Nuclear Engineering and Technology 56 (2024) 819–823

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

SSC risk significance in risk-informed, performance-based licensing of non-LWRs

James C. Lin

ABSG Consulting Inc, 420 Exchange, Suite 200, Irvine, CA, 92602, USA

ARTICLE INFO

Keywords:
SSC
risk significance
risk-informed
performance-based licensing
non-LWR
licensing basis event
F-C target
integrated plant risk

ABSTRACT

The main criteria used in NEI 18–04 to define SSCs as risk-significant include (1) the SSC is required to keep all LBEs within the F–C target, and (2) the total frequency with the SSC failed exceeds 1% of the limit for at least one of the three cumulative risk metrics used for evaluating the integrated plant risk. The first one is a reasonable criterion in determining the risk significant SSCs. However, the second criterion may not be adequate to serve the purpose of determining the risk significance of SSCs. In the second criterion, the cumulative risk metric values representing the integrated plant risk (less the preventive and mitigative effects of the SSC being evaluated) are compared to a risk limit that represents a very small contribution to the overall integrated plant risk, which corresponds appropriately to the contributions from individual SSCs. The easiest approach to redefine the NEI 18-04 definition of risk-significant SSCs in relation to the integrated plant risk metrics is to compare the difference, between the risk metric value calculated with the SSC failed and the risk metric value calculated with the SSC credited, with 1% of the risk limit established for the integrated plant risk metrics.

1. Introduction

To demonstrate that a specific design provides reasonable assurance of adequate radiological protection, NEI Technical Report 18–04 (Ref. [1]) provides a risk-informed, performance-based process for addressing the selection of licensing basis events (LBEs), safety classification of structures, systems, and components (SSCs) and associated risk-informed special treatments, and determination of defense-in-depth (DID) adequacy for non-light water reactors (non-LWRs).

As part of this method, the following safety classification categories are established to facilitate the development and maintenance of requirements necessary to support SSC performance of functions in the prevention and mitigation of LBEs modeled in the probabilistic risk assessment (PRA): safety-related (SR), non-safety-related with special treatment (NSRST), and non-safety-related with no special treatment (NST).

NSRST SSCs include those non-safety-related (non-SR) SSCs that perform risk-significant functions and those that perform functions necessary to meet defense-in-depth criteria. Safety significant SSCs include those SSCs classified as SR and NSRST. The performance and special treatment requirements for SR and NSRST SSCs are to provide reasonable confidence in the SSC capabilities and reliabilities in performing functions that prevent and/or mitigate LBEs from exceeding the frequency-consequence (F–C) target (see the F–C target in Fig. 1, reproduced from Fig. 3–1 in NEI 18–04 [Ref. [1]]).

The criteria for determining risk-significant SSCs are defined in NEI 18–04 as:

- *A prevention or mitigation function of the SSC is necessary to meet the design objective of keeping all LBEs within the F–C Target. This is determined by assuming failure of the SSC in performing a prevention or mitigation function and checking how the resulting LBE risks compare with the F–C Target.*
- *The SSC makes a significant contribution to one of the cumulative risk metrics used for evaluating the risk significance of LBEs. A significant contribution to each cumulative risk metric limit is satisfied* <u>*when total frequency of all LBEs with failure of the SSC exceeds 1% of the cumulative risk metric limit*</u> *…. The cumulative risk metrics and limits include:*

o *The total mean -frequency of exceeding a site boundary dose of* 100 mrem $<$ *1/plant-year*
o *The average individual risk of early fatality within 1 mile of the EAB* $< 5 \times 10^{-7}$*/plant-year (QHO)*
o *The average individual risk of latent cancer fatalities within 10 miles of the EAB shall not exceed* 2×10^{-6}*/plant-year*

E-mail address: jlin@absconsulting.com.

https://doi.org/10.1016/j.net.2023.09.024
Received 17 May 2023; Accepted 16 September 2023
Available online 17 September 2023

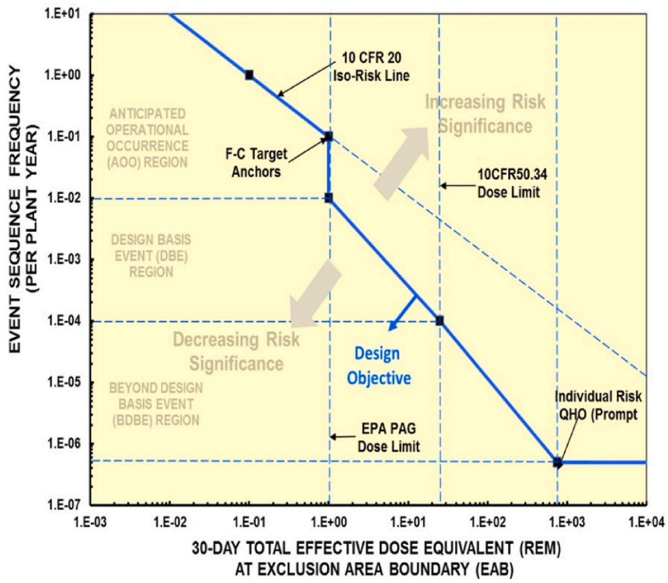

Fig. 1. Frequency-consequence target (reproduced from Fig. 3–1 in NEI 18–04 [Ref. [1]]).

As can be seen in the definition for risk significant SSCs presented above, NEI 18-04 classifies an SSC as risk-significant based on both absolute (first criterion) and relative (second set of criteria) risk metrics. The main concept in the criteria used to define an SSC as risk significant can be rephrased and summarized as follows:

- Based on the 95th percentile uncertainty on both the LBE frequency and dose consequence, the SSC is required to keep all LBEs within the F–C target.
- Based on the mean estimates of frequencies and dose consequences, the total frequency of all LBEs with the SSC failed exceeds 1% of the limit for at least one of the three cumulative risk metrics used for evaluating the integrated plant risk.

2. Issue with NEI definition of SSC risk significance

The first criterion in the definition of SSC risk significance is based on an absolute risk metric being maintained within a risk goal; i.e., the F–C target. Each SSC evaluated is to provide the necessary prevention or mitigation function so that the frequency-dose metric does not exceed its target curve. In other words, with a risk-significant SSC failed, the calculated frequency-dose risk metric for at least one LBE would exceed the F–C target curve. This is considered a reasonable criterion to determine the risk significance of an SSC.

However, there appears to be an issue with the second criterion in the NEI 18-04 definition as to whether it is adequate to serve the purpose of determining the risk significance of SSCs. This criterion is meant to calculate the cumulative risk metric value from all LBEs with the SSC unavailable and then compare this calculated value against 1% of the integrated plant risk limit established for the corresponding cumulative risk metric (to be done for all three cumulative risk metrics).

It would have been an acceptable criterion if the SSC were defined as risk significant when the calculated, cumulative risk metric value with the SSC failed exceeds the integrated plant risk limit or is within 1% of the limit. This is because, if the prevention and/or mitigation function of the SSC is minimal, the calculated cumulative risk metric value with the SSC failed should be very close to the value without failing the SSC, in which case, the calculated cumulative risk metric value is really a risk prevention/mitigation characteristic of the overall design less the SSC being evaluated. This does not really reflect the importance of the SSC being considered. In this situation, the calculated cumulative risk metric value reflecting the overall plant design less the SSC could possibly already exceed 1% of the integrated plant risk limit established for the cumulative risk metric. Yet, the importance of the SSC being considered could be much, much less.

3. Use of risk importance measure to determine risk significance

As part of the risk-informed, decision-making process applied to nuclear facilities, it is often necessary to characterize whether SSCs are risk significant or risk insignificant so that different requirements (e.g., in design, manufacturing, operation, test, maintenance) may be imposed to ensure the required SSC performance. This categorization of SSCs in terms of risk significant versus risk insignificant is usually accomplished by selecting a risk metric, quantifying the value of this risk metric, and comparing the calculated value of the risk metric with the criterion established for determining risk-significant SSCs.

Thus, the use of risk metrics and importance measures facilitates the determination and ranking of risk contributions from SSCs as well as the risk worth of various design and operation features. This process can also be used to evaluate the impact of decision options and helps decision makers allocate resources toward an effective management of plant risk and the associated uncertainty.

Each risk metric selected may be expressed in terms of one or more risk parameters. In the case of light water reactors (LWRs) PRA analysis, one risk parameter such as core damage frequency (CDF) and large early release frequency (LERF) are often used as the risk metrics which can be calculated directly from the parameters of risk model elements associated with the SSCs; e.g., component failure rates, probability of occurrence of component failure modes.

Since CDF and LERF represent the cumulative total risk from all initiating events along with the associated SSC failure modes that may occur in response to these initiating events, the values of the risk metrics can be quantified and expressed in terms of contributions from the model elements associated with their corresponding SSCs (in addition to initiating event contributions). With this association between the risk metrics and model elements, measures of the SSC importance to the risk metrics can be quantitatively calculated through these relationships. Importance measures obtained in this manner are routinely used in the LWR PRAs to determine the SSC risk significance.

In the case of a risk limit originated directly from the F–C risk target curve developed for the non-LWRs in NEI 18–04, the corresponding risk metric is typically defined by two parameters; e.g., frequencies and dose consequences of LBE event scenarios, as specified in NEI 18–04 for the criterion defining the risk-significant LBEs. When this risk metric is used to determine the LBE risk significance, it does not really embody the cumulative, total risk for the entire plant. It simply represents the combined contributions from the family of event sequences (with similar scenario characteristics) associated with that one LBE. Since it is not a cumulative risk from all accident sequences of the plant and represents only risk contribution from an individual LBE, the calculated risk metric (i.e., frequency and dose consequence) values for that LBE can be compared directly with the risk limits derived from the F–C target curve to determine whether it is a risk-significant LBE.

For example, the risk-significant LBEs are defined in NEI 18–04 as those with frequencies within 1% of the F–C target with site boundary doses exceeding 2.5 mrem (see Fig. 2, reproduced from Fig. 3–4 in NEI 18–04 [Ref. [1]]). To consider the effects of uncertainties, the upper 95th percentile estimates of both frequency and dose are used in determining the risk-significant LBEs. In this case, the calculated frequency and dose consequence for each LBE are compared directly with the risk limit (i.e., the threshold value) which is 99% of the LBE risk target; i.e., the F–C target curve. If the 95th percentile of an LBE's calculated frequency at the 95th percentile of its calculated dose consequence exceeds the 99% value of the F–C target curve, this LBE is categorized as risk significant.

The first criterion specified in Section 4.2.2 of NEI 18–04 for determining risk-significant SSCs (presented in Section 1 of this paper) uses

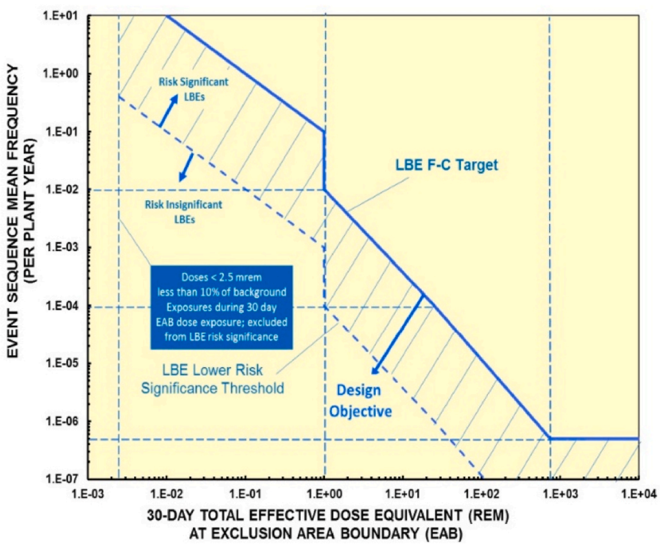

Fig. 2. Use of the F–C target to define risk-significant LBEs (reproduced from Fig. 3–4 in NEI 18–04 [Ref. 1]).

the F–C target curve as the risk limit. Although risk importance measures for SSCs similar to those used in the case of LWRs can also be derived for the frequency parameter separately for each individual LBE, the calculated dose consequence value cannot be easily expressed in terms of the SSC model element parameters. Besides, the risk metric values for frequency and dose consequence calculated in this case are for each individual LBE; i.e., not cumulative from all LBEs. Since the risk metric used is not the total, cumulative risk from all LBEs, any measure of the SSC importance using this risk metric cannot reflect the overall SSC significance for the entire plant.

As such, risk importance measures used in this situation are typically based primarily on the change in risk or, for the second set of criteria for the risk-significant SSC determination, additional single-parameter, cumulative risk metrics related to the quantitative health objectives are defined to complement the decision-making process and used for importance measure to determine risk significance. Therefore, depending on whether the risk metrics used can be calculated directly by the risk model parameters associated with the SSCs, SSC importance measure and threshold for risk-significant SSCs may be defined differently.

In the first criterion for determining risk significant SSCs (presented in Section 1), an SSC is categorized as risk significant if one of the calculated risk metric (frequency or dose) values for at least one LBE exceeds the F–C target curve when the prevention and mitigation function of the SSC is not credited. This is essentially a representation of change in risk. The increased (i.e., changed), calculated risk metric values with the SSC unavailable is compared with the risk limit; i.e., F–C target curve. The increase in the calculated risk metric values results from the unavailability of the functions performed by the SSC, and thus reflects the contribution from the prevention and mitigation role of the SSC being evaluated.

In the second set of criteria for the risk-significant SSC determination, three frequency-based, integrated plant risk metrics are used: total mean frequency of exceeding a site boundary dose of 100 mrem (with a plant risk limit of 1/plant-year), average individual risk of early fatality within 1 mile of the exclusion area boundary (EAB, with a plant risk limit of 5×10^{-7}/plant-year), and average individual risk of latent cancer fatalities within 10 miles of the EAB (with a plant risk limit of 2×10^{-6}/plant-year). The risk limit selected for determining risk significant SSCs is 1% of the integrated plant risk limit. An SSC is categorized as risk significant if at least one of the three calculated, cumulative risk metric values exceeds 1% of its integrated plant risk limit when no credit is taken for the prevention and mitigation function of that SSC.

The risk metric adopted in NEI 18–04 for this second set of criteria is the increased frequency values calculated for the integrated plant risk metrics from all LBEs, which are cumulative in nature. The baseline cumulative risk metric values reflect the overall plant design to protect against the LBEs. The increased cumulative risk metric values calculated for the determination of risk-significant SSCs reflect the overall protective and mitigative features of the plant without crediting the SSC being evaluated. As indicated previously, these “increased values” of cumulative risk metric themselves do not actually exhibit the contribution from the preventive and mitigative functions of each SSC evaluated. Instead, the contribution from the prevention and mitigation functions of the SSC is manifested by the “increase” in the calculated cumulative risk metric values; i.e., difference between the calculated risk metric value without crediting the SSC and the calculated value with the SSC credited.

On the other hand, the risk limit used in this case is 1% of the integrated plant risk limit, which implies a very small fraction of the integrated plant risk limit; i.e., signifying the definition for an insignificant contribution to the integrated plant risk values. Therefore, this set of criteria for determining risk-significant SSCs are actually comparing the cumulative risk metric values from all LBEs (less the preventive and mitigative effects of the SSC being evaluated) to a risk limit that represents the dividing line between an insignificant contribution and a significant contribution to the overall integrated plant risk, which corresponds approximately to the similar order of magnitude of contributions from individual SSCs. In essence, it is not an apples-to-apples comparison. That is why it is argued in this paper that the second set of criteria for determining risk-significant SSCs are inadequately defined and should be revised.

4. Viable approach to define SSC risk significance

As alluded to in the preceding, a logical approach to measure the worth of a feature in maintaining (or achieving) the present level of integrated plant risk is to remove the feature and then determine how much the risk will increase. If the feature were assumed to be unavailable (or failed), the increase in risk is called risk achievement, which is of special interest in reliability assurance programs and inspection and enforcement activities [2].

As such, one of the basic principles for evaluating the importance or contribution of an element to the total risk associated with an overall design is to examine the change in risk provided by the preventive and mitigative functions of that element. Based on this rationale, importance measure can also be appropriately expressed in terms of “change in risk” between the case with that element credited and the case with that element removed. The most common measures of risk changes are differences in risk values (i.e., on an interval scale) or ratios of different risk values [3]. When the measure of risk achievement is defined as a ratio, it is named as the risk achievement worth (RAW). The RAW presents a measure of the “worth” of the feature in “achieving” the present level of risk and indicates the importance of maintaining the current level of reliability for the feature.

Since the second set of criteria for determining risk significant SSCs as specified in NEI 18–04 consider the case with no credit taken for the SSC being evaluated (i.e., with SSC failed), it is also considered reasonable in this paper to measure the risk importance of an SSC by the difference in risk resulting from crediting and not crediting the SSC. Therefore, to reflect the significance of an SSC, one approach is to compare the difference in the cumulative risk metric value between the base case (with the SSC credited) and the case with the SSC failed against 1% of the risk limit for the cumulative, integrated plant risk metric. This approach is consistent with the traditional approach to evaluating risk importance by examining the risk achievement when the SSC fails.

The traditional approach determines the risk worth of an SSC by also normalizing its risk achievement by the base case risk value. An alternative method is to normalize the risk achievement by the risk limit (or goal) established, which is similar to the approach adopted in NEI 18–04 in determining the risk significance of individual LBE and SSC. Either using the base case risk metric value or adopting the risk limit value as the normalization factor would be a better approach than the second set of criteria currently defined in NEI 18–04.

In conclusion, the easiest approach to revise the NEI 18-04 definition of risk-significant SSCs in relation to the integrated plant risk metrics is to compare the difference between the risk metric value calculated with the SSC failed and the risk metric value calculated with the SSC credited with 1% of the risk limit established for the integrated plant risk metrics. This approach will only involve a minimal change to the second set of criteria specified in NEI 18–04 for determining risk significant SSCs.

5. Considerations for using additional importance measures

In the preceding, the use of importance measures to determine risk significance for a risk-informed, performance-based development of licensing basis is discussed. In this section, the considerations of additional importance measures are also described, including for applications beyond licensing; e.g., design, operation, test, maintenance.

As discussed previously, both absolute and relative importance measures are used in NEI 18–04 for the development of licensing basis for advanced non-LWRs. The determination of risk-significant LBEs and the first criterion for the determination of risk-significant SSCs adopt the absolute importance, while the second set of criteria for determining the risk-significant SSCs are based on relative importance. As implied in NEI 18–04, due to the relatively small frequencies of release and relatively small source terms that may potentially result from the advanced non-LWRs, importance measures on relative basis alone may not be sufficient because the calculated relative importance results may, in some cases, be highly sensitive and involve significant uncertainties.

With respect to the relative importance measure, only risk achievement (or RAW) is employed in NEI 18–04 for the determination of risk-significant SSCs. As defined in the preceding section, risk achievement (or RAW) is the measure of the worth of a plant feature in achieving or maintaining the present level of plant risk. The features with the greatest risk achievement worths are generally the features that are most important to maintaining the present risk level of the plant. As stated previously, risk achievement (or RAW) can be expressed in terms of “change in risk” either in the difference or the ratio format. However, when the features of different plants are compared or when cost-benefit evaluations are performed, even for a single plant, the difference definition is generally more appropriate [2].

A number of different risk metrics are used in NEI 18–04 for determining the risk-significant LBEs and SSCs. This includes:

- Frequencies and dose consequences of LBEs.
- Total frequency of exceeding a specified site boundary dose.
- Individual risk (in terms of annual frequency) of prompt and latent fatality within a specified distance of the EAB.

There is another type of risk metrics that are mentioned in NEI 18–04, but was not used in defining the risk-significant LBEs and SSCs. These include the expected dose at a specified distance from the plant, the expected number of early fatalities and expected number of latent cancer fatalities within a specified distance from the plant, etc. These additional risk metrics can also be used to help identify important risk contributors.

Risk importance measure is a very useful and practical method that can be easily implemented to unravel, identify, and rank-order the contributors to plant risk from various different perspectives by using different risk metrics. The results of the risk importance calculations can be used as one of the inputs to prioritize activities and resources in a risk management program. For example, reliability assurance programs and maintenance and surveillance of plant features can be prioritized using the risk achievement worths of the plant features as one of the important inputs.

It should be noted that, however, for different risk metrics, their rank-orders of model elements and the associated plant features are most likely not identical, which can result in different priorities for risk management considerations. This characteristics has long been observed in the PRAs for LWRs. Therefore, it is a good practice to examine the results of a number of different risk importance measures in conjunction with different risk metrics to ensure that a more complete understanding of the risk worth of all plant features, events, accident sequences, etc. is attained. To this end, NEI 18-04 has listed a number of risk importance measures including risk achievement (risk achieve worth), risk reduction (RRW), Fussell-Vesely, Birnbaum importance, criticality importance, and partial derivative. Since risk achievement (RAW) has already been discussed in detail previously, the following (which is extracted from information available in selected literature) discusses the key characteristics of three of the most commonly used importance measures; i.e., risk reduction (risk reduction worth), Birnbaum importance, and Fussell-Vesely importance.

The risk reduction worth measures the worth of a feature in reducing the present plant risk. It calculates the decrease in risk if the modeled feature were assumed to be made perfectly reliable. Risk reduction worth can also be used to prioritize activities with the purpose of reducing the risk. This may involve modifications of plant design, operation, surveillance test, and maintenance to those plant features with high risk reduction worths. Since risk reduction worth measures the maximum decrease in risk possible for an improvement to the feature, it can also be used to screen out modifications for which their maximum risk reduction effects are small in relation to the costs [2]. The risk reduction importance is useful for bounding the impacts of proposed improvements on the risk metric.

The Birnbaum importance is the risk difference when a plant feature is down versus when the feature is up; i.e., it is the impact of the assumed failed state of the plant feature relative to its perfectly operational state. It is useful for evaluating the risk model elements that the risk metric is most sensitive to changes in. The Birnbaum importance can be calculated as the sum of the risk achievement and risk reduction of the plant feature expressed in the form of risk difference. It is independent of the present value of the unavailability of the plant feature being evaluated and, by and large, can be used to represent safety significance. Birnbaum importance evaluates the relative contribution of plant features to the risk metric and is helpful when selecting the feature to improve when the efforts for improvement is the same for all features. Birnbaum importance is applicable in prioritizing actions knowing the feature is unavailable. Such actions include determining the amount of allowed downtime to allot for repair after a component failure has been detected and determining the importance of corrective activities which are carried out after the failure is discovered [3].

Another frequently applied importance measure is the Fussell-Vesely measure of importance, which determines the fractional contribution of a feature to the risk metric. The Birnbaum importance is the importance of a feature which is assumed to be unavailable relative to a state in which the feature is always available. In addition to this, the Fussell-Vesely importance also accounts for the likelihood that the feature could actually fail or could actually be unavailable, by multiplying the Birnbaum importance by the likelihood of the feature being unavailable (or fails). Since Fussell-Vesely importance is proportional to the unavailability (or failure likelihood) of the feature being evaluated, it represents the direct effect of the feature unavailability (failure likelihood) on the risk metric. As such, Fussell-Vesely importance is frequently used as a measure of risk importance in that it is useful for measuring the importance of a risk model element given the current state of the plant.

On the other hand, RAW does not represent the failure likelihood of the feature itself, but essentially signify the defense of the remaining facility against the plant configuration with a loss of the feature. Thus, a low RAW reflects a strong plant defense against a state in which the plant feature in question is absent. As such, RAW can be used as a measure of safety importance [4]. The risk achievement importance is useful for estimating the significance of taking specific equipment out of service, thereby assuring that they cannot operate.

To provide consistent interpretation of results between applications, all of the risk importance measures discussed above are typically normalized by the mean point estimate of the risk metric.

The Fussell-Vesely importances are quite different from the Birnbaum importances as to where they are applicable. The Birnbaum importance assumes the feature is unavailable or fails. Since the Fussell-Vesely importance includes the likelihood of the feature failing or being down, it is applicable for determining risk importances when the feature is not known to be failed or unavailable. It is useful in helping to prioritize where inspections should be carried out to determine if failures have occurred or if the plant features are unavailable. Therefore, Fussell-Vesely importance measure is useful in the general areas of failure inspection and preventive maintenance while Birnbaum importances are useful in the general areas of failure repair and corrective maintenance [3].

Risk importance measures can not only be used to establish risk-based quantitative rankings of plant features, but also provide an easy way to document sensitivity results for a series of single model element changes to a baseline probabilistic risk model. For many applications, the combinations of two importance measures are desirable. For some applications, one importance measure could be sufficient [4].

Fussell-Vesely importance can be high either due to a high unavailability (or failure likelihood) of the plant feature or a weak defense in depth for the loss of the feature. When both Fussell-Vesely and Birnbaum importances are high, safety can be improved by decreasing the unavailability (or failure likelihood) of the plant feature or by improving the defense in depth against the plant configuration with a failure of the feature. The combination in which the Fussell-Vesely importance is high but Birnbaum importance is low is very unlikely except when the present unavailability (or failure likelihood) of the feature is extremely low [4].

For maintenance and operation optimization applications, the use of two importance measures is advisable; e.g., a combination of Fussell-Vesely and RAW (or Birnbaum importance). In applications where risk ranking is important, perhaps, only one importance measure is needed. To identify potential safety improvements to plant features, for example, Fussell-Vesely importance alone can be used. To identify plant features for potential test and maintenance relaxation, one could possibly just use the Birnbaum importance alone [4].

6. Conclusions

The second set of criteria for the determination of risk-significant SSCs specified in NEI 18–04 inappropriately compare the increased frequency values (with the SSC failed) calculated for the integrated plant risk metrics from all LBEs with 1% of the risk limit established for the integrated plant risk metrics. In essence, it is comparing the increased, cumulative total plant risk with a very small fraction of the integrated plant risk limit which corresponds roughly to the similar order of magnitude of contributions from individual SSCs; i.e., not an apples-to-apples comparison.

The easiest approach to revise the NEI 18-04 definition of risk-significant SSCs in relation to the integrated plant risk metrics is to compare the difference between the risk metric value calculated with the SSC failed and the risk metric value calculated with the SSC credited with 1% of the risk limit established for the integrated plant risk metrics. This approach will only involve a minimal change to the second set of criteria specified in NEI 18–04 for determining risk-significant SSCs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] NEI, *Risk-informed performance-based technology inclusive guidance for non-light water reactor licensing basis development*, Revision 1 (August 2019). NEI 18-04.

[2] W.E. Vesely, T.C. Davis, R.S. Denning, N. Saltos, *Measures of Risk Importance and Their Applications*," NUREG/CR-3385, U.S. Nuclear Regulatory Commission, July 1983.

[3] W.E. Vesely, T.C. Davis, *Evaluations and Utilizations of Risk Importances*, NUREG/CR-4377, U.S. Nuclear Regulatory Commission, August 1985.

[4] M. Van Der Borst, H. Schoonakker, An overview of PSA importance measures, Reliab. Eng. Syst. Saf. 72 (2001) 241–245.