Application of Probabilistic Safety Assessment to a Non-Reactor Nuclear Facility - European Spallation Source ERIC

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Abstract: The IAEA General Safety Requirements (GSR Part 4) emphasize the role of probabilistic methods in safety assessment for all nuclear facilities. While Probabilistic Safety Assessment (PSA) is well established for nuclear power plants and research reactors, its application to non-reactor facilities remains less standardized and presents specific methodological challenges.

This paper presents the application of PSA to the European Spallation Source (ESS), a neutron scattering research facility with a high-power proton accelerator hitting a tungsten target. Although ESS is not a nuclear facility, it represents a complex non-reactor nuclear installation due to its high content of activated material. The study demonstrates how traditional PSA elements, including hazard identification, initiating event and scenario analysis, likelihood estimation, and consequence assessment, can be adapted using a graded approach to reflect the characteristics of non-reactor facilities.

Compared to reactor PSAs, key differences include a broader distribution of hazardous materials, diverse operational configurations, and distinct initiating event sets. Additionally, traditional reactor risk metrics may not be directly applicable, especially for facilities located closer to the public, where consequence-based metrics such as release magnitude and off-site dose are more appropriate. Further challenges include limited reliability and initiating event data.

The ESS case study shows that, despite these differences, PSA provides valuable insights for identifying dominant risk contributors, supporting design optimization, and strengthening risk-informed decision-making for non-reactor nuclear facilities.

Keywords: Non-reactor PSA, PRA, ESS

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1. INTRODUCTION

Probabilistic Safety Assessment (PSA) has become an essential component of nuclear safety analysis, providing a systematic framework for evaluating risk and supporting risk-informed decision-making. IAEA GSR Part 4 [1], emphasizes the importance of incorporating probabilistic methods alongside deterministic approaches for all types of nuclear facilities. While PSA methodologies are well developed and widely applied for nuclear power plants and research reactors, their implementation in non-reactor nuclear facilities remains comparatively limited and less standardized.

Non-reactor nuclear facilities present distinct challenges for PSA. Unlike reactors, these facilities often involve distributed inventories of radioactive material and a wide range of operational configurations. As a result, the identification of initiating events, the modeling of accident scenarios, and the quantification of associated risks require methodological adaptations. Furthermore, traditional reactor-oriented risk metrics, such as core damage frequency or large release frequency, are often neither directly applicable nor meaningful in these contexts.

Additional challenges arise from the relative scarcity of operational experience for non-reactor systems, as well as from the diversity of technologies and designs. This limits the direct transferability of established PSA methods and data developed for reactor applications. Consequently, there is a growing need for flexible, graded approaches that tailor the level of detail and modeling effort to the magnitude

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and nature of the hazards, while still maintaining sufficient rigor to support safety assessments and regulatory decision-making.

The European Spallation Source (ESS) (Figure 1)[2], currently under commissioning in Lund, Sweden, represents a new generation of high-power accelerator-driven neutron sources. Its complex configuration, combining high-energy proton beams, a tungsten target, cryogenic systems, and relatively high radioactive inventories distributed across multiple systems, makes it a representative example of a modern non-reactor nuclear facility. These characteristics provide both challenges and opportunities for the application of PSA methodologies.

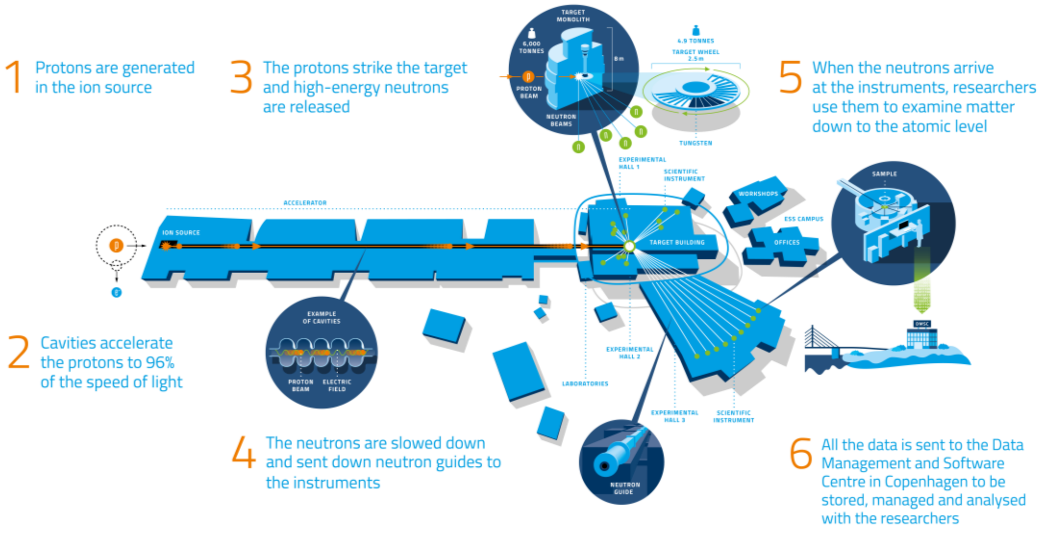

Figure 1. The ESS facility at a glance [2]

This paper presents the development and application of a PSA framework for the ESS, demonstrating how established PSA techniques can be adapted to address the specific features of non-reactor installations. A graded approach is employed to structure the analysis, encompassing hazard identification, initiating event analysis, scenario modeling, frequency estimation, and consequence assessment. Particular attention is given to the selection of appropriate risk metrics, with an emphasis on consequence-based measures such as release magnitude and off-site dose.

The objectives of this work are threefold: (i) to illustrate the practical implementation of PSA for a complex non-reactor facility, (ii) to identify key methodological differences and challenges compared with reactor PSA, and (iii) to demonstrate the value of PSA in supporting design optimization and risk-informed decision-making. The insights gained from the ESS case study are intended to contribute to the ongoing development and harmonization of PSA approaches for non-reactor nuclear facilities.

2. PSA FOR ESS

Traditionally, in nuclear reactors, the sources of hazards considered in PSA are primarily limited to the reactor core and the spent fuel pool. In Sweden, the current regulations were developed mainly for existing nuclear power plants and state that probabilistic analyses shall be carried out as a complement to deterministic evaluations in order to provide a comprehensive picture of the protection of the public and the environment against exposure to ionizing radiation, and to support the evaluation of issues relevant to such protection. For nuclear power plants, the Swedish regulations require that probabilistic analyses include: (i) nuclear fuel damage frequency (PSA Level 1), and (ii) the frequency of radioactive releases to the environment resulting from fuel damage (PSA Level 2) [4]. The Swedish Radiation Safety Authority (SSM) has given ESS similar regulations as for a nuclear installation, i.e probabilistic methods shall complement the deterministic analyses. However, SSM has not submitted any guidelines of how the probabilistic studies shall be applied.

Nuclear fuel damage can occur in the reactor pressure vessel during normal operation, low-power operation, transition regimes, and maintenance outages, as well as in the spent fuel pool during normal operation or fuel handling activities. In principle, this means that the analysis covers not only the reactor core, but also other parts of the facility.

Given the size of the Exclusion Area Boundaries (EABs) for existing nuclear power plants, nuclear fuel generally represents the dominant contributor to public exposure from ionizing radiation. Other radioactive sources, such as activated media in process systems, are typically excluded because their potential impact on the public is relatively small compared with that of the fuel inventory, particularly considering the large EABs.

However, for Small Modular Reactors (SMRs) and non-reactor nuclear facilities, which may be located closer to populated areas and may have significantly smaller EABs, other sources of ionizing radiation can become relevant.

Furthermore, in non-reactor nuclear facilities such as ESS, hazardous sources and radioactive inventories are distributed throughout the facility and present a variety of unique risks, including prompt radiation hazards, residual radiation hazards, and risks associated with the release of radioactive materials inside or outside the facility.

The conceptual representation of the ESS PSA is illustrated in Figure 2. In this framework, initiating events, which may originate in any part of the facility, are evaluated using the Event Tree/Fault Tree (ET/FT) approach and linked to the corresponding end states according to the severity of the consequences associated with the respective accident sequences.

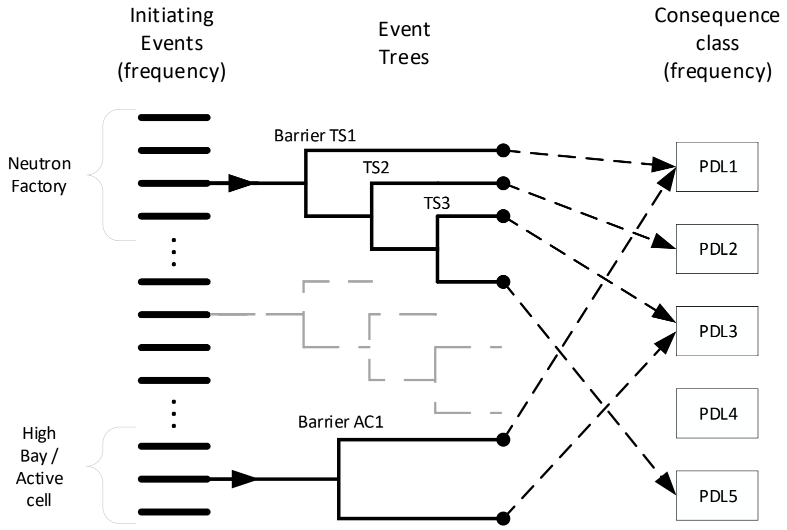

Figure 2. Conceptual overview of ESS PSA

In general PSA for ESS follows the process outlined in IAEA TECDOC-1267 [3], which covers the standard steps in performing Probabilistic Safety Assessment. The main steps include:

- Hazards identification and screening.
- Selection of initiating events
- Identification of undesirable states
- Accident sequence analysis
- Human reliability analysis
- Consequence analysis
- Data analysis
- Scenario quantification

2.1. Hazard identification

The radiation safety hazard analysis for ESS considers three types of radiation hazards: prompt radiation, residual radiation, and contamination hazards. The objective is to analyze all Structures, Systems, and Components (SSCs) that perform any of the three primary radiation safety functions of the facility:

- Limit external exposure to prompt radiation
- Limit external exposure to residual radiation, and
- Limit internal and external exposure to contamination.

Hazard identification is primarily a qualitative process that forms the basis for the subsequent stages of radiological risk assessment. In later steps, the identified hazards provide the basis for the selection of Postulated Initiating Events (PIEs), as part of the Deterministic Safety Assessment (DSA), as well as initiating events for the PSA.

The analysis of PIEs involves the evaluation of event severity in terms of radiological consequences and the definition of appropriate control measures to ensure an acceptable level of risk. The PSA performs a quantitative evaluation of accident sequences and quantifies the integrated risk associated with operation of the facility.

2.2. Initiating event identification

The analysis of initiating events for the ESS PSA focuses on events that may lead to radiological consequences for the public, as identified in the radiological hazard analysis. These events may occur either as a direct result of equipment failures, maintenance or testing errors, or other operator actions.

Following criteria are employed when performing screening of initiating events:

- Initiating event frequency is below 10^{-7} threshold. Initiating event belongs to residual risk event class based on ESS general safety objectives [5]. This screening criterion is not applied to initiating events caused by failures of system components. Such events are analyzed using Failure Modes and Effects Analysis (FMEA), and frequency quantification is performed using the Fault Tree (FT) approach.
- Events that result in an effective dose to an unprotected member of the public at the Exclusion Area Boundary (EAB) below 0.1 mSv, and that do not require any mitigating actions at DiD Level 2 or higher, may be screened out.
- Events for which the undesired end states are not reached within the mission time may also be screened out.

Following identification, initiating events are categorized and grouped according to the type of initiating event, accident progression, release pathway, and associated consequences.

Based on the analysis of initiating events for the target building, the following initiating event groups have been identified:

Loss of target cooling with beam on target:

- Loss of target cooling due to loss of the Target Helium Cooling System (THCS) inventory:
  - <u>Causes:</u>
    Equipment malfunctions, which may cause depressurization of the system and He coolant release, resulting in loss of coolant inventory in THCS (Figure 7). These events are analyzed in the System FMEA for THCS and FMEAs performed for interfacing systems. Breaks in the THCS or any interfacing systems which result in a loss of coolant inventory in THCS. These events are analyzed in the system FMEA for THCS and FMEAs performed for interfacing systems.
  - <u>Consequences:</u>
    If unmitigated, the proton beam continues to deposit energy into the tungsten target wheel, increasing the temperature of the spallation material and the shroud leading to overheating, damage of the target wheel, spallation material and release of the target wheel inventory
- Loss of target cooling due to loss of THCS
  - <u>Causes:</u>
    Equipment failures in THCS (Figure 7) and interfacing systems that result in loss of target cooling. These events are analyzed in the system FMEA for THCS and FMEAs performed for interfacing systems.
  - <u>Consequences:</u>
    If unmitigated, the proton beam continues to deposit energy into the tungsten target wheel, increasing the temperature of the He coolant, spallation material and the shroud leading to overheating, damage of the target wheel, spallation material and release of the target wheel inventory.

Loss of target when rotation with beam on target:

- Loss of target wheel rotation (Figure 3):
  - Causes:
    Equipment failures in the Target Wheel, Drive and Shaft System (TWDSS)
  - Consequences:
    If unmitigated, loss of target wheel rotation will lead to overheating, damage of the tungsten target wheel, spallation material and release of the target wheel inventory.

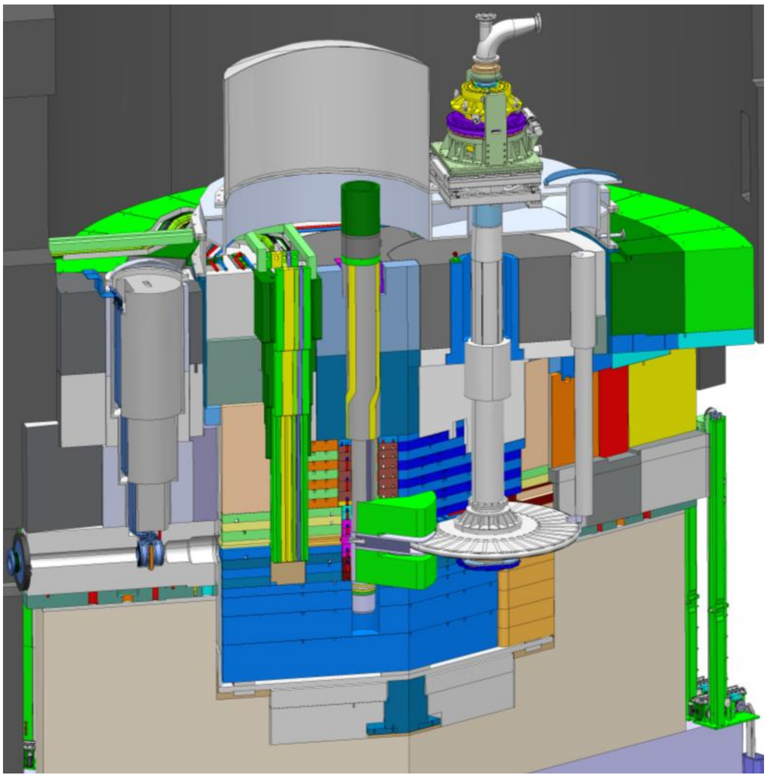

Figure 3. Cross section of the Target Monolith[†]

Load Handling Events in the High Bay or Active Cell:

There are several load handling events in the high bay that involve loading, unloading and transportation across the high bay of the casks containing activated target wheel components, and instrumentation (Figure 4).

- Causes:
  - Lifting equipment failures or human errors.
- Consequences:
  - Loss the mechanical integrity/ loss of the confinement function of transportation casks that can lead to release of activated components (e.g. activated tungsten dust can be released)
- Identified events:
  - Dropped Cask at the Monolith
  - Dropped Cask at the Active Cell Floor
  - Dropped Cask at the High Bay
  - Dropped Cask at the Transport floor
  - Dropped Instrument Exchange Tool Cask at the High Bay, Active Cell Floor, Experimental Hall

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[†] The target wheel is shown at the level of the incoming proton and outgoing neutron beamlines. The wheel drive is shown on top of the drive shaft.

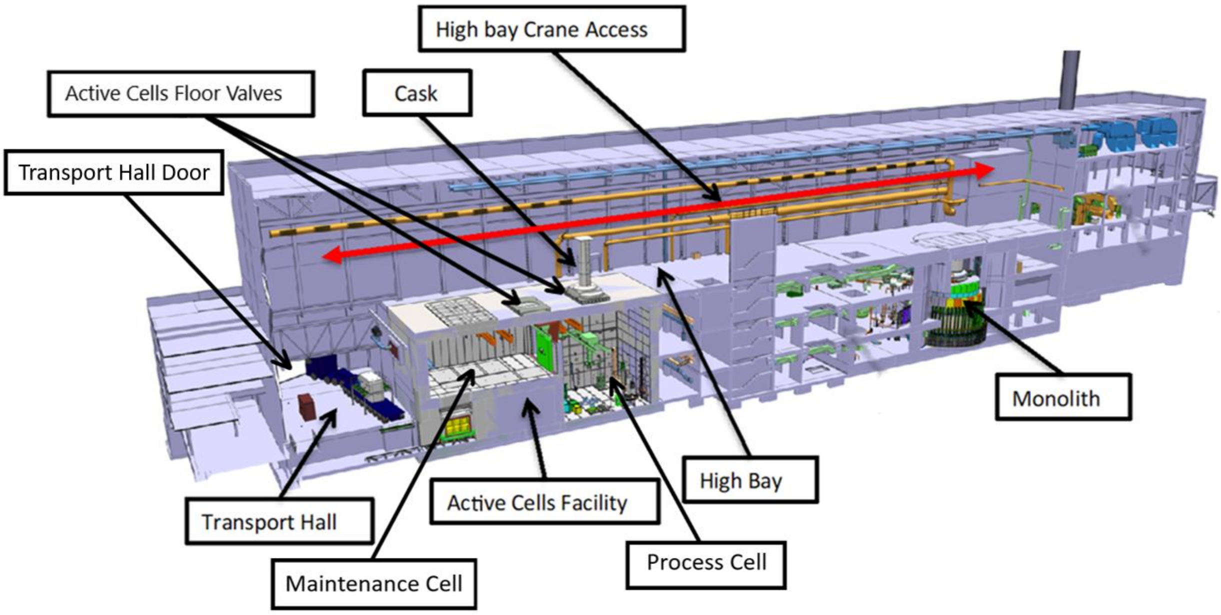

Figure 4. Cross section of the Target Building

Traditionally, the quantification of initiating event frequencies in nuclear power plants is performed using a direct estimation approach based on historical operating data, typically employing Bayesian methods. However, due to the limited operating experience available for non-reactor facilities such as ESS, as well as the unique characteristics of the facility design, the direct estimation approach is not directly applicable.

Instead, internal initiating events involving failures within operational systems composed of multiple components were modeled using fault trees. These fault trees define the combinations of component failures and human errors that could lead to an initiating event.

2.3. Accident Scenario Development (Event Trees)

Following the identification and categorization of initiating events, accident scenarios are developed using the Event Tree/Fault Tree (ET/FT) methodology. The objective of the event tree analysis is to systematically evaluate the progression of accident sequences, considering the success or failure of preventive and mitigative safety functions, human actions, and supporting SSCs. Each accident sequence is linked to a defined end state representing the resulting radiological consequences. This approach enables quantification of both the frequency and severity of accident scenarios and provides the basis for evaluating compliance with the ESS probabilistic safety goals.

If an accident sequence does not lead to any of the end states listed in Table 1, it is assumed that the sequence ends in the OK end state (safe state). This effectively means that the human actions, radiation safety functions, and SSCs in the Operational Group were effective, and no significant deviation from normal operation, in terms of radiological consequences, have occurred.

The end states, radiological acceptance criteria and probabilistic safety goals shall be interpreted as follows. In the event tree analysis, every accident sequence is connected to an end state defined in Table 1. Then, the purpose of ESS PSA is to ensure that the likelihood of occurrence of every end state is within acceptable limits defined by the probabilistic safety goals, for all initiating events and associated accident sequences in the entire ESS facility, as schematically illustrated in Figure 2.

In the context of PSA of the ESS facility, “end states” refer to the final state in terms of radiological release following a sequence of events (initiating events, and successes or failures of preventing or mitigative measures) that have been analyzed.

Table 1. ESS PSA end states and event class requirements

End state (consequence class)	Acceptance Criteria	Event class (SSMFS)	Event Frequency (year^{-1})	Probabilistic Safety Goal (year^{-1})
PDL1	Public dose limit (dose$\leq$ 0.1) mSv/event	H2	$10^{-2} \leq F < 1$	$F < 1$
PDL2	Public dose limit (0.1<dose$\leq$ 1) mSv/event	H3	$10^{-4} \leq F < 10^{-2}$	$F < 10^{-2}$
PDL3	Public dose limit (1<dose$\leq$ 20) mSv/event	H4(A&B)	$10^{-6} \leq F < 10^{-4}$	$F < 10^{-4}$
PDL4	Public dose limit (20<dose$\leq$ 100) mSv/event	H5	$10^{-7} \leq F < 10^{-6}$	$F < 10^{-6}$
PDL5	Public dose limit (dose$\geq$ 100) mSv/event	Residual risk	$F < 10^{-7}$	$F < 10^{-7}$

In addition to the end states defined in Table 1, the accident sequence analysis for the target station includes intermediate states referred to as *target damage states*, shown in Table 2.

Table 2. Target damage states considered in the ESS PSA model

Target Damage State ID	Description
TW-DE-2-1	Target Damage due to lack or inadequate He cooling
TW-DE-2-2	Target damage due to loss of rotation
TW-DE-2-2A	Target damage due to loss of rotation – Slow stop
TW-DE-2-2B	Target damage due to loss of rotation – Direct stop

Target damage is assumed for all accident sequences considered for the target station in the event of failure of the Machine Protection System (MPS) to terminate beam delivery to the target. These target damage states may be regarded as precursor states. The primary purpose of introducing the target damage states is to evaluate the integrated performance of the MPS and to assess the risk of economic consequences associated with target damage, including unplanned downtime and costs related to repair or replacement of key facility components.

Figure 5 illustrates an example of the event trees produced for the target station. The accident sequences represented by this event tree is initiated by the loss of target primary cooling system (TPCS).

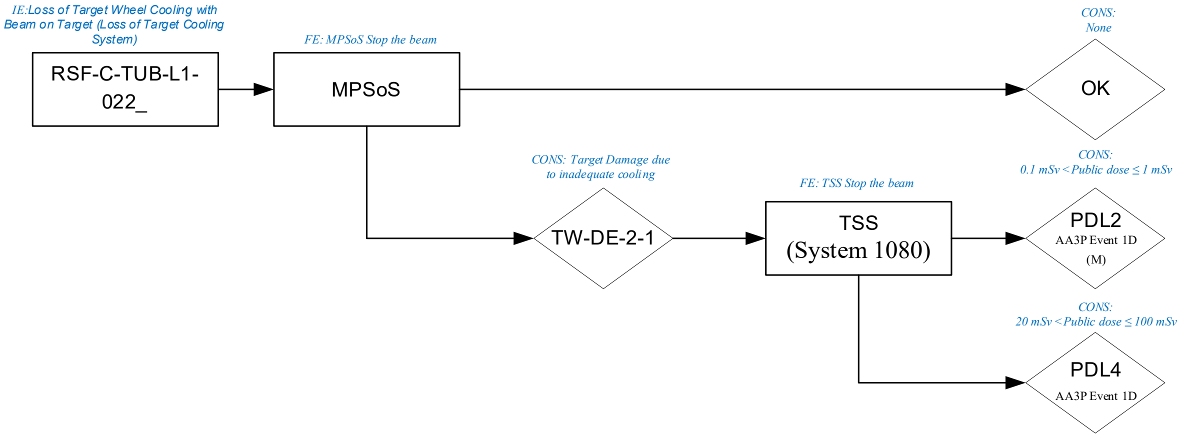

Figure 5. Success block diagram for the Loss of Target Wheel Cooling due to Loss of Primary Helium Cooling System

Successful operation of the MPS results in termination of beam delivery to the target, thereby terminating the accident sequence. Provided that the target wheel and the TPCS remain intact, no public radiological consequences are expected if the MPS operates successfully.

If the MPS fails, however, target damage occurs, resulting in target damage state TW-DE-2-1.

Further accident progression and the resulting consequences associated with target damage state TW-DE-2-1 depend on the performance of the Target Safety System (TSS). Successful operation of the TSS shuts down the beam in response to abnormal helium coolant system parameters or elevated pressure in the monolith vessel, resulting in the PDL2 end state. If the TSS also fails to terminate the beam, the sequence progresses to the PDL4 end state.

Figure 6 presents an example of an event tree developed for load-handling events. Since no barriers are credited in any of the DiD Levels, the event sequence leads directly to the end state PDL3 in the case of a dropped cask containing target wheel components in the transport hall.

Figure 6. Success block diagram for the Load Handling Event - Dropped Cask at the Transport Hall

All initiating events and event trees were implemented in the ESS PSA model using RiskSpectrum® PSA software. By applying the ET/FT methodology, it is possible to evaluate the integrated risk of the facility for initiating events originating in all parts of the installation, as conceptually illustrated in Figure 2.

The results of the ET/FT analysis are presented and discussed in Section 3.

2.4. System Analysis

System analysis was performed for all systems whose failure could result in an initiating event (e.g., THCS, Figure 7) or for systems credited for mitigating the consequences of initiating events (e.g., MPS and TSS). In addition to the analysis of front-line systems, the system analysis also addressed important inter-system dependencies that could lead to failures of the front-line systems, as schematically illustrated in Figure 8.

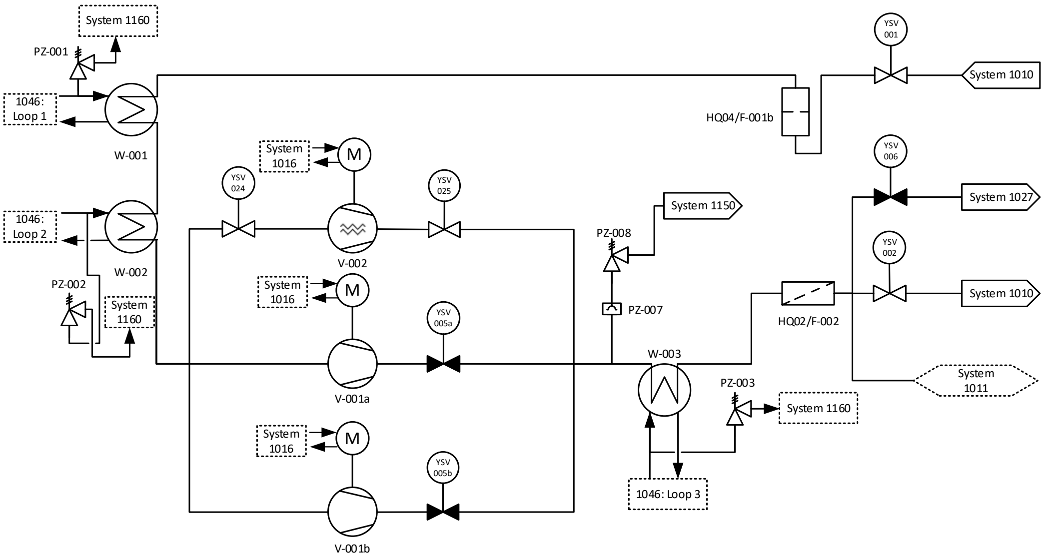

Figure 7. Schematic representation of main components in THCS

The approach employed for the system analysis involved the following major steps:

- Definition of system success criteria derived from the accident sequence analysis and associated event trees, including definition of the corresponding top events in the fault tree structure.
- Performance of a system Failure Modes and Effects Analysis (FMEA) to identify relevant component failure modes, including functional dependencies, for the functions performed by the system and the associated success criteria.
- Collection of reliability data, primarily based on manufacturer data and, where unavailable, supplemented by generic reliability data sources.
- Development of fault tree models representing system failures and dependencies.
- Analysis of Common Cause Failures (CCFs), including identification and definition of CCF groups. At the current stage, the ESS PSA employs the Beta Factor model with a constant value of $\beta=0.1$ for all CCF groups, regardless of group size.

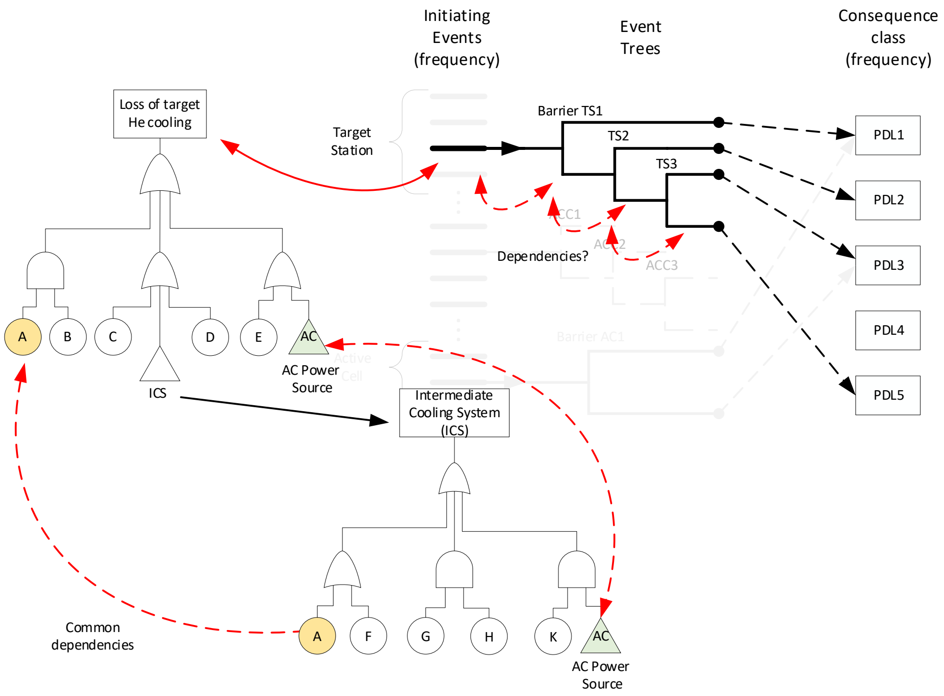

Figure 8. Treatment of inter-system dependencies

2.5. Other Considerations

Additional PSA development tasks, including Data Analysis and Human Reliability Analysis (HRA), were performed but are not discussed in detail in this paper.

The Human Reliability Analysis considered both Type A human errors (pre-initiator human errors) and Type B human errors (initiating-event-related human errors). At the current stage of development, the accident sequences included in the ESS PSA do not credit any manual operator actions for mitigation of initiating event consequences (Type C).

Finally, the current scope of the ESS PSA is limited to internal events and does not include analyses of internal hazards (such as fire and flooding), seismic events, or other external hazards.

3. RESULTS

The results of the PSA analysis are summarized in Table 3, which presents the annual frequencies of the Public Dose Limit (PDL) end states (year^{-1}) and the annual frequency of target wheel damage. The results demonstrate that all PDL frequencies satisfy the corresponding probabilistic safety goals and indicate an overall balanced risk profile.

Table 3. Consequence analysis results for the ESS PSA model

Consequence	Description	Frequency (year^{-1})	Probabilistic Safety Goal (year^{-1})
PDL1	Public dose level (dose<=0.1 mSv/event)	2.1E-02	F < 1
PDL2	Public dose level (0.1<dose<=1) mSv/event	4.6E-03	$F < 10^{-2}$
PDL3	Public dose level (1<dose<=20) mSv/event	2.4E-05	$F < 10^{-4}$
PDL4	Public dose level (20 < dose <= 100) mSv/event	1.8E-10	$F < 10^{-6}$
TW-DE-2-1	Target wheel overheats due to loss of He cooling	5.5E-04	-
TW-DE-2-2	Target wheel overheats due to loss of rotation	4.3E-04	-
TW-DE-2-2A	Target wheel overheats due to loss of rotation – Slow stop	4.3E-04	-
TW-DE-2-2B	Target wheel overheats due to loss of rotation – Direct stop	1.4E-10	-

Figure 9 presents the fractional contributions of the initiating event groups to the different PDL categories. The results show that the dominant contribution to the risk in PDL2 and PDL3 originates from load-handling events in the target building, whereas the contribution from target events with beam on target is limited to 12% and 14%, respectively.

The consequence class PDL1 includes only success paths in the event trees for target-related events, meaning that the frequency of PDL1 essentially reflects the frequency of occurrence of the initiating events themselves.

PDL4 represents the most severe consequence considered in the analysis, with the effective dose at the Exclusion Area Boundary (EAB) approaching 100 mSv.

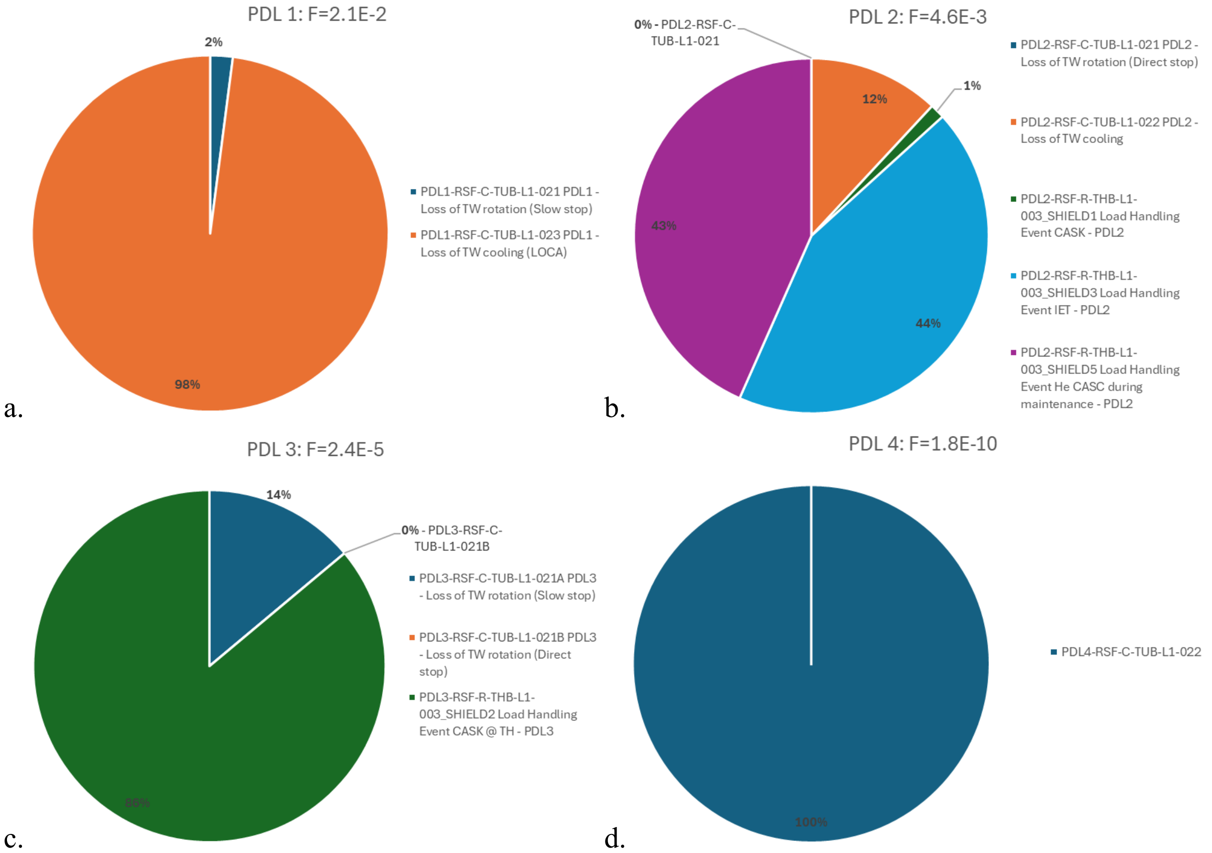

Figure 9. Fractional contributions from initiating events to (a) PDL1, (b) PDL2, (c) PDL3, (d) PDL4

Analysis of the cut sets generated for the PDL1-PDL4 end states shows that PDL1 is dominated by sequences initiated by loss of target cooling due to loss of coolant inventory in the THCS, leading to the release of helium and activation products to the environment. In these sequences, the MPS successfully terminates the accident, and the release is limited to the helium inventory of the THCS. The dominant cut sets involve leakages in major mechanical components of the THCS.

PDL2 is dominated by load-handling events and by loss of target cooling sequences in which the MPS fails, but the TSS successfully mitigates the accident after onset of target damage. The dominant cut sets include failures of major mechanical components in the THCS (e.g., the screw compressor) and common-cause failures (CCFs) of electronic components in the MPS.

PDL3 is primarily driven by cask-drop events involving monolith components in the transport hall, followed by loss of target wheel rotation sequences involving failure of both the MPS and TSS, where the dominant cut sets include failures of the target wheel drive motor or motor controller, as well as CCFs of electronic equipment in the MPS and TSS.

PDL4 is dominated by unmitigated loss of target cooling sequences. The most significant cut sets include failures of major mechanical components in the THCS (e.g., the screw compressor) together with CCFs of electronic equipment in the MPS and TSS.

4. CONCLUSIONS

This paper presented the development and application of a PSA framework for the European Spallation Source (ESS), demonstrating how established PSA methodologies can be adapted to complex non-reactor nuclear facilities. Unlike traditional reactor PSA, the ESS PSA addresses distributed radioactive inventories, various types of radiation hazards, and accident scenarios originating across multiple facility systems.

The PSA was developed using the Event Tree/Fault Tree (ET/FT) employing a graded approach tailored to the specific characteristics of ESS. The results show that all analyzed consequences meet the corresponding probabilistic safety goals and that the overall risk profile is balanced. The analysis identified load-handling events and failures associated with target cooling and protection systems as the dominant contributors to risk.

The study demonstrates the value of PSA in supporting design evaluation and that it can be employed for risk-informed decision-making for non-reactor nuclear facilities.

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