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Advancing Nuclear Safety: A Benchmarking Study of Extreme Event Analysis Beyond Design Basis Conditions

Ingenuity.
Imagination.
Insight.

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OVERVIEW

Benchmarking EEA for plant robustness against beyond-design-basis external hazards

Study basis

- Applied to Armenian NPP
- Based on IAEA Fault Sequence Analysis methodology
- Integrates deterministic and probabilistic approaches
- Uses the full PSA logic to evaluate system-level vulnerabilities

Benchmarking focus

- Compared against IAEA FAST-EE case studies
- Examined minimal cut set logic
- Evaluated individual and combined external hazards
- Identified additional valid sequences

Value delivered

- Hazard thresholds
- SSC vulnerability insights
- Cliff-edge identification
- Improved defence-in-depth
- Stronger complementary safety assessment

Key message: EEA enhances understanding of plant robustness by capturing critical scenarios that may be missed by restricted pre-generated logic.

Why Extreme Event Analysis Matters Now

The original Fukushima-era motivation is even more relevant for today's deployment of new nuclear technologies

Drivers for 2026 and beyond

1	**FOAK licensing**	Advanced designs require evidence beyond classical design basis assumptions.
2	**Climate resilience**	External hazards are becoming more intense, correlated and site-specific.
3	**SMR deployment**	Multi-module sites and shared systems create new dependency questions.
4	**Passive safety**	Long coping times and natural circulation must be tested under coupled hazards.
5	**Risk-informed regulation**	Decision makers need transparent links between hazards, SSCs and safety functions.

EEA provides a practical bridge between external hazard assessment, PSA logic and safety case decision-making.

Methodological Basis

Combining deterministic insights with probabilistic logic to evaluate beyond-design-basis conditions

IAEA FSA

- Fault sequence logic
- Functional safety paths
- Extreme event combinations

PSA Model

- Event trees + fault trees
- Full plant logic
- Minimal combinations

Engineering Inputs

- Hazard thresholds
- SSC susceptibilities
- Human actions and access

Extreme Event Analysis

Systematic assessment of individual, combined and sequential hazards leading to loss of safety functions

Extreme Event Analysis Workflow

From hazard screening to actionable design and licensing insights

1 **Screen hazards**
Identify relevant external hazards and combinations

2 **Prepare PSA logic**
Confirm event tree / fault tree quality and safety functions

3 **Map susceptibilities**
Assign thresholds to SSCs, buildings, operators and initiators

4 **Run EEA cases**
Evaluate individual and combined hazard scenarios

5 **Benchmark logic**
Compare MCS logic and sequence consistency

6 **Apply insights**
Strengthen defence-in-depth and plant robustness

The workflow converts extreme event assumptions into traceable, risk-informed decisions.

Hazards, Thresholds and Susceptibilities

EEA evaluates how external hazards challenge SSCs, initiators and operator actions

External hazard examples

- Seismic
- Flooding
- Heavy rainfall
- High wind
- Wind missiles
- Heatwaves
- Extreme cold
- Snow / ice
- Dust storm

Susceptibility mapping

Component	Design limits, location, power supply, cooling need
Building	Elevation, compartments, flood path, structural margin
Initiator	Hazard-induced LOOP, LOCA, loss of service systems
Human action	Accessibility, timing, procedures, environmental constraints

Critical insight: the same hazard can affect multiple safety barriers through common location, common support systems and limited operator access.

Benchmarking Study: EEA vs IAEA FAST-EE

A consistency check of technical logic and a test of completeness

IAEA FAST-EE case studies

- Reference comparison cases
- Pre-defined / restricted analysis logic
- Useful for verification of scenario logic
- Limited by practical number of MCSs handled

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Benchmark comparison

Extreme Event Analysis

- Direct interface with full PSA model
- Evaluates complete event tree / fault tree logic
- Generates MCSs combinations directly
- Captures additional valid sequences

Benchmarking confirmed consistency where logic overlaps and showed improved completeness where full PSA logic is used.

Key Benchmarking Findings

Results confirmed both consistency and added value of the EEA approach

Consistent MCS logic

EEA and IAEA case studies produced similar technical logic for overlapping analysis cases.

Additional valid sequences

EEA identified accident sequences not captured by restricted FAST-EE logic.

Full system evaluation

Direct PSA interface ensured complete fault tree and event tree logic was included.

Hazard thresholds

Results provided thresholds for individual and combined hazards affecting SSCs.

Defence-in-depth insights

The approach highlighted vulnerabilities that can inform design and procedure improvements.

What EEA Reveals About Plant Robustness

Turning benchmarking results into safety improvement opportunities

SSC vulnerability

Common support systems

Operator access limits

Extreme Hazards → Plant Response → Safety Functions

Cliff-edge effects

Passive safety margins

Recovery capability

Plant robustness is not only about surviving one hazard; it is about maintaining safety functions when hazards interact with systems, buildings and human actions.

Relevance to SMRs and Advanced Reactors

The benchmarking lessons are directly applicable to new nuclear safety cases

BWRX-300 / AP300	Passive cooling, long coping time, external hazards
NuScale / multi-module SMRs	Shared systems, module interactions, emergency planning
Natrium / sodium fast reactors	Sodium-specific hazards, heat removal dependencies
Lead-cooled SMRs	Natural circulation, novel coolant system interactions
Molten salt reactors	Salt freezing, decay heat removal and chemistry interfaces
Microreactors	Remote sites, transportation, limited operator support

For advanced reactors, EEA supports early design optimisation, licensing confidence and evidence of defence-in-depth before late-stage redesign becomes costly.

Benefits of EEA-Type Studies

A complementary safety assessment that creates value across the nuclear lifecycle

For reactor vendors

- Early vulnerability screening
- Design optimisation before freeze
- Evidence for FOAK licensing
- Support for passive safety claims

For utilities / operators

- Plant robustness demonstration
- Climate resilience assessment
- Targeted modifications
- Improved emergency procedures

For regulators / TSOs

- Transparent risk-informed review
- Defence-in-depth evaluation
- Traceable safety case evidence
- Better understanding of cliff-edges

Benefit: more complete safety insight with a clear line of sight from external hazard assumptions to risk-informed engineering decisions.

Conclusions and Key Takeaways

Benchmarking confirms EEA as an efficient and robust complementary safety analysis methodology

1	**Consistent technical logic**	Benchmarking showed similar MCS logic for common cases.
2	**Improved completeness**	Additional valid accident sequences were identified by using full PSA logic.
3	**Actionable safety insights**	Hazard thresholds and SSC vulnerabilities can inform defence-in-depth.
4	**Modern relevance**	The approach is highly valuable for SMRs, advanced reactors and climate resilience.

Extreme Event Analysis strengthens nuclear safety by identifying critical scenarios, supporting risk-informed decisions and improving confidence in defence-in-depth.

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Thank you