DOI: 10.13434/j.cnki.1007-4546.2014.0203

Research on Reliability of Automatic Capping Device for Nuclear Power Plant

ZHANG Feng, HE Ying-yong, Ren Xian-chang, YANG Jin-chun, ZHENG Zhi-shou

China Nuclear Power Design Co., Ltd, Shenzhen 518172, P. R. China

Abstract: Automatic capping device is a complex and non-standard equipment, its reliability directly impacts the safety operation of Solid Waste Treatment System (TES) in nuclear power plant. In order to improve the reliability automatic capping device, the equipment function and machine structure are analyzed. And Failure Mode and Effects Analysis (FMEA) method is applied to systematically analyze all possible failure modes and their reliability. Through establishing the FMEA worksheet, all failure causes, failure effects and their severity are analyzed comprehensively. Base on these analyzing results, it is easy to find out the product function design defects and weak links. Finally, through putting forward design prevention and improvement measures in design, the mission reliability of automatic capping device is improved, and most serious failure mode occurrence is avoided efficiently. Thus the safety operation of TES has been guaranteed in technology.

Key words: equipment reliability; nuclear power; failure mode; failure effect

1 Introduction

In the process of radioactive solid waste disposal for nuclear power plant, equipment reliability is very important. Especially key equipment failure is likely to lead to excessive radiation dose, directly affects the safe operation of the whole system. To improve the reliability of equipment and the safety of nuclear power plant, it is great significance that reliability theory is conducted and applied to the design of equipment [1-2].

Automatic capping device is critical and major equipment for Solid Waste Treatment System (TES) in nuclear power plant. It is used for capping or uncapping 400 L metallic drum, which is used for loading low and intermediate level radioactive solid wastes. Because it is a complex and non - standard equipment, its reliability can not be simply attributed to the reliability of parts and manufacturing technology level, and should be comprehensive considered [3-4].

Failure Mode and Effects Analysis (FMEA) is a systematic procedure for analyzing and identifying the potential failure modes, their causes and effects on system performance, and it is extremely efficient method applied to complex products extensively [5-8].

Once a detailed FMEA is created for automatic capping device, it shows the ways for components and their failure modes that would be the cause of system

Received 10 March 2014

failure in the product design phase. Accordingly, it is easy to find out the product function design defects and the weak links. When compensating provisions against failure are provided and carried out, automatic capping device can be updated and improved for the succeeding generations of that design, which constitutes a significantly less effort than the entirely new analysis. And it is very efficient and valuable for improving the equipment reliability and the safe operation of the TES.

In addition, for a nuclear power equipment to identify the potential failure modes, their causes and effects on system performance, it is great significance that the FMEA is conducted and applied to the design of equipment. Not only the reliability of nuclear power equipment can be improved, but also it is very beneficial to equipment maintenance and design refinement. Furthermore, it has a great enlightening for the similar design and research.

2 Equipment functions

Metallic drum uses ten screws to bring together mated flanges.

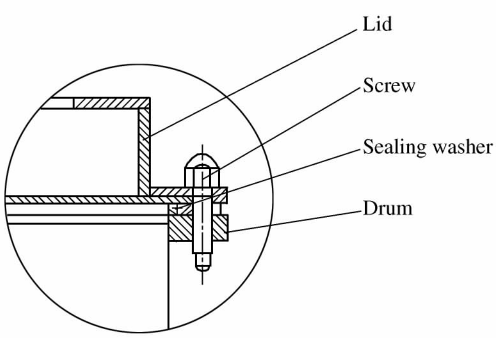

Figure 1 Metallic drum

A drum has to be transferred to the capping position with the remote operated roller conveyor, and is located and clamped by the roller conveyor. Then a capped drum will be uncapped as follows:

Uncapping process: First, automatic capping device finds the drum. Then torque wrenches are positioned over the screws, and aligned to the central axis of the screws. After the screws are loosened completely, the lid and screws are captured and lifted. The lid is separated from the drum and stored into the lid magazine. The uncapped drum can be processed to further treatment.

In order to uncap or cap continually, the removed lid can be stored into the lid magazine. The lid magazine can store eight lids.

Capping process: First, automatic capping device finds the lid. The lid is picked up from the lid magazine and positioned over the drum. Then automatic capping device carries the lid to rotate and makes sure the central axis of screws coincide with screw holes of the drum. After covering the lid, screws are tightened to designated torque. Automatic capping device is moved back to the original position. The capped drum can be processed to further treatment.

3 Machine structure and principle

Automatic capping device depends on translational motion mechanism, lifting and lowering mechanism and rotating mechanism to achieve horizontal movement, vertical movement and rotation movement respectively.

Above the rotating mechanism is a floating mechanism that can be achieve movement and lock in X, Y tow direction.

Below the rotating mechanism is a tightening machine that contains a gripper to hold the lid, ten torque wrenches to tighten screws and a positioning device.

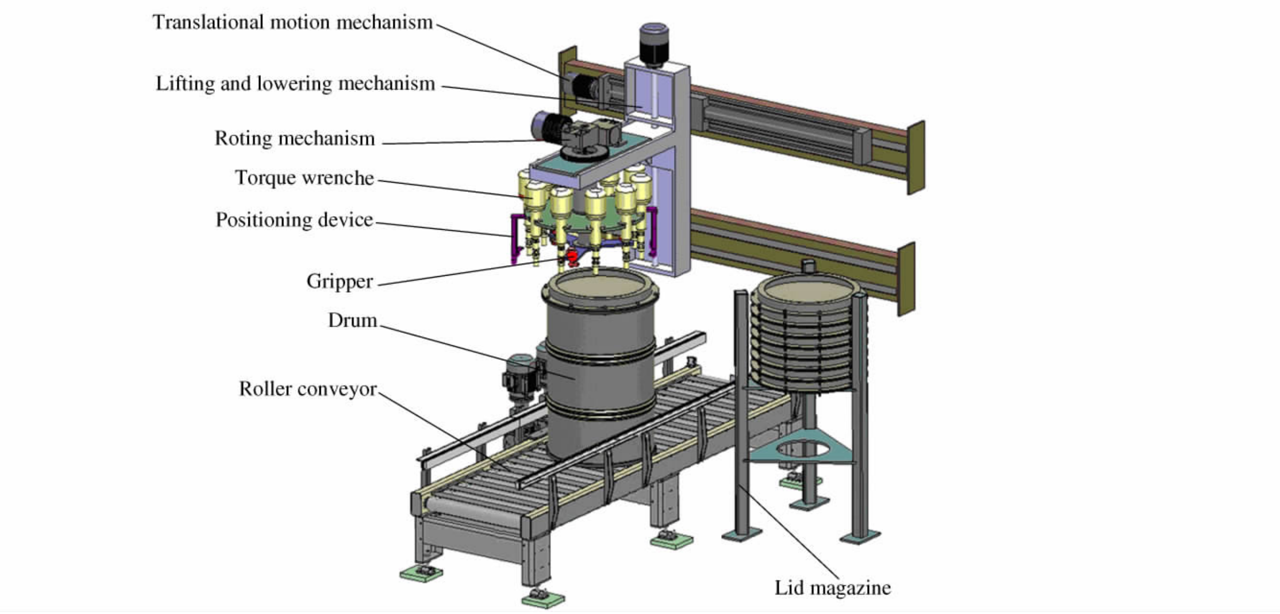

Figure 2 Design model of automatic capping device

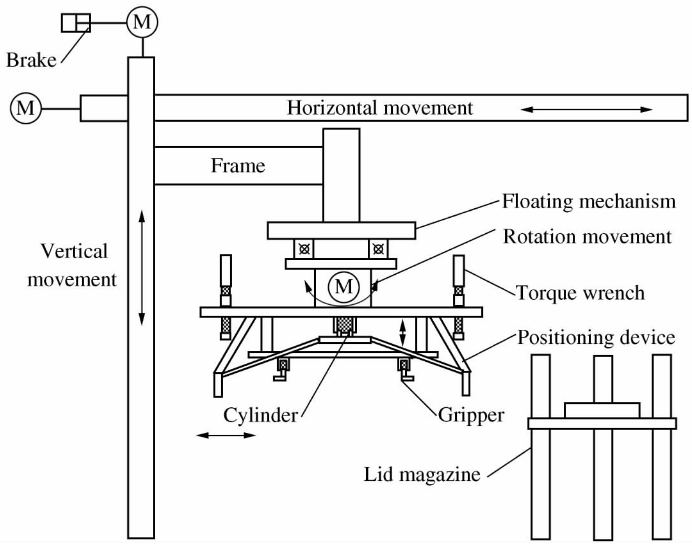

Figure 3 Schematic diagram of automatic capping device

Flange outer circumference of the lid is taken as the position reference for positioning device. During clamping the lid process, the positioning device makes sure the rotation axis of the tightening machine with the central axis of the drum depended on the floating mechanism. Then driving the rotating mechanism, the tightening machine can find the screws or screw holes depended on sensors, and it makes alignment between screws and torque wrenches.

4 FMEA

FMEA is extremely efficient when it is applied to the analysis of elements that cause a failure of the entire system or of a major function of the system.

Some of the detailed applications and benefits of FMEA are listed below [5-8]:

1) To provide designers with an understanding of the factors which influence the reliability of the system.

2) To avoid costly modifications by the early identification of design deficiencies.

3) To determine the need for the design methods for reliability improvement (redundancy, operational stresses, fail safe, component selection and de-rating, etc.).

4) To focus upon key areas in which to concentrate quality control, inspection and manufacturing process controls.

5) To facilitate or support the determination of test criteria, test plans and diagnostic procedures, for example: performance testing, reliability testing.

6) To assist in defining various aspects of the general preventive maintenance strategy and schedule.

The FMEA consists of the following main stages:

1) Define system boundary for the analysis

2) Establish reliability model

3) Identify failure modes

4) Identify potential causes of the failure mode

5) Identify effect of the failure mode and severity of the final effect

6) Develop design prevention and improvement measures

4.1 Defining system boundary for the analysis

The system boundary forms the physical and functional interface between the systems. Automatic capping device is mainly composed of electrical system, pneumatic system, control system and mechanical system. The first three is based on a mature design, which has a good reliability, maintainability and safety record. But the mechanical system is non-standard design, which has newly designed elements and unknown reliability history. Therefore, greater detailed analysis should be indicated for the mechanical system.

The mechanical system is represented in a hierarchical block diagram form, seen as Figure 4.

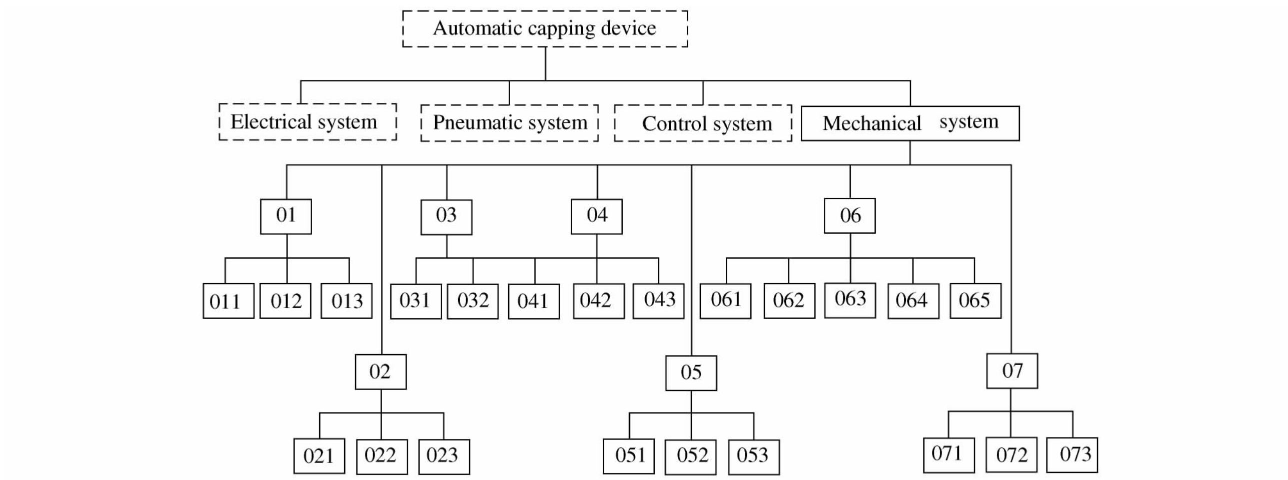

Figure 4 System block diagram of automatic capping device

Table 1 List of composition parts

Code	Item ref.	Code	Item ref.
01	Translational motion mechanism	041	Rail
02	Lifting and lowering mechanism	042	Rail
03	Steel structure	043	Brake
04	Floating mechanism in X direction	051	Rail
05	Floating mechanism in Y direction	052	Rail
06	Rotating mechanism	053	Brake
07	Lid magazine	061	Gear pair
011	Linear guide rail	062	Motor
012	Linear guide rail	063	Positioning device
013	Motor	064	Gripper
021	Linear guide rail	065	Torque wrenches
022	Brake	071	Landing leg
023	Motor	072	Supporting plate
031	Supporting structure	073	Guide block
032	Bolts		

4.2 Reliability model

The reliability of equipment can be represented by the models of basic reliability and mission reliability. The former is used to represent the equipment reliability in the service life; the latter is used to represent the reliability of equipment to complete the task during operation. Based on the function requirement of automatic capping device, it is the key to ensue the mission reliability of the equipment for the safe operation of TES.

Reliability model is composed of reliability block diagram and mathematical model. In order to indicate fault logical relationship among composition parts, a mission reliability block diagram is established based on the system block diagram and the equipment principle, seen as Figure 5.

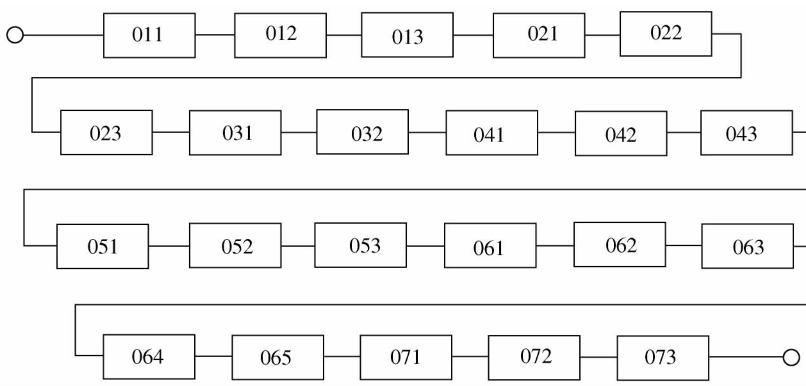

Figure 5 Reliability block diagram

In order to describe the mission reliability of automatic capping device by mathematical model, a formula is established based on the mission reliability block diagram. Because any part of the failure will cause the whole of automatic capping device failure, so it is series model [7].

$$R_s(t) = \prod_{i=1}^{n} R_i(t) \qquad (1)$$

Where $R_s(t)$ is eliability degree of the system; $R_i(t)$ is eliability degree of composition parts; n is umber of composition parts.

From the formula, the reliability degree of automatic capping device is the product of reliability degree of composition parts.

4.3 Failure mode and effect

Failure criterion: based on the function requirement of automatic capping device, the definition of failure criterion is: if any part of automatic capping device doesn´t complete the mission according to the requirements or orders, it is a failure mode.

A failure effect is the consequence of a failure mode in terms of the operation, function or status of a system. A failure effect may also influence the next level up and ultimately the highest level under analysis. Therefore, at each level, the effect of failures on the level above should be evaluated.

Severity classification: Severity is an assessment of the significance of the failure mode´s effect on item operation.

The FMEA worksheet captures the details of the analysis in a tabularized manner.

Table 2 Failure effects at the system level

Level	Definition
Local effect	1 class: composition part complete loss function. 2 class: composition part function degradation. 3 class: no loss or significant degradation of composition part function.
Higher level effect	1 class: the mechanical system complete loss function or can not return safe state. 2 class: the mechanical system function degradation. 3 class: no significant degradation of the mechanical system function. 4 class: no loss function.
Final effect	1 class: TES is badly damaged. 2 class: TES can not normal operation or automatic capping device is badly damaged. 3 class: automatic capping device is mild damaged or can not complete the mission. 4 class: automatic capping device can complete the mission, but need maintenance.

Table 3 Severity classification for final effects

Severity level	Definition
Ⅰ Class(Catastrophic)	A failure mode which could potentially result in the failure of primary functions and therefore causes serious damage to TES and radioactivity pollution or personal injury.
Ⅱ Class(Critical)	A failure mode which could potentially result in the failure of primary functions and therefore causes considerable damage to TES and excessive radiation dose, but which does not constitute a serious threat to life or injury.
Ⅲ Class(Marginal)	A failure mode, which could potentially degrade automatic capping device function without appreciable damage to the system or threat to life or injury.
Ⅳ Class(Insignificant)	A failure mode which could potentially degrade automatic capping device function but will cause no damage to the system and does not constitute a threat to life or injury.

Table 4 FMEA worksheet

Code	Failure mode	Possible failure causes	Failure effect			Severity
			1	2	3	
01	Horizontal beam deformation	Stiffness is not enough	2	2	3	Ⅲ
	Guide rail gap become bigger	Guide rail wear	2	2	3	Ⅲ
	Motor failure	Wiring loose or motor damage	1	1	2	Ⅱ
02	Vertical beam deformation	Stiffness is not enough	2	2	3	Ⅲ
	Guide rail gap become bigger	Guide rail wear	2	2	3	Ⅲ
	Motor failure	Wiring loose or motor damage	1	1	2	Ⅱ
03	Supporting beam deformation	Stiffness is not enough	2	3	3	Ⅲ
	Connection loose	Caused by vibrations	3	4	4	Ⅳ
04	Supporting beam deformation	Stiffness is not enough	3	4	4	Ⅳ
	Guide rail gap become bigger	Guide rail wear	3	4	4	Ⅳ
	Brake failure	Long-term use	2	2	3	Ⅳ
05	Supporting beam deformation	Stiffness is not enough	3	4	4	Ⅳ
	Guide rail gap become bigger	Guide rail wear	3	4	4	Ⅳ
	Brake failure	Long – term use	2	2	3	Ⅳ
06	Beyond tolerance limits of gear pair	Gear pair wear	2	2	3	Ⅲ
	Motor failure	Wiring loose or motor damage	1	1	2	Ⅱ
	Beyond tolerance limits of positioning	Positioning device wear	2	2	3	Ⅲ
	Gripper failure	Cylinder failure	2	1	2	Ⅱ
	Torque wrenches failure	Clamping stagnation for foreign bodies or insufficient air supply	1	1	3	Ⅳ
07	Landing leg deformation	Stiffness is not enough	2	2	3	Ⅲ
	Supporting plate isn´t stable	Long-term use	3	4	4	Ⅳ
	Guide block loose	Caused by vibrations	2	2	3	Ⅲ

5 Design defects and weak links

From the FEMA worksheet, it is indicated that the severity level of automatic capping device is Ⅱ class for the most serious failure effects. These failure modes may cause considerable damage to TES and excessive radiation dose.

Two main reasons caused serious failure are as follows:

First, the function of horizontal movement, vertical movement and rotation movement is failure. These failure modes will make the tightening machine of automatic capping device difficult to move, and can't keep a safe distance with the metallic drum. It also prevents the transportation of the metallic drum on roller conveyor.

Second, the gripper of tightening machine is failure. This could happen in the following situations:

1) During uncapping process, the gripper can not grip the lid well. The lid has a risk of falling, which affects the safe operation of TES;

2) During capping process, the gripper can not loosen the lid well. The tightening machine can not break away from the metallic drum, which prevents the transportation of the metallic drum on roller conveyor.

Therefore, in order to avoid failure mode that severity level is Ⅱ class and ensure the safe operation of TES, this requires no matter what automatic capping device happened, it would not affect the safe operation of TES or prevent the transportation of the metallic drum on roller conveyor.

6 Design prevention and improvement measures

The reliability of automatic capping device can be improved in both ways.

1) Improve the mission reliability of automatic capping device and the ability of resistance to failure, and ensure automatic capping device completing the task well.

2) Avoid the most serious failure mode occurrence, and ensure the safe operation of TES, which can not cause considerable damage to TES and excessive radiation dose.

First measure: Improving the mission reliability.

From the formula (1), the mission reliability of automatic capping device is series model. The reliability degree of automatic capping device is the product of reliability degree of composition parts. The more number of composition parts, the lower of the reliability degree of automatic capping device. From reliability design consideration, to improve the reliability of series system can take the following measures:

1) As far as possible to reduce the number of composition parts, it means that the design should be more simplified.

2) As far as possible to improve the reliability of composition parts through using mature design or production that has a good reliability.

3) For composition parts that affect the safety or pivotal missions to perform, adopting the design method of reducing rating. Especially, for various supporting

structure and electrical components, its rated load should be reduced to ensure enough safety margin, thus reducing failure probability during operation.

Second measure: Avoiding the most serious failure mode occurrence.

Redundancy design is an effective method to improve the ability of resistance to failure and system reliability. After using the redundancy design, the non-working standby unit will increase. Even if the unit of work fails, the system can continue to work by switching to another unit until all the unit fails. Then the mission reliability of automatic capping device is non - work standby model[7].

Assume the reliability degree of switching device is constant R_D, for two work units that the life obey exponential distributions, if their failure rates are λ_1, λ_2, respectively, then the reliability degree of the system is the formula(2).

$$R_s(t) = e^{-\lambda_1 t} + R_D \frac{\lambda_1}{\lambda_1 - \lambda_2}(e^{-\lambda_2 t} - e^{-\lambda_1 t}) \quad (2)$$

The mean time between significant failures of the system is the formula (3).

$$T_s = \frac{1}{\lambda_1} + R_D \frac{1}{\lambda_2} \quad (3)$$

From the formula (2) and (3), non - working standby unit can improve the reliability degree of the system, but because of increasing the switching device, the basic reliability of the system will be reduced. Therefore, redundancy design is applied only for most serious failure mode of automatic capping device.

Based on the FMEA, one can draw a conclusion that the key resulting in most serious failure mode occurrence is translational motion mechanism, lifting and lowering mechanism and rotating mechanism. According to the failure effect, one can identify that the motor failure is the most important failure mode. Therefore, the redundancy design setting up non - work standby motors is an effective method to avoid most serious failure mode occurrence on the translational motion mechanism, lifting and lowering mechanism and rotating mechanism.

7 Conclusions

Using FMEA method and analyzing the function, structure and principle of automatic capping device, we find out that the severity level of automatic capping device is Ⅱ class for the most serious failure effect. These failure modes may be cause considerable damage to TES and excessive radiation dose. The key resulting in most serious failure mode occurrence is the translational motion mechanism, lifting and lowering mechanism and rotating mechanism of automatic capping device.

In order to avoid failure mode that severity level is Ⅱ class and ensure the safe operation of TES, it is suggested that no matter what automatic capping device happened, it would not affect the safe operation of TES or prevent the transportation of the metallic drum on roller conveyor.

Finally, specific design prevention and improvement measures are provided and carried out. And the reliability of automatic capping device is improved form both ways: improving the mission reliability and avoiding most serious failure mode occurrence.

References

[1] Yang M, Zhang Z J. Study on quantitative reliability analysis by multilevel flow models for nuclear power plants [J]. Nuclear Power Engineering, 2011, 32(4): 72-76 (in Chinese)

[2] Lu W Y, Li X M. Exploration & practice of reliability management system for nuclear power station equipment [J]. Nuclear Power Engineering, 2005, 26(6): 65-72 (in Chinese)

[3] Zeng S K, Ma J M, Li F X. Design optimization considering performance and reliability [C] //Reliability and Maintainability Symposium, 2009

[4] Ke W, Ren C, Jin K, *et al*. System performance, degradation, and reliability assessment [C] //Proc. on IEEE International Conference of Industrial Engineering and Engineering Management, 2007

[5] Zhang H, Zhou Z B. The Process of FMEA [J]. Technology of Navigate Manufacture, 2007, (8): 66-68 (in Chinese)

[6] Yang Z L, STEVE Bonsall, Wang J. Fuzzy rule-based bayesian reasoning approach for prioritization of failures in FMEA [J]. IEEE Transactions on Reliability, 2008, 57 (3): 517-528

[7] Gong Q X, Zhao Y. Engineering handbook of modeling reliability [M]. Beijing: National Defense Industry Press, 2007 (in Chinese)

[8] GB/T 7826 - 2012, Analysis Techniques for System Reliability-Procedure for Failure Mode and Effects Analysis (FMEA) [S]. 2012 (in Chinese)

Brief Biographies

ZHANG Feng is a master degree, and is now a engineer in China Nuclear Power Design Co., Ltd (Shenzhen). His research interests include equipment design, equipment reliability and virtual prototyping technology. zhangfeng1@cgnpc.com.cn

HE Ying-yong is a bachelor degree, and is now a engineer in China Nuclear Power Design Co., Ltd (Shenzhen). His research interests include equipment design and virtual prototyping technology.

Ren Xian-chang is a master degree, and is now a engineer in China Nuclear Power Design Co., Ltd (Shenzhen). His research interests include equipment design and equipment reliability.

YANG Jin-chun is a bachelor degree, and is now a senior engineer in China Nuclear Power Design Co., Ltd (Shenzhen). His research interests include equipment design and virtual prototyping technology.

ZHENG Zhi-shou is a bachelor degree, and is now a researcher-level senior in China Nuclear Power Design Co., Ltd (Shenzhen). His research interests include equipment design, equipment reliability and virtual prototyping technology.