

Chemical equipment failure probability correction model based on the Multi-layer Grey Evaluation Method

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ABSTRACT

At present, the role of basic leak probability of chemical equipment cannot be distinguished from the influence of many other factors on failure probability in the petrochemical field. Due to the defects in other methods, in this study, by applying Analytic Hierarchy Process (AHP) and introducing grey theories, the chemical equipment failure probability correction model based on the multi-layer grey evaluation method was proposed. By applying AHP, six first level indicators including safety management, production equipment, process, production environment, natural environment, and personal quality were analyzed, as well as twenty-seven second level indicators. The influence of various factors in the chemical equipment failure system was obtained. Then, the correction factor value was calculated according to grey system theories, and the correction coefficient was applied to correct the failure probability. By taking a vinyl chloride tank of a chlor-alkali company as an example, the results indicated that the corrected factor value of failure probability for the tank was 3.335, the correction coefficient was 1.25, and the actual failure probability of the tank was larger than the basic leak probability. This method provides a new way to measure the failure probability correction, and has a theoretical significance and practical value on accurate calculation of the quantitative risk evaluation.

KEYWORDS: chemical equipment; failure probability; multi-layer grey evaluation method; whitening weight function; index system

1. INTRODUCTION

With the development of China's industrial economy, the safety situation of the petroleum chemical industry is becoming more and more serious (Wu, 2008). Therefore, quantitative risk assessment in the petroleum chemical industry is very important. The core of quantitative risk assessment is the fitting together of the accident occurrence probability and the accident consequence. The accuracy of chemical equipment failure probabilities can greatly affect the rationality and applicability of quantitative risk assessment results. At present, the statistical data of basic leak probabilities in the petroleum chemical industry are mainly from abroad, which generally represent the industry, but do not reflect actual failure probabilities of particular plants. The equalization of statistical figures makes effects of many factors on failure probabilities indistinguishable; therefore, these defects must be corrected.

Although the calculation of failure probabilities has been realized to a certain degree in the literature (Shi et al., 2011; American Petroleum Institute, 2000; Qingdao Safety Engineering Institute of SINOPEC, 2007; Zhu, 2005; Liu and Li, 2007; Koutsourelakis et al., 2004; Au and Beck, 2001; Yuan et al., 2007), the

current methods are subject to many problems, such as: some methods completely depend on experiences, calculation processes are too simple, the index systems are not comprehensive, indicators are not primary or secondary, and calculation processes are long and complicated in order to improve calculation accuracy. For these reasons, they could untruthfully reflect actual failure probabilities of chemical equipment, especially where there are greater differences in the aspects of personal quality, production equipment, process, production environment, and safety management.

Because the main chemical equipment of petroleum chemical industries are large scale, high speed, and complex, internal factors and risks are only partially known. Therefore, it is very difficult to realize objectivity by applying traditional methods. The method proposed in this study calculates failure probability correction by the multi-layer grey evaluation method, which combines the advantages of AHP and the grey evaluation method, and has better adaptability for complex systems with distinct layers. This method not only makes full use of existing information and focuses on internal connections among behavioural data in the internal system, but also effectively corrects the lack of a single evaluation method. This makes evaluation

results more accurate (Liu et al., 2004; Huang et al., 2015). Basing on the multi-layer grey evaluation method, the multi-layer grey evaluation model of the chemical equipment failure probability correction factor was established, and the model application was illustrated with examples.

2. THE MULTI-LAYER GREY EVALUATION MODEL OF THE CHEMICAL EQUIPMENT FAILURE PROBABILITY CORRECTION FACTOR

2.1 Establishing evaluation index systems

According to accident analysis theories (He et al., 2000; Tian and Jing, 2009; Xu et al., 2012), and by combining properties and environment conditions of chemical equipment, the evaluation index system of the chemical equipment failure probability correction factor was established.

Through the investigation of some petroleum chemical production plants, and by combining with the analysis situations of investigated relevant safety accident statistics, as well as expert investigation, practical experiences of safety, and environmental protection staff and technicians, the comprehensive evaluation index system of the chemical equipment failure probability correction factor was established, as shown in Figure 1.

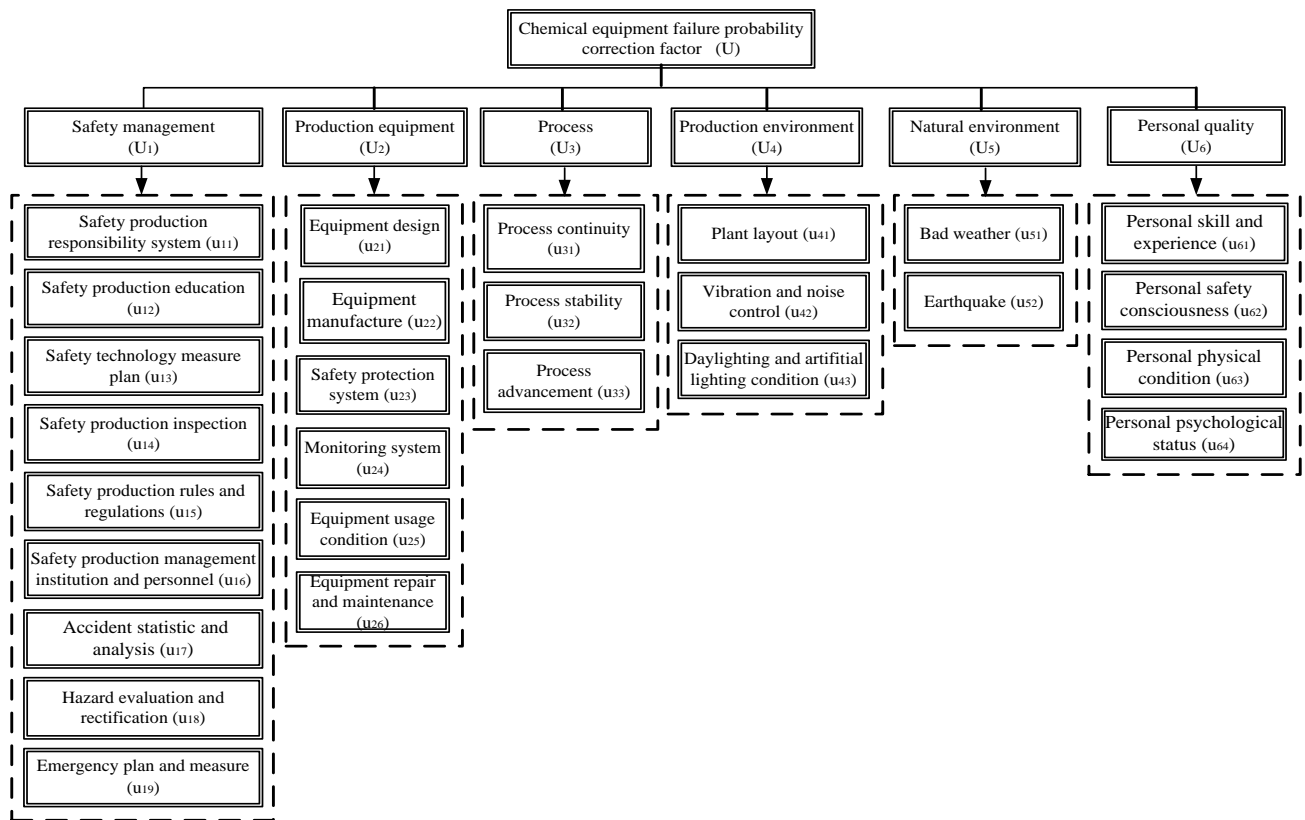


Figure 1: The chemical equipment failure probability correction factor model.

2.2 Determining weights of evaluation indicators

The influence of factors on evaluation objects (chemical equipment failure probability correction factors) was reflected by the weight set of evaluation indicators. In this paper, by using AHP, the judgment matrix was constructed by applying the scaling value method, and weight values of factors were calculated by the asymptotic normalization coefficient.

2.3 Set scoring criteria of evaluation indicators

Evaluation index grades were divided into “low”, “general”, “higher”, “high” and “very high”. Corresponding values were 1, 2, 3, 4 and 5, respectively. When the index grade was between adjacent grades, the corresponding score values were 1.5, 2.5, 3.5 and 4.5, respectively.

2.4 Organizing evaluation experts to score and establish evaluation sample matrixes

The evaluation expert number was supposed k , $k=1,2,3,\dots,p$, that was to say, there were p evaluation experts. According to the scoring criteria, the p evaluation experts were organized to score the evaluation index u_{ij} and filled the score table. Basing on the score value d_{ijk} of the k th evaluator, the evaluation sample matrix D was obtained as follows:

$$D = \begin{bmatrix} d_{111} & d_{112} & \cdots & d_{11p} \\ d_{121} & d_{122} & \cdots & d_{12p} \\ \vdots & \vdots & & \vdots \\ d_{211} & d_{212} & \cdots & d_{21p} \\ \vdots & \vdots & & \vdots \\ d_{ij1} & d_{ij2} & \cdots & d_{ijp} \end{bmatrix} \begin{matrix} u_{11} \\ u_{12} \\ \vdots \\ u_{21} \\ \vdots \\ u_{ij} \end{matrix} \quad (1)$$

$$i=1,2,\dots,m; j=1,2,\dots,n; k=1,2,\dots,p.$$

2.5 Determining evaluation grey-grades

This study used 5 evaluation grey-grades. The evaluation grey-grade number was supposed e , so that $e=1,2,3,4,5$. The corresponding grey number and definite weighted function were as follows (Wen, 2010; Ren and Zhu et al., 2008).

(1) “low” ($e=1$), the grey number \otimes_1 was supposed $\otimes_1 \in [0,1,2]$, and the definite weighted function $f_1(d_{ijk})$ was supposed as follows:

$$f_1(d_{ijk}) = \begin{cases} 1 & d_{ijk} \in [0,1] \\ (2-d_{ijk})/1 & d_{ijk} \in [1,2] \\ 0 & d_{ijk} \notin [0,2] \end{cases} \quad (2)$$

(2) “general” ($e=2$), the grey number \otimes_2 was supposed $\otimes_2 \in [0,2,4]$, and the definite weighted function $f_2(d_{ijk})$ was supposed as follows:

$$f_2(d_{ijk}) = \begin{cases} d_{ijk}/2 & d_{ijk} \in [0,2] \\ (4-d_{ijk})/2 & d_{ijk} \in [2,4] \\ 0 & d_{ijk} \notin [0,4] \end{cases} \quad (3)$$

(3) “higher” ($e=3$), the grey number \otimes_3 was supposed $\otimes_3 \in [0,3,6]$, and the definite weighted function $f_3(d_{ijk})$ was supposed as follows:

$$f_3(d_{ijk}) = \begin{cases} d_{ijk}/3 & d_{ijk} \in [0,3] \\ (6-d_{ijk})/3 & d_{ijk} \in [3,6] \\ 0 & d_{ijk} \notin [0,6] \end{cases} \quad (4)$$

(4) “high” ($e=4$), the grey number \otimes_4 was supposed $\otimes_4 \in [0,4,8]$, and the definite weighted function $f_4(d_{ijk})$ was supposed as follows:

$$f_4(d_{ijk}) = \begin{cases} d_{ijk}/4 & d_{ijk} \in [0,4] \\ (8-d_{ijk})/4 & d_{ijk} \in [4,8] \\ 0 & d_{ijk} \notin [0,8] \end{cases} \quad (5)$$

(5) “very high” ($e=5$), the grey number \otimes_5 was supposed $\otimes_5 \in [0,5,10]$, and the definite weighted function $f_5(d_{ijk})$ was supposed as follows:

$$f_5(d_{ijk}) = \begin{cases} d_{ijk}/5 & d_{ijk} \in [0,5] \\ 1 & d_{ijk} \in [5,10] \\ 0 & d_{ijk} \notin [0,10] \end{cases} \quad (6)$$

2.6 Calculating grey evaluation coefficients

The grey evaluation coefficient was recorded as X_{ije} , then there was:

$$X_{ije} = \sum_{k=1}^p f_e(d_{ijk}) \quad (7)$$

For the evaluation index u_{ij} , the total grey evaluation coefficient of each evaluation grey-grade was recorded as X_{ij} , then there was:

$$X_{ij} = \sum_{k=1}^p X_{ije} \quad (8)$$

2.7 Calculate grey evaluation weight vectors and weight matrixes

All evaluators advocated that the grey evaluation weight r_{ije} of the e th evaluation grey-grade was $r_{ije}=X_{ije}/X_{ij}$, the grey evaluation weight vector r_{ij} of the evaluation index u_{ij} was:

$$r_{ij}=(r_{ij1},r_{ij2},r_{ij3},r_{ij4},r_{ij5}) \quad (9)$$

So the grey evaluation weight matrix R_i of each evaluation grey-grade was obtained, for the index u_{ij} affiliated to U_i . Then there was:

$$R_i = \begin{bmatrix} r_{i1} \\ r_{i2} \\ \vdots \\ r_{ij} \end{bmatrix} = \begin{bmatrix} r_{i11} & r_{i12} & r_{i13} & r_{i14} & r_{i15} \\ r_{i21} & r_{i22} & r_{i23} & r_{i24} & r_{i25} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ r_{ij1} & r_{ij2} & r_{ij3} & r_{ij4} & r_{ij5} \end{bmatrix} \quad (10)$$

2.8 Comprehensive evaluation

The comprehensive evaluation results were:

$$B_i=A_i \cdot R_i=(b_{i1},b_{i2},b_{i3},b_{i4},b_{i5}) \quad (11)$$

The grey evaluation weight coefficient matrix was:

$$R = \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_5 \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} & b_{15} \\ b_{21} & b_{22} & b_{23} & b_{24} & b_{25} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ b_{51} & b_{52} & b_{53} & b_{54} & b_{55} \end{bmatrix} \quad (12)$$

Therefore, U_i was made comprehensive evaluation, and its results were recorded as B , then there was:

$$B = A \cdot R = (b_1, b_2, b_3, b_4, b_5) \quad (13)$$

The comprehensive evaluation value W of U_i was calculated. When each evaluation grey-grade was assigned through "grey level", then each evaluation grey-grade value vector C was $C=(1,2,3,4,5)$. Therefore, the comprehensive evaluation value W of the evaluation index U could be calculated according to the following formula:

$$W = B \cdot C^T B \quad (14)$$

Where, C^T was transposition of each evaluation grey-grade value vector.

2.9 Determining correction coefficients

Values of correction coefficients were as shown in Table 1. After the comprehensive evaluation value W was obtained, according to Table 1 and W the correction coefficient of the failure probability was determined. The product of the correction coefficient and the basic leak probability was the corrected chemical equipment failure probability.

Table 1: Values of correction coefficients.

Comprehensive evaluation value	Value of the correction coefficient r
[4.5, 5.0]	>2.00
[4.0, 4.5)	1.50~2.00
[3.5, 4.0)	1.50
[3.0, 3.5)	1.25
[2.5, 3.0)	1.05
[2.0, 2.5)	1.00
[1.5, 2.0)	0.95
[1.0, 1.5)	0.90

3. CASE ANALYSIS

In order to illustrate the validity of this model, a vinyl chloride tank of polyvinyl chloride (PVC) plant of a chlor-alkali company in China was taken as an example. The tank was horizontal type, and its volume was 112m³. There were 8 flanges with different sizes on tank body connections. It was e, and its volume was 112m 112mThe failure probability was corrected based on the multi-layer grey evaluation model.

3.1 Weight coefficient matrixes

The index weight of each layer was calculated through AHP. According to the 1-9 scale method,

judgment matrixes of six first level indicators in the criterion layer were constructed by experts, which were shown as Table 2. The weight vector of each factor was calculated by the "scaling value method", and the consistency test was made.

Table 2: Values of correction coefficients

Criterion layer	U ₁	U ₂	U ₃	U ₄	U ₅	U ₆
U ₁	1	3	4	7	7	3
U ₂	1/3	1	3	5	5	1
U ₃	1/4	1/3	1	3	3	1/3
U ₄	1/7	1/5	1/3	1	1	1/5
U ₅	1/7	1/5	1/3	1	1	1/5
U ₆	1/3	1	3	5	5	1

The weight of U was $A=(0.413,0.202,0.098,0.042,0.042,0.202)$, $\lambda_{max}=6.159$, $CR=0.026 < 0.1$, and the consistency test passed.

In the same way, weights of the second level indicators for the criterion layer were obtained as follows:

$$A_1=(0.019,0.052,0.288,0.090,0.037,0.026,0.128, 0.128,0.232);$$

$$A_2=(0.068,0.111,0.289,0.035,0.192,0.306);$$

$$A_3=(0.106,0.633,0.260);$$

$$A_4=(0.143,0.571,0.286);$$

$$A_5=(0.500,0.500);$$

$$A_6=(0.584,0.286,0.080,0.050).$$

3.2 Organizing evaluation experts to score and establish evaluation sample matrixes

According to score sheets filled by 10 experts, the evaluation sample matrix D was obtained.

$$D = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 2 & 1 & 1.5 & 1.5 \\ 2 & 2 & 2 & 1.5 & 1.5 & 2 & 2 & 1 & 1 & 1.5 \\ 2.5 & 3 & 3 & 1.5 & 1.5 & 2 & 2 & 1 & 1.5 & 1 \\ 1.5 & 2 & 2 & 1.5 & 1.5 & 1.5 & 1.5 & 1 & 1.5 & 1 \\ 1 & 1 & 2 & 1.5 & 1.5 & 1.5 & 2 & 1 & 1.5 & 1.5 \\ 1.5 & 2 & 1 & 1 & 2 & 1.5 & 2 & 1 & 2 & 1.5 \\ 1.5 & 1 & 2 & 1.5 & 2 & 2 & 2 & 1 & 1.5 & 1 \\ 1 & 1.5 & 2 & 1 & 2 & 1.5 & 1.5 & 1 & 2 & 1.5 \\ 2 & 2 & 2 & 1.5 & 2.5 & 1.5 & 2 & 1 & 1 & 1 \\ 1 & 1.5 & 3 & 2 & 1.5 & 2 & 2 & 1.5 & 1 & 1.5 \\ 1.5 & 2 & 3 & 1.5 & 2 & 2 & 2.5 & 1 & 1.5 & 1 \\ 2 & 1.5 & 2 & 1.5 & 1.5 & 1.5 & 1.5 & 1 & 1.5 & 1.5 \\ 2 & 2.5 & 2 & 1.5 & 1.5 & 1.5 & 2.5 & 1.5 & 1.5 & 1 \\ 1.5 & 2 & 3 & 1.5 & 2.5 & 1.5 & 3 & 1.5 & 2 & 2 \\ 2.5 & 3 & 3 & 1.5 & 2.5 & 1.5 & 2.5 & 2.5 & 1 & 2 \\ 1.5 & 1.5 & 2 & 1.5 & 1.5 & 1.5 & 2 & 1 & 1 & 1.5 \\ 1.5 & 1.5 & 2 & 2 & 1.5 & 1.5 & 1.5 & 1.5 & 1 & 2 \\ 1.5 & 2 & 2 & 2 & 1.5 & 2 & 1 & 2 & 1 & 1 \\ 1 & 1 & 3 & 1 & 3 & 2 & 1 & 1.5 & 1 & 1 \\ 1 & 1 & 1 & 1.5 & 1.5 & 2 & 2.5 & 1.5 & 2 & 2 \\ 1 & 1 & 1 & 1.5 & 1.5 & 1.5 & 1 & 1 & 1 & 1.5 \\ 1.5 & 2 & 2 & 1.5 & 2 & 2 & 2 & 1 & 2 & 1 \\ 1.5 & 2 & 2 & 1.5 & 2 & 2 & 1 & 1.5 & 2 & 1 \\ 2.5 & 2.5 & 3 & 1.5 & 1.5 & 2 & 2 & 2 & 2.5 & 1.5 \\ 1.5 & 2 & 2 & 1 & 2 & 2 & 2.5 & 1.5 & 1.5 & 2 \\ 1 & 1 & 2 & 1 & 1.5 & 1.5 & 1.5 & 1.5 & 2 & 1.5 \\ 2 & 2 & 2 & 1.5 & 2 & 1.5 & 3 & 3.5 & 2 & 1 \end{bmatrix}$$

$$R_3 = \begin{bmatrix} 0.235 & 0.353 & 0.235 & 0.176 & 0.235 \\ 0.188 & 0.375 & 0.250 & 0.188 & 0.188 \\ 0.188 & 0.375 & 0.250 & 0.188 & 0.188 \end{bmatrix};$$

$$R_4 = \begin{bmatrix} 0.305 & 0.270 & 0.243 & 0.182 & 0.305 \\ 0.211 & 0.352 & 0.250 & 0.188 & 0.211 \\ 0.381 & 0.286 & 0.190 & 0.143 & 0.381 \end{bmatrix};$$

$$R_5 = \begin{bmatrix} 0.140 & 0.397 & 0.265 & 0.198 & 0.140 \\ 0.164 & 0.386 & 0.257 & 0.193 & 0.164 \end{bmatrix};$$

$$R_6 = \begin{bmatrix} 0.069 & 0.368 & 0.322 & 0.241 & 0.069 \\ 0.116 & 0.395 & 0.279 & 0.209 & 0.116 \\ 0.259 & 0.342 & 0.228 & 0.171 & 0.259 \\ 0.094 & 0.363 & 0.304 & 0.240 & 0.094 \end{bmatrix}.$$

3.3 Calculating grey evaluation weight matrixes

According to formulas 2-6, 9, and 10, calculated results were as follows:

$$R_1 = \begin{bmatrix} 0.342 & 0.256 & 0.171 & 0.128 & 0.103 \\ 0.164 & 0.386 & 0.257 & 0.193 & 0.164 \\ 0.162 & 0.324 & 0.293 & 0.220 & 0.162 \\ 0.235 & 0.353 & 0.235 & 0.176 & 0.235 \\ 0.259 & 0.342 & 0.228 & 0.171 & 0.259 \\ 0.211 & 0.364 & 0.243 & 0.182 & 0.211 \\ 0.211 & 0.364 & 0.243 & 0.182 & 0.211 \\ 0.235 & 0.353 & 0.235 & 0.176 & 0.235 \\ 0.187 & 0.363 & 0.257 & 0.193 & 0.187 \end{bmatrix};$$

$$R_2 = \begin{bmatrix} 0.187 & 0.350 & 0.265 & 0.198 & 0.187 \\ 0.163 & 0.349 & 0.279 & 0.209 & 0.163 \\ 0.211 & 0.364 & 0.243 & 0.182 & 0.211 \\ 0.163 & 0.361 & 0.272 & 0.204 & 0.163 \\ 0.092 & 0.357 & 0.315 & 0.236 & 0.092 \\ 0.092 & 0.321 & 0.336 & 0.252 & 0.092 \end{bmatrix};$$

3.4 Comprehensive evaluation

Evaluation indicators affiliated to U_i were evaluated. The results were recorded as B_i , where:

$$B_1=A_1 \cdot R_1=(0.198,0.348,0.258,0.193,0.194)$$

$$B_2=A_2 \cdot R_2=(0.143,0.347,0.292,0.219,0.143)$$

$$B_3=A_3 \cdot R_3=(0.193,0.372,0.248,0.187,0.193)$$

$$B_4=A_4 \cdot R_4=(0.273,0.321,0.232,0.174,0.273)$$

$$B_5=A_5 \cdot R_5=(0.152,0.392,0.261,0.196,0.152)$$

$$B_6=A_6 \cdot R_6=(0.099,0.373,0.301,0.226,0.099)$$

The grey evaluation weight coefficient matrix of U_i for each evaluation grey-grade was obtained by B_i .

$$R = \begin{bmatrix} 0.198 & 0.348 & 0.258 & 0.193 & 0.194 \\ 0.143 & 0.347 & 0.292 & 0.219 & 0.143 \\ 0.193 & 0.372 & 0.248 & 0.187 & 0.193 \\ 0.273 & 0.321 & 0.232 & 0.174 & 0.273 \\ 0.152 & 0.392 & 0.261 & 0.196 & 0.152 \\ 0.099 & 0.373 & 0.301 & 0.226 & 0.099 \end{bmatrix}$$

The evaluation weight vector of the failure probability correction factor grey-grade for the vinyl chloride tank was obtained, that was:

$$B=A \cdot R=(0.167,0.356,0.271,0.203,0.166)$$

The comprehensive evaluation value of the tank failure probability correction factor was:

$$W=B \cdot C^T=3.335$$

3.5 Determine the correction coefficient

The correction coefficient was obtained according to W and Table 1., The failure probability correction coefficient of the vinyl chloride tank was determined to be 1.25, which when multiplied with the basic leak probability gave the corrected failure probability.

4. CONCLUSIONS

By combining with actual situations of chemical equipment and by objectively and reasonably choosing evaluation indicators, the chemical equipment failure probability correction model based

on the multi-layer grey evaluation method was established, and then was applied to the case study.

By using AHP to determine index weights, and applying the multi-layer grey evaluation method, the failure probability of the vinyl chloride tank in a chlor-alkali company was corrected. Comprehensive evaluation results showed that the failure probability correction factor value of the vinyl chloride tank in the chlor-alkali company was 3.335, and the determined correction coefficient was 1.25. So the failure probability correction factor value of the tank was between “higher” and “high”, and its actual failure probability value was larger than that of the basic leak probability. This model not only provides a new approach to the correction of the chemical equipment failure probability, but also has important practical significance with the accurate calculation of the quantitative risk assessment.

The comprehensive evaluation of the chemical equipment failure probability correction factor was a very complicated research topic. However, the determination of scientific and reasonable comprehensive evaluation index systems and evaluation methods was necessary to correct failure probabilities. Established models should constantly be optimized.

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