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Research on Safety Evaluation of Nuclear Power Plant Based on Entropy Weight Method

ZHOU Shijie[a],*

[a]School of Economics and Management, Southwest University of Science and Technology, Mianyang, China.
*Corresponding author.

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Abstract

Since the 18th National Congress of the Communist Party of China, China's nuclear security has entered a new era of safety and efficiency. At the same time, the first white paper "China's nuclear security" emphasizes the need to deal with various nuclear security challenges and maintain nuclear security. In this paper, an index system of nuclear power plant safety assessment is constructed, which includes three first-class indexes: internal risk assessment, external risk assessment and human risk assessment of nuclear power plant. Each index is weighted and evaluated by entropy weight method, and the safety of all nuclear power plants in operation during 2013-2018 in China is researched vertically as well as Ling'ao, Yangjiang, Ningde and Fangchenggang nuclear power plant is researched horizontally.

Key words: Nuclear power plant; Safety evaluation; Entropy weight method

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1. INTRODUCTION

Compared with wind power, photovoltaic, hydropower and other renewable energy, nuclear energy, as a safe and reliable new energy, has the advantages of long-term and stable power generation (Wang, 1987). In 1942, Fermi led dozens of scientists to build the world's first reactor, Chicago I, at the University of Chicago in the United States, which opened the era of nuclear energy in the world. In 1957, the establishment of the International Atomic Energy Agency (IAEA) reflected the international community's attention to nuclear safety. In 1994, the first 40 countries signed the International Convention on nuclear safety, and new progress has been made in international nuclear safety activities. In September 2019, the State Council of China published the first white paper on China's nuclear security, stressing that we should not only maintain our own nuclear security, but also take a path of nuclear security with Chinese characteristics, and earnestly fulfill international obligations on nuclear security.

As one of the most important energy sources in the world, the rapid development of nuclear energy is accompanied by risks and challenges in safety. Since the Fukushima nuclear accident, nuclear power plant safety has become a very important political and social issue. Many scholars have carried out relevant research on nuclear power plant safety from multiple perspectives. As early as the 1980s, some scholars defined the safety standard of nuclear reactor risk from two aspects of personal risk and social risk (Solomon, Nelson, Chiesa, et al, 2010). Makiko tazaki (2012) optimized the multilateral nuclear approach (MNA) to provide recommendations for the SNA roadmap and evaluation criteria (Tazaki & Kuno, 2012). Wu (2013) conducted evaluation and Research on the location of inland nuclear power plants in China (Wu, Tan, Xu, et al, 2013), Chen Lu (2014) constructed the safety operation performance index system of nuclear power plants from four aspects of reactor safety, radiation safety, emergency preparation and power plant security according to the nuclear safety regulations (Chen, Zhang, & Zhang, 2014), Barzehkar (2016) proposed that the site selection of new nuclear power plants should consider the evaluation of environmental carrying capacity, so as to improve the safety and sustainable development

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of nuclear power plants (Barzehkar, Dinan, & Salemi, 2016), Gallucci (2017) evaluated the temperature of cable failure in case of fire (Gallucci, 2017), Sung yeop (2018) innovated the number of units and evaluation level when using PSA method (Kim, et al, 2018), Feng Jian, Shanshan Ding, et al. (2018) analyzed all the loss of offsite power (Loop) events in China's nuclear power plants from 1993 to 2017, summarized the common characteristics of the loop events, found the shortcomings and defects, and then put forward suggestions to improve the reliability of power supply (Jiao, et al, 2018). Ye Yan (2018) built a three-level evaluation system consisting of knowledge and experience, internal and external trust, and perception mode. He pointed out that China should strengthen the popularization of nuclear science and security, so as to enhance the confidence of public security, and further develop more detailed and specific nuclear security measures to promote the development of nuclear security (Yan & Lu, 2018). Mi-Yeon Kang and Yeheun Jeong (2019) proposed a comprehensive configuration management (CM) framework for nuclear power plant (NPP) by comparing the concepts of seven different industries that actively use configuration management, and promoted the practical application of CM (Kang, Jeong, & Jung, 2019). Entropy was originally a concept in the field of thermodynamics. Shannon (1948) first proposed the concept of information entropy and applied it to the study of information theory (Shannon & Weaver, 1949). The application of entropy weight method mainly focuses on assessment research, such as risk assessment of flood (Xu, Ma, Lian, Xu, & Chaima, 2018) and fire (Liu, Zhao, Weng, et al., 2017), as well as assessment research in other fields. In the field of safety assessment of nuclear power plants, the safety assessment and verification of nuclear power plants (HAD102) issued by the State Nuclear Safety Administration of China specifies that the method of combining determinism and probability theory should be used for safety analysis of nuclear power plants. The international mainstream PSA method is to study all kinds of possible accident scenarios and make a comprehensive analysis of all kinds of potential threats in the whole process of nuclear power construction projects. Based on the operation events of China's nuclear power plants in the past five years, this paper evaluates the safety of all nuclear power plants in China in this period, while entropy weight method reduces the impact of human factors, retains the effectiveness of objective data, and makes the evaluation results more reasonable (Zhang,Zhang, & Chi, 2010, pp.34-42), so it guarantees the objective evaluation of the safety of nuclear power plants.

In this paper, the safety evaluation index system of nuclear power plant is constructed, and entropy weight method is used to weight each index. On this basis, the vertical evaluation research on the safety of all nuclear power plants in operation in China during 2013-2018 is carried out. At the same time, the horizontal evaluation research on the safety of Ling'ao, Yangjiang, Ningde and Fangchenggang nuclear power plant is carried out. Finally, according to the results of the cross data, the relevant conclusions are drawn.

2. INDEX SYSTEM CONSTRUCTION

In the process of selecting and determining indicators, special attention should be paid to the consistency of the whole range. On the premise of ensuring the operability and easy access of quantifiable data, the horizontal and vertical comparability of data should also be ensured. The selected indexes should be representative and complete, excluding secondary and less influential indexes and reflecting the overall safety of nuclear power plant, so as to make the purpose and conclusion of evaluation more targeted. The safety evaluation indexes of nuclear power plants comprehensively consider the occurrence factors of their own operation events, the impact of nuclear power plants on the environment and the impact on people. There is a specific logical relationship between the safety evaluation indexes of nuclear power plants, reflecting the main characteristics and current situation of ecological and social subsystems from different aspects.

P.C.cacciabue (Cacciabue, 1988, pp.417-431) has considered the influence of human factors in the safety evaluation of nuclear power plants. The regulations on supervision and administration of civil nuclear safety equipment issued by the State Council of China fully explains the importance of safety factors of nuclear equipment (State Council of China,2007). Li Qin (Li,2004) put forward the scientific system of safety and disaster reduction and the comprehensive management mode of civil nuclear safety OSHE, and explained the importance of the management mechanism. Zhao Junfang (Zhao, et al, 2018, pp.693-701) and others used the monitoring data of global aerosol network to quantitatively evaluate the direct radiation effect of aerosols at three typical high pollution stations under the condition of clear sky for many years, indicating that aerosols have the greatest impact on the surface direct radiation. At the same time, Chen Jingjuan (Chen, et al, 2018, pp.67-69) pointed out that in the operation process of nuclear power plants, C-14 is an important nuclide in the global collective dose contribution nuclide. Ma Pengxun (Ma,et al,2014, pp.124-128) put forward some targeted measures for solid radioactive waste management through the whole process tracking management of Sanmen Nuclear Power Plant. Chen Xiaoqiu (Chen, Yang,& Jiao,2011, pp.1-6) analyzed and evaluated the public dose caused by the operation of nuclear power plants in mainland China based on the test data of nuclear power plants over the years, and obtained the corresponding data of the annual average individual effective dose of the public (adults) and the average individual effective dose caused by the annual

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average release of radioactive effluents from Daya Bay and Qinshan nuclear power plants. The construction of nuclear power plant safety evaluation index system and the indicators are shown in Table 1.

Table 1
Nuclear Power Plant Safety Evaluation Index System

Goal	Level I indicator	Level II indicator	Indicator type	Indicator standards	Indicator units	Description of the indicator
Nuclear power plant safety risk evaluation A	Internal risk evaluation of nuclear power plants A_1	Human factor A_{11}	Quantitative	0	Item	Number of incidents arising from related human issues
		Management factor A_{12}	Quantitative	0	Item	Number of events arising from management link issues
		Device factor A_{13}	Quantitative	0	Item	Number of incidents arising from equipment operation and maintenance issues
		Integrated factor A_{14}	Quantitative	0	Item	Number of events arising from interaction and action between the links
	External risk Evaluation for nuclear power plants A_2	Radioactive gas emissions from nuclear power plants – aerosol A_{21}	Quantitative	Annual limit of 3.8	GBq	Annual emission safe limit of 3.8GBq since the end of 2012
		Radioactive liquid emissions from nuclear power plants - C-14 A_{22}	Quantitative	Annual limit of 300	GBq	Annual emission safe limit of 300GBq since the end of 2012
		Radioactive solid emissions from nuclear power plants A_{23}	Quantitative	Design standards	%	Percentage of design value
	Nuclear power plant to human risk evaluation A_3	Normalized collective effective dose A_{31}	Quantitative		man'mSv/ Gwh	Dose per billion watt hours of radiation to a group
		Annual effective dose per capita A_{32}	Quantitative	20	mSv	Basic standards for ionizing radiation protection and radiation safety

Note: The indicator standard value extraction is derived from the annual report of the National Nuclear Safety Administration of China 2013-2018 and from the official website of the relevant nuclear power plant operator.

The first level indicators "internal risk assessment of nuclear power plants" and "human risk assessment of nuclear power plants" are based on the classification of the causes of the operation events in the annual report of the nuclear safety administration. The second level indicators "comprehensive factors" are composed of human factors / management and equipment / management in the classification of the causes of the operation time in the annual report of the national nuclear safety administration. All secondary indicators under the primary indicator "external risk assessment of nuclear power plant" are directly extracted from the official website of the nuclear power plant operation company. Therefore, based on the indicators extracted from the annual report of the National Nuclear Safety Administration of China and the official website, the problem of correlation collinearity between indicators is no longer considered.

3. EVALUATION MODEL CONSTRUCTION

Using the annual report of China National Nuclear Safety Administration and the indexes published on the official website to build the safety evaluation model of nuclear power plants, the relative weight of each index in the index system is determined by entropy weight method. At the same time, on this basis, the safety of nuclear power plants is evaluated and researched, including the longitudinal research on the safety of all nuclear power plants in operation in China during 2013-2018, and the horizontal research on the safety of Ling'ao, Yangjiang, Ningde and Fangchenggang nuclear power plant.

Step1: Set the index value of row i and column j of m evaluation objects and n evaluation indexes as $X_{ij,}$ and get the evaluation index matrix $X = (x_{ij})_{m\times n}$

Step2: Standardize the evaluation indexes.

The indexes with large value and excellent value are as follows:

$$y_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max_j(x_{ij}) - \min(x_{ij})} \quad (1)$$

The indexes with smaller value are as follows:

$$y_{ij} = \frac{\max_j(x_{ij}) - x_{ij}}{\max_j(x_{ij}) - \min_j(x_{ij})} \quad (2)$$

Step3: Find the information entropy of each index.

$$E_n = -\ln(m)^{-1}\sum_{i=1}^{m} p_{ij} \ln p_{ij} \quad (3)$$

And

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$$p_{ij} = y_{ij} \Big/ \sum_{i=1}^{m} y_{ij}$$ If Pij = 0 , then define ln(Pij) = 0

Step4: Determine the weight of each index, and calculate the weight of each index through information entropy.

$$w_j = \frac{1 - En_j}{n - \sum_{j=1}^{n} En_j} \quad (4)$$

Step5: Set up the safety evaluation factor set and evaluation object of nuclear power plant.

Step6: The membership matrix of nuclear power plant safety assessment is constructed.

The membership matrix of nuclear power plant safety assessment

$$R_i = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ r_{i1} & r_{i2} & \cdots & r_{im} \end{bmatrix}$$

r_{im} is the total data participating in the evaluation. When evaluating the i year indicators, the evaluation indicator year is the data of P_m.

Step7: The final evaluation result is obtained by comprehensive evaluation.

According to the previous R, the weight set W is used for composite operation.

According to

P = W * R (5)

Get matrix

$$P = \begin{bmatrix} \rho_1 & \rho_2 & \rho_3 & \cdots & \rho_{1j} \\ \rho_2 & \rho_2 & \rho_3 & \cdots & \rho_{2j} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ \rho_{i1} & \rho_{i2} & \rho_{i3} & \cdots & \rho_{ij} \end{bmatrix}$$

And

$$P_i = \sum_{i=1}^{n} \rho_{i1} \quad P = \begin{bmatrix} P_1 & P_2 & \cdots & P_i \end{bmatrix},$$

4. EMPIRICAL RESEARCH

4.1 Determine the Relative Weight of Safety Evaluation Indexes of Nuclear Power Plant

The data involved in this paper are from 2013-2018 annual report of China National Nuclear Safety Administration and related official website of nuclear power plant, and the specific data is shown in Table 2.

Table 2
Raw Data Table for Nuclear Power Plant Safety Evaluation Indicators 2013-2018

Goal	Level I Indicator	Level II Indicator	2013	2014	2015	2016	2017	2018
A	A_1	A_{11}	15.000000	16.000000	23.000000	38.000000	13.000000	15.000000
		A_{12}	0.000000	0.000000	1.000000	6.000000	3.000000	2.000000
		A_{13}	16.000000	21.000000	17.000000	17.000000	19.000000	22.000000
		A_{14}	0	0	0	9.000000	3.000000	1.000000
	A_2	A_{21}	0.004560	0.003420	0.003040	0.003800	0.003914	0.003990
		A_{22}	28.860000	18.540000	12.810000	20.220000	13.830000	14.493000
		A_{23}	12.800000	22.370000	17.030000	16.200000	16.090000	14.210000
	A_3	A_{31}	0.103814	0.053756	0.231594	0.216389	0.017220	0.062240
		A_{32}	0.398714	0.246727	0.060797	0.057961	0.206128	0.207050

Note: The index standard value comes from 2013-2018 annual report of China National Nuclear Safety Administration and the official website of relevant nuclear power plant operation companies. The smaller the index value is, the higher the safety of nuclear power plant under the evaluation index is.

According to formula (1) - (4), the relative weight of safety evaluation index of nuclear power plant is calculated. Among the first level indexes, the relative weight of internal risk index of nuclear power plant is the largest (0.568352), among the second level indexes, the relative weight of comprehensive factor index is the largest (0.214208), and the relative weight of radioactive gas emission index of nuclear power plant is the smallest (0.057226). The specific results are shown in Table 3.

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Table 3
List of the Relative Weights of the Indicators of the Nuclear Power Plant Safety Evaluation Index System

Goal	Weight	Level I indicator	Weight	Level II indicator	Weight
Nuclear power plant safety risk evaluation W	1	Internal risk evaluation of nuclear power plants W_1	0.568352	Human factor $_{W1}1$	0.141767
				Management factor W_{12}	0.126817
				Device factor W_{13}	0.08556
				Integrated factor W_{14}	0.214208
		External risk evaluation for nuclear power plants W_2	0.248691	Radioactive gas emissions from nuclear power plants – aerosol W_{21}	0.057226
				Radioactive liquid emissions from nuclear power plants - C-14 W_{22}	0.114070
				Radioactive solid emissions from nuclear power plants W_{23}	0.077395
		Nuclear power plant to human risk evaluation W 3	0.182958	Normalized collective effective dose W_{31}	0.085873
				Annual effective dose per capita W_{32}	0.097085

Note: The smaller the index value is, the higher the safety of nuclear power plant under the evaluation index is.

4.2 Research on Safety Assessment of Nuclear Power Plant

Step1:The safety evaluation object and weight set of nuclear power plant are constructed.

The safety evaluation object of nuclear power plant is $P = [P_1 \quad P_2 \quad P_3 \quad P_4 \quad P_5 \quad P_6]$, in which P_1 is to evaluate the safety of nuclear power plant in 2013 and P_6 is to evaluate the safety of nuclear power plant in 2018.

According to the relative weight list of nuclear power plant safety evaluation indexes, the weight sets of evaluation indexes at all levels are constructed as follows.

$$W = [W_1 \quad W_2 \quad W_3] = [0.568352 \quad 0.248691 \quad 0.182958]$$

$$W_1 = [W_{11} \quad W_{12} \quad W_{13} \quad W_{14}] = [0.141767 \quad 0.126817 \quad 0.085560 \quad 0.214208]$$

$$W_2 = [W_{21} \quad W_{22} \quad W_{23}] = [0.057226 \quad 0.114070 \quad 0.077395]$$

$$W_3 = [W_{31} \quad W_{32}] = [0.085873 \quad 0.097085]$$

Step2:A single factor membership matrix is constructed.

According to table 2, the original matrix B of nuclear power plant safety assessment is constructed.

$$B = \begin{bmatrix} 5 & 6 & 3 & 8 & 3 & 5 \\ 0 & 0 & 1 & 6 & 3 & 2 \\ 6 & 2 & 7 & 7 & 9 & 2 \\ 0 & 0 & 0 & 9 & 3 & 1 \\ 0.004560 & 0.003420 & 0.003040 & 0.00380 & 0.003914 & 0.003990 \\ 8.80000 & 8.40000 & 2.80000 & 0.20000 & 3.80000 & 1.493000 \\ 2.800000 & 2.30000 & 7.00000 & 6.00000 & 6.90000 & 1.20000 \\ 0.103814 & 0.053756 & 0.231594 & 0.216389 & 0.017220 & 0.06224 \\ 0.398714 & 0.246727 & 0.060797 & 0.027961 & 0.206128 & 0.20705 \end{bmatrix}$$

The membership matrix R is obtained by normalizing the original matrix B of nuclear power plant safety evaluation.

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$$R = \begin{bmatrix} 0.125000 & 0.133333 & 0.191667 & 0.316667 & 0.108333 & 0.125000 \\ 0 & 0 & 0.083333 & 0.500000 & 0.250000 & 0.166667 \\ 0.142857 & 0.187500 & 0.151789 & 0.151786 & 0.169643 & 0.196429 \\ 0 & 0 & 0 & 0.692308 & 0.230769 & 0.076923 \\ 0.200669 & 0.150502 & 0.133779 & 0.167224 & 0.172241 & 0.175585 \\ 0.265372 & 0.704780 & 0.117790 & 0.185926 & 0.127169 & 0.133265 \\ 0.129686 & 0.226646 & 0.172543 & 0.164134 & 0.163019 & 0.143972 \\ 0.151550 & 0.078474 & 0.338087 & 0.315890 & 0.025138 & 0.090860 \\ 0.347500 & 0.215036 & 0.052988 & 0.024369 & 0.179652 & 0.180455 \end{bmatrix}$$

Step3: The final evaluation result is obtained by comprehensive evaluation.

According to formula (5), the specific evaluation results of nuclear power plant safety evaluation index objects are obtained, as shown in Table 4.

Table 4
Evaluation of Nuclear Power Plant Safety Evaluation Indicators

Goal	Level I Indicator	Level II Indicator	P_1	P_2	P_3	P_4	P_5	P_6
A	A_1	A_{11}	0.017721	0.018902	0.027172	0.039583	0.015358	0.017721
		A_{12}	0.000000	0.000000	0.010568	0.063409	0.031704	0.021136
		A_{13}	0.012223	0.016043	0.012987	0.012987	0.014515	0.016806
		A_{14}	0.000000	0.000000	0.000000	0.148298	0.049433	0.016478
	A_2	A_{21}	0.011483	0.008613	0.007656	0.009570	0.009857	0.010048
		A_{22}	0.030271	0.019446	0.013436	0.021209	0.014506	0.015202
		A_{23}	0.010037	0.017541	0.013354	0.012703	0.012617	0.011143
	A_3	A_{31}	0.013014	0.006739	0.029033	0.027126	0.002159	0.007802
		A_{32}	0.033737	0.020877	0.005144	0.002366	0.017441	0.017519

Note: The smaller the indicator value, the higher the safety of the nuclear power plant under the evaluation index.

According to

$$P_i = \sum_{i=1}^{n} \rho_{i1}, \quad P = \begin{bmatrix} P_1 & P_2 & P_3 & P_4 & P_5 & P_6 \end{bmatrix}$$

can be obtained.
P1=0.128486 P2=0.108161 P3=0.119350
P4=0.337250 P5=0.167589 P6=0.133855

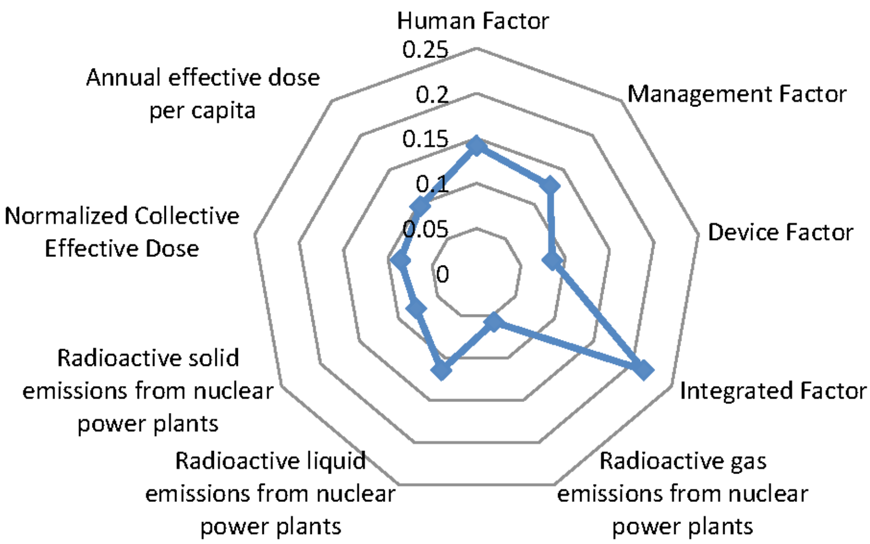

Figure 1
Nuclear Power Plant Safety Evaluation Index System Relative Weight Index Radar

The results show that from 2013 to 2018, the safety level of nuclear power plants in China is on the rise. Although the safety of nuclear power plants decreased in 2014, it did not affect the overall trend. Compared with

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other years, in 2016, due to the sharp increase of operation events in Ningde nuclear power plant (7 operation events in 2015 and 21 operation events in 2016) and the largest relative weight of internal risk assessment level I indicators of nuclear power plant, the value of safety assessment indicators of nuclear power plant in that year increased significantly. However, in the following years, in the statistics of operation events in Ningde nuclear power plant, 7 operation events occurred in 2017 and 2 operation events in 2018, so the safety trend of nuclear power plant is fluctuating and rising.

A unified safety evaluation index system of nuclear power plant is adopted to ensure the horizontal and vertical comparability principle of the index safety evaluation of nuclear power plant. Ling'ao nuclear power plant is a large-scale commercial nuclear power plant built by China Guangdong group in accordance with the policy of "nuclear maintenance and rolling development" determined by the State Council of China. It is a successful practice of this policy. At the same time, it lays the foundation for the realization of its own brand million kilowatt nuclear power technology route - CPR1000, and has a strong representation of nuclear power plants. Yangjiang nuclear power plant is the second nuclear power base in Guangdong Province, which adopts the independent brand CPR1000 and its improved technology. It is also a successful practice under the policy of "actively promoting nuclear power construction" in China. Fangchenggang nuclear power plant is a commercial nuclear power plant built in Guangxi. Its successful construction marks the beginning of China's nuclear bomb construction from the east to the west, from the coast to the inland. In the longitudinal evaluation research, the large fluctuation of the evaluation value of the relevant measurement indexes of Ningde nuclear power plant in 2016 led to the large change of the safety evaluation value of the nuclear power plant in that year. In this empirical study, Lingao, Yangjiang, Ningde and Fangchenggang nuclear power plant are selected as the research objects, and the above four nuclear power plants are taken as the horizontal case study objects. Under the unified index system, the data from 2015 to 2018 are counted, and the horizontal safety evaluation is carried out for the above four nuclear power plants.

The determination of the relative weight of the safety evaluation indexes of nuclear power plants and the construction of the safety evaluation objects $P = [P_1 \quad P_2 \quad P_3 \quad P_4]$, and P_1、P_2、P_3、P_4、 are the safety evaluation values of Ling'ao nuclear power plant, Yangjiang nuclear power plant, Ningde nuclear power plant and Fangchenggang nuclear power plant in 2015-2018. Based on the 2015-2018 annual report data of China National Nuclear Safety Administration and the built safety evaluation index system of nuclear power plants, the relevant data of the above four nuclear power plants are extracted, and the following matrix B is constructed.

$$B = \begin{bmatrix} 3 & 13 & 20 & 8 \\ 1 & 6 & 17 & 2 \\ 0 & 1 & 1 & 2 \\ 0 & 0 & 2 & 0 \\ 0.004460 & 0.009330 & 0.004896 & 0.005814 \\ 12.636000 & 23.625000 & 20.540000 & 13.083330 \\ 81.740000 & 20.79950 & 82.650000 & 59.916670 \\ 0.680150 & 0.2\ 0000 & 0.450750 & 0.145375 \\ 0.138043 & 0.10290 & 0.087000 & 0.055000 \end{bmatrix}$$

The membership matrix R is constructed from the extracted raw data.

$$R = \begin{bmatrix} 0.068182 & 0.295455 & 0.454545 & 0.181818 \\ 0.038462 & 0.230769 & 0.653846 & 0.076923 \\ 0 & 0.250000 & 0.250000 & 0.500000 \\ 0 & 0 & 1 & 0 \\ 0.181551 & 0.381110 & 0.199926 & 0.237413 \\ 0.274275 & 0.299489 & 0.260381 & 0.165855 \\ 0.102907 & 0.114216 & 0.453856 & 0.329021 \\ 0.454562 & 0.147032 & 0.301248 & 0.097158 \\ 0.360479 & 0.268709 & 0.227188 & 0.143625 \end{bmatrix}$$

According to P = W * R, the specific results are shown in Table 5 below.

Table 5
Evaluation of Nuclear Power Plant Safety Evaluation Indicators

Goal	Level I indicator	Level II indicator	Lingao nuclear power plant[1]	Yangjiang nuclear power plant[2]	Ningde nuclear power plant[3]	Fangchenggang nuclear power plant[4]
A	A_1	A_{11}	0.009666	0.041886	0.064440	0.025776
		A_{12}	0.004878	0.029265	0.082919	0.009755
		A_{13}	0	0.021390	0.021390	0.042780
		A_{14}	0	0	0.214208	0
	A_2	A_{21}	0.010389	0.021809	0.011441	0.013586
		A_{22}	0.031287	0.034163	0.029702	0.018919
		A_{23}	0.007964	0.008840	0.035126	0.025465
	A_3	A_{31}	0.039035	0.012626	0.025869	0.008343

Note: The smaller the indicator value, the higher the safety of the nuclear power plant under the evaluation index.

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According to $P_i = \sum_{i=1}^{n} \rho_{i1}$, $P = [P_1 \quad P_2 \quad P_3 \quad P_4 \quad P_5 \quad P_6]$, can be obtained.

P1=0.138216 P2=0.196067 P3=0.507151 P4=0.158568

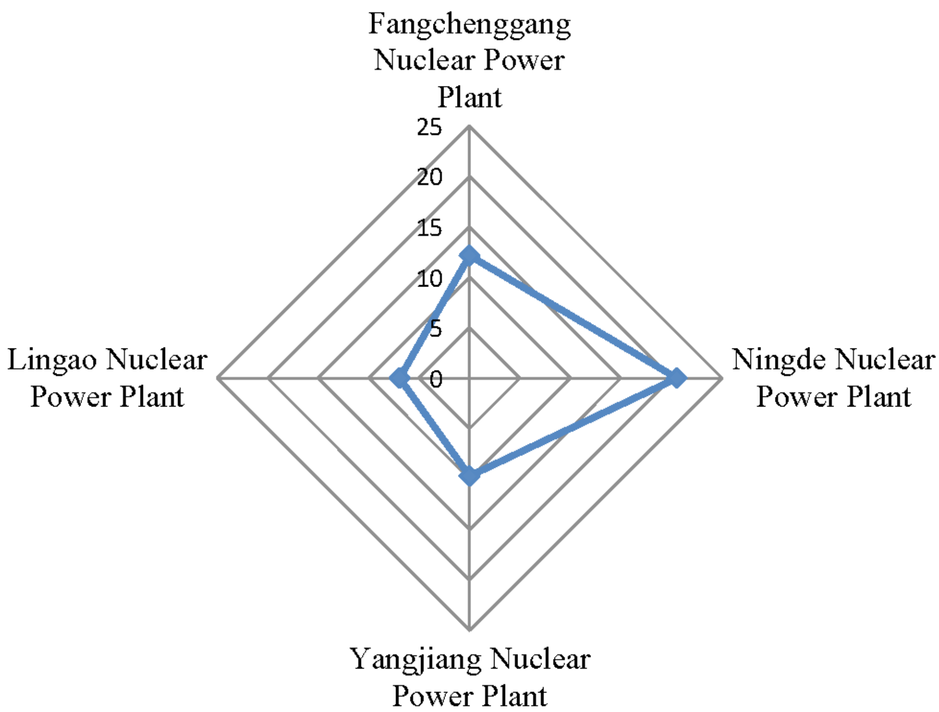

Figure 2
Safety Evaluation Index of Four Nuclear Power Plants Radar Chart

The results show that from 2015 to 2018, Ling'ao nuclear power plant has the highest degree of safety, while Ningde nuclear power plant has the lowest degree of safety.

5. CONCLUSION

The safety of nuclear power plant is related to the safety of the whole country and society. It is indispensable to evaluate the safety of nuclear power plant. Under the guidance of systematic, comparable, operable, quantifiable and dominant principles, this paper designs the safety evaluation index system of nuclear power plant, which includes three first level indexes and nine second level indexes. At the same time, the entropy weight method is introduced into the safety evaluation of nuclear power plant, and the information carried by data is used to calculate the index weight, which reduces the influence of human factors and ensures the objectivity. The safety evaluation model of nuclear power plant constructed in this paper has a longitudinal comprehensive safety evaluation of all nuclear power plants operated in China from 2013 to 2018. The data shows that China's nuclear power plants performed the best in 2018, with the highest safety performance, and performed the worst in 2016, which is consistent with the fact that the number of safety incidents of nuclear power plants in 2016 is the largest in the annual report of China Nuclear Safety Administration. At the same time, a horizontal research was conducted on Ling'ao nuclear, Yangjiang, Ningde and Fangchenggang nuclear power plant. It was found that the safety risk of Ningde nuclear power plant was far higher than that of the other three nuclear power plants. Through horizontal and vertical cross comparison, it was found that the reason was that Ningde nuclear power plant had the most incidents in 2016.

Based on the evaluation of vertical and horizontal safety of nuclear power plants, this paper puts forward relevant suggestions in terms of personnel, equipment and the overall aspects. In the past six years, there are 121 accidents caused by human factors, which lead to the most accidents. Therefore, we should pay attention to the role of personnel in the safety of nuclear power plant. The unit should carry out professional safety education and training for relevant personnel, and carry out assessment, so as to minimize the safety accidents caused by human factors. The qualification of suppliers of nuclear power plant equipment shall be strictly reviewed, and the equipment shall be overhauled regularly. The qualification of suppliers is closely related to the quality of equipment

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and can reduce the probability of equipment failure from the source. At the same time, regular maintenance of nuclear power plant equipment can not only guarantee the high-performance operation of equipment, but also extend the service life of equipment. Pay attention to the role of each individual nuclear power plant in safety assessment. Nuclear power plant safety assessment is not only a single indicator or a single nuclear power plant, but also to achieve coordinated development.

Due to the limited research conditions, there are still some shortcomings and limitations in this paper. For example, some data of the official website of relevant nuclear power plant operating companies outside the research period (before 2013) are missing or the attribution criteria of events in the annual report of China National Nuclear Safety Administration are inconsistent. Therefore, the relevant data of nuclear power plants before 2013 cannot be counted. The single way of data source acquisition and the limitation of data availability will have certain deviation and influence on the research results of this paper. The unification of the attribution classification of nuclear power plant incidents before 2013 in the annual report of China National Nuclear Safety Administration can make the safety evaluation results of nuclear power plants more completely reflect the safety level of China's overall nuclear power plants under the condition that the index system is more perfect.

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FOOTNOTES

[1] Lingao Nuclear Power Plant:http://www.dnmc.com.cn/dnmccn/c1017461/nlyz.shtml

[2] Yangjiang Nuclear Power Plant:http://www.yjnp.com.cn/yjnp/c100617/lcwgl.shtml

[3] Ningde Nuclear Power Plant:http://www.ndnp.com.cn/ndnp/c101524/nlyz.shtml

[4] Fangchenggang Nuclear Power Plant:http://www.fcgnp.com.cn/fcgnp/aqcn/listt.shtml

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