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Development of Risk Criteria in Nuclear Power Plants – Problems and Solutions

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Abstract

A worldwide need for development of risk criteria exists, which would support risk-informed decision-making. Definition of quantitative risk criteria considering probabilistic safety assessment is presented. It bases on world review and on consideration of a specific situation in Slovenia (one nuclear power plant with one unit). Development of risk criteria is considered separately for permanent and separately for temporary changes in the nuclear power plant. Developed criteria can represent a standpoint for risk-informed decision-making. Problems connected with definition of risk criteria are identified and investigated. The key contributors, which are connected with risk criteria and which have the largest impact on achieving those criteria, are evaluated and discussed. The most important fact for success of establishing the risk criteria is to have as most detailed guidelines as possible for performing the models, for making their analysis and for interpretation of the results.

Keywords: Risk criteria, Probabilistic safety assessment, Nuclear, Decision-making.

1. Introduction

A worldwide need for development of risk criteria exists, which would support risk-informed decision-making [1, 2, 3]. The objective of this development is to establish the prerequisites for wider application of the results of probabilistic safety assessment (PSA) and to facilitate the risk-informed decision-making. The risk criteria are needed at least in two aspects of evaluating the acceptability of changes in a nuclear power plant (NPP):

- Assessment of permanents changes: e.g. assessment of acceptability of plant modifications.
- Assessment of temporary changes: e.g. consideration about on-line maintenance (OLM).

Assessment of acceptability of plant modifications requires the risk criteria for permanent changes in the plant, because modification is a permanent change and it represents a potential for permanent change in risk.

Consideration about on-line maintenance requires the risk criteria for temporary changes in the plant, because each activity of the on-line maintenance is a temporary change and it represents a potential for temporary change in risk. In addition, consideration about on-line maintenance

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requires the risk criteria for permanent changes in the plant, because the approval of the overall concept of the on-line maintenance represents a potential for permanent change in risk.

The risk criteria determine, if a selected change in a plant can be acceptable or if it cannot be acceptable. The general concept goes along with the following idea:

- If the risk decreases due to the change, the change would normally be acceptable.
- If the risk increases only for a negligible increment due to the change, other benefits (if there are any significant ones) can prevail and the change may be accepted in spite of the risk increase.
- If the risk increases significantly due to the change the change cannot be allowed.

The review of current state of risk criteria is limited to selected countries and it is performed from Slovenian perspective (Slovenia: one NPP with Pressurized Water Reactor, two loops, 707 MWe, 40% of national electricity):

- USA, because it is the country of origin of vendor of Nuclear Power Plant Krško and because the risk-informed activities are developed very well [4, 5, 6, 7].
- Finland, because it is a European country, where a new nuclear power plant is built and because the risk-informed activities are developed very well [8, 9].
- Spain, because it is a European country, where majority of NPPs are of similar design as NPP Krško in Slovenia and because the risk-informed activities are developed very well [10, 11].
- Slovenia, because it is a country, where the results are applied [12, 13].

In USA and in Spain, an increase of risk due to a selected modification (permanent change in the plant) can be allowed and on-line maintenance (temporary change in the plant) can be tolerated.

In Finland, an increase of risk is not allowed for any modification, but on-line maintenance can be tolerated. This can be understood as paradox, if the following is considered:

- Every single action within on-line maintenance can be treated as a temporarily change in the plant, because every single action can temporary increase the risk.
- The whole process of enabling on-line maintenance can be treated as a permanent change in the plant, because adopting whole process of on-line maintenance can result in some increase of mean value of risk.

2. Risk Measures

The core damage frequency (CDF) and large early release frequency (LERF) are among the most common risk measures in probabilistic safety assessments of nuclear power plants [13, 14, 15, 16, 17, 18, 19]. Both represent also the standpoint for determining some other risk measures [20, 21].

The following risk measures are considered for determining the risk criteria for permanent changes in the plant [13]:

- the core damage frequency,
- the change in core damage frequency (dCDF) due to unavailability of selected equipment,
- the large early release frequency,
- the change in large early release frequency (dLERF) due to unavailability of selected equipment.

As the nature of permanent changes is such, that they may change the risk permanently, the mean values of the selected risk criteria are mostly used. Mathematical background of risk measures is written in literature [4, 13, 14].

The following risk measures are considered for determining the risk criteria for temporary changes in the plant [4, 13, 14]:

- risk measure for temporary changes per activity,
- risk measure for temporary changes per week
- risk measure for temporary changes per three months,
- risk measure for temporary changes per time between two consecutive outages.

As the nature of temporary changes is such, that they may change the risk temporarily, which may also be the cause of change of the mean values, the time dependent values of the selected risk criteria are mostly used, in addition of considering time duration of the changes and in addition of considering the cumulative impact of several temporary changes.

3. Concept

The concept of defining risk criteria includes consideration about the values of risk measures in several modes of operation of the considered NPP. The concept is based on the assumption that the extent of risk is different in different modes of operation, as operation in different modes of operation results in different equipment configurations.

Identification of considered risk measures includes the mean overall risk and the risk of certain mode of operation (or configuration).

Two risk limits are determined, which represent the risk criteria, and which define the allowed values of selected risk measures. Fig. 1 shows both risk limits:

- The mean core damage frequency over all considered modes of the operation - CDF (equation for calculating CDF is presented on Fig. 1) has to be lower than the prescribed limit CDFsr.
- The risk of each mode of operation CDFmi (mi ... identification of i – th mode of operation) has to be lower than the prescribed limit CDFvrh.

The second risk limit implies also that the risk of each plant configuration has to be lower than the prescribed limit CDFvrh.

Similarly, one can understand the definition of those two risk limits with respect to time:

- The mean core damage frequency over a longer time interval has to be lower than the prescribed limit.
- And, short peaks of core damage frequency over short time interval have to be lower than prescribed limit.

Similarly, the definition of those two risk limits applies to risk measures based on LERF.

The quantitative risk criteria present only one of the inputs for decision-making about the changes in the nuclear power plant in addition to qualitative risk analysis and in addition to four issues:

- the change is in accordance with the legislation,
- the change is consistent with defense in depth,
- the change maintains sufficient safety margins, and
- allows performance measurement strategies to monitor the changes.

The risk-informed decision-making is based on a spectrum of analyses, which are being expanded with the quantitative risk analyses.

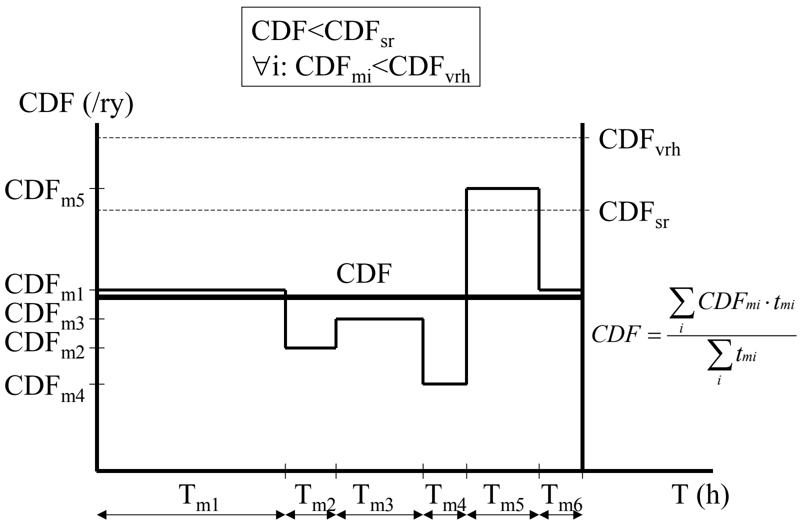

Fig. 1 Concept of defining the risk criteria (two risk limits)

4. Risk Criteria for Permanent Changes

Consideration about acceptability of permanent changes in the plant follows the following scheme.

Permanent changes in the plant are sorted in four cases according to risk measures: core damage frequency and large early release frequency and the change of core damage frequency and the change of large early release frequency due to implementation of the proposed change. While decreases or small increases of risk measures should not prevent the acceptability of the proposed changes, the larger increases of any of both risk measures can be acceptable only under other strong arguments otherwise they cannot be acceptable. The largest increases of risk measures cannot be acceptable at all.

Fig. 2 shows the acceptance guidelines for core damage frequency, where all four mentioned cases are indicated. The acceptance guidelines are similar to ref. [6], but have some unique features, which are described in the following subsections.

Case I

A permanent change in a NPP is considered by the regulatory authority if:

- The change of the core damage frequency (dCDF) due to the proposed permanent change is lower than 0 (the core damage frequency after the change is lower than the core damage frequency before the change).

A proposed change, which corresponds to case I, would have the highest chances to be considered as acceptable by the regulatory authority.

Case II

A permanent change in a NPP is considered by the regulatory authority, if all of the following statements are true:

- The core damage frequency (CDF), which is calculated with independently verified and validated complete model of probabilistic safety assessment, which represent the real and updated current state of the plant before the change and which is based on consideration of standard on PSA [1], does not exceed significantly the value of 1E-4/ry.
- The change of core damage frequency due to the proposed change does not exceed 1% of the core damage frequency and also, it does not exceed the value of 1E-6/ry.
- An assessment of the permanent change can be performed realistically in probabilistic safety assessment and is done in an appropriate way (if a realistic assessment of the permanent change from a risk viewpoint is not possible with probabilistic safety assessment, the change has to be evaluated in a different manner; in such case, the quantitative criteria written in this paper are not applicable).
- The cumulative risk contribution of previous permanent changes is not too high (recommendation: the sum of changes of core damage frequency due to previous permanent changes does not exceed 5% of the core damage frequency calculated before the proposed permanent change).

A proposed change, which corresponds to case II, would have high chances to be considered as acceptable by the regulatory authority.

Case III

A permanent change in a NPP can be considered by the regulatory authority if all of the following statements are true:

- The core damage frequency (CDF), which is calculated with independently verified and validated complete model of probabilistic safety assessment, which represent the real and updated current state of the plant before the change and which is based on consideration of standard on PSA [1], does not exceed the value of 1E-4/ry.
- The change of core damage frequency due to the proposed change does not exceed 10% of core damage frequency and it does not exceed the value of 1E-5/ry (the larger the risk contribution, the more seriously the change is investigated).

- An assessment of the permanent change can be performed realistically in probabilistic safety assessment and is done in an appropriate way (if a realistic assessment of the permanent change from a risk viewpoint is not possible with probabilistic safety assessment, the change has to be evaluated in a different manner; in such case, the quantitative criteria written in this paper are not applicable).
- The cumulative risk contribution of previous permanent changes is not too high (recommendation: the sum of changes of core damage frequency due to previous permanent changes does not exceed 10% of the core damage frequency calculated before the proposed permanent change).

A proposed change, which corresponds to case III, may have chances to be considered as acceptable by the regulatory authority.

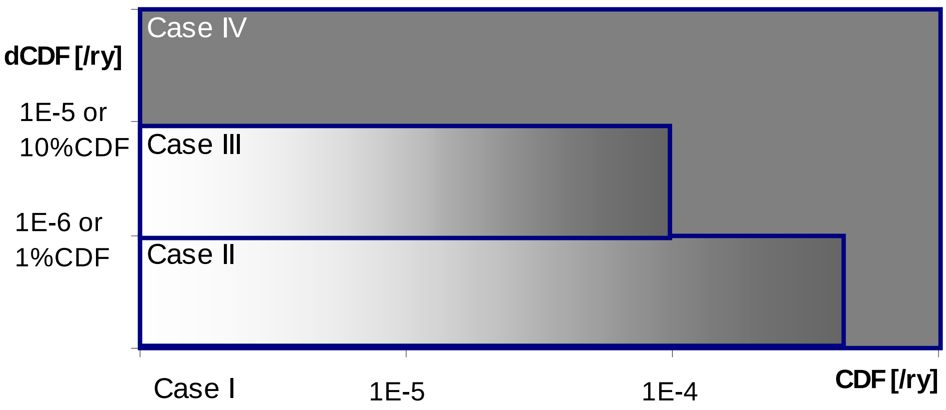

Fig. 2 Acceptance guidelines for core damage frequency

Case IV

A permanent change in a NPP cannot be considered by the regulatory authority, if the following is true:

- The change of core damage frequency due to the proposed permanent change exceeds 10% of the core damage frequency or exceeds the value of 1E-5/ry; or if CDF exceeds the value of 1E-4/ry with dCDF exceeding 1E-6/ry; or if CDF significantly exceeds the value of 1E-4/rl.

A permanent change in the plant cannot be considered by the regulatory authority if it cannot be classified into one of cases I, II or III.

Similar requirements are defined for risk measures based on LERF, but the risk limits are lower for one order of magnitude for LERF. In a PSA model under consideration, LERF values are approximately 5% of values of CDF, so CDF and risk measures based on CDF are expected as more restrictive of both risk measure sets. Although, this statement has to be confirmed at every application separately.

5. Risk Criteria for Temporary Changes

Consideration about acceptability of temporary changes in the plant follows the following scheme.

Temporary changes in the plant are considered as single changes and as a set of several changes. While decreases or small increases of risk measures should not prevent the acceptability of proposed changes, larger increases of risk measures can be acceptable only under other strong arguments, otherwise they cannot be acceptable. The largest increases of risk measures cannot be acceptable at all.

Fig. 3 shows the standpoint for determining the risk criteria for temporary changes. The change of core damage frequency due to temporary change is multiplied with duration of such change in order to estimate the risk measure for temporary changes considering CDF [4, 13]:

$$CDP = dCDF * dT \tag{1}$$

where CDP = the risk measure for temporary changes considering CDF; dCDF = change of core damage frequency; dT = time interval of temporary change.

Actually, in some literature [4] CDP is defined as core damage probability, which is obtained by multiplying CDF and time interval. But, such a multiplication may not be mathematically correct, so CDP is defined as the risk measure for temporary changes considering CDF.

Similarly, the change of large early release frequency due to temporary change is multiplied with duration of such change in order to estimate the risk measure for temporary changes considering LERF [4, 13]:

$$LERP = dLERF * dT \tag{2}$$

where LERP = the risk measure for temporary changes considering LERF; dLERF = change of large early release frequency; dT = time interval of temporary change.

Fig. 3 shows that non-risk significant change is such that causes CDP smaller than 1E-6 and LERP smaller than 1E-7.

Determination of risk criteria for temporary changes in a NPP can include requirements on one or on more steps from the following set of steps:

- consideration of single temporary change,
- consideration of several temporary changes within weekly cumulative contribution,
- consideration of several temporary changes within quarterly cumulative contribution,
- consideration of several temporary changes within cumulative contribution between outages.

The variations of the steps can include a fix time intervals or current-time intervals, or it can include requirements with other time intervals.

The listed steps are considered sufficient for definition of the risk criteria for temporary changes.

Single temporary change

The CDP for a single event i is kept below CDPsev.

$$CDPi = dCDFi * dTi < CDPsev \tag{3}$$

where CDPi = CDP considering event i; dCDFi = change of core damage frequency due to the event i; dT = time interval of temporary change caused by the event i and where:

$$dCDFi = CDF1i - CDF \tag{4}$$

where CDF1i = core damage frequency considering failure probability of equipment i set to 1. And, the core damage frequency due to any event does not increase to or over frequency of 1E-3/ry:

$$CDF1i < CDF\max = 1E - 3 / ry \tag{5}$$

where CDFmax = limit of maximal allowed core damage frequency due to any event.

Several temporary changes within weekly cumulative contribution

The weekly cumulative contribution of the CDP is limited with CDPwimax.

$$CDPwi = \sum_{j=1}^{J} CDPj < CDPwi\max \quad (6)$$

where CDPwi = cumulative CDP due to all temporary changes (from temporary change j=1 to temporary change J) in week i; CDPj = CDP of temporary change j; CDPwimax = limit of maximal allowed cumulative CDP due to all temporary changes in week i.

Several temporary changes within quarterly cumulative contribution

The quarterly cumulative contribution of the CDP is limited with CDPqimax (period of three months represents a quarter of the year).

$$CDPqi = \sum_{j=1}^{J} CDPj < CDPqi\max \quad (7)$$

where CDPqi = cumulative CDP due to all temporary changes (from temporary change j=1 to temporary change J) in quarter i; CDPj = CDP of temporary change j; CDPqimax = limit of maximal allowed cumulative CDP due to all temporary changes in quarter i.

Several temporary changes within cumulative contribution between outages

The outage cumulative contribution of the CDP is limited with CDPoimax.

$$CDPoi = \sum_{j=1}^{J} CDPj < CDPoi\max \quad (8)$$

where CDPoi = cumulative CDP due to all temporary changes (from temporary change j=1 to temporary change J) in outage i; CDPj = CDP of temporary change j; CDPoimax = limit of maximal allowed cumulative CDP due to all temporary changes in outage i.

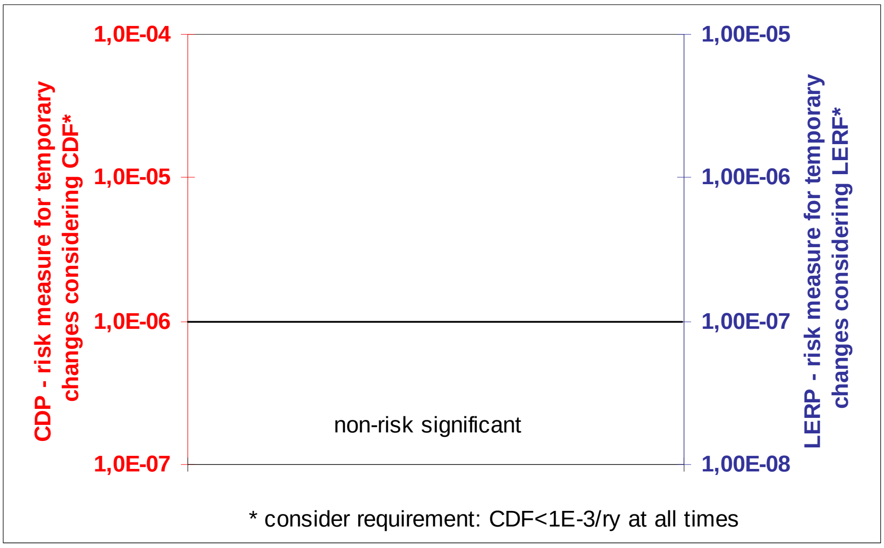

Fig. 3 Standpoint for temporary risk criteria

Similarly to equations 3 to 8, which represent risk measures based on CDF, equations, which represent risk measures based on LERF, may be derived. And, analog risk criteria may be defined, which differ for an order of magnitude from risk criteria for risk measures connected with CDF. If the risk measures connected with LERF are not available for a specific plant or the use of risk measures based on CDF is much easier, the risk measures connected with CDF may be sufficient, if there are indications, that the unavailable risk measures connected with LERF would not affect significantly the results.

6. Application of Risk Criteria – Problems and Solutions

Problems

The most important problem of definition of risk criteria is the following. The models of probabilistic safety assessment, which may represent a prerequisite for application of defined risk criteria, have very wide area of acceptability. It is difficult to define risk criteria, which would be applicable to all models without conditions and prerequisites. Several factors exist, which, if changed, may impact the results in such extend, that the results are either in one or in the other case of risk criteria from Fig. 2.

Selected illustrative examples:

1. Different modeling of the same or very similar plant can lead to the results, which may differ for orders of magnitude.
2. The same modeling of sequences and systems with different choice of considering the dependency between human failure events may lead to significant differences of results.
3. The same modeling of sequences and systems with same choice of considering dependency between human failure events with different choice of truncation limit may lead to significant differences of results [14].

Example 3 is selected for more detailed illustration, because as it is evidently much less known as the first and the second example and it is connected by far the less expected sensitivity of results.

Fig. 4 graphically shows the problem from example 3. Truncation is a term, which defines cutting off the negligible contribution of the results of the probabilistic safety assessment (PSA), i.e. fault tree/event tree analysis, when evaluating complex facilities. When analysis of complex facilities faces situation, when billions of minimal cut sets can contribute to the resulting fault tree or event tree evaluation, the contribution of less significant combinations is usually neglected. Truncation limit (TL) defines the boundary of what is considered in the analysis and what is neglected.

If truncation is selected as it was selected in the past (TL=1E-9/ry), when computers were not so capable as they are today, the results may be so different from results of the smaller truncation (TL=1E-13/ry) that they fall in different case (of cases from Fig. 2).

Fig. 4 represents results of a PSA model NPP_A performed for TL=1E-9/ry and for TL=1E-13/ry for a specific proposed change in a nuclear power plant. The change under investigation is relatively small and is related to change of only one basic event (i.e. basic event BE87A in PSA model NPP_A) in the respective PSA model [14].

The main characteristics of PSA model NPP_A for internal events are the following: 21 initiating events, 21 event trees, 112 functional events (event tree headings), 602 sequences, 1484 fault trees, 3510 basic events, 3546 gates, 74 house events.

Results indicate that the proposed change is unacceptable, if the model is analyzed using for TL=1E-13/ry, because the analysis of this change gives: dCDF=4,38E-5/ry>1E-5/ry.

Results also indicate that different selection of truncation limit, i.e. TL=1E-9/ry, would show that the change can conditionally be acceptable, because dCDF=7,50E-6/ry, which is between 1E-5/ry and 1E-6/ry (case III on Fig. 2).

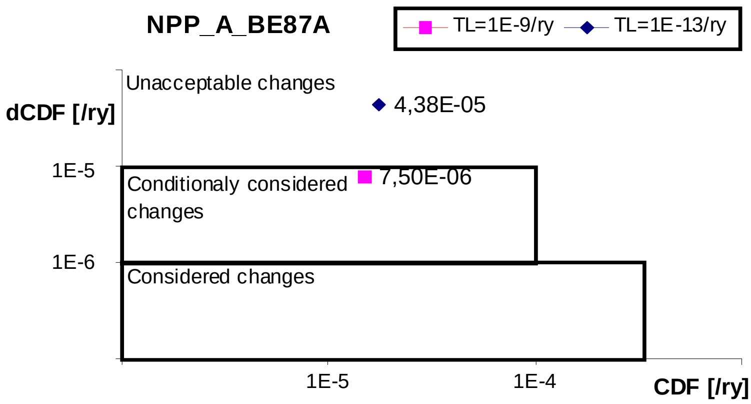

Fig. 4 Comparison of applicability of plant specific change according to defined risk criteria for component BE87A with truncation limit (TL=1E-9/ry and TL=1E-13/ry), both used for evaluation of the same PSA model NPP_A

Results show that selection of truncation limit may be a factor, which would drive the acceptance of the proposed change. To avoid the possibility that selection of truncation limit would be a driving factor for acceptance of a specific change, more specific guidance is needed for setting up the truncation limit. An example of such guidance is presented in ref. [14] and contributes to more efficient application of risk criteria.

Solutions

More detailed guidelines for performing PSA are needed (and they are under establishment at the moment). This is important:

- for more general documents, such as standards on PSA,
- for more specific documents such as guidelines for performing human reliability analysis including consideration of dependency between human failure events and other more specific guidelines and
- for identification of issues, which seem to be of less importance on the first sight, but detailed analysis shows their higher importance, such as the problem of defining the truncation limit, which is illustrated and described above.

The first from a series of standards on PSA is issued: e.g. the one for consideration of internal events [1]. Some others are under preparation. An approach for determining the technical adequacy of probabilistic risk assessment results for risk-informed activities was issued [15], which is a good standpoint to unify PSA framework of activities. A wide set of efforts in the field of human reliability analysis with emphasis on consideration of dependencies between human failure events is ongoing, e.g. ref. [22], which will contribute to more unified and more accurate consideration of contribution from human operator in complex systems.

Conclusions

The need for quantitative risk criteria for permanent and for temporary changes in a nuclear power plant is identified and the criteria are developed. The risk criteria are developed primarily for their application in a specific country with one nuclear power plant with one unit. The concept of the defined risk criteria enables small increase of risk measures, if other benefits can be proven as more important than the small risk increase. The risk criteria for permanent changes are developed similarly as it is in ref. [6] with couple of exceptions.

The relative value of dCDF versus CDF also limits the extent of risk increase, which is not the case in ref. [6]. Such a relative limitation of risk increase prevents situations where plants with very small CDF (and very small LERF) could make changes that would increase CDF very much, relatively.

The largest cumulative impact of the proposed change and previously considered changes in the periodic safety review period is recommended. The cumulative impact is limited by a 5% increase of initial CDF for less than 1% increase of dCDF and less than 1E-6/ry increase of dCDF. This means that at most 5 changes of nearly 1% increase of CDF are allowed in the time interval of the periodic safety review. The cumulative impact is limited by a 10% increase of initial CDF for less than 10% increase of dCDF and less than 1E-5/ry increase of dCDF. This means that the most 1 change of nearly 10% increase of CDF is allowed in the time interval of periodic safety review. The similar risk criteria for permanent changes apply to LERF.

The risk criteria for temporary changes are developed in a way that each temporary change is dealt with and the cumulative effects of more temporary changes are dealt with, in addition. Cumulative effects are collected weekly, they are collected quarterly and they are collected through the time interval between two consecutive outages, which is mostly: e.g. a year (which was a period normally used in the past), 15 months or 18 months (which is a period, which is normally used now).

The most important problem with definition of risk criteria lays in the following fact: the models of probabilistic safety assessment, which may represent a prerequisite for application of defined risk criteria, have very wide area of acceptability. It is difficult to define risk criteria, which would be applicable to all models without conditions and prerequisites. Several factors exist, which, if changed, may impact the results in a larger extend.

As a solution, more detailed guidelines for all stages of performing PSA are needed, from general guidance documents to more specific guidance documents about more detailed issues, which will reduce impact of variability of PSA results and which will foster the application of risk criteria for decision-making.

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