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Safety Goals and Risk Metrics in Probabilistic Safety Assessment: An International Overview from the OECD NEA CSNI WGRISK

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Introduction

- Probabilistic Safety Assessment (**PSA**) is widely recognized as an essential component of nuclear safety analysis
- OECD Nuclear Energy Agency (**NEA**) Working Group on Risk Assessment (**WGRISK**) plays a central role in coordinating international efforts to advance PSA methodology and its use in improving nuclear safety
- One WGRISK key activity is the periodic (~ every 5 years) publication of a status report “Use and Development of Probabilistic Safety Assessment” in member countries
  - Reports cover PSA frameworks, methodologies, applications, results, safety goals, risk metrics as well as new research and developments
  - Latest update under publication after CSNI endorsement is based on contributions from more than 20 national organisations who attend and contribute to WGRISK
  - ➢ Report reflects evolving PSA landscape, with emphasis on new developments and growing applications of PSA results for safety management and risk-informed decision-making (RIDM)

PSA Applications and Safety Goal Frameworks

- PSA role in national nuclear safety frameworks has grown steadily being meanwhile routinely used to inform safety decisions, regulatory evaluations, and plant operational practices
- Many regulatory regimes require operating NPPS to maintain PSA models as living tools that are updated with plant changes or new data on a regular basis.
- PSA provides a means to compare plant risk estimates against safety goals through use of **risk metrics** commonly corresponding to different PSA levels:
  - **Level 1:** Typical risk metric is CDF (Core Damage Frequency) or in some cases **FDF** (Fuel Damage Frequency), which extends to fuel damage in spent fuel pools and reactor core
  - **Level 2**: risk metrics gauge the frequency of significant radioactive releases from containment, most common **LRF** (Large Release Frequency) or **LERF** (Large Early Release Frequency)
  - **Level 3**: Focus on consequences of radiological releases, risk is quantified in terms of impacts on the public or environment; Common measures include **individual risk** (risk of death or serious health effects to a person in the vicinity of a plant) and **societal risk** (risk from accidents causing a high number of casualties or having a wide-spread impact

International Safety Goals and Numerical Risk Criteria (1)

- WGRISK status report finds significant differences among participating countries in the definition of safety goals and use of risk metrics in a regulatory context, with two patterns emerging:
  - **Explicit quantitative criteria:** Many countries set one or more numerical risk criteria serving as formal safety goals or limits for plant risk, usually specifying maximum allowable frequencies for core damage or large release
  - **Qualitative goals with numeric guidelines**: Other regulatory frameworks emphasize qualitative safety goals (e.g. maintaining defense-in-depth, ensuring no significant off-site consequences, reducing risk as reasonably practicable (ALARP)) using numeric risk estimates and targets
- Many national frameworks combine elements of both approaches
- Several countries differentiate between new and operating plants with more stringent criteria applied to new designs, reflecting modern safety expectations

International Safety Goals and Numerical Risk Criteria (2)

- Numerical risk criteria are not defined in all WGRISK member countries
    - Countries without numerical criteria by regulators: Belgium, Germany, Spain, Sweden
    - Some countries, e.g. United Kingdom, have goal setting frameworks (e.g. to reduce risks ALARP) with numerical risk targets established by regulator
    - Other countries use numerical criteria as an indicative figure: e.g., Czech Republic, France, India
    - Few countries have specified safety criteria only for new builds: e.g., Canada, Slovenia
    - In some countries, criteria for existing and new built plants: e.g., Hungary, Netherlands, Slovenia
- The following tables 1 to 3 (complete tables in paper) contain examples of safety goals and risk metrics for PSA Level 1, 2 and 3 used in NEA member states

➢ Use of Level 1 PSA metric: CDF is common, with 1 E-05 /ry as a commonly adopted benchmark used in many jurisdictions, but with significant variation in the standard expected for new and existing designs

Level 1 PSA Numerical Risk Criteria

Country / Economy	Organisation	Risk Metric	Frequency [1 /ry]	Remarks
Canada	Regulator	CDF	1 E-05	Objective for new plants
	Licensee	CDF	1 E-04 / 1 E-05	Limit / Objective for existing plants
China, Korea, Romania, Slovenia	Regulator	CDF	1 E-04 / 1 E-05	Objective for existing / new plants
Czech Republic	Licensee	CDF	1 E-04 / 1 E-05	Objective for existing / new plants, full scope
Finland	Regulator	CDF	1 E-05 / 1 E-05	Objective for existing / Limit for new plants
Hungary	Regulator	CDF	1 E-04 / 1 E-05	Limit for existing / new plants
Japan, USA	Regulator	CDF	1 E-04	Objective
Netherlands	Regulator	CDF	1 E-06	Limit for existing / new plants
Poland	Regulator	CDF	1 E-05	Objective for new plants
Switzerland	Law	CDF	1 E-04	Limit for existing plants
	Regulator	CDF / FDF	1 E-05 / 1 E-05	Limit / Objective for existing plants
…	…	…	…	…

Level 2 PSA Numerical Risk Criteria

Country / Economy	Organisation	Risk Metric	Frequency [1 /ry]	Remarks
Canada	Regulator	SRF* / LRF	< 1 E-05 / 1 E-06	Objective for new plants
	Licensee	SRF* / LRF	1 E-05 / 1 E-06	Limit / Objective for existing plants
China	Regulator	LRF	1 E-05 / 1 E-06	Objective for existing / new plants
Hungary	Regulator	LER / LERF	1 E-05 / 1 E-06	Limit for existing / new plants
Japan	Regulator	Containment failure / 100 TBq Cs-137	1 E-05 / 1 E-06	Objective
Korea	Regulator	LERF	1 E-05 / 1 E-06	Objective for existing / new plants
Netherlands	Regulator	LERF	practically eliminated	Limit for new plants
Poland	Regulator	LRF or LERF	1 E-06	Objective for new plants
Switzerland	Regulator	LERF	1 E-06	Limit / Objective for existing plants
USA	Regulator	LERF	1 E-05	Objective
…	…	…	…	…

* **Note:** Canada defines small release frequency (SRF): sum of frequencies of all event sequences that can lead to any release to the environment requiring temporary evacuation of local population or release to the environment >10^{15} Bq I-131

Level 3 PSA Numerical Risk Criteria

<table>
<tr><th>Country / Economy</th><th>Organisation</th><th>Risk Metric</th><th colspan="3">Frequency [1 /ry]</th><th>Remarks</th></tr>
<tr><td>Korea</td><td>Regulator</td><td>Early fatality
Latent fatality</td><td colspan="3">5 E-07 /yr
1 E-06 /yr</td><td>Calculated for each individual unit</td></tr>
<tr><td rowspan="8">Netherlands</td><td rowspan="8">Regulator</td><td>Individual risk</td><td colspan="3">1 E-06 /yr</td><td>Risk of death off-site, also considering stochastic effects</td></tr>
<tr><td>Group risk,
risk of death
of n persons</td><td colspan="3">1 E-03/n^2 /yr, n > 10</td><td>Risk of death off-site, only considering deterministic effects</td></tr>
<tr><td rowspan="6">Dose (off-site)</td><td>Frequency</td><td colspan="2">Dose [mSv]</td><td rowspan="6">For design basis accidents</td></tr>
<tr><td></td><td>< 16 yrs</td><td>> 16 yrs</td></tr>
<tr><td>F ≥ 1 E-01</td><td>0.1</td><td>0.04</td></tr>
<tr><td>1 E-01 > F ≥ 1 E-02</td><td>1</td><td>0.4</td></tr>
<tr><td>1 E-02 > F ≥ 1 E-04</td><td>10</td><td>4</td></tr>
<tr><td>F < 1 E-04</td><td>100</td><td>40</td></tr>
<tr><td>United Kingdom</td><td>Regulator</td><td>Risk of death
(persons off-site)</td><td colspan="3">BSL = 1 E-04 /yr
BSO = 1 E-06 /yr</td><td>Calculated for site</td></tr>
<tr><td>USA</td><td>Regulator</td><td>Offsite individual fatality risk</td><td colspan="3">Average individual risk of prompt fatalities from reactor accidents in NPP vicinity should not exceed 0.1 % of the sum of prompt fatality risks resulting from other accidents to which members of U.S. population are generally exposed.
Population risk of cancer fatalities that might result from NPP operation in area near NPP should not exceed 0.1 % of the sum of cancer fatality risks resulting from all other causes.</td><td>Offsite individual fatality risk</td></tr>
</table>

Safety Systems Reliability Criteria

- Attention has broadened to Level 2 PSA metrics (LRF/LERF), recognizing that preventing large releases is a distinct safety objective beyond preventing core damage

  Note: The notion of "large" or "early" release is not always uniformly defined. Some countries define it by a specific radiological quantity (e.g. 100 TBq of Cs-137), others define it qualitatively, e.g. requiring "long-term relocation of the public" or "off-site emergency measures".

- Level 3 PSA metrics extend to the end consequences of accidents, e.g. risk of early or latent fatalities in the exposed population or radiation dose-based criteria
  - ➢ These are less common, but are being discussed as a way to address multi-unit risk, new technologies and to adopt a technology-neutral approach

Country / Economy	Reliability Criteria
Canada	Safety systems and their support systems shall be designed to ensure that probability of failure per demand from all causes < 1 E-03 Probability of failure to shut down on demand < 1 E-05 LRF due to failure of shutdown < 1 E-07 /ry
India	Failure probability of the safety system < 1.0 E-03 (SDS-1, SDS-2, ECCS, containment Isolation)
Romania	Safety systems shall be designed to ensure that probability of failure per demand from all causes < 1 E-03

Incremental Risk Increase Numerical Criteria

Country / Economy	Numerical Criteria
Czech Republic	Change allowed if: ΔCDF (ΔFDF) < 5 E-06 /ry, ΔLERF < 1 E-06 /ry Change not allowed if: overall FDF > 1 E-04 /ry, overall LERF > 1 E-05 /ry FDF = CDF + frequency of fuel damage in the SFP *Note: Numerical criteria for incremental risk increase have not been set specifically for new plants*.
Hungary	No risk increase is allowed due to plant changes
Korea	Changes are not allowed if: ΔCDF > 1 E-05 /ry, ΔLERF > 1 E-06 /ry Changes are allowed if: ΔCDF < baseline CDF (for baseline CDF < 1 E06 /ry), ΔCDF < 1 E-06/ry (for baseline CDF < 1 E-04 /ry), ΔLERF < baseline LERF (for baseline LERF < 1 E-07 /ry), ΔLERF < 1 E-07 /ry (for baseline LERF < 1 E-05/ry) Area with detailed assessment: between allowable area and not allowable area
Netherlands	Instantaneous TCDF shall never exceed the value of 1 E-04 /ry
Slovakia	Changes are considered non-risk significant if: ΔCDF < 1 E-04 /ry, ΔLERF > 1 E-05 /ry, and their cumulative effects do not cause the safety goals to be exceeded. Changes are considered unacceptable if: ΔCDF > 1 E-04 /ry, ΔLERF > 1 E-05 /ry
Slovenia	Limits for risk increase: ΔCDF < E-07 /ry, ΔLERF < E-08 /ry
Switzerland	Changes are allowed if: ΔCDF < 1 E-07 /ry, ΔFDF < 1 E-07 /ry, ΔLERF < 1 E-08 /ry, and: average CDF < 1 E-05 /ry: Additional requirements for the extension of test intervals apply
USA, Mexico, Spain, Chinese Taipei	Criteria provided in U.S. NRC Regulatory Guide 1.174

Emerging Issues and Trends (1)

- WGRISK status report identifies several emerging and cross-cutting challenges related to safety goals and risk metrics, reflecting the evolution of nuclear power and PSA practice in recent years with a major theme: **PSA scope expansion beyond single reactor unit at full power**
  - Fukushima Dai-ichi accidents highlighted importance of considering site-level risks and accidents that might involve multiple reactors or other collocated sources (e.g. SFPs) simultaneously
  - ➢ This has raised interest in multi-unit PSA and questions about how to define safety goals for whole site, such as through Level 3 PSA metrics
- Overall PSA scope and use in decision-making continue to broaden, influencing application of safety goals
- PSAs now more frequently address:
  - Multiple plant operational modes (incl. low-power and shutdown conditions)
  - Full spectrum of internal and external hazards, and
  - Combinations of hazards, reflecting learning from events like Fukushima

Emerging Issues and Trends (2)

- PSA techniques are also being applied to emerging reactor types such as small modular reactors (SMRs), which present new considerations for risk metrics (e.g., multi-module risk, interplay of multiple small reactors collocated at one site)
- With more comprehensive PSAs, RIDM in regulatory and operational contexts is growing
- PSA results are increasingly used to support decisions on plant modifications, optimize maintenance and inspection intervals, prioritize safety backfits, and evaluate design alternatives.

➢ The expanding influence of PSA strengthens the relevance of safety goals: decision-makers often refer to numerical risk metrics (CDF, LERF, etc.) to judge the significance of changes

Conclusions and Outlook

- Recent WGRISK "Use and Development of Probabilistic Safety Assessment" report confirms that safety goals and risk metrics are central to interpretation and use of PSA results, but their application remains diverse
- A core set of metrics, CDF at Level 1, LRF or LERF) at Level 2, and individual or societal risk measures at Level 3, are widely used as benchmarks for assessing nuclear safety
- However, the role of these metrics varies from formal regulatory requirements in some countries to advisory targets supporting qualitative safety goals in others
- There is strong convergence in underlying practice with many countries applying numerical criteria broadly consistent with international guidance, typically in the order of E-05 /ry for CDF and E-06 /ry for large releases
- WGRISK s report also highlights ongoing evolution in both safety goals and risk metrics, including increasing attention to Level 3 consequence-based measures, need for site-level and multi-unit risk aggregation, and extension of metrics to include spent fuel pools and other sources of risk

➢ These developments indicate a shift towards more comprehensive and integrated representations of nuclear risk

Thank you for your attention!

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