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Original Article

A new method for safety classification of structures, systems and components by reflecting nuclear reactor operating history into importance measures

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ABSTRACT

Risk-informed safety classification of structures, systems and components (SSCs) is very important for ensuring the safety and economic efficiency of nuclear power plants (NPPs). However, previous methods for safety classification of SSCs do not take the plant operating modes or the operational process of SSCs into consideration, thus cannot concentrate on the safety and economic efficiency accurately. In this contribution, a new method for safety classification of SSCs based on the categorization of plant operating modes is proposed, which considers the NPPs operating history to improve the economic efficiencies while maintaining the safety. According to the time duration of plant configurations in plant operating modes, average importances of SSCs are accessed for an NPP considering the operational process, and then safety classification of SSCs is performed for plant operating modes. The correctness and effectiveness of the proposed method is demonstrated by application in an NPP's safety classification of SSCs.

1. Introduction

Safety is the most fundamental factor for the development of nuclear energy, especially after the Fukushima Daiichi nuclear accident. The safety classification of structures, systems and components (SSCs) is not only very important for the operation and maintenance of nuclear reactors or power plants (NPPs), but also is the basis for supervision activities, for example, meeting the corresponding requirements and rules [1]. The deterministic safety classification method divides SSCs into two classifications: "safety related" and "non-safety related", for which different requirements are specified in the design, manufacture, inspection, and testing. In the deterministic method, SSCs are classified according to systems functions, which are relatively ambiguous and even subjective. On the one hand, some components that are not significant to the NPP safety will be classified as "safety related" just because the system that they belong to is "safety related", and this obviously affects the economic efficiencies of NPPs. On the other hand, some components that are important to safety will be classified as "non-safety related" because the system that they belong to dose not perform safety function, and this will bring out potential risk to NPPs.

In 2004, the Nuclear Regulatory Commission (NRC) issued risk-informed categorization and treatment of SSCs for nuclear power reactors (10 CFR 50.69) [2], and two new subcategories were introduced, "high safety significant (HSS)" and "low safety significant (LSS)". SSCs are further classified according to their risk importances assessed by probabilistic safety assessment (PSA). HSS refers to SSCs with high contribution to the risk, while LSS refers to SSCs with low contribution. This method further identifies the risk characteristics of SSCs, and determines what are important for NPPs. For example, in Daya Bay NPP, about 33% of the "safety related" components were re-classified as LSS, while 64% of the "non-safety related" components were re-classified as HSS [3].

In past decades, there were some studies on risk-informed safety classification both in the methodology and application fields. There were most comprehensive and in-depth engineering

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applications in the United States [4], for example, the South Texas Project Nuclear Power Plant conducted a comprehensive study and a reclassification of its 68 systems and nearly 70,000 components. Based on the research, many regulatory exemptions were proposed, and eventually approved by the NRC. At present, the application researches mainly focus on disaster scenarios and on SSCs of some advanced reactors, such as applications for seismic probabilistic risk assessments [5], passive safety systems of a fluoride salt cooled high temperature reactor [6], safety classification of SSCs for pool-type research reactors [7], small population effects on a floating nuclear power plant [8], special requirements for advanced non-light-water reactors [9], etc. These studies expand the scope of risk-informed safety classification, and prove its significant improvement on the safety and economic efficiencies of NPPs.

However, the risk-informed safety classification commonly used in NPPs is based on the expert panel and the basic PSA for the full power operation modes. The effectiveness and uncertainties of PSA models and importance measures, as a basis, have a great impact on the safety classification. In addition, there is no adjustment on the safety classification during operation, although the risk importances of SSCs often change. Thus, the safety classification of SSCs based on the basic PSA model does not fulfill the requirements of testing and maintenance activities well. Aiming at solving these issues, researches have been conducted to improve the safety classification method. In 2004, a method was proposed by Jun Su Ha, which used the analytic hierarchy process and Bayesian belief networks to overcome the demerits of the qualitative and linear decision-making process in the conventional method, and to arrive at a final decision effectively [10]. Kilyoo Kim proposed a balancing method in 2005 to calculate the risk value (Risk achievement worth, RAW) of a component from the basic event RAW during the safety classification. The validity of his method was demonstrated by applications in an NPP [11]. In 2017, Wang Jiaqun proposed the use of a Risk Monitor PSA model in the risk-informed safety classification, instead of the basic PSA model. Return to service worth (RTS) was also introduced in his research to obtain the risk value of out-of-service SSCs [12], which provided the importance measurement that was more realistic for the safety classification. In 2018, Lyons studied the role of earthquake probabilistic risk assessment in risk-informed safety classification, and quantified the impact of various assumptions on the results [13]. Sun Ming proposed an integrated SSCs safety classification method based on relative importance and functions importance in 2020 [14]. Some methods were also proposed for the safety classification of hybrid I&C systems [15], and safety-related information systems [16], etc. These studies addressed the above issues to a certain extent, and fulfilled the requirements of the testing and maintenance activities better.

However, excessively frequent adjustments of the safety classification are not necessary, because the maintenance, inspection, and testing activities are performed periodically [17,18]. Moreover, neither the basic PSA model nor the Risk Monitor PSA model reflects the specific operating history of an NPP or reliability status of its SSCs [19], although these are very important for the safety and economic efficiencies [20]. Addressing these problems, we analyze the characteristics of plant operating modes, then study the configuration changes and SSCs characteristics in the plant operating modes of NPPs, and propose to perform safety classification for every plant operating mode respectively. The average risk importances of SSCs could be assessed according to plant configurations of each operating mode by their operational data. Thus, safety classifications could be performed for every plant operating mode to improve the future operation of NPPs. Such a new method for safety classification is proposed in this contribution, which is conducive to improving the economic efficiencies of NPPs while maintaining the safety.

2. Conventional method

2.1. Safety classification of SSCs

From the perspective of safety functions, the importances are different for SSCs in NPPs, it is necessary to manage SSCs accordingly [1]. In this way, the requirements for the design, manufacture, inspection, maintenance, and test of different equipment need to be specified. In NPPs, the maintenance of SSCs consists of preventive and corrective maintenance. In the preventive maintenance, the refueling maintenance is generally performed during the shutdown modes, and its time interval is about 12–18 months. For regular testing, inspection, and preventive maintenance during the normal operation modes, such as the replacement of sealing materials, periodic and non-periodic testing of SSCs performances, their intervals are based on the importance and reliabilities of SSCs [21], which is generally a few days or a few weeks. Corrective maintenances are performed after failures, so their intervals are not fixed and usually measured in days, weeks or months.

These time characteristics and SSCs importances that often change in the operation, should be considered in the safety classification to achieve a balance in cost benefit analysis. In addition, after operating for some time, the reliabilities of SSCs will change, which are very important for the inspection, maintenance, and testing activities, and should be properly used in the safety classification for improving subsequent SSCs management. Based on these analyses, we find out that one main issue of risk-informed safety classification is essentially how to perform safety classification to reflect the actual status of NPPs better. In this contribution, we propose an improved method of risk-informed safety classification, seeking a more reasonable safety classification to improve the economic efficiencies of NPPs while ensuring the safety.

2.2. Current risk-informed SSCs classification

For the current risk-informed SSCs classification, the process mainly consists of four steps: risk characterization, defense-in-depth characterization, risk sensitivity study, and integrated decision panel review. The first step is to calculate the importance measures of SSCs by the basic PSA model, and then classify SSCs into HSS or LSS by importance measure criteria. Secondly, defense-in-depth characterization re-determines the safety significance of safety-related LSS, with respect to core damage mitigation and other functions by a set of deterministic criteria. Thirdly, risk sensitivity study is performed for SSCs that are initially identified as LSS, based on the assumption of their reliabilities changes, to identify the potential impact on core damage frequency (CDF) and large early release frequency (LERF). Finally, the integrated decision panel will review the results of the safety classification and finally determine the SSCs' classifications.

3. Proposed method

With respect to the timeliness of SSCs management activities, an improved safety classification method based on plant operating modes identification and plant configurations sampling is proposed in this contribution, considering the SSCs status in an NPP operation process. In the following, Section 3.1 mainly introduces the framework of proposed method; Section 3.2 and Section 3.3 describes the identification of plant operating modes, and the sampling of plant configurations in the proposed method; Section 3.4 depicts the calculation method for importance measures; Section 3.5 gives an example on the importance measures calculation and the criteria for safety classification.

3.1. Framework of the proposed method

There are three major steps in the proposed safety classification method of SSCs based on reflecting nuclear reactor operating history into importance measures, which includes the identification of plant operating modes, SSCs safety classification for every plant operating mode, and safety classification determination. These steps and processes of the proposed method are shown in Fig. 1.

The conventional safety classification of SSCs is the same for different plant operating modes, while the proposed safety classification is dynamic and changed with the plant operating mode. As described in Fig. 1, in addition to the conventional risk-informed SSCs classification method, the first step is to identify the different plant operating modes according to the characteristics of operation and PSA models. The SSCs involved in each operating mode may be different, and for a single component, its importance measures may also change with the plant operating mode. Hence, the entire cycle of plant operation is divided into various plant operating modes for an NPP in the proposed method, and then safety classification is performed for each plant operating mode, which is conducive to the respective specification of safety requirements for SSCs.

Secondly, a complete safety classification is performed for each plant operating mode, which includes risk characterization, defense-in-depth characterization, risk sensitivity study, and integrated decision panel review namely. In addition to the conventional method, all configurations will be sampled randomly according to their time duration in the risk characterization and risk sensitivity study of a plant operating mode. The longer an NPP is operating with a plant configuration, the greater the probability will be for this configuration being selected. The importance measures of SSCs are calculated for all samples of configurations. Then, weighted average of SSCs importances will be obtained according to the duration of these configurations, in order to represent the plant operating mode. Finally, SSCs are classified based on these average importances.

Lastly, the final safety classifications of SSCs are determined according to the classifications of plant operating modes, as shown in Fig. 1. On one hand, in terms of the test, inspection, and maintenance of SSCs for a specific plant operating mode, their safety classification are determined by the classification corresponding to this plant operating mode, which is obviously more resilient than the safety classification by conventional method. On the other hand, while for the design, manufacture, and installation of SSCs, such as redundancy, performance in seismic, etc., their safety classifications are determined according to the highest level of safety classification in all operating modes, which can better ensure the safety of an NPP.

In addition, risk importances of out-of-service components should also be involved to support the proposed method. RAW and Fussell Vesely (FV) importance measures are usually used as risk indicators for conventional risk-informed safety classification. In most of the cases, they are useful, but are not suitable for the importance measures of out-of-service components. Therefore, we also propose appropriate indicators, in the following, to characterize the importances of out-of-service components to the overall risk of NPPs according to the requirements of the proposed method.

3.2. Identification of plant operating modes

The plant operating modes should be appropriately identified to represent the integral parts of plant operations. Although there is no standardized methodology for the identification of plant operating modes, they can be well identified and categorized according to the main differences in the characteristics of the operation and PSA models, for example, the plant operating modes can be identified as power operation mode, hot standby mode, normal cold shutdown mode, etc. Thus, there will be about 10 operating modes for a typical water cooled reactor, which reflects the changes in safety systems, differences in the initiating events, etc.

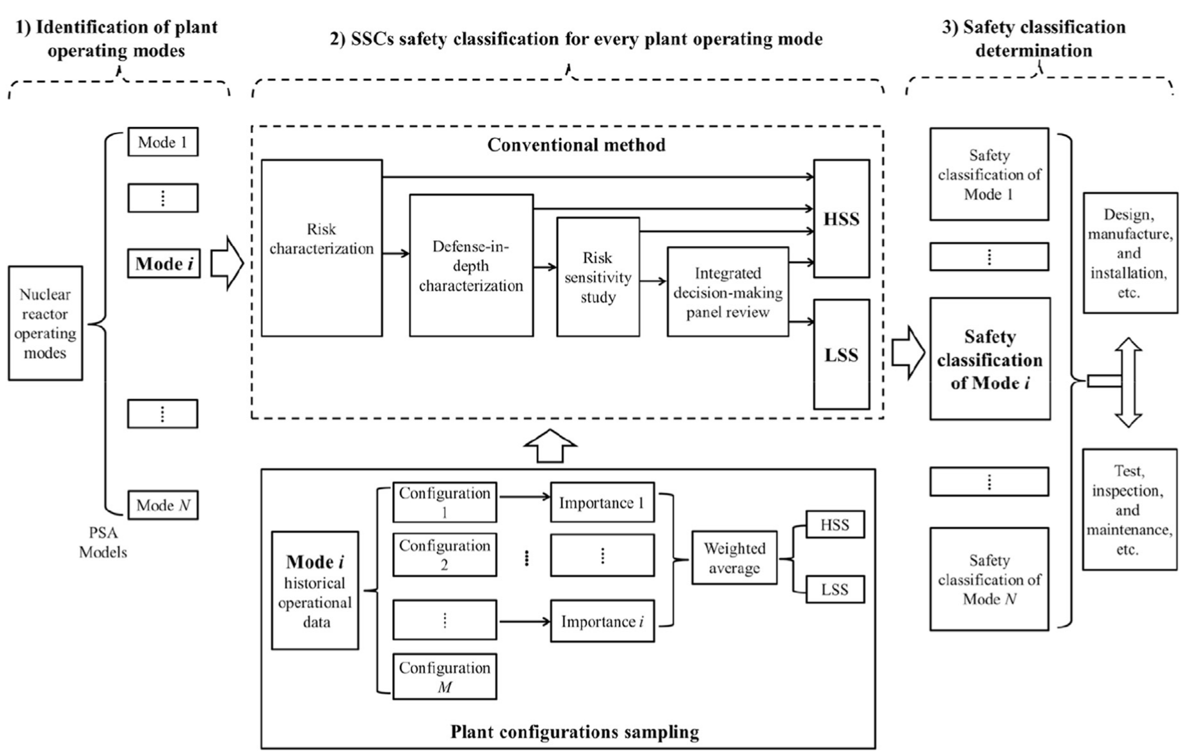

Fig. 1. Flow chart of the proposed safety classification method.

There are usually hundreds or thousands of plant configurations in a certain plant operating mode for different nuclear reactors. These configuration changes include the switching of running/standby trains, and components being out-of-service due to failure, periodic testing, or components restoring, etc. With these configurations reflected in the PSA model of a certain plant operating mode, the risk importances of SSCs can be assessed for every plant configuration.

3.3. Sampling of plant configurations

Generally, for different plant operating modes, the SSCs status will be different, the time duration of each plant configuration is usually not the same, and the risk importances of SSCs are also changed accordingly. Therefore, we propose that in the safety classification, the sampling of configurations needs to be performed according to the operating history of NPPs, and the time duration of configurations in one specific plant operating mode. The probability of a plant configuration being selected in the sampling are proportional to its time duration. Then the importance measures of SSCs can be calculated for every selected configuration, and finally the weighted average importance measures of SSCs for each plant operating mode can be calculated in proportion to the time durations of selected configurations. The safety classifications of SSCs are performed according to the weighted average importance measures.

Attention should be paid to the random sampling of plant configurations. The number of samples should be appropriate and suitable for estimating the overall characteristics of plant operating modes to perform the safety classification with less time consuming. For example, according to the typical number of potential configurations of plant operating modes, dozens to hundreds of configurations may be suitable for a plant operating mode of a nuclear reactor.

3.4. Risk importances

Different importance parameters illustrate the impacts of SSCs on an NPP's risk from different perspectives, such as corresponding physical or structural aspects. For the performing of independent safety classification to various plant operating modes, it is inevitable to assess the risk importances of SSCs for in-service and out-of-service configuration. Therefore, we have to choose suitable importance measures as one of the bases for safety classification.

Two importance measures are suitable for the calculation of the risk contribution of in-service SSCs. One is Risk achievement worth (RAW), which reflects the degree of risk increased if SSCs are out of service, especially SSCs that can prevent core damage or radioactive release. The other is Fussell-Vesely importance (FV), a structural risk importance, which describes the contribution of an SSC unavailability to the entire NPP risk when the unavailability changes to zero from its actual value.

In addition, we also selected Return to service worth (RTS) to measure the risk importance of the out-of-service SSCs when restored to operation normally, which reflect the reduction of an NPP risk. The higher the RTS value is, the more important an SSC is for the reduction of risk level, which means it should be restored more quickly. It is a suitable measure for the safety significance of SSCs in plant configurations. The calculation formulas of these importance measures are shown as follows.

$$\text{Risk Achievement Worth} \; : RAW = \frac{Q(x_i = 1)}{Q(top)} \tag{1}$$

$$\text{Fussell} - \text{Vesely} : FV = \frac{Q(top) - Q(x_i = 0)}{Q(top)} \tag{2}$$

$$\text{Return to service worth} : RTS = \frac{Q(x_i = 1) - Q(top)}{Q(x_i = 1)} \tag{3}$$

where, $Q(top)$ is the top event's frequency/probability of the PSA model (i.e. CDF or LERF/LRF); x_i represents the unavailability of component *i;* $Q(x_i = 0)$ is the top event's frequency or probability with the unavailability of component *i* set to zero, $Q(x_i = 1)$ is the top event's frequency or probability with the unavailability of component *i* set to 100%.

The calculation of component importance is not completely equivalent to the calculation of basic event importance in PSA. However, the method proposed in this contribution does not require specific risk indicators or criteria for the safety classification. Therefore, the calculation method of component importance is introduced here briefly. There are several commonly used component importance calculation methods, and the core idea is to use the sum of all basic events importances relevant to a component or the maximum one to represent the component importance. For example, in NEI 00–04, the sum of FV importance of all basic events relevant to a component is used as the component importance; For the RAW importance of a component, the maximum importance of basic events related to the component is taken [22].

In the proposed method, FV and RAW measures are calculated for in-service SSCs, and RTS will be calculated for SSCs that is out of service. Then SSCs are classified as HSS or LSS according to the importance measures criteria. If any one of the measures of an SSC exceeds its criteria, the SSC will be classified as a candidate of HSS, or if all these three measures are less than the corresponding criteria, the SSC will be classified as a candidate of LSS.

3.5. Example for importance measures and the classification criteria

Here, we take the FV and RAW importance measures and their criteria suggested by NEI 00–04 as an example, to explain how the SSCs safety classification is performed. The importance measure criteria are 0.005 for FV, and 2 for RAW [22]. For the basic PSA model, RTS can be derived by RAW importance. Therefore, the criteria value of 2 for RAW may be chosen as the basis of criteria derivation for RTS by equations (1) and (3) given above, and the derivation result is 0.5 for RTS. Thus, importance measure criteria can be summarized as: if $FV > 0.005$, or $RAW > 2$, or $RTS > 0.5$, and the corresponding SSC will be considered high safety significant, else it will be low safety significant. An example of the importance measures calculation method and classification criteria is shown in Table 1.

In Table 1, the formulas for components importance are as following. The weighted average risk importances of the component for plant operating mode 1 can be obtained in proportion to the time durations of plant configurations A, B, D, F, C and E.

$$T_1 = T_A + T_B + T_D + T_F; T_2 = T_C + T_E \tag{4}$$

$$FV_m = \frac{T_A}{T_1} FV_A + \frac{T_B}{T_1} FV_B + \frac{T_D}{T_1} FV_D + \frac{T_F}{T_1} FV_F \tag{5}$$

$$RAW_m = \frac{T_A}{T_1} RAW_A + \frac{T_B}{T_1} RAW_B + \frac{T_D}{T_1} RAW_D + \frac{T_F}{T_1} RAW_F \tag{6}$$

Table 1
Importance measures and classification criteria example for a component.

	Configuration sampling	FV	RAW	RTS	Duration time
Plant operating mode 1	Configuration A	FV_A	RAW_A	N/A	T_A
	Configuration B	FV_B	RAW_B	N/A	T_B
	Configuration C	N/A	N/A	RTS_C	T_C
	Configuration D	FV_D	RAW_D	N/A	T_D
	Configuration E	N/A	N/A	RTS_E	T_E
	Configuration F	FV_F	RAW_F	N/A	T_F
Average importance for operating mode		FV_m	RAW_m	RTS_m	–
Importance measure criteria		>0.005	>2	>0.5	–
Candidate safety significant?		Yes/No	Yes/No	Yes/No	–
At least one is safety significant?		Yes/No			–
Final safety significant?		Yes/No			–

Footnote: N/A = Not applicable.

$$RTS_m = \frac{T_C}{T_2} RTS_C + \frac{T_E}{T_2} RTS_E \tag{7}$$

where, T_A, T_B, T_D, T_F, T_C and T_E is the duration time of plant configuration A, B, D, F, C and E. T_1 is the total duration time of configurations that is selected for plant operating mode 1 when the component is in-service, and T_2 is the total time when the component is out-of-service. FV_m, RAW_m and RTS_m represent the component importances for plant operating mode 1, while FV_A and RAW_A represent the component importances for plant configuration A, RTS_C is the component importance for plant configuration C, and so forth.

4. Results and discussion

4.1. Case study and results

Taking a nuclear reactor in China as an example, the proposed method on safety classification of SSCs is verified. The plant operating modes are identified, and the proposed safety classification method is carried out for SSCs. Then, the correctness and effectiveness of the proposed method are illustrated by comparing its results with those of the conventional risk-informed safety classification method.

In this example, the operation states are divided into 9 plant operating modes, which are shown in Table 2, together with their corresponding configurations. Except for the normal cold shutdown for refueling mode and core totally unloaded mode, other 7 operating modes can be suitable for safety classification according to the corresponding PSA models. The PSA models involve about 20 event trees and 60 fault trees. The initiating events of this study include all important internal initiating events in the level 1 PSA.

In this contribution, safety classifications are performed to compare the two methods for 3 typical plant operating modes: operating mode one, operating mode four, and operating mode five, which are different in the characteristics of the operation and their PSA models. FV, RAW and RTS importance measures are calculated for 6 components to reflect the changes in SSCs importance, which are solenoid valve-1, circuit breaker-1, control separator, release valve-1, photoelectric limit switch, and limit signal switch. The results of safety classifications are shown in Table 3 for the conventional risk-informed method.

The results for safety classifications of the proposed method are shown in Table 4. The comparison of the results from these two methods is shown in Table 5, which include various situations of comparison between the two methods.

In the tables, only the safety classification of the control separator is completely consistent for these two methods. In other words, the safety classification of the other 5 components for the proposed method, is inconsistent with those of the conventional method for one or more operating mode. For example, although the safety classification of photoelectric limit switch in the proposed method is the same as that in the conventional method for operating mode one, its safety classifications are not the same for the operating mode four or five. This means that the proposed method can demonstrate the changes of SSCs importances with the plant operating mode, which is conducive to the timely adjustment of safety classification, to support more reasonable SSCs management including maintenance, testing and inspections. As for the design, manufacture, and installation, the safety classifications of SSCs are determined according to the highest level of the safety classification in all operating modes. This illustrates that, all of these 6 components could be classified as the HSS to ensure the safety of nuclear reactor in the design, manufacture, and installation activities.

In addition, for the release valve-1 and photoelectric limit switch in the operating mode four, and for the photoelectric limit switch and limit signal switch in the operating mode five, the components are HSS by the proposed method, higher than those of conventional method. For example, the RAW and RTS values of the photoelectric limit switch in the operating mode four are lower than their limits, but the FV value is greater than 0.005. This means

Table 2
Plant operating modes and SSCs configurations.

No.	Plant operating mode	Number of configurations
1	Operating mode one	~100
2	Operating mode two	~100
3	Operating mode three	~100
4	Operating mode four	~100
5	Operating mode five	~100
6	Normal cold shutdown	~100
7	Normal cold shutdown for maintenance	~100
8	Normal cold shutdown for refueling	N/A
9	Core totally unloaded	N/A

Footnote: N/A = Not applicable.

Table 3
Conventional risk-informed safety classification.

Components	FV	RAW	Safety significance
Solenoid valve-1	3.60E-2	1.00 E+0	HSS
Circuit breaker-1	2.25E-2	1.00 E+0	HSS
Control separator	1.98E-1	1.75 E+3	HSS
Release valve-1	1.17E-3	1.02 E+0	LSS
Photoelectric limit switch	4.86E-4	1.04 E+0	LSS
Limit signal switch	1.03E-5	1.04 E+0	LSS

Footnote: (a) HSS = High safety significant; (b) LSS = Low safety significant.

Table 4
Safety classification by proposed method.

Operating mode	Components	FV	RAW	RTS	Safety significance
Operating mode one	Solenoid valve-1	4.02E-3	1.00 E+0	1.80E-5	LSS
	Circuit breaker-1	2.52E-3	1.00 E+0	2.90E-5	LSS
	Control separator	4.19E-2	3.76 E+2	9.97E-1	HSS
	Release valve-1	1.31E-4	1.00 E+0	2.41E-3	LSS
	Photoelectric limit switch	5.46E-5	1.00 E+0	4.13E-3	LSS
	Limit signal switch	1.16E-5	1.00 E+0	4.17E-3	LSS
Operating mode four	Solenoid valve-1	6.03E-1	1.00 E+0	2.70E-3	HSS
	Circuit breaker-1	3.78E-1	1.00 E+0	4.34E-3	HSS
	Control separator	3.70E-1	3.31 E+3	1.00 E+0	HSS
	Release valve-1	1.97E-2	1.36 E+0	2.66E-1	HSS
	Photoelectric limit switch	8.19E-3	1.62 E+0	3.83E-1	HSS
	Limit signal switch	1.73E-3	1.63 E+0	3.86E-1	LSS
Operating mode five	Solenoid valve-1	9.84E-1	1.00 E+0	4.39E-3	HSS
	Circuit breaker-1	1.54E-2	1.00 E+0	1.78E-4	HSS
	Control separator	3.70E-1	3.32 E+3	1.00 E+0	HSS
	Release valve-1	8.02E-4	1.01 E+0	1.46E-2	LSS
	Photoelectric limit switch	1.34E-2	2.01 E+0	5.04E-1	HSS
	Limit signal switch	2.83E-3	2.02 E+0	5.06E-1	HSS

Footnote: (a) HSS = High safety significant; (b) LSS = Low safety significant.

Table 5
Comparison of results for the conventional method and proposed method.

Operating mode	Components	Results of conventional method	Results of proposed method	Comparison
Operating mode one	Solenoid valve-1	HSS	LSS	Lower
	Circuit breaker-1	HSS	LSS	Lower
	Control separator	HSS	HSS	Same
	Release valve-1	LSS	LSS	Same
	Photoelectric limit switch	LSS	LSS	Same
	Limit signal switch	LSS	LSS	Same
Operating mode four	Solenoid valve-1	HSS	HSS	Same
	Circuit breaker-1	HSS	HSS	Same
	Control separator	HSS	HSS	Same
	Release valve-1	LSS	HSS	Higher
	Photoelectric limit switch	LSS	HSS	Higher
	Limit signal switch	LSS	LSS	Same
Operating mode five	Solenoid valve-1	HSS	HSS	Same
	Circuit breaker-1	HSS	HSS	Same
	Control separator	HSS	HSS	Same
	Release valve-1	LSS	LSS	Same
	Photoelectric limit switch	LSS	HSS	Higher
	Limit signal switch	LSS	HSS	Higher

Footnote: (a) HSS = High safety significant; (b) LSS = Low safety significant.

the failure of this component will cause relatively high risk in the operating mode four and five, but it is classified as LSS by conventional method. Therefore, for some situations, the safety classification by conventional method may be not enough reasonable for the safety considerations of NPPs.

4.2. Discussion

Limited by the PSA models and data of the reactor, the above case study only demonstrates the level 1 PSA model with internal initiating events. However, it is easy to judge by descriptions that the proposed method can be effective for other initiating events, for example internal disasters (such as flooding, fire), and external disasters (such as seismic events), and the proposed method is also effective for level 2 PSA. For the importance criteria of RTS, a derived value is used here for demonstrating the process of the proposed method. However, it will be more suitable if it is obtained by statistics from operational data, especially from the performance of components and their previous safety classifications.

The operational data that safety classification referred to can be plant configurations records of an NPP under the last one or several same operating modes. In fact, if there is lack of operational data, a practical application of this method can be based on the average operational data of the same type NPPs, which is approximate to the conventional risk-informed safety classification method. In addition, if SSCs status of an NPP has been changed greatly, the average importance measures can also be combined with a correction, so that the safety classification results can reflect the conditions of NPPs more accurately. For example, the weighted average measures can be firstly calculated based on the operational data, and then be modified according to the current SSCs status by using a Bayesian formula or some average methods.

The proposed safety classification method is based on the operational data of plant operating modes and plant configurations, which can be a predictive safety classification for SSCs in same operating modes in the future. Compared with conventional risk-informed safety classification methods, the results of the proposed method could be closer to the actual SSCs status of an NPP. Thus, the safety classification of the proposed method can meet the safety management requirements of the NPP better, especially, improve the economic efficiencies while maintaining or even increasing the safety level.

5. Conclusions

To achieve a balance between the cost and benefit of safety classification, and ensure the safety of nuclear reactors at a cost as low as possible, we propose a new safety classification method based on the identification of plant operating modes and operational data of NPPs, which considers the characteristics of an NPP by performing safety classification for plant operating modes to improve the safety management. This method makes use of the SSCs status by plant configurations sampling, and calculates the weighted average risk importances by their time durations. The comparison to the conventional risk-informed safety classification of a nuclear reactor demonstrates the correctness and effectiveness of the proposed method. This method is important for making use of the specific operating history of an NPP and up-to-date status of SSCs to improve the economics of the NPP while ensuring its safety. In the future, more researches may focus on the application of the proposed method, and on the utilization and modification of the operational data to develop a predictive safety classification method of 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.

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References

[1] IAEA, Specific Safety Guide, No. SSG-30, Safety Classification of Structures, Systems and Components in Nuclear Power Plants, 2014.
[2] NRC, 10 CFR 50.69, Risk-informed Categorization and Treatment of Structures, Systems and Components for Nuclear Power Reactors, 2004.
[3] J. Zhao, J. Tong, X. He, Risk-informed SSC categorization method in nuclear power plant, J. Tsinghua Univ. (Sci. Technol.) 3 (2007).
[4] V. Patel, P. O'Regan, E. Sweat, In 2012 20th International Conference on Nuclear Engineering and the ASME 2012 Power Conference, ICONE 2012-POWER 2012, July 30, 2012 - August 3, 2012.1 Edn 195-205, American Society of Mechanical Engineers (ASME)), 2012.
[5] S. Vasavada, M. Reisi-Fard, 16th International Topical Meeting on Probabilistic Safety Assessment and Analysis, PSA 2019, April 28, 2019 - May 4, 2019. 419-425, American Nuclear Society), 2019.
[6] D.E. Holcomb, In 9th International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies, NPIC and HMIT 2015, February 22, 2015 - February 26, 2015. 1089-1098, American Nuclear Society), 2015.
[7] T.R. Kim, Safety classification of systems, structures, and components for pool-type research reactors, Nuclear Engineering and Technology 48 (4) (2016) 1015–1021.
[8] J. Wang, et al., in 14th Probabilistic Safety Assessment and Management, PSAM 2018, September 16, 2018 - September 21, 2018, in: Center for Risk and Reliability; Electric Power Research Institute; et al.; International Association for Probabilistic Safety Assessment and Management (IAPSAM); Lloyd's Register; The B.John Garrick Institute for the Risk Sciences, UCLA Engineering, (International Association for Probabilistic Safety Assessment and Management (IAPSAM)), 2018.
[9] J. Redd, K. Fleming, A. Afzali, In 14th Probabilistic Safety Assessment and Management, PSAM 2018, September 16, 2018 - September 21, 2018, in: Center for Risk and Reliability; Electric Power Research Institute; et al.; International Association for Probabilistic Safety Assessment and Management (IAPSAM); Lloyd's Register; The B.John Garrick Institute for the Risk Sciences, UCLA Engineering, (International Association for Probabilistic Safety Assessment and Management (IAPSAM)), 2018.
[10] J.S. Ha, P.H. Seong, A method for risk-informed safety significance categorization using the analytic hierarchy process and Bayesian belief networks, Reliab. Eng. Syst. Saf. 83 (2004) 1–15.
[11] K. Kim, D.I. Kang, J.E. Yang, On the use of the Balancing Method for calculating component RAW involving CCFs in SSC categorization, Reliab. Eng. Syst. Saf. 87 (2005) 233–242, https://doi.org/10.1016/j.ress.2004.04.017.
[12] J. Wang, et al., A new importance assessment method for risk-informed SSC categorization, Int. J. Energy Res. 42 (2018) 1779–1786, https://doi.org/10.1002/er.3985.
[13] S. Lyons, S. Vasavada, ASME 2018 International Mechanical Engineering Congress and Exposition, IMECE 2018, November 9, 2018 - November 15, 2018, American Society of Mechanical Engineers (ASME) (American Society of Mechanical Engineers (ASME)), 2018.
[14] M. Sun, et al., A new integrated SSCs safety classification method and a case study on CN HCCB TES, Ann. Nucl. Energy 145 (2020), 107594.
[15] K.U. Rahman, K. Jin, G. Heo, Risk-informed design of hybrid I&C architectures for research reactors, IEEE Trans. Nucl. Sci. 63 (2016) 351–358.
[16] J.E. Mateer, R.W. Jones, 13th IEEE Conference on Industrial Electronics and Applications, ICIEA 2018, May 31, 2018 - June 2, 2018. 2752-2757, Institute of Electrical and Electronics Engineers Inc., 2018.
[17] S. Martorell, et al., The use of maintenance indicators to evaluate the effects of maintenance programs on NPP performance and safety, Reliab. Eng. Syst. Saf. 65 (1999) 85–94, https://doi.org/10.1016/s0951-8320(98)00088-x.
[18] S.M. Hoseyni, F. Di Maio, E. Zio, Condition-based probabilistic safety assessment for maintenance decision making regarding a nuclear power plant steam generator undergoing multiple degradation mechanisms, Reliab. Eng. Syst. Saf. 191 (2019), https://doi.org/10.1016/j.ress.2019.106583.
[19] OECD NEA, NEA/CSNI/R(2004)20, Risk Monitors - the State of the Art in Their Development and Use at Nuclear Power Plants, 2004.
[20] IAEA, Specific Safety Guide, No. SSG-4, Development and Application of Level 2 Probabilistic Safety Assessment for Nuclear Power Plants, 2010.
[21] K. Jankala, M. Heliseva, in 11th International Probabilistic Safety Assessment and Management Conference and the Annual European Safety and Reliability Conference 2012, PSAM11 ESREL 2012, June 25, 2012 - June 29, 2012. 3623-3631, International Association for Probabilistic Safety Assessment and Management (IAPSAM)), 2012.
[22] NEI, NEI 00-04, 10 CFR 50.69 SSC Categorization Guideline, 2003.