Vysus Group

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

Ingenuity.
Imagination.
Insight.

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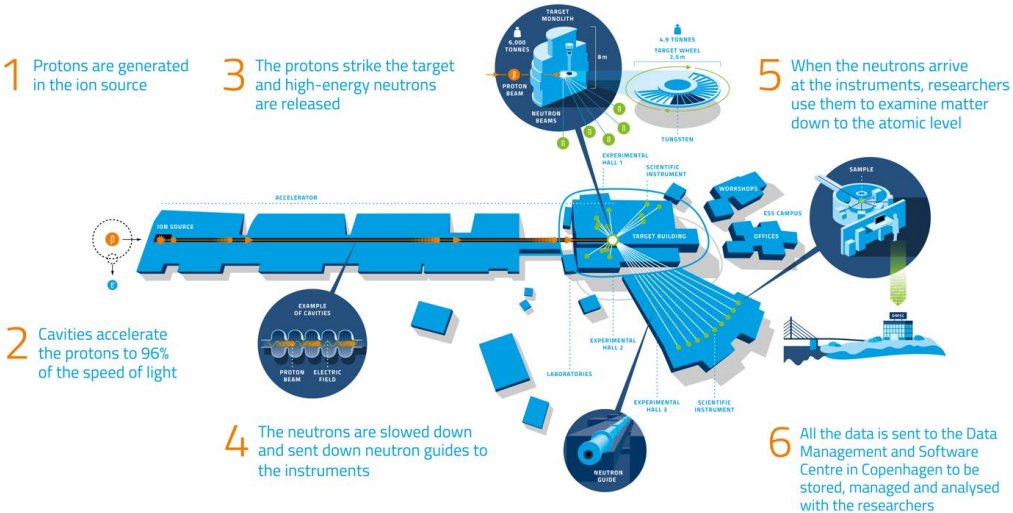
The European Spallation Source

The European Spallation Source (ESS) currently under commissioning in Lund, Sweden, represents a new generation of high-power accelerator-driven neutron sources.

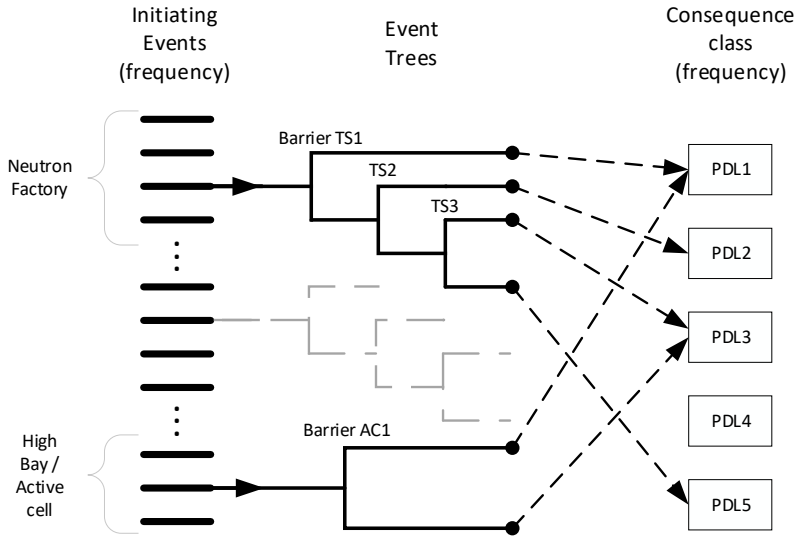


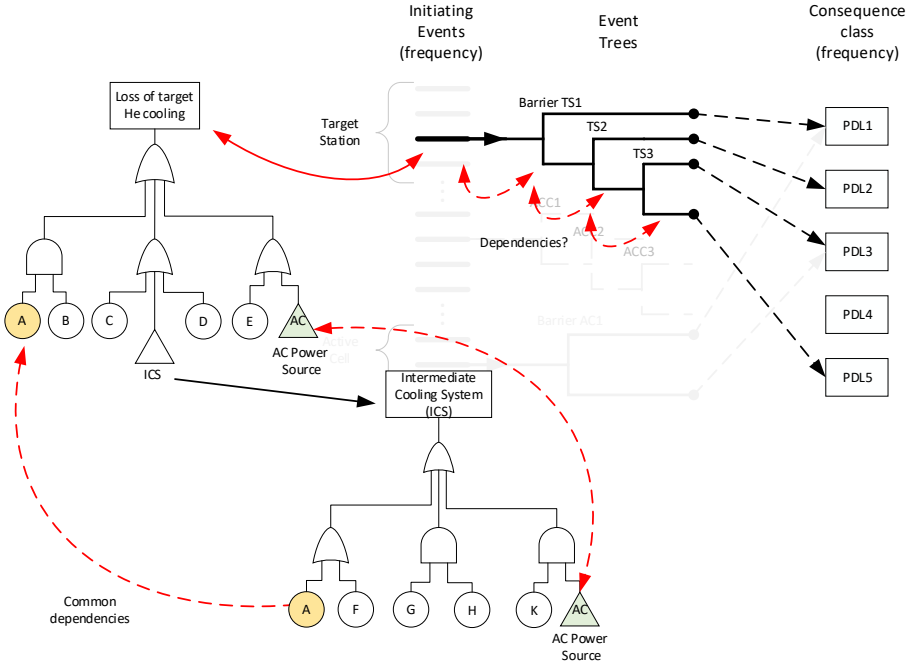
Why PSA for Non-Reactor Facilities?

- **IAEA GSR Part 4** emphasizes probabilistic methods alongside deterministic safety assessment - for *all* nuclear facility types, not just power reactors.
- Main challenges:
  - Distributed inventories
    - *Hazardous & radioactive material spread across many systems, not concentrated in a single core*
  - Diverse configurations
    - *Wide range of operating modes and facility layouts compared with standardized reactor designs*
  - Different risk metrics
    - *Core damage or LERF frequency doesn't apply – consequence-based metrics (public dose) are more meaningful*
  - Limited data & experience
    - *Sparse operating history and reliability data limit direct transfer of reactor PSA methods*

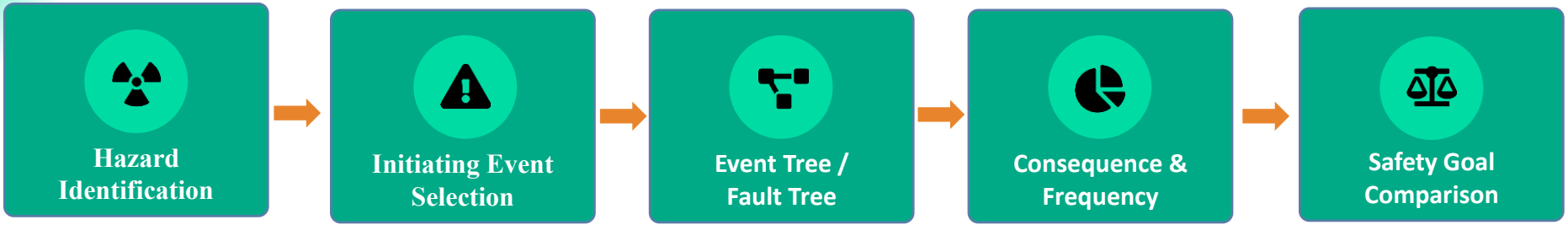
Conceptual Framework of the ESS PSA

Initiating events originating anywhere in the facility are evaluated with an Event Tree / Fault Tree approach, linked to end states by consequence severity.





Analysis Steps



Main steps (IAEA TECDOC-1267):

- hazard screening
- initiating event selection
- undesirable state identification
- accident sequence analysis
- HRA consequence analysis
- data analysis
- quantification

Key contrast with classical reactor PSA:

- hazards are distributed across the whole facility (target, casks, cryogenics, handling operations) rather than concentrated in a single reactor core.

Hazard Identification

- The radiation safety hazard analysis considers three hazard types, each tied to a primary radiation safety function that SSCs must perform:

Prompt radiation

Limit external exposure to prompt radiation during beam operation

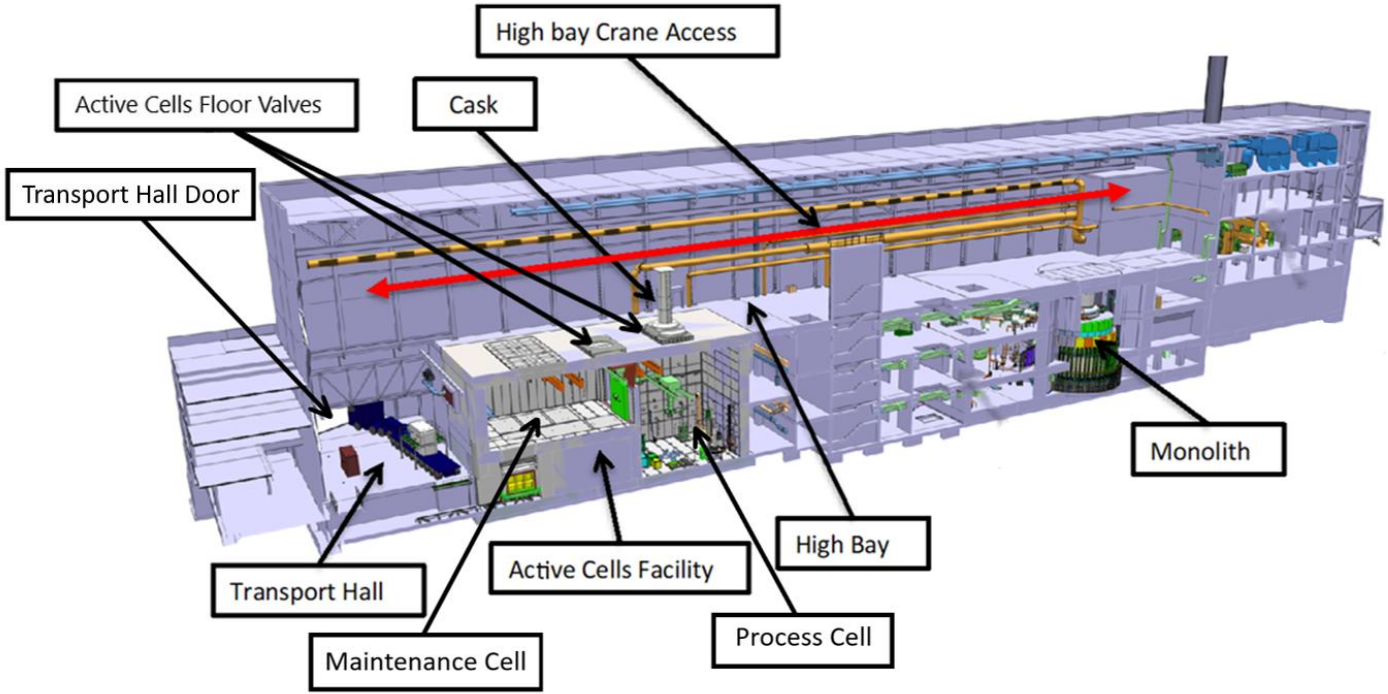
Residual radiation

Limit external exposure to residual (activation) radiation

Contamination

Limit internal and external exposure to radioactive contamination

Hazard Identification – Locations within the Facility (Target Building)



Monolith: Tungsten target wheel, beam interface - source of prompt & target-damage hazards

Active Cells / Process Cell: Handling of activated components

High Bay / Transport Hall: Cask lifting, transport and load-handling operations

Hazardous and radioactive inventories are distributed across the Monolith, Active Cells, Process Cell, High Bay, and Transport Hall - unlike a reactor's single core.

Initiating Events & Screening Criteria

Initiating events for ESS PSA focus on equipment failures, maintenance/testing errors, and operator actions that could cause radiological consequences for the public.

Screening criteria:

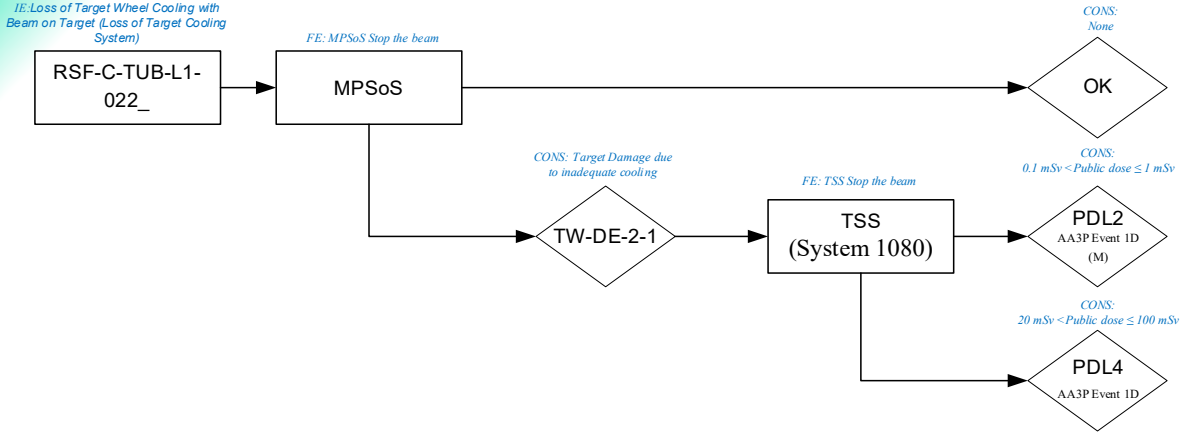
- Frequency below 1.E-7 (residual risk) - except component-failure events, which are quantified via FMEA/Fault Tree regardless the frequency.
- Effective dose at the EAB below 0.1 mSv, with no DiD Level 2+ mitigation required.
- Undesired end states not reached within the mission time.

Initiating event groups (target building)

- Loss of target cooling with beam on target (THCS inventory loss or system loss)
- Loss of target rotation (with beam on target (TWDSS equipment failures)
- Load handling events in the High Bay / Active Cell (cask drops, lifting failures).

Because operating experience for non-reactor facilities is limited, initiating event frequencies are derived from fault tree models of component/human failures rather than direct historical-data estimation.

Accident Scenario Development (Example)



- MPS success → beam terminated, no consequence
- MPS fails → target damage (TW-DE-2-1) → TSS success → PDL2
- MPS fails → target damage (TW-DE-2-1) → TSS fails → PDL4

How event trees connect to risk:
Every accident sequence terminates in an end state from Table 1 (PDL1–PDL5) or the OK (safe) state.
The PSA goal is to confirm the frequency of every end state stays within its probabilistic safety goal, across all initiating events facility-wide.

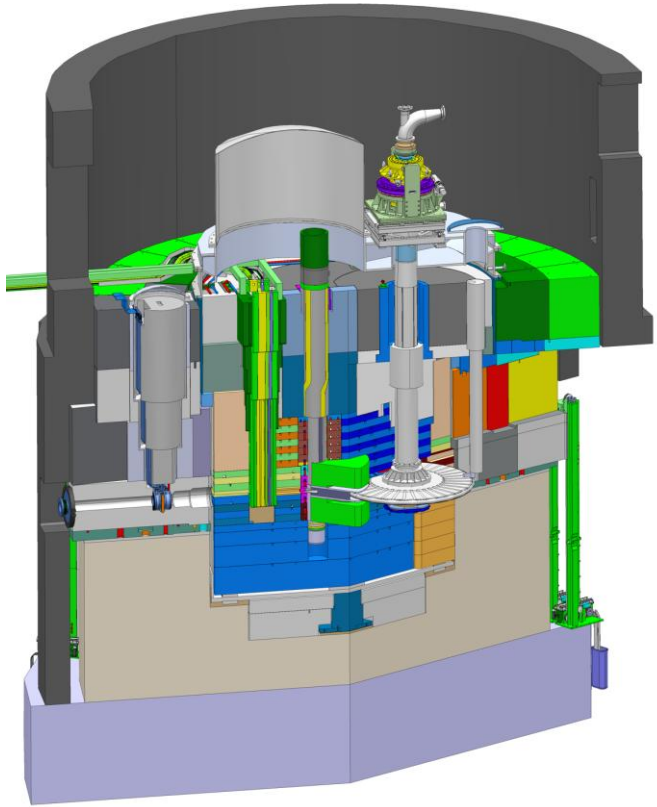
Load-handling events (e.g. dropped cask in the Transport Hall) credit no barriers across any Defence-in-Depth level, so the sequence proceeds directly to its end state (e.g. PDL3).

System Analysis & Dependencies

System analysis steps

1. Define system success criteria from accident sequence / event tree top events
2. Failure Modes & Effects Analysis (FMEA) per system, including functional dependencies
3. Collect reliability data - manufacturer data first, generic sources where manufacturer data unavailable.
4. Develop fault tree models of system failures and dependencies
5. Analyze Common Cause Failures (CCFs) and define CCF groups

CCF treatment: Beta Factor model with a constant $\beta = 0.1$ applied to all CCF groups, regardless of group size - a deliberately simplified, conservative starting point given data scarcity.



Target Monolith cross-section

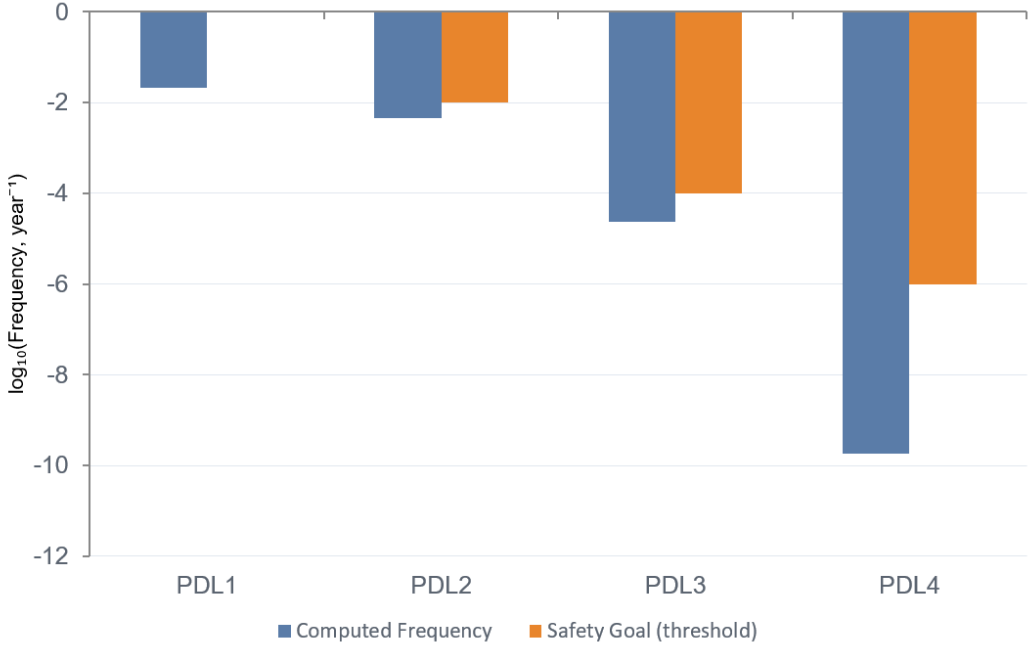
End States & Probabilistic Safety Goals

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

In addition, target damage states (e.g. TW-DE-2-1, TW-DE-2-2) are tracked as intermediate precursor states to evaluate Machine Protection System (MPS) performance and target-damage economic risk.

PSA Results

- Computed annual frequencies for each PDL end state, compared against their probabilistic safety goals (log scale).

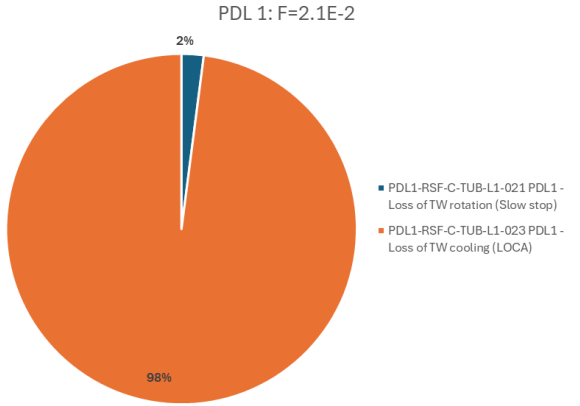


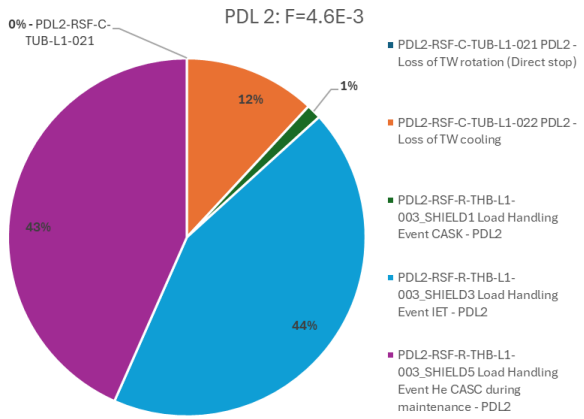
Key results:

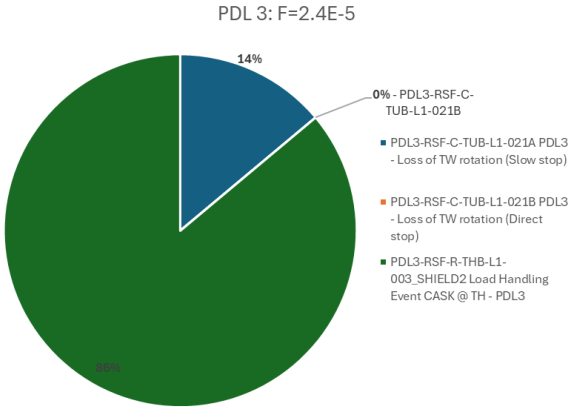
All PDL frequencies satisfy their corresponding probabilistic safety goals, indicating a balanced overall risk profile.

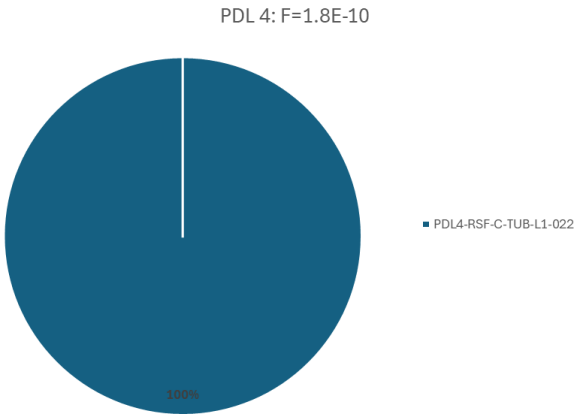
- PDL1: 2.1E-2 < 1
- PDL2: 4.6E-3 < 1.E-2
- PDL3: 2.4E-5 < 1.E-4
- PDL4: 1.8E-10 < 1.E-6

Dominant Risk Contributors by End State









Current Scope & Limitations

- Internal events only
  - Current PSA scope excludes internal hazards (fire, flooding), seismic events, and other external hazards.
- No credited manual actions
  - Type C (initiating-event mitigation) operator actions are not yet credited in accident sequences.
- Simplified CCF treatment
  - Constant $\beta = 0.1$ applied uniformly; not yet refined by group size or component-specific data.
- Current analysis does not include Sensitivity and Uncertainty Analyses

Conclusions

- PSA methodology adapts successfully
  - Established ET/FT techniques, applied with a graded approach, address distributed inventories and multi-system hazards at ESS.
- All probabilistic safety goals satisfied
  - Computed PDL1-PDL4 frequencies fall within their respective acceptance bands, with a balanced overall risk profile.
- Clear dominant contributors identified
  - Load-handling events and target cooling/protection system failures (with CCF contributions) drive the risk profile.

The ESS case shows PSA can support design evaluation and risk-informed decisions for non-reactor nuclear facilities broadly.

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Thank you