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Status and Experience with the Technical Basis and Use of Probabilistic Risk Criteria for Nuclear Power Plants

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Abstract: Probabilistic safety criteria, including safety goals, have been progressively introduced by regulatory bodies and utilities. They range from high level qualitative statements to technical criteria. They have been published in different ways, from legal documents to internal guides. They can be applied as legal limits down to “orientation values”. The OECD/NEA Working Group on Risk (WGRISK) prepared a questionnaire on the probabilistic risk criteria for nuclear power plants. Answers were received from 13 nuclear safety organizations and 6 utilities. The reported probabilistic risk criteria can be grouped into 4 categories, in relation with the tools to be used for assessing compliance: core damage frequency, releases frequency, frequency of doses and criteria on containment failure. Introduction of probabilistic safety criteria is generally considered to result in safety improvements. Opinion is widespread on the benefits of using probabilistic safety criteria for communication with the public, ranging from bad to good experiences. The responses to the questionnaire suggested that more work should be considered in the definition of releases frequencies: some regulators include a time range (generally 24 hours) in the criterion while others do not limit the time to be considered. It is suggested that, in the first case, the existing PSAs should be revisited to assess if long development accident sequences were considered.

Keywords: probabilistic safety criteria, risk criteria, safety goal, nuclear safety

1. INTRODUCTION

Probabilistic Safety Criteria, including Safety Goals, have been progressively introduced by regulatory bodies and utilities. They range from high level qualitative statements (e.g., “the use of nuclear energy must be safe”) to technical criteria (e.g., probability of fuel cladding temperature being higher than 1204 °C). They have been published in different ways, from legal documents to internal guides. They can be applied as legal limits (i.e., not meeting them is an offence) down to “orientation values”.

The OECD/NEA Working Group on Risk (WGRISK) prepared a questionnaire on the probabilistic risk criteria for nuclear power plants [1]. Answers were received from 13 nuclear safety organizations (Canada, Belgium, Chinese Taipei, Finland, France, Hungary, Japan, Korea, Slovakia, Sweden, Switzerland, UK and USA) and 6 utilities (Hydro-Québec, Fortum, OKG, Ontario-Power-Generation, Ringhals and TVO). Two of the regulatory bodies (Belgium and Chinese Taipei) declared they have not set (and do not intend to set) any probabilistic risk criterion. This paper will focus on the technical basis and use of risk criteria in different countries and organisations.

2. OVERVIEW OF THE CRITERIA

2.1. Status of probabilistic risk criteria

There are differences in the status of the numerical risk criteria that have been defined in different countries. Some have been defined in law or regulations and are mandatory, some have been defined by the regulatory authority (which is the case in the majority of countries where numerical risk criteria

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have been defined), some have been defined by an authoritative body and some have been defined by plant operators or designers. Hence there is a difference in the status of the numerical risk criteria which range from mandatory requirements that need to be addressed in law to informal criteria that have been proposed by plant operators or designers for guidance only.

The following categories of statuses can be seen:

- A legally strict value to be fulfilled. Design must be changed, if the criterion is not met. In some countries probabilistic risk criteria are applied in this manner for new nuclear power plants (NPPs).
- A strict value but not legally bounding. The value should not normally be exceeded. Some utilities define this kind of status for their NPPs.
- Target value, orientation value, expectation, or safety indicator. If the target is not met, design improvements should be considered taking into account cost-benefit considerations or ALARP (As Low As Reasonably Practicable) principle. They denote a boundary that, if surpassed, will often lead to increased regulatory oversight. It is only used as one piece of information in the regulatory process (risk-informed not risk-based).

For most respondents probabilistic risk criteria are target values, orientation values or safety indicators.

2.2. Differences in criteria for existing plants, life extension, new builds, new design

In several countries, different criteria apply to existing plants and for new plants or the criteria have different status. The following categories of statuses can be seen:

- Probabilistic risk criteria are the same for existing and future plants
- Probabilistic risk criteria use a similar metric for existing and future plants. The numerical values for the frequencies are a factor (typically 10) lower for future plants.
- Probabilistic risk criteria involve the same numerical values for the frequencies, considered as limits for future plants and targets for existing plants.
- Probabilistic risk criteria are defined only for existing plants.
- No numerical risk criteria have been defined for new plants. However, there is a general requirement that the level of risk should be comparable to (or lower than) the risk from existing plants.

For modernization and life extension, generally same criteria are applied as for operating plants.

3. TYPES OF RISK CRITERIA

3.1. Society Level Criteria

Society level criteria are not probabilistic. However, they are of interest as they are the basis for the probabilistic criteria. Of the 13 responding regulatory bodies, 8 have defined society level criteria. These criteria are generally set in the mandate of the regulatory body. One out of the six responding utilities has declared having a society level criterion. These criteria can mainly be abstracted into "Prevent unreasonable risk to the public and the environment". In some countries, the criterion is strict.

3.2. Intermediate Level Criteria

Of the 13 responding regulatory bodies, 8 have defined intermediate level criteria, although the separation between society level and intermediate level is not always clear. One out of the six responding utilities has declared having an intermediate level criterion. The criteria generally indicate that "The risk from use of Nuclear Energy shall/should be low compared to other risks to which the public is normally exposed”. These “other risks”, when defined, are characterized as one or several criteria:

- the background risk of cancer,
- the risk from other sources of energy production,
- the risk of fatality for all other sources (early or late).

Some regulators define the “risk” in a quantitative way:

- with amount of radionuclide (for instance 100 TBq of Cs137, in relation with the risk of long term relocation of public),
- with a given dose (for instance 0.1 mSv from normal operation of a nuclear power plant),
- with a probability of consequences (less than 1% of other causes of cancer),
- with a frequency of occurrence (should not exceed approximately 1E-6 per year).

3.3. Technical Level Criteria

The reported probabilistic risk criteria can be grouped into 4 categories, in relation with the tools to be used for assessing compliance:

- core damage frequency (CDF) – level 1 PSA – 16 respondents
- releases frequency (large early release frequency (LERF), large release frequency (LRF), small release frequency (SRF)) – level 2 PSA – 14 respondents
- frequency of doses – Level 3 PSA – 4 respondents
- criteria on containment failure – system level – 2 respondents.

Several respondents use more than one criterion, e.g., CDF and LERF while some others use a range of values for a given criterion (e.g., frequency of doses to the public, to the workers, during accidents, during normal operations).

While originally set, considering the state of the art of PSA, the CDF criterion is presently considered as based on defence-in-depth considerations. Also, the criterion on containment failure, recently introduced in Japan and USA, is an expression of defence-in-depth, as new designs could meet the LERF criterion without taking the containment into account.

3.3.1. Core Damage Frequency Criterion

The criterion core damage frequency is used by 14 of the respondents. However, the definition of the criterion differs considerably with the reactors technology. Some countries have very precise technical definitions of CDF, e.g. defining core damage as local fuel temperature above 1204 ºC, i.e., the limit defined in section 1b of 10 CFR 50.46 (Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors). Other countries have more general definitions referring, for instance to prolonged core uncover or long-term cooling.

The frequency limits regarding core damage vary between 1 E-4 and 1 E-6 per year. Requirements for new plants are typically stricter (in terms of frequency) than for existing ones, and are mandatory as opposed to indicative. For instance, in Switzerland and Finland it is required by regulation that the applicant for a permit to build a new nuclear power plant shall demonstrate that the core damage frequency is below 1 E-5 per year. Figure 1 summarizes numerical criteria defined for core damage.

Of the 14 respondents that use CDF as a criterion, 13 express the frequency as a single value. Only Ontario Power Generation expresses it as a band. As mentioned above this frequency varies between 1 E-4 and 1 E-6 per year. Where a single value was not used, the criterion was defined as a band with a limit and a target value. The USNRC also noted that for decision-making purposes, there are several bands of varying CDF and ΔCDF values.

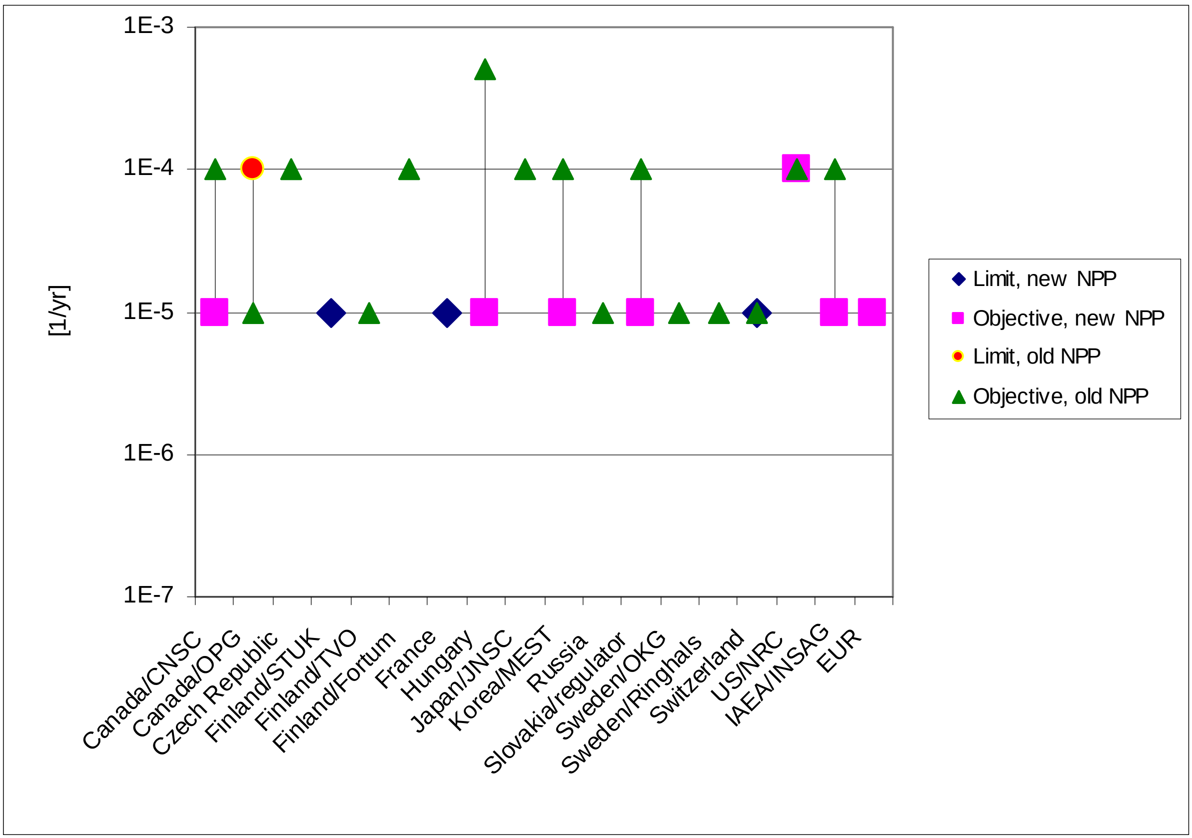

Figure 1: Numerical criteria defined for the core damage frequency.

In every country the criterion is applicable at reactor level. In general, all countries aim at using full scope (internal and external events, full power and shutdown operating modes) PSA to assess CDF. The vast majority of the respondents require full scope PSA, but some comments are given on the degree of maturity for some parts of the analysis, and the degree of uncertainty associated with some initiating event categories.

In most cases CDF had been selected as a criterion according to the defence-in-depth concept, e.g., to avoid the design of a plant whose safety relies too strongly on a strong containment. Some respondents gave reasons to why they used CDF. The general main reason seems to be the achievement of a high safety level, whether set as an internal goal or a requirement from an external regulatory body. Furthermore some countries pointed out the benefits of the criteria being a well known measure that is used by several countries all over the world, thus allowing comparisons of results. The criterion is also frequently used for decision making regarding plant modifications.

Almost every country has documentation supporting the criterion. In some cases the documentation consists of U.S.NRC or IAEA documents. For utilities, internal documents are sometimes complemented with national documents. In those cases where there is no documentation supporting the CDF, the proposed CDF has been compared with international practice.

3.3.2. Release Frequency Criterion

There is both a considerably larger variation in the frequency limits, and very different answers to the question of what constitutes an unacceptable release. As with the CDF, the magnitudes are sometimes based on IAEA safety goals suggested for existing plants, i.e., on the level of 1 E-5 per year [2]. However, most countries seem to define much stricter limits, between 1 E-6 per year and 1 E-7 per year.

The definition of what constitutes an unacceptable release differs a lot, and there are many parameters involved in the definition, the most important ones being the time, the amount and the composition of the release. Additionally, other aspects may be of interest, such as the height above ground of the point of release. The underlying reason for the complexity of the release definition is largely the fact that it constitutes the link between the PSA level 2 results and an indirect attempt to assess health effects from the release. However, such consequence issues are basically addressed in PSA level 3, and can only be fully covered in such an analysis.

The release for which a numerical criterion is given is also defined in several different ways:

- Large release. This is defined as an absolute magnitude of activity and isotope released, e.g., 100 TBq of Cs137.
- Large early release. These definitions are more qualitative, e.g., "Large off-site releases requiring short term off-site response," "Significant, or large release of Cs137, fission products before applying the off-site (?) protective measures," "Rapid, unmitigated large release of airborne fission products from the containment to the environment, resulting in the early death of more than 1 person or causing a severe social effect."
- Small release. CNSC from Canada has set criteria both for large and small release. A small release is defined as a release of 1000 TBq of I131.
- Unacceptable consequence. This is a French definition which is fully open and rather old (1977). In the meantime a more precise definition was proposed by EDF and is still under discussion between EDF and the safety authority. It should be noted that the performance of level 2 PSA was not required in France by the safety authority for existing reactors but has been carried out on a voluntary basis. In case of new reactors, a level 2 PSA is required.
- Containment failure. The Japanese Nuclear Safety Commission proposes a criterion for containment failure frequency. This is a requirement that aims at assuring the robustness of the defence-in-depth.

Figure 2 summarises numerical criteria defined for large release. As explained above, the definitions for "large release" is not the same for all organisations. However, it can be seen that objectives vary from 1 E-7/year to 1 E-5/year, which is a quite large spread, larger than for core damage frequency, where objectives vary between 1 E-5/year and 1 E-4/year.

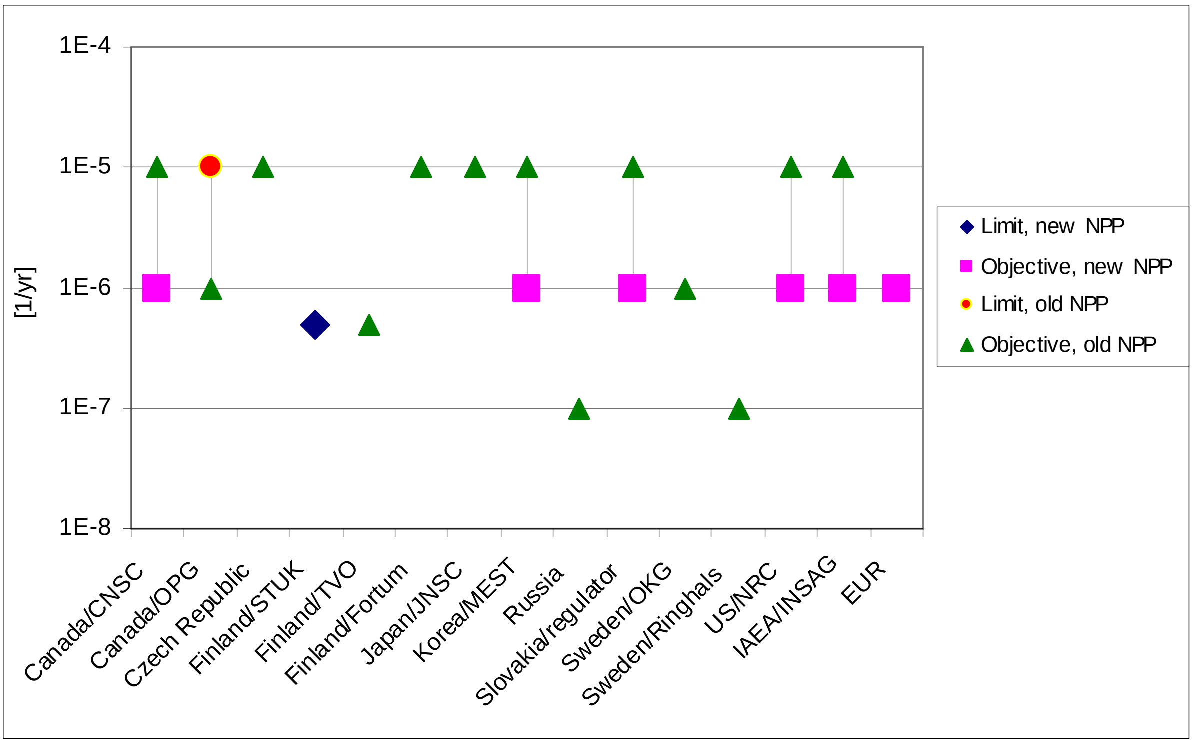

Figure 2: Numerical criteria defined for large release frequency. Definition and timing of "large release" varies.

In most cases, the release frequency criterion is based on protecting the public against prompt fatalities and radiological-induced cancers. The LERF criterion is based on the time being sufficient for public evacuation before a significant release occurs. Some countries (such as Canada, Finland and Sweden) do not consider the releases timing and base their criteria on land contamination, i.e. the long term consequences of an accident. Canada explains this choice on societal effects, considering that impact on the public from relocation and land banning goes largely beyond the radiological effects.

3.3.3. Criteria on Containment Failure

The criterion for a containment failure frequency (CFF) is only defined by the Japanese Nuclear Safety Commission (NSC). In addition, for new or advanced nuclear power plants the US NRC has set a target for conditional containment failure probability.

In Japan, NSC stated that a performance goal for each type of nuclear facility be examined and set as safety benchmark to demonstrate compliance with these quantitative health objectives for measuring plant performance. For LWRs, the containment failure criterion 1 E-5/year was derived from the quantitative health objective value, and the conditional average probabilities of acute fatality or cancer fatality of the individuals in the surrounding area determined for a hypothetical large release (< 0.1). Here the containment failure frequency means the sum of the frequencies of various containment function failure modes ranging from relatively small leaks to a large and early break of the containment. If the same number is used for the frequency criterion, this definition of containment failure frequency yields a stricter requirement for containment performance than a LERF (large early release frequency) criterion. The reason for using CFF and not using LERF is that, although the LERF has closer relationship to individual risks, the CFF gives more conservative assessment when the same value is taken for CFF and LERF and it is a way to cope with the uncertainties in the quantification of source terms and the effectiveness of emergency protective measures, etc.

In the USA, the NRC expects new or advanced nuclear power plants to present a higher level of severe accident safety performance consistent with the NRC's Severe Accident Policy Statement [3]. The numerical criteria are given in Table 1.

Table 1: U.S.NRC's Severe Accident Policy Statement [3].

	CDF	LERF	Conditional Containment Failure Probability
Operating plants & License renewal	<1E-04	<1E-05	n/a
New plants	<1E-04	<1E-06	< 0.1

3.3.4. Frequency of Doses Criterion

While being generally the basis for the 'technical level' criteria, only two respondents (Canada-OPG and UK) use frequency of doses as a technical level criterion per-se. Risks are divided into fatal acute or fatal late health risks and these can be calculated for an individual or a group. In both cases, risk is defined as the risk to the member of a critical group that receives maximum exposure from an accident.

Typically acute health effects have a threshold dose value under which the probability of health effect is zero, but above which the probability of acute health effect is increased with increasing dose. On the other hand most late health effects do not have threshold values for dose. Based on these assumptions acute health effects can be expected in the vicinity of the release point, whereas late health effects appear in the public exposed to radiation over larger areas.

Dose frequency criterion is expressed as Rate of exposure in Sv/yr to the individual and/or probability of latent health effects. For Canada/OPG, the criterion applies at station level, for the UK at site level. This criterion is generally considered as meeting directly the high level goal of "no added significant risk to the public".

4. USE OF RISK CRITERIA

The risk criteria are mostly used to assess the impact on risk of design modifications in the plant and within the periodic safety review. The evaluation frequency varies between

- the PSA supporting evaluation of the Risk Criteria shall be updated within the framework of the Periodic Safety Review (generally 10 years),
- the PSA supporting evaluation of the Risk Criteria to be updated every 3 years, or after significant modifications to the plant,
- the PSA supporting evaluation of the Risk Criteria to be kept up to date (on design modifications).

Four respondents indicate they use the Risk Criteria for assessing the impact on risk (and the appropriate response) from incidents or on discovery of new information.

Regarding actions engaged if the probabilistic risk criteria are exceeded, the received response show considerable differences between the different countries regulatory regimes. As the risk criteria are generally considered as indicators or orientation values, no hard regulatory actions are expected on non-compliance with a probabilistic risk criterion. Practically, there is a consensus on finding the reasons for the non-compliance and identification on the way to overcome it. However, when indicated, there is also a consensus for new builds, where not meeting the probabilistic risk criteria would prevent the regulatory body granting an operating license.

5. EXPERIENCE FROM THE IMPLEMENTATION, INTERPRETATION AND COMMUNICATION OF RISK CRITERIA

The general experience from the implementation of risk criteria is positive. Respondents who have implemented criteria have experienced various benefits. In a number of cases, design or procedural weaknesses in NPPs have been identified using PSA and PSA criteria, resulting in the introduction of safety improvements. More than half of the respondents describe how the implementation of risk criteria and safety goals have lead to plant modifications in order to meet probabilistic risk criteria. One of the respondents also described how, using PSA, changes suggested on a deterministic basis have been avoided.

Furthermore, the implementation of probabilistic risk criteria often emphasizes the need for more detailed and realistic PSA models, since conservative assumptions in the PSA often make the calculated risk unnecessarily high. It appears that the use of probabilistic risk criteria has increased the focus on the correctness and quality of PSA models. One problem that may be highlighted, is the scope of the PSAs, i.e., results from limited scope PSAs may be harder to assess and difficult to compare to probabilistic risk criteria.

Some respondents emphasize the importance of using PSA as an integrated part of the total safety analysis concept, i.e. as a complement to other relevant information such as deterministic analyses, human reliability analysis and operating experience.

Some respondents pointed out a general concern about using probabilistic risk criteria and defined safety goals as absolute limits, as this might indirectly have an negative impact on the quality and relevance of the PSA models. According to these respondents, the defined goals should rather be used as triggers for identifying potential deficiencies, and as indicators showing that changes made have a positive effect.

A number of the respondents express skepticism towards a strict application of quantified risk criteria, and the use of criteria does not appear to be prioritized within the over-all PSA activities of these respondents.

When it comes to the interpretation of the criteria, several of the respondents agree that more work is needed in the definition of the various criteria. Thus, there seems to be a need for a common definition as to what constitutes severe core damage and large release. A more precise and common definition would facilitate comparison of risks and results between different plants.

Responses regarding communication of probabilistic risk criteria to the public vary widely between the respondents. Some respondents focus on the need for (and difficulty of) communicating very complex information, both regarding the analysis process and the definition of the risk criteria.

In those cases where probabilistic risk criteria are met, many of the respondents have found the results useful when communicating the level of safety to the public. For example, Ontario Power Generation explains how the fact that their plants meet the probabilistic risk criteria has been cited to support the adequacy of plant safety at public hearings and public inquiries related to nuclear power.

In case the PSA results exceed the safety goals, communication would be more complex.

One experience is that public risk perception is more concerned with the consequence part of a criterion than with the frequency part, e.g., a “radioactive release” is perceived to be more easily understandable than a frequency of “1 E-7/year”. Another concern is with the complexity of the risk assessment process itself, and the ability of the general public to interpret results correctly.

If the results of PSA and probabilistic risk criteria should be made easier to understand to the public, it is important that it can be clearly demonstrated that PSA results and probabilistic risk criteria have lead to safety improvements in plants. However, the format in which PSA results and risk or safety criterion are presented needs to be carefully considered, in order to minimize the risk for misinterpretation or misunderstanding.

6. CONCLUSIONS

Probabilistic Safety Criteria, including Safety Goals, have been progressively introduced by regulatory bodies and utilities. They range from high level qualitative statements to technical criteria. They have been published in different ways, from legal documents to internal guides. They can be applied as legal limits down to “orientation values”. For most respondents probabilistic risk criteria are target values, orientation values or safety indicators.

The reported probabilistic risk criteria can be grouped into 4 categories, in relation with the tools to be used for assessing compliance: core damage frequency, releases frequency, frequency of doses, and criteria on containment failure. Several respondents use more than one criterion, e.g., CDF and LERF while some others use a range of values for a given criterion (e.g., frequency of doses to the public, to the workers, during accidents, during normal operations).

Generally, all respondents considered that introduction of probabilistic risk criteria had resulted in safety improvements. There is a considerable spread in opinions on the benefits of using probabilistic risk criteria for communication with the public, ranging from bad to good experiences. It seems that there is a strong relation with each country culture and circumstances.

The responses to the questionnaires suggested that more work should be considered in the definition of releases frequencies: some regulators include a time range (generally 24 hours) in the release criterion while others do not limit the time to be considered. It is suggested that, in the first case, the existing PSAs should be revisited to assess if long development accident sequences were adequately considered.

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