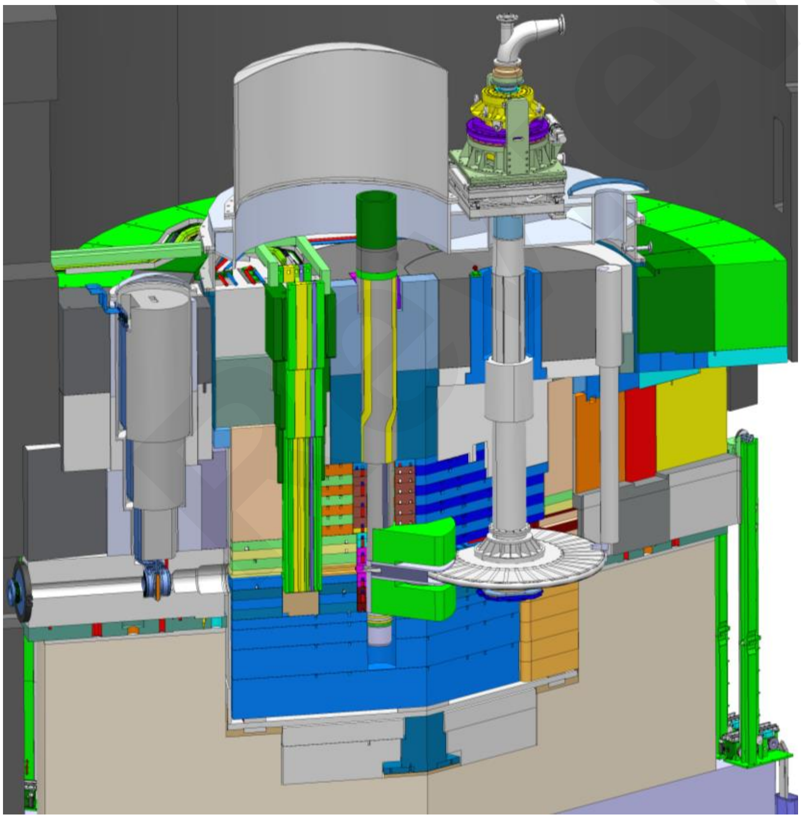

Figure 3 – Cross section of the Target Monolith showing the target wheel at the level of the incoming proton and outgoing neutron beamlines. The wheel drive is shown on top of the drive shaft.

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.

1.2. System description- Target wheel and internal parts

The accident scenarios treated in this report are based on a hazard analysis related to internal failures in the target itself.

Therefore , the various parts and their intended function as well as inherent limits must be described.

1.2.1. Rotating feedthrough

The technology chosen for allowing helium coolant to enter and exit the rotating target wheel is a Ferrofluidic rotating feedthrough.

The principal function of these seals is a ferrofluid, based on lubricating oil, which is made magnetic by the presence of magnetic iron oxide nano particles.

Using rare earth magnets, the fluid is used to block a narrow passage between rotor and stator. Each Ferrofluidic step can accommodate a small pressure change, therefore a number of steps are needed to accommodate higher pressure difference.

If the seal fail, or for some reason blow out the ferrofluid, the leak path will consist of the circumferential gap between stator and rotor.

A principal view of the ferrofluidic seal intended for the ESS Target rotating feedthrough is described in Figure 4.

Important limitations and characteristics of the feature, relevant for safety are listed in Table 1

Inlet holes, diameter	Inlet passage, inlet and outlet, distance/ diameter	Clearance within Ferroseal, distance/ diameter
25 mm	20 mm/160 mm	0,15 mm /250 mm

Table 1 Relevant parameters for Ferroseal

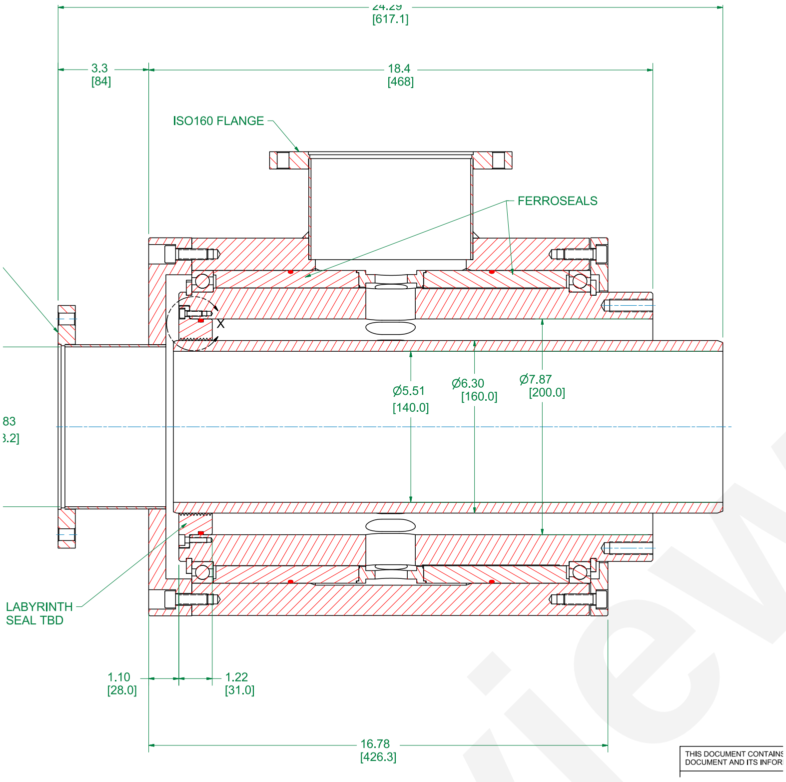

Figure 4 Ferrofluidic seal/ feedthrough

1.2.2. Helium flow path, central piece and separating plates

The target is designed for robustness. An important feature in the design has been to be able to make the coolant flow of all sectors of the wheel parallel to each other. Therefore there is a large volume in front of the inlet paths to each sector, and a large volume which is common to the sectors downstream.

The rim of the target, the so called beam entrance window, serves as an intermediate volume, assuring that a local blocking of the inlet of one sector can be compensated from other sectors. Therefore, outlet flow through a sector is independent from inlet flow through it.

Of central importance in this respect is the central distribution piece. It separates the flow to inlet of the cassette from the outlet flow.

In figure 5 the central piece is shown.

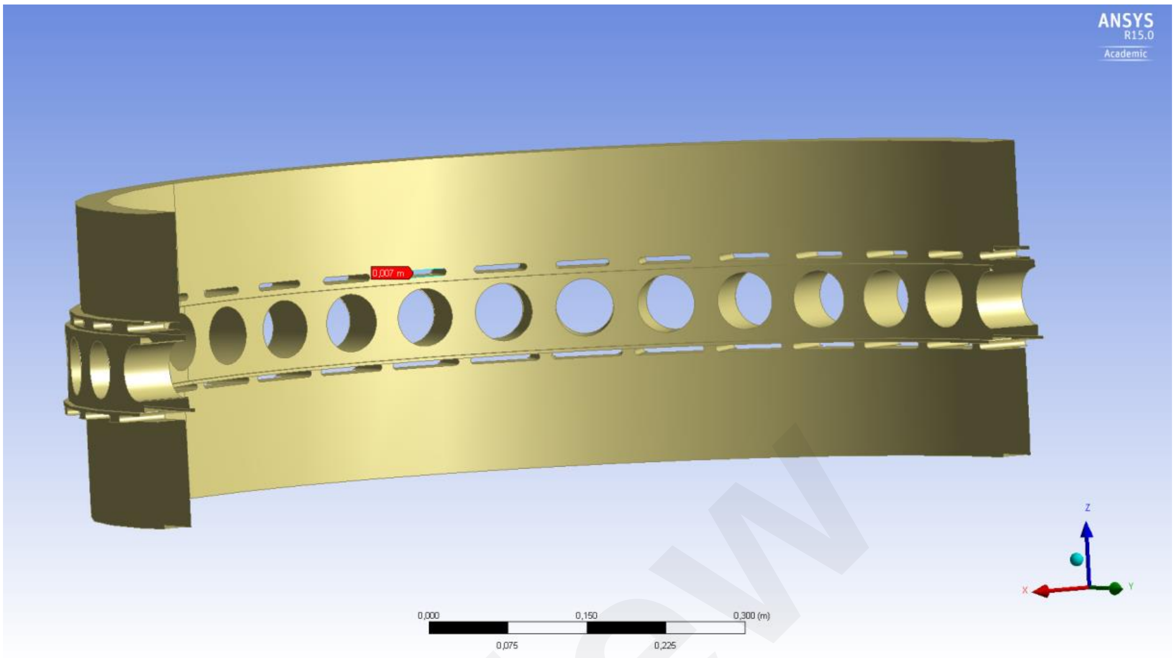

Figure 5 Central distribution piece

Inlet holes, length times width	Outside diameter in position of welding separating plates	Distance between separating plates
7 mm by 30 mm	960 mm	10 mm

Table 2 Relevant parameters for Central piece

1.2.3. Cassette and beam entrance window

The spallation material is assembled into a separate structure, named cassette. On top and bottom of these, there are channels directing the Helium flow, from the separating plates attached to the central piece out towards the periphery of the wheel. The channels are diverging due to the geometry of the wheel. In table 3 relevant parameters for the flow geometry from cassette to beam entrance window is described.

Passage between cassettes and shroud, average	Passage between turbulators, inlet to cassettes
5 mm by 15 mm	2 mm

Table 3 Relevant parameters for cassettes

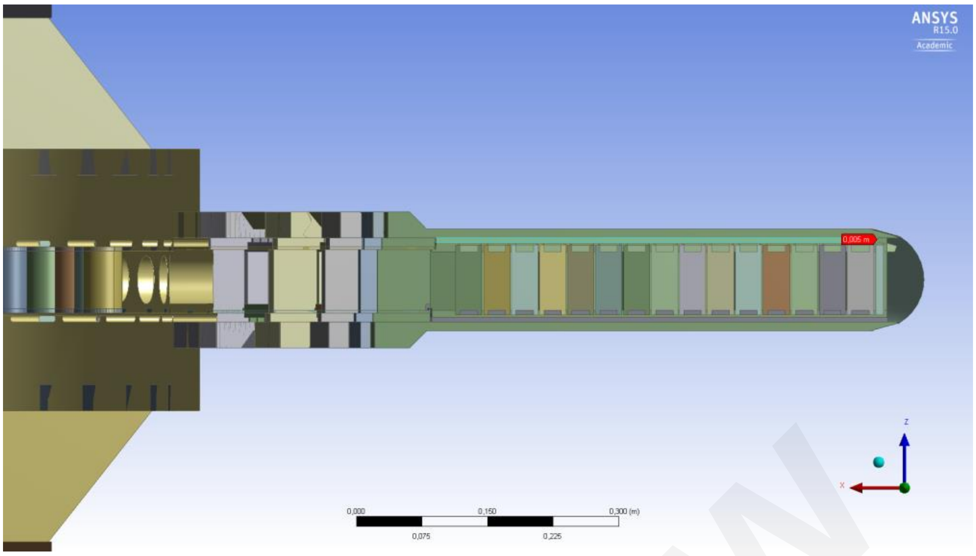

Figure 6 Passage between cassette and shroud

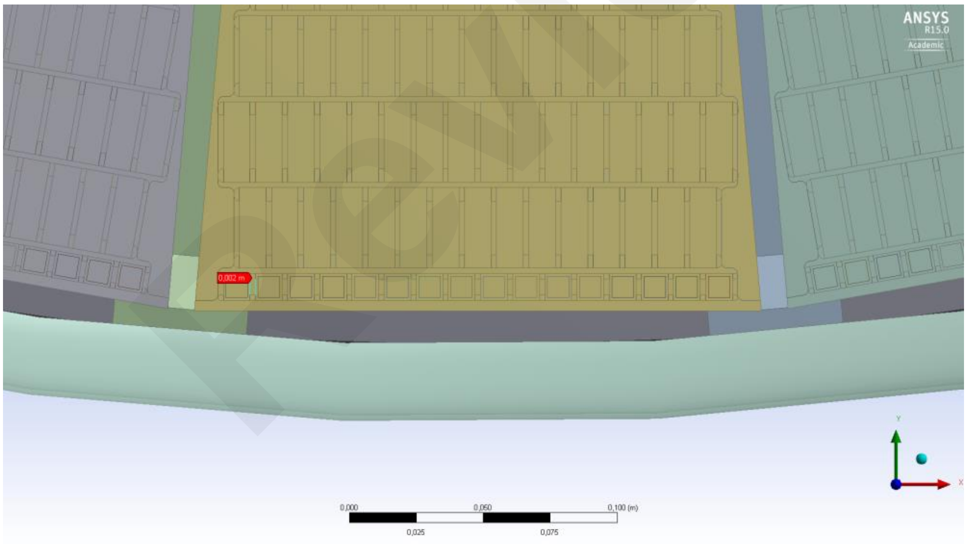

Figure 7 Passage between turbulators at inlet to cassette

1.3. Possible errors, events and consequences.

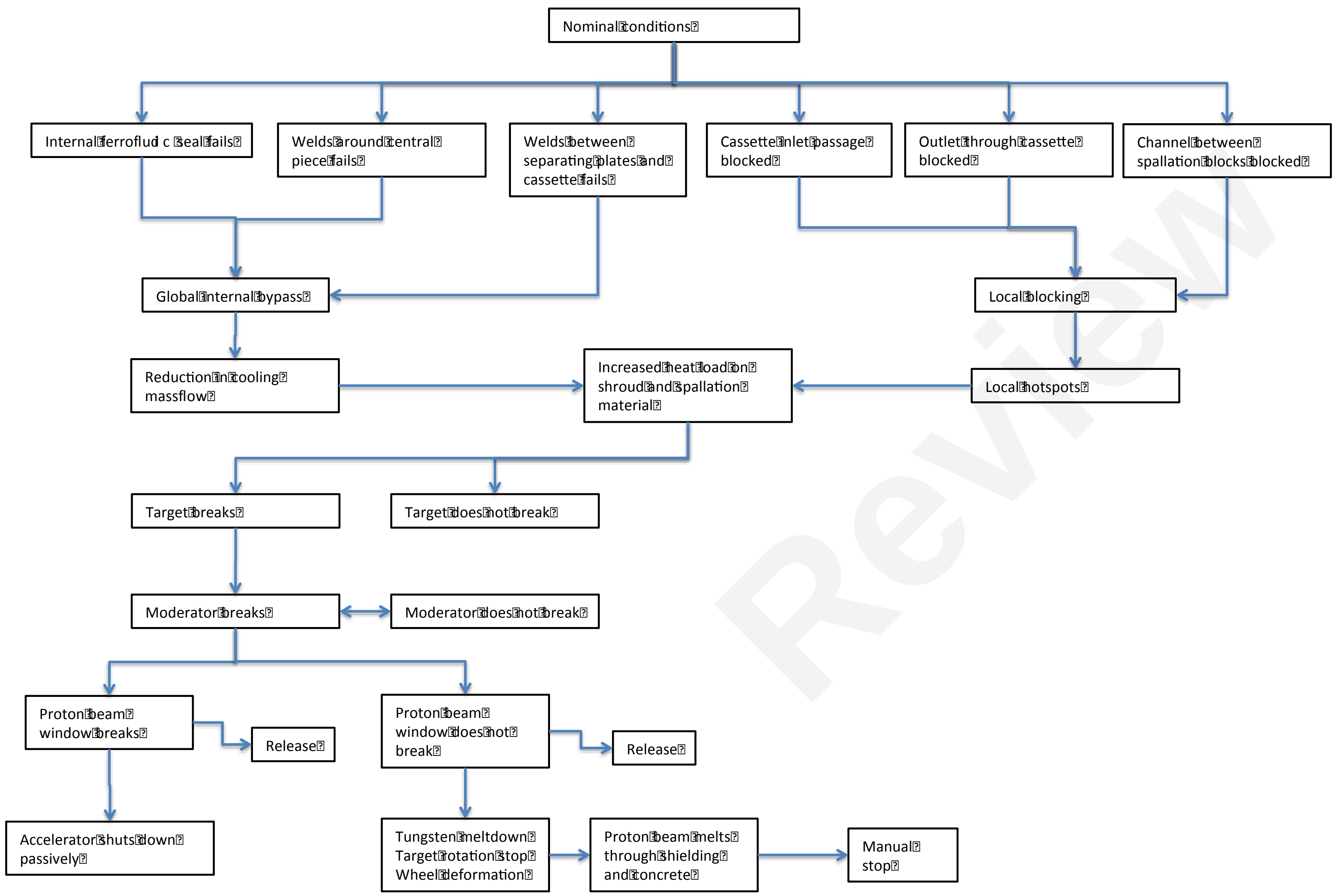

Figure 8 – Overview of event progression

The possible failure modes and consequences of various internal errors in Target are illustrated in Figure 8 – Overview of event progression.

1.4. 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

Target Systems Work Package (WP12.2), Target Division.

3. ACCIDENT SCENARIO OVERVIEW

At the start of the event progression the facility is in operation and a 5 MW high power beam impinge on the target at a rate of 14 Hz. After an event thermal stress increase on spallation material and shroud.

In this report, the following Postulated Initiating Events (PIEs) and their consequences are discussed:

Table 4 Analyzed events

Event	Consequence
Internal ferrofluidic seal fails	Global bypass- loss of cooling
Welds between separating plates and cassette fails	Global bypass- loss of cooling
Complete blocking of one channel between spallation blocks	Local blocking

Other possible scenarios are regarded as being covered by the evaluated scenarios.

3.1. Internal ferrofluidic seal fails

Consequences of a failure of the internal ferrofluidic seal has been analysed.[20] The result showed a reduction in flow through target of less than 0,1 kg/s.

3.2. Welds between separating plates and cassette fails

Consequences of a postulated gap of 3 mm all around the perimeter of the separating plate and the cassettes has been analysed. This is the most serious local bypass scenario that can be imagined. The result showed a reduction in massflow over target by 1,5 kg/s. The reduction in massflow will not lead to radiological consequences because the remaining massflow is sufficient to provide cooling for the target.[20]

3.3. One channel between spallation bricks blocked.

Finally, the event where passage between two tungsten bricks is blocked has been studied.[20]. The result showed an increased temperature in the block, but below tungsten oxidation temperature. Target shroud will not be affected adversely.

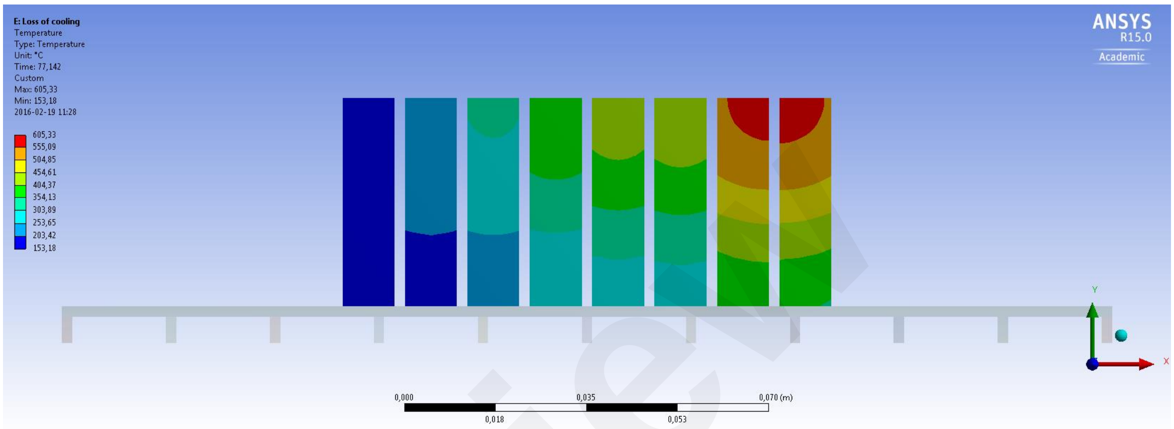

Figure 9 Temperature with one passage blocked.

3.4. Assumptions

The list of assumptions applied to this analysis are given in Table 5.

Table 5 Assumptions

ID	Assumption
A1	The target wheel, drive and shaft system is in operation in mode ‘Synchronized’ **Error! Reference source not found.** A beam permit is issued to he accelerator to send proton beam to the target.
A2	ESS is in mode ‘Operation – Beam ON’ and the accelerator operates at full power (5 MW) with a 2 GeV proton beam.
A3	The Helium Cooling System [5] is in operation and running normally at the beginning of the event.
A4	Helium parameters at the Target Wheel inlet are 10 bar(g) and 40 °C. Helium massflow is 3 kg/s.
A5	The helium purification system is in operation and functioning normally. The inventory in the helium is considered to be that for normal operation [9].

Table 5 Assumptions

ID	Assumption
A7	The event takes place after 5 years of operation with radiation embrittlement of beam entrance window and shroud according to [11].
A8	The event is evaluated for the two alternative ambient conditions[12] within the monolith vessel (see Table **6**). The baseline design for the monolith includes a PBW and a helium atmosphere within the monolith vessel. However, the option of a vacuum environment with no PBW is under consideration. Therefore, both options are considered in the event analysis.
A9	The standard control volume of 56 m^3 is used for dose calculation to workers.
A10	It is conservatively assumed that all leakage enters the control volume directly.
A11	It is conservatively assumed that the entire inventory goes through each release path.
A12	For the dose to worker calculations, assumptions and procedures from AA4 are applied. This includes the following: Maintenance/installation work is occurring in only one instrument room during the event. It is shielded from neutrons coming from the target and personnel are permitted in the room. All other instruments are taking neutron beam data, are shielded, and are locked off from entry with a safety access control system (PSS).
A13	During the event, access to the accelerator tunnel is prevented by a safety control system (PSS). Therefore, no workers are present in the accelerator tunnel.
A14	There is an operational HVAC system in the accelerator tunnel that exhausts through the stack.

Table 6 Options for ambient conditions within the monolith vessel

Monolith Atmosphere	**Pressure**	**Temperature**
Vacuum	10^{-4} mbar	50°C
Helium	1 bar(a)	50°C

4. UNMITIGATED ACCIDENT SCENARIO ANALYSIS

4.1. Dependencies

The list of dependencies applied to this analysis is given in Table 7.

Table 7 Dependencies

ID	**Description of Dependency**
D1	No safety control system is monitoring accelerator parameters.
D2	The function of a monolith vessel rupture disc is not credited.
D3	The breaking of the shroud limits the event progression – either a passive or active beam shutdown occurs.

4.1.1. Detailed scenario description, including limitations described above

A. ESS is in mode "Operation – Beam ON'[3] at 5 MW beam power.
B. The target wheel is rotating and is synchronized with the proton beam.
C. The helium cooling system is running normally with 30 kg helium at 10 bar.
D. An internal error occurs in the target vessel
E. Temperature increase in target spallation material and shroud
F. No case listed in this analysis leads to radiological release.

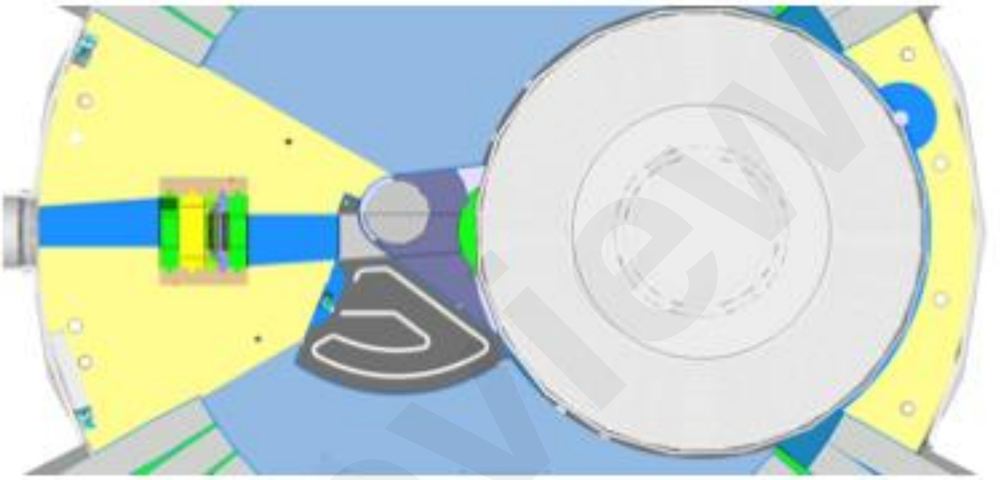

Figure 10 – Cross section of wheel and moderator - view from above

4.2. Probability calculations

In the analysis, initiating events have been assigned different probabilities, described in [13].

Table 8 Probability for different postulated initiating events

Postulated Initiating Event	Occurrence probability [y^{-1}]	Occurrence interval	Reference for the occurrence probability
Failure of ferrofluidic seal	$1x10^{-2}$ y^{-1}	H2	Event expected in the lifetime of ESS
Failure of weld between separating plate and cassette	$1x10^{-2}$ y^{-1}	H2	Event expected in the lifetime of ESS
Total blocking of one channel between tungsten bricks	$1x10^{-2}$ y^{-1}	H2	Event expected in the lifetime of ESS

4.3. Radiological consequences

For the events in this analysis, there will be no radiological consequences.

4.4. Risk Assessment

Table 9 Risk ranking of unmitigated accident – Dose to workers

Postulated Initiating Event	Occurrence interval	Radiological Consequences Worker	Risk Ranking
Failure of ferrofluidic seal	$1x10^{-2}$ y^{-1}	No consequences	ACCEPTABLE
Failure of weld between separating plate and cassette	$1x10^{-2}$ y^{-1}	No consequences	ACCEPTABLE
Total blocking of one channel between tungsten bricks	$1x10^{-2}$ y^{-1}	No consequences	ACCEPTABLE

Table 10 Risk ranking of unmitigated accident – Dose to public

Postulated Initiating Event	Occurrence interval	Radiological Consequences Public	Risk Ranking
Failure of ferrofluidic seal	$1x10^{-2}$ y^{-1}	No consequences	ACCEPTABLE
Failure of weld between separating plate and cassette	$1x10^{-2}$ y^{-1}	No consequences	ACCEPTABLE
Total blocking of one channel between tungsten bricks	$1x10^{-2}$ y^{-1}	No consequences	ACCEPTABLE

5. SUMMARY

The consequences of and mitigations for a possible chain of events starting with the unexpected failure of different parts of target has been investigated. None of the investigated events has been judged leading to radiological consequences.

6. REFERENCES

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[2] ESS-0020435 Sjögreen, Target Wheel, Drive and Shaft System Description Document- Requirements
[3] ESS-0026412 Sjögreen, Target Wheel, Drive and Shaft System Description Document- Solution
[4] ESS-0012524 Harborn, SDD- Req helium cooling system
[5] ESS-0012527 Harborn, SDD-Solution Helium Cooling system
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[7] ESS-00xxxx, Shea, Instrumentation and machine protection strategy for the ESS target station
[8] ESS-0036141, AA#8 – Accident Analysis Report: Target helium system release into Utility Rooms
[9] ESS-0045261, Muhrer, Target He inventory for normal operations
[10] ESS-003310 Pitcher et al, Beam on Target Requirements
[11] ESS-0037287 Sordo, Radiation Damage Analysis for the ESS Target
[12] ESS-0044348 SDD Solution monolith atmosphere
[13] ESS-0041755 Presteng, ESS Guideline for Target Station Radiological Hazard Analysis
[14] DOE-STD-3009-2014
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[16] ESS-0052231, Muhrer, Moderator water inventory for normal operations
[17] ESS-0051742 Y. Lee, Integrity of spallation material in the target wheel during operation and accidents
[18] ESS-0055987, Helium shock propagation to accelerator vacuum
[19] ESS-0051403, Spanier, dose to public calculations
[20] ESS-xxxxxx Sjögreen, Assumptions and estimates for AA5

7. APPENDIX A

Table 11 Safety functions – Safety-related SSCs

Safety Function	SSC Description	Event class	Defence in depth
Confine helium	Target shroud	H1-H2	L1-L2
Confine helium	Pipe system and components	H1-H2	L1-L2
Limit inventory	Helium purification system	H1-H2	L1-L2
Limit inventory	Getters in helium purification system to remove isotopes not captured by filters	H1-H2	L1-L2
Limit inventory	Radiation monitoring in loop and filters	H1-H2	L1-L2
Wheel cooling	Process control system for helium cooling system functional	H1-H2	L1-L2
Wheel cooling	Helium flowing and cooling as designed, monitor process variables	H1-H2	L1-L2
Wheel cooling	Monitor critical process variables, turn off beam – MPS	H2	L2
Wheel cooling	Internal helium cooling channels and inner rotational seal	H1	L1
Wheel cooling	Pressure relief valve bleeds off into Off-gas extraction system	H1-H2	L1-L2
Wheel rotates	Drive motor functional	H1	L1
Wheel rotates	Process control system for wheel drive functional	H1-H2	L1-L2
Wheel rotates	Wheel rotates as designed, monitor process variables	H1-H2	L1-L2
Wheel rotates	Monitor rotation if fluctuates too far, turn off beam – MPS	H2	L2
Wheel rotates	Pedestal in bottom of monolith constrains target wheel and shaft movement	H1-H2	L1-L2
Wheel rotates	Monolith cover constrains target wheel and shaft movement	H1-H2	L1-L2
Limit exposure	Ventilation in utility rooms is functional (proper air renewal rate)	H1-H2	L1-L2
Reduce dose	*Administrative Control:* The workers shall be trained and educated in radiation safety.	H2	L2
Confine monolith atmosphere in order to limit contamination production and to control release of inventory (with PBW)	Monolith vessel, PBW, NBWs	H1-H2	L1-L2

Table 11 Safety functions – Safety-related SSCs

Safety Function	SSC Description	Event class	Defence in depth
Confine monolith atmosphere in order to limit contamination production and to control release of inventory (No PBW)	Monolith vessel and NBWs	H1-H2	L1-L2
Confine monolith atmosphere in order to limit contamination production and to control release of inventory (No PBW)	Vacuum system	H1-H2	L1-L2
Confine monolith atmosphere in order to limit contamination production and to control release of inventory (No PBW)	Process control system functional for vacuum system, monitoring system parameters	H1-H2	L1-L2
Confine monolith atmosphere in order to limit contamination production and to control release of inventory (No PBW)	Exhaust from vacuum pumps routed to stack through Off-gas extraction system	H1-H2	L1-L2
Prevent exposure when Beam OFF	Valve in beam pipe between monolith and tunnel	H1-H2	L1-L2

Note:
Event – H1 for Normal Operations, H2.
Defence in Depth (DiD) – L1, L2, L3, L4 or L5

DOCUMENT REVISION HISTORY

Revision	Reason for and description of change	Author	Date
1	First issue	K. Sjögreen	2016-02-04