Application of the reliability-centered maintenance techniques for dynamic equipment in the petrochemical ammonia-related systems

Wei Hua Wang, Ning Bai, Lei Wang, Guang Kui Liu, Gong Qian and Xu Yang*

China Special Equipment Inspection and Research Institute, Beijing, China, 100029

Abstract. The reliability-centered maintenance (RCM) analysis method and the RCM implementation process for dynamic equipment in petrochemical ammonia-related systems were introduced. The operation situation, key roles, and potential risks were clarified through data analysis and system screening in ammonia dynamic equipment, and FMEA was used to analyze the failure mode. Then the risk of each failure mode was managed hierarchically, a suitable risk assessment standard and risk matrix were developed for the enterprise, and a suitable maintenance strategy was formulated for the risk level of each failure mode.

1. Introduction

With the increase in domestic energy demand, the petrochemical industry is developing towards large, complex and continuous, the dynamic equipment in the petrochemical industry is the key factor to affect productivity. Improving the reliability of dynamic equipment, increasing equipment maintenance, inspection and repair is a necessary method to ensure the long-cycle operation of the petrochemical industry. The management model of equipment maintenance has gone through three main development stages [1,2], in the 1940s, the main maintenance form is after-the-fact, where repairs were started after the equipment broke down. In the 1960s and 1970s, the main maintenance form was preventive maintenance, and all equipment in operation was included in the scope of maintenance, which could effectively reduce downtime and accident rates, but increased the cost of maintenance. Since the 1980s, condition-based maintenance was the main method, after evaluating the operating status of the equipment and then performing maintenance to reduce the downtime and accident rate, the maintenance cost can be further reduced. Reliability-centered maintenance (RCM) approach, which also belongs to the development stage of condition-based maintenance, is a new form of maintenance management model [3-5]. In recent years, RCM assessment has only been conducted for dynamic equipment in individual scenarios. For example, Qingpeng Meng et al. used the RCM approach to analyze potential safety hazards during crane operation, and established a set of reliability maintenance strategies for offshore cranes to improve equipment reliability [6]. Chao Li analyzed the dynamic equipment of the alkylation unit using the RCM approach to propose a data-driven method for building the failure mode library, and integrated the maintenance records and failures diagnosis of the equipment to improve the traditional RCM method [7]. Nan Zhou et al. introduced the RCM model in the maintenance of oxygen and nitrogen production equipment, which explicitly started from the functional failure of the system, analyzed the causes and consequences of the failure mode, and provided a decisive analysis for making a maintenance strategy [8]. The RCM theory has been proven to effectively improve the reliability of equipment operation and reduce maintenance costs [9].

However, there is limited research on the implementation scheme of integrity technology based on RCM theory for dynamic equipment in the petrochemical industry. Therefore, it is necessary to establish the implementation strategy for the technical integrity of dynamic equipment under the corresponding scenario of petrochemical enterprises, which played an important role in the safety and long-term operation of dynamic equipment in this industry. This paper will evaluate the operational status of the ammonia-related dynamic equipment in a petrochemical enterprise using the RCM approach, and construct the RCM technology implementation process of the ammonia-related system dynamic equipment.

2. RCM assessment of ammonia dynamic equipment

The dangerous forms of ammonia were liquid and gas ammonia. At room temperature, liquid ammonia rapidly vaporizes into gaseous ammonia. Gaseous ammonia can cause respiratory problems, eye and skin irritation, poisoning, and even death. In addition, ammonia gas may also produce an explosion when it came into contact with oxygen or other oxidants in the air [10]. Therefore,

*yangxu@csei.org.cn

ammonia leakage has great harm to personal and environmental safety, it is extremely important to ensure the safety of ammonia-related equipment. The ammonia-related dynamic equipment in petrochemical equipment generally includes a continuous reforming unit, paraffin forming unit, ketone-benzene dewaxing and deoiling combined unit, and thermoelectric denitration system. To assess the operation status and equipment failure risk in a series of ammonia-related dynamic equipment, and comprehensive analysis and management of the key factors that affect the integrity of dynamic equipment, establishing a management system for ammonia-related dynamic equipment and maintaining its continued integrity are important methods to ensure the efficiency of petrochemical enterprises and reduce the probability of accidents. RCM is to determine the maintenance task of the equipment and formulate the maintenance plan according to a certain problem-solving process. The failure mode and impact of the equipment are considered in the analysis scope, which will contribute to finding the best way to improve the system reliability and realize the optimization of the economy.

The main research contents of RCM maintenance strategy for ammonia-related dynamic equipment are as follows: data collection; System division and define the high and middle-risk subsystems according to screened analysis; Conduct failure mode impact analysis (FMEA) for relevant risk subsystems [7]; Failure mode risk assessment; Determine the risk level; Develop maintenance strategy. The specific implementation flow chart is shown in Figure 1.

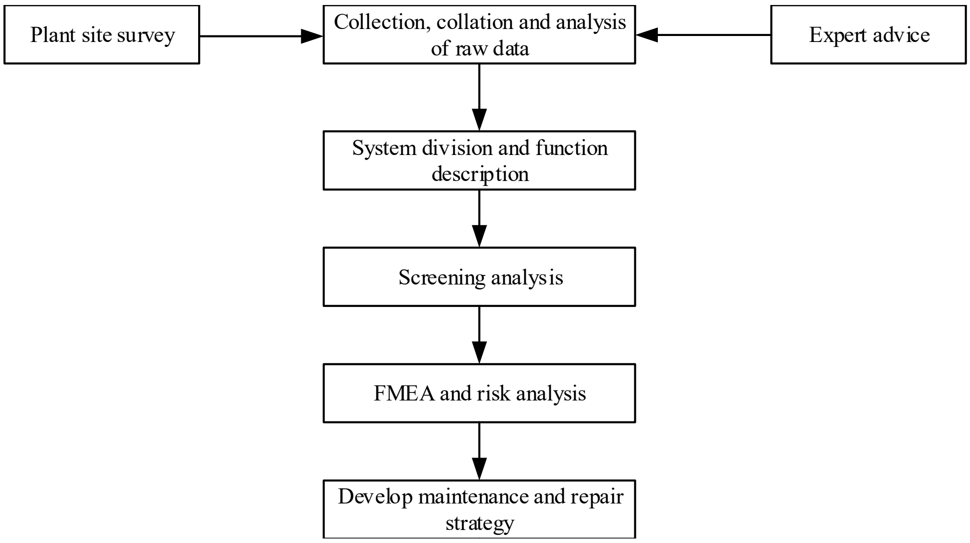

Figure 1. RCM evaluation implementation process of ammonia-related dynamic equipment

3. Application of RCM evaluation technology for dynamic equipment of the ammonia-related system

A petrochemical enterprise entrusted China Special Equipment Inspection & Research Institute (CSEI) to conduct an RCM evaluation on some dynamic equipment of its ammonia-related system. It aims to establish a rigorous, scientific, standardized and reliability-centered management mode of dynamic equipment. The establishment of this mode will play an important role in finding equipment defects in time, reducing equipment downtime, improving equipment operation, extending equipment service life, and effectively controlling equipment maintenance and repair costs. The workflow is as follows:

3.1 Data collection and statistical analysis

The establishment of accurate basic data is the basis of RCM analysis. The data, mainly including device overview, operating procedures, equipment account, equipment installation site, pipeline and instrument diagrams, equipment management system, equipment failure statistics and maintenance and inspection records, have been collated, summarized and analyzed, then the main equipment information and operation status have been understanding clearly, and clarify whether the equipment management system and the quality of operators are factors affecting the safe operation of equipment, finally determine the scope of RCM implementation. After comprehensive consideration, it was decided to implement RCM analysis for the equipment of the continuous reformer, dewaxing and deoiling combined unit, paraffin unit and thermoelectric denitrification system of this petrochemical enterprise. The details cover 1 lube oil pump, 2 ammonia presses, 9 screw compressors, 9 ammonia pumps (–20 ℃), and 1 discharge compressor.

3.2 System Screening

The various units of a petrochemical enterprise are interconnected and relatively independent. The production units are systematically divided by identifying the specific functions performed by each system in the production process. Screening analysis of each equipment to clarify the key role of the equipment in the operation.

According to the actual petrochemical plant process, the CSEI divided the ammonia-related dynamic equipment of petrochemical enterprises into system units. All ammonia-related dynamic equipment in the continuous reforming plant is divided into one unit-one cooling unit dynamic equipment; all ammonia-related dynamic equipment in the ketone-benzene unit is divided into one unit-20 unit of cooling dynamic equipment; All ammonia-related dynamic equipment in the paraffin unit is divided into one unit-5 units of cooling dynamic equipment; all ammonia-related dynamic equipment in the cogeneration system is divided into one unit-1 unit of feeding unit dynamic equipment. Through the system division, we summarized the name, model, types and quantity of equipment needed to be evaluated for each key equipment unit, and had general control of the key equipment to be evaluated.

3.3 FMEA analysis

FMEA analysis, as a failure evaluation method, is widely used in nuclear power, chemical and mechanical fields. Its main contents include failure mode analysis, failure cause analysis, and failure impact analysis [11]. It is a procedural evaluation method combining qualitative and quantitative analysis. For the failure mode analysis of ammonia-related equipment in petrochemical enterprises, the failure modes that have occurred and that have occurred in similar equipment abroad have been analyzed. The hierarchical diagram of failure mode analysis is shown in Figure 2. In addition to identifying the explicit failure modes, special attention should be paid to hidden failure modes. The impact of hidden failure modes can be reduced by increasing protection and detection frequency. The possible failure modes shall be evaluated in terms of safety, economy, environment, production loss and maintenance cost, determining the frequency of accidents and the failure modes affecting the equipment's long-term safe and stable operation.

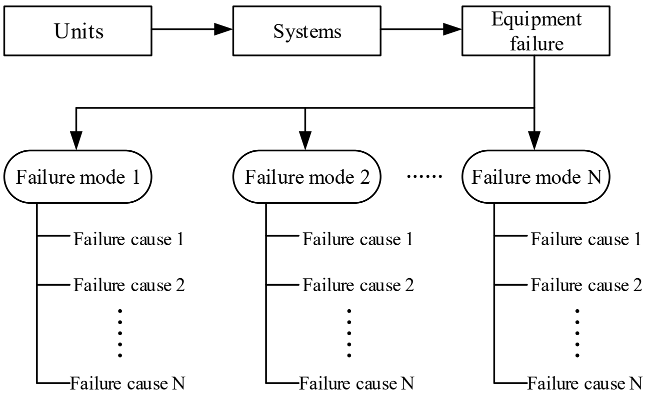

Figure 2. The hierarchical diagram of failure mode analysis

3.4 Failure mode risk assessment and risk level determination

After clarifying the frequency and impact of each failure mode, risk acceptability criteria and risk matrix were developed based on the equipment operation, management status, and relevant regulations/standards on the safety and environment of the petrochemical enterprise. Based on the results of FMEA analysis, the failure probability/frequency of ammonia-related dynamic equipment, the safety consequences, environmental consequences, production loss consequences, and maintenance cost consequences of failure modes are evaluated. The RCM analysis process classified the consequence levels into five levels: A, B, C, D, and E. The corresponding evaluation guidelines for equipment failure probability/frequency (Table 1), safety consequence (Table 2), environmental consequence (Table 3), production loss consequence (Table 4), and maintenance cost were established. The RCM analysis process classified failure modes into three levels: high risk (H), medium risk (M), and low risk (L), and established a risk matrix for each failure mode (Tables 6-9) to determine the risk level of each system unit device failure mode. The risk level of the equipment was clearly defined to develop different repair and maintenance strategies to prevent risky accidents.

Table 1. Failure probability/frequency evolution criteria

Failure probability / frequency level	Frequency of breakdowns within one overhaul cycle
A	Failure occurred 0: ＜X≤0.75 times / within 1 overhaul cycle
B	Failure occurred 0.75: ＜X≤1.5 times / within 1 overhaul cycle
C	Failure occurred 1.5: ＜X≤3 times / within 1 overhaul cycle
D	Failure occurred 3: ＜X≤5 times / within 1 overhaul cycle
E	Failure occurred: ＞ times / within 1 overhaul cycle

Table 2. Security consequence level evaluation guidelines

Consequence level	Degree Description	Safety consequences (million yuan)
A	No injuries	≤1
B	1~2 person slightly injured	1~5
C	More than 3 people were slightly injured; 1~2 people were seriously injured	5~50
D	3~9 people seriously injured;1~2 casualties	50~200
E	More than 3 casualties; more than 10 people seriously injured	＞200

Table 3. Environmental consequence level evaluation guidelines

Consequence level	Degree Description	Environmental consequences (million yuan)
A	Slight impact, within the permissible range of environmental indicators	≤ 5
B	Lighter impact, pollution factors are simple and can be solved within the enterprise	5~20
C	Local impact, complex pollution factors, the need to focus the branch's efforts to solve	20~100
D	Large impact, generating a large number of pollutants; more toxic; social impact, but can be solved through the group companies to solve the environmental impact	100~500
E	Significant impacts, resulting in major changes in ecosystem structure or significant loss of ecological functions and large social impacts that must be solved through government and external assistance	＞500

Table 4. Guidelines for evaluating the consequence level of production loss

Consequence level	Degree Description	Production loss consequence (million yuan)
A	Slight loss	⩽2 hrs of lost production
B	Minor loss	2 ~ 4 hrs of lost production
C	Partial loss	4 ~ 8 hrs of lost production
D	Major loss	8 ~ 24 hrs of production loss
E	Major loss	＞24 hrs of production loss

Table 5. Maintenance cost consequence level evaluation guidelines

Consequence level	Degree Description	Maintenance cost consequence (million yuan)
A	Slight impact	≤1
B	Minor impact	1~10
C	Local impact	10~20
D	Major impact	20~50
E	Significant impact	＞50

After the evaluation of the failure modes of ammonia-related dynamic equipment of a petrochemical enterprise by the CSEI, a total of 179 failure modes were found, of which no high-risk failure modes, medium-risk modes accounted for 20% and low-risk failure modes accounted for 80%. The continuous reformer has one unit with five failure modes, one of which is a medium-risk failure mode, and the rest are low-risk failure modes. The ketone-benzene unit has 20 units with 135 failure modes, 2 of which are medium-risk failure modes and the rest are low-risk failure modes. Paraffin unit has 5 units with 32 failure modes, 1 medium--risk failure mode and the rest low--risk failure modes. There is 1 unit of thermoelectric denitrification system with 7 failure modes, all of which are low-risk failure modes.

Table 6. Security risk matrix

Possibilities		Consequences of failure				
5	>5 times/4 years	M	M	H	H	H
4	3-5 times/4 years	L	M	M	H	H
3	1.5-3 times/4 years	L	L	M	M	H
2	0.75-1.5 times/4 years	L	L	L	M	M
1	0-0.75 times/4 years	L	L	L	L	M
Failure frequency/consequences		A	B	C	D	E

Table 7. Environmental impact risk matrix

Possibilities		Consequences of failure				
5	>5 times/4 years	M	M	H	H	H
4	3-5 times/4 years	L	M	M	H	H
3	1.5-3 times/4 years	L	L	M	M	H
2	0.75-1.5 times/4 years	L	L	L	M	M
1	0-0.75 times/4 years	L	L	L	L	M
Failure frequency/consequences		A	B	C	D	E

Table 8. Production loss impact risks matrix

Possibilities		Consequences of failure				
5	>5 times/4 years	M	M	H	H	H
4	3-5 times/4 years	L	M	M	H	H
3	1.5-3 times/4 years	L	L	M	M	H
2	0.75-1.5 times/4 years	L	L	L	M	M
1	0-0.75 times/4 years	L	L	L	L	M
Failure frequency/consequences		A	B	C	D	E

Table 9. Maintenance cost risk matrix

Possibilities		Consequences of failure				
5	>5 times/4 years	M	M	H	H	H
4	3-5 times/4 years	L	M	M	H	H
3	1.5-3 times/4 years	L	L	M	M	H
2	0.75-1.5 times/4 years	L	L	L	M	M
1	0-0.75 times/4 years	L	L	L	L	M
Failure frequency/consequences		A	B	C	D	E

3.5 Develop a maintenance and repair strategy

According to the risk level assessment of the failure modes, the maintenance level of in-service equipment is required. The risk level assessment of 26 units of in-service ammonia-related systems in petrochemical enterprises was conducted to determine the maintenance level of ammonia-related equipment dynamic equipment, which provides an accurate basis for establishing an equipment maintenance strategy. The analysis showed that there were 22 low-risk devices, 4 medium-risk devices, and no high-risk devices among the ammonia-related dynamic equipment of the enterprise. Therefore, general maintenance recommendations were provided to the petrochemical enterprise, and no special requirements for maintenance strategy development were made for the time being.

4. Conclusion

(1) Implementation of reliability-centered maintenance (RCM) assessment of ammonia-related dynamic equipment is a key part of the integrity management of ammonia-related dynamic equipment. Through data analysis and system screening to clarify the operation status, key roles, and potential risks of each ammonia-related equipment;

(2) FMEA is used to analyze failure mode, develop suitable risk assessment criteria and risk matrix, determine the risk level of each dynamic equipment, and develop maintenance strategy.

References

1. Adefarati T and Bansal R C 2019 Reliability, economic and environmental analysis of a microgrid system in the presence of renewable energy resources *Appl. Energ.* **236** 1089-1114
2. Taili J 2010 Research on the maintenance decision based on RCM theory (Wuhan: Wuhan University of Technology)
3. Hanlin L 2019 Reliability and maintenance modeling for competing risk processes with Weibull inter-arrival shocks *Appl. Math. Model.* **71** 194-207
4. Navarro I J, Marti J V and Yepes V 2018 Reliability-based maintenance optimization of corrosion preventive designs under a life cycle perspective *Environmental Impact Assessment Review* **74** 23-34
5. Tang Y, Liu Q Y and Jing J J 2017 A framework for identification of maintenance significant items in reliability centered maintenance *Energ.* **118** 1295-1303
6. Meng Q P, Gao L Y and Shi J L 2020 Application of RCM risk analysis technology on offshore platform cranes *China Equip. Engineer* **17** 2
7. Li C 2020 Research and application of integrity evaluation technology for hudrofluoric acid alkylation unit (Beijing: Beijing University of Chemical Technology)
8. Zou N, Han G Y and Liu S Y 2011 RCM analysis method and its application to the oxygen and nitrogen production plant maintenance *Sci. Tech. Engineer.* **11**(2) 5.
9. Wu B Q 2007 An introduction to reliability centered maintenance (Shanghai: Proceedings of China Shipbuilding Engineering Society)
10. Tian S J and He G S 2009Analysis and research on the cause of explosion of liquid ammonia cylinder[J]. *Chem. Saf. Environ.* **30** 2
11. He C B, Gu Y J and Xing C 2011 Failure mode analysis of wind turbine based on FMEA method *Renew. Energ.* **229(3)** 120-6