Development of Risk Criteria for an Integrated Nuclear Safety and Security Potential Facility Risk Index (PFRI)

Keywords: nuclear security, nuclear safety, integration, risk assessment, modeling

Abstract

Risk assessment is used to determine the likelihood and consequences of harmful events occurring at a nuclear facility. Regardless of the cause of the event, the goals of nuclear safety and nuclear security are the same: to protect people, property, society, and the environment from the harmful effects of ionizing radiation. Although security issues are receiving more attention than in the past, the security regime of nuclear industry is still far less developed than the safety regime. For this reason, the Potential Facility Risk Index (PFRI) was developed to evaluate and quantify the security risks associated with nuclear facilities. The PFRI assesses the nuclear security risk of nuclear facilities by developing scenarios and carrying out quantitative assessments that include threat, vulnerability, and consequence analysis. Nevertheless, the goal of PFRI is to cover not only security, but the overall risk of nuclear facilities. In order to achieve this, traditional safety probabilistic risk assessment (PRA) techniques have been added to coordinate risk units of both the PFRI and other safety risk assessment methods. While assessment is important, valid indicators of safety and security risk must also be established for the decision-making process. To this end, the indicator should clearly present the risk index of the facility by comparing the evaluated risk with convincing risk criteria. Therefore, this study investigated and compared accident risk standards established by various industries to devise risk criteria for nuclear facilities. This allowed for the establishment of risk determination criteria and risk levels for PFRI, enabling integration of the overall safety and security risk of nuclear facilities. These criteria were also used to calculate PFRI examples based on available information regarding safety PRA results from other nuclear facilities. The development of an integrated risk index for nuclear facilities in this study is expected to aid in the rational and quantitative assessment of overall facility risk.

1. Introduction

Risk is a key concept in many fields, ranging from engineering and finance to public policy. It involves assessing the likelihood of an adverse event occurring and the severity of its consequences. In the field of the nuclear industry, risk assessment is critical to ensure the safety and security of people, property, society, and the environment from the harmful effects of ionizing radiation. To guide decision-making, industries that deal with hazardous materials or activities establish risk criteria, which reflect their risk tolerance and objectives.

Risk criteria are used to compare the evaluated risk of a facility or activity with the industry's acceptable risk levels. If the evaluated risk exceeds the acceptable levels, additional risk-reducing measures must be implemented to bring the risk within the acceptable range. A Potential Facility Risk Index (PFRI) was developed in 2020 to assess and quantify the security risks associated with nuclear facilities [1]. The PFRI integrates safety and security using probabilistic risk assessment (PRA) techniques, which involve scenario development and quantitative assessments that include threat, vulnerability, and consequence analysis.

Therefore, this study aims to investigate and compare the accident risk criteria established by various industries to devise risk criteria for nuclear facilities. The development of risk criteria for nuclear facilities is expected to aid in the rational and quantitative assessment of overall facility risk and to provide decision-makers with a reliable basis for evaluating the adequacy of risk-reducing measures.

2. Risk Criteria

2.1 Risk Matrix

The risk matrix is a popular risk evaluation tool that is widely used in various fields such as engineering and software. This method does not have a fixed form, and its specific form and content can vary depending on the decision-makers involved [2]. Essentially, a risk matrix is a grading function that helps to evaluate risks and their potential impacts.

A risk matrix can be described in the form of a grading function as shown in the equation (1) [3]:

$$R = f(p,c) = [R_{ij}], when \begin{cases} p_i \leq p < p_{i+1} \\ c_i \leq c < c_{i+1} \end{cases} \quad (1)$$

Table 1 exhibits a typical risk matrix in the form of table. A risk matrix is a table with three key components: the category of consequence and probability, the number of risk ratings, and the mapping of a risk rating with the combination of a consequence and a probability. To use a risk matrix, we categorize consequence and probability, determine the number of risk ratings (Low, Medium, High), and understand the mapping of a risk rating with the combination of consequence and probability. Risk factors are typically described using discrete categories or ratings with linguistic definitions and a definite order on a five-point scale. For instance, a particular risk factor might be rated as very low, low, moderate, high, or very high as shown in Table 2 [3].

Table 1. A Typical Risk Matrix

Probability level	Consequence level				
	1	2	3	4	5
1	Negligible	Negligible	Receivability	Receivability	Reasonable Control
2	Negligible	Negligible	Receivability	Reasonable control	Strict control
3	Receivability	Receivability	Reasonable control	Strict control	Unacceptable
4	Receivability	Reasonable control	Strict control	Unacceptable	Unacceptable
5	Reasonable control	Strict control	Unacceptable	Unacceptable	Unacceptable

Table 2. Description of three different types of risk matrices [3]

Risk matrix type	Category 1	Category 2	Category 3	Category 4	Category 5
Qualitative risk matrix	Very low	Low	Medium	High	Very High
Cox risk matrix	[0, 20%]	[20, 40%]	[40, 60%]	[60, 80%]	[80, 100%]
SUA risk matrix	[0, 20%]	[20, 40%]	[40, 60%]	[60, 80%]	[80, 100%]

2.2 Risk Criteria in Industry

Risk criteria vary across different industries and fields due to the unique characteristics and potential hazards present in each setting. For example, the risk criteria for a chemical manufacturing plant will be different from those for a nuclear power plant or a construction site. As a result, it is essential to have specific risk criteria tailored to each industry to ensure effective risk management. For instance, the Australian New South Wales Department of Planning has developed an integrated approach to assess hazardous developments [4]. Table 3 shows their guidelines outlining individual fatality risk criteria to evaluate the safety of proposed development locations. Similarly, other industries have established their own risk criteria to address specific hazards and ensure the safety of workers, consumers, and the general public.

Table 3. New South Wales Individual Facility Risk Criteria [4]

Land use	Suggested criteria [fatalities per year]
Hospitals, schools, child-care facilities, old age housing	5×10^{-7}
Residential, hotels, motels, tourist resorts	1×10^{-6}
Commercial developments including retail centers, offices and entertainment centers	5×10^{-6}
Sporting complexes and active open space	1×10^{-5}
Industrial	5×10^{-5}

Furthermore, the Federal Railroad Administration (FRA) funded a research study that conducted a literature review to compare risk criteria used in different government and industry fields, as part of an effort to establish standardized risk criteria and assessment methods for stationary facilities and hazardous material transportation via rail, road, or marine vessels. The study reviewed various individual risk criteria and compared them to inform the development of objective and consistent risk acceptability measures as shown in Figure 1 [5].

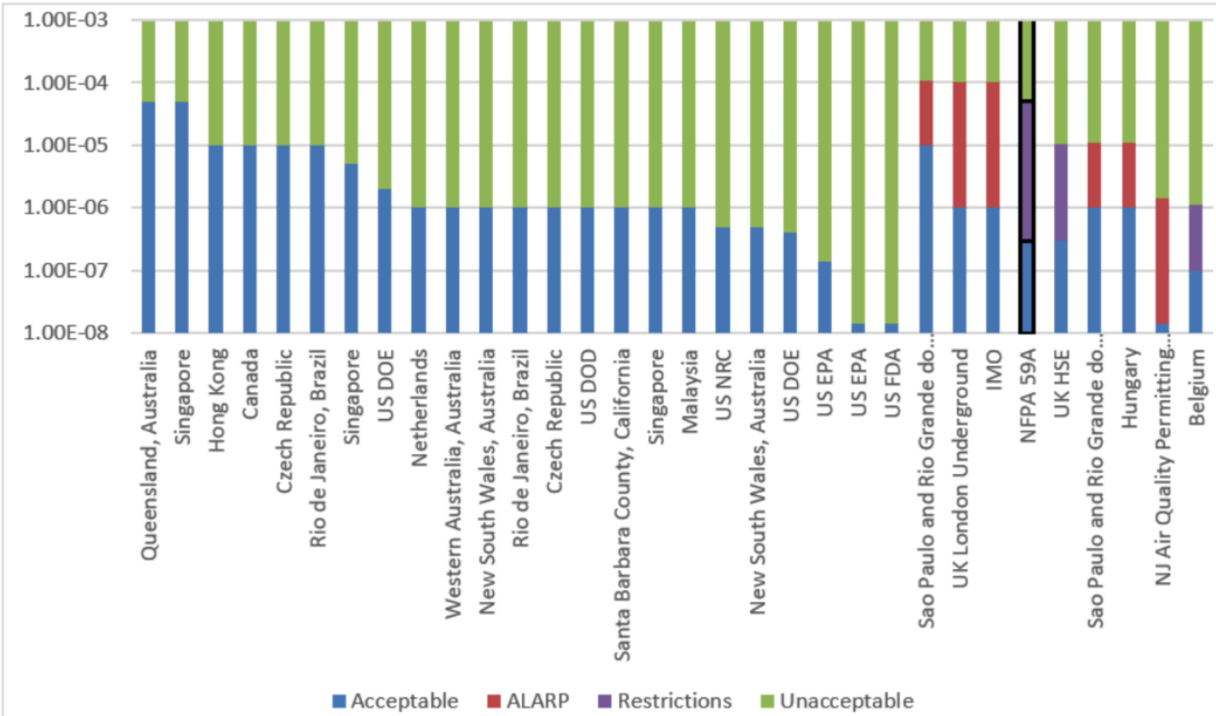

Figure 1. Individual Risk Criteria Used by Governments and Regulatory Bodies

In addition, the International Atomic Energy Agency (IAEA) has published guidelines that offer practical guidance and a reference framework for conducting integrated health and environmental risk assessment studies, as well as developing and implementing coordinated health and environmental management strategies for large industrial areas. This includes areas that accommodate energy-producing facilities, as presented in Table 5 [6]. These guidelines serve as a valuable resource for organizations looking to improve their risk management practices and ensure the health and safety of their workers and the environment.

Table 4. Overview Summary of Risk Criteria [6]

Year	Advisory Body/Government	Risk Level per year
1976	Advisory Committee on Major Hazards	1×10^{-4}
1976	Royal Commission on Environmental Pollution	$< 1\times10^{-6}$ – Individual fatality risk
1981	HSE Canvey Study	20×10^{-6} to 400×10^{-6} – Risk acceptable
1983	Royal Society Study Group	$< 1\times10^{-6}$ – Risk acceptable
1989	HSE, UK	$< 1\times10^{-6}$ – Risk acceptable
1989	Dutch National Environmental Policy Plan	1×10^{-6} – Max permissible 1×10^{-8} – Negligible
1990	Department of Planning NSW, Australia	$<1\times10^{-6}$ – Risk acceptable

Although different fields may have varying risk criteria, it is generally acceptable for the risk of death to each individual to be below 1 in a million per year [7].

2.3 Risk criteria in Nuclear Industry

The nuclear industry primarily uses PRA as a tool for risk assessment, with the focus on Core Damage Frequency (CDF) and Large Early Release Frequency (LERF) as regulatory risk criteria resulting from the level 1 and level 2 PRAs, respectively. However, these criteria only address systemic accident probability and fail to encompass the full scope of a facility's risk and consequences. Following the TMI-2 accident, the Quantitative Health Objectives (QHOs) played a crucial role in indicating the level of risk deemed significant by the Commission, although they were not requirements. They were intended to communicate to reactor designers, operators, and the public the safety level that regulations aimed to achieve. To evaluate the effectiveness of the QHOs in addressing important plant safety issues, one may examine the QHOs calculated in the level 3 PRAs [8].

The QHOs provide quantitative guidelines for the level of risk considered as no significant risk to the public from nuclear facilities. They were developed based on the risk of radiation exposure to the public from accidental releases of radioactivity that could lead to either a prompt fatality or an induced cancer fatality. The first QHO stipulates that the risk of prompt fatalities from reactor accidents should not exceed one-tenth of one percent of the sum of prompt fatality risks from other accidents that the general population may be exposed to. The second QHO states that the risk of cancer fatalities resulting from nuclear power plant operation should not exceed one-tenth of one percent of the sum of cancer fatality risks from all other causes.

The Nuclear Regulatory Commission (NRC) suggests guidelines for the QHO in the 10 CFR Part 53: risk-informed, technology-inclusive regulatory framework for commercial nuclear plants [9]. The NRC recommends maintaining the overall cumulative plant risk from licensing basis events other than design basis accidents analyzed such that the calculated risk to an average individual in the vicinity of the commercial nuclear plant of prompt fatalities remains below five in 10 million years and the calculated risk to the population in the area near a commercial nuclear plant of cancer fatalities remains below two in one million years.

3. Risk Criteria for PFRI

The PFRI was developed to comprehensively assess the risks associated with nuclear facilities, considering both safety and security. To accomplish this, specific risk criteria were developed for nuclear facilities by reviewing risk criteria from various industries. Meanwhile, it would be beneficial to establish general criteria that define the ‘intolerable’ and ‘negligible’ levels of risk considering inherent uncertainties and variations between situations [7]. Thus, we determined an ‘acceptable’ risk level of 10^{-6} per years, which is more conservative than the NRC’s criteria but widely accepted. Conversely, a risk level of 10^{-4} per year is deemed ‘unacceptable.’

The PFRI score categories into five based on the general risk matrix categorization rule. Specifically, a risk level that is considered ‘acceptable’ results in a PFRI score of 2, while a risk over 10^{-4} classified as ‘unacceptable’ was assigned a PFRI score of 8. To establish a clear correlation between PFRI and risk assessment outcomes, a linear regression analysis using a logarithmic scale was conducted, which is necessary due to the vast range of values typically encountered in risk assessments. The resulting equation (2) enables the risk level to be categorized into ten levels, providing a more nuanced understanding of the potential risks associated with nuclear facilities.

$$PFRI = 3\log(Risk) + 20 \qquad (2)$$

Table 5. Risk Levels of PFRI

Risk level	Acceptable		Low risk		Mid risk		High risk		Unacceptable	
PFRI	1	2	3	4	5	6	7	8	9	10
Risk	$< 1.00\times10^{-6}$		$< 4.64\times10^{-6}$		$< 2.15\times10^{-5}$		$< 1.00\times10^{-4}$		$> 1.00\times10^{-4}$	

4. Conclusion

The PFRI was developed to comprehensively assess the risks associated with nuclear facilities, considering both safety and security. To accomplish this, specific risk criteria were developed for nuclear facilities by reviewing risk criteria from various industries. These criteria enable the determination of acceptable and unacceptable risk levels. The PFRI result shows the overall risk score, which has been categorized into five levels to provide a clear understanding of the potential risks associated with nuclear facilities. Additionally, a linear regression analysis was conducted using a logarithmic scale to establish a clear correlation between the PFRI and risk assessment outcomes. The development of an integrated risk index for nuclear facilities in this study is expected to aid in the rational and quantitative assessment of overall facility risk.

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