Reliability Assessment of RIC Neutron Flux Measurement System

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Abstract. Nuclear power core neutron flux measurement system is a special tool for real-time accurate measurement of nuclear reactors, which requires not only high technically demanding, but also has high requirements for reliability. Compared with the advanced level in foreign countries, there is still a certain gap between the reliability and stability of domestically produced products. Taking the prefabricated water level monitoring system as an example, this paper adopts the risk priority number method to carry out the failure mode and impact analysis, and divides the system into various agreements. Level, a detailed analysis of all possible failure modes, causes of failure, severity of consequences, probability of occurrence, and degree of damage. Meanwhile, the reliability prediction model is established to carry out quantitative analysis. According to the fmea result and the reliability prediction model, more serious failure modes and modules with higher failure rate are discussed. Based on this, the design improvement direction of the water level monitoring system of the core operation state monitor is proposed.

1. Introduction
The physical functional layer, mechanical layer and signal layer of the core neutron temperature detector assembly are organically combined to comprehensively realize the monitoring of key parameters of the core operating state, and perform functions from the perspective of system theory. Decomposition and functional coupling, using qualitative analysis and quantitative analysis to the reliability analysis of the combined method.

The core neutron flux measurement subsystem enables on-line continuous monitoring of core neutron flux by measuring a series of simultaneous signals generated by seven SPND placed along the height of the reactor core. The core neutron flux measurement subsystem includes a neutron-temperature detector for neutron flux and temperature detection, as well as a neutron signal processing cabinet.

It consists of self-powered detectors, thermocouples, thermal resistors, connectors, and cladding materials. The core neutron flux, the coolant temperature at the outlet of the fuel assembly, and the head temperature on the pressure vessel are measured.

The core neutron flux signal processing cabinet adopts a 5-layer layout: the first layer is the power supply chassis for processing the power input part; the second to fourth floor chassis is the signal processing chassis, which can process 12 detector signals; The fifth layer is the monitoring chassis, which is used to display and monitor the cabinet status, board status, and related tests for the cabinet. It is mainly composed of the following parts: the power processing part is used to supply power to the entire cabinet; the processing part provides detector signal conversion. The acquisition and processing of the signal and the signal; the transfer part transfers the signal to the front current collecting module through the backplane; the data processing part is responsible for combining the data from the three-
layer processing chassis into a certain format and sending the data to the monitoring module and online. Monitor the cabinet; and the local monitoring section and the fan section. The core neutron flux signal processor communication architecture is shown in the figure below.

Figure 1. Core neutron flux signal processing architecture

2. System Reliability Analysis
The US military standard mil-std-721b gives a more formal definition of reliability, which refers to the ability of a product to perform a specified function within specified conditions and within a specified time. This definition has also been adopted in other countries, and the definition of reliability given by China's standard gb-3187-82 is also the same. The reliability analysis of the core operation status monitor is oriented to the key functional characteristics of the core operation status monitor, and establishes the failure model of the instrument to solve the problem that the nuclear safety equipment may not be able to perform safety functions due to component and device failure. Provide quality and reliability work guidance for the entire project by developing an overall quality and reliability design.

Reliability analysis, which means the failure mode, impact, mechanism and consequences of the product [1]. In terms of qualitative analysis, fmea analysis is generally carried out according to the relevant national standard gjb/z 1391-2006; at the same time, in the prefabrication stage of the product, reliability is expected to be an effective quantitative analysis method to find weaknesses in advance and effectively reduce the cost and time of R&D changes. This paper combines quantitative analysis and qualitative analysis to conduct a more comprehensive reliability analysis.

2.1 Introduction to Fmea Analysis
Fmea is an internationally recognized and effective reliability design analysis technology, which is widely used in engineering practice [2]. Through the three-level analysis and evaluation of the instrument, module and device, the whole process is analyzed from bottom to bottom, and each failure mode of each device is used to ensure that it can be fully considered within the possible range and indicate various potentials. Failure mode and its associated cause/mechanism. The final product and each associated system, subsystem, and component [6] should be evaluated.

Fmea failure mode impact analysis is to analyze the various failure modes that may occur in each component constituting the product and its impact on the overall function of the product during the design process of the entire system, and all possible failures. The model is categorized according to the severity of the impact it can have, and the corrective measures that can be taken are identified accordingly.

2.2 Define the Agreed Hierarchy, Severity and Probability of Occurrence
In the fmea analysis, according to the relevant standards, it is necessary to first divide the agreement
level, the severity and the probability level. The significance of this is to quantify the severity level of each failure mode and mechanism and the frequency of failure occurrence. This is the key to determining key failure modes and mechanisms, and improving product quality and reliability [6].

According to its accurate measurement signal acquisition function for water level information, its structure is decomposed and the division level is as follows:

1) Initial agreement level: neutron flux monitoring system.
2) Second agreement level: each module.
3) Minimum agreement level: the lowest level of the circuit, including the connector, mcu and so on. The agreed hierarchy of fmea analysis is shown in the figure:

![Figure 2. Level of FMEA analysis agreement for neutral cabinet](image)

The fault severity level (esr) is the level of severity of the impact on the failure mode. In the neutron flux monitoring system, it refers to possible mission failures, loss of function, and economic loss. The fmea method determines the fault severity rating (esr) scoring criteria according to the impact of each fault mode on the water level monitoring system as shown in Table 1. The probability of occurrence (opr), according to the probability of occurrence of each failure mode of the water level monitoring system, defines its occurrence probability level and the definition of the scoring standard as shown in Table 2:

### Table 1. Fmea severity definition

| Category | Esr rating | Esr score | Definition                                             |
|----------|------------|-----------|--------------------------------------------------------|
| I        | disaster   | 9, 10     | Loss of major or critical functions                    |
| II       | fatal      | 7, 8      | Loss of major or partial critical functions            |
| III      | serious    | 4, 5, 6   | Part of the key performance degradation, affecting the execution of the main functions |
| IV       | Mild       | 1, 2, 3   | Mild damage does not affect the execution of major functions |

### Table 2 Fmea occurrence probability definition

| Grade | Opr score | Possibility of occurrence |
|-------|-----------|----------------------------|
| A     | 9, 10     | very high                  |
| B     | 7, 8      | high                       |
| C     | 4, 5, 6   | medium                     |
| D     | 2, 3      | Lower                      |
| E     | 1         | Very low                   |
Multiply the severity rating of each failure mode by the failure mode occurrence probability score to obtain the risk priority number (rpn) of the failure mode:

$$\text{RPN} = \text{ESR} \times \text{OPR}$$

Rpn represents the magnitude of the hazard generated by this failure mode. The larger the value, the more important it is to analyze and eliminate hidden dangers in the prefabrication process.

2.3 Determine the Fmea Form

Analysis of the reliability prediction below, we can know that the weak link, that is, the part with high failure rate is the main control module, input and output module, so the main potential failure mode, cause and influence are determined according to the agreed level. See Table 3.

| Module | Unit name | Main control module, input and output module |
|--------|-----------|---------------------------------------------|
| Circuit name | chip | Power supply | Reset | Configuration |
| | | 16MHz clock output is out of tolerance or no output | 16MHz clock output is unstable | Cold reset failure |
| | | Crystal degradation | Crystal or peripheral circuit drift | Series resistance open circuit |
| | | Arm reset | Armjitag interface is invalid |
| Failure mode | Data processing error | Unstable work |
| | | 16MHz clock output is out of tolerance or no output |
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| Module | Main control module, input and output module |
|--------|---------------------------------------------|
| Unit name | WD | FPGA |
| Circuit name | Clock | Reset chip | power supply |
| Failure mode | Jtag reset failure | Wd-jtag interface is invalid | Not working | Data processing error | Unstable work | No 1.2v voltage input | No 3.3v voltage input |
| the reason | Series resistance open circuit | Open connector, series open circuit, capacitor short | Fpga failure | Fpga status is abnormal | Fpga or peripheral circuit parameter drift | Capacitor short circuit | Capacitor short circuit |
| Local influence | Wd cannot be reset during debugging | Unable to debug wd via jtag | Data communication failure | Data communication error | Unstable data communication | Fpga power down does not work | Fpga power down does not work |
| Detection method | no | no | Wd monitoring | Fpga monitoring redundancy | Fpga communication diagnostics or wd monitoring | Arm voltage monitoring | Arm voltage monitoring |
| Compensation measure | no | no | Choose a highly reliable fpga chip and take into account device cooling | Fpga internal redundancy design | Choose a highly reliable fpga chip and take into account device cooling | Decoupling capacitor derating to improve reliability | Decoupling capacitor derating to improve reliability |
| Overall impact | No significant impact on the runtime | No significant impact on the runtime | Stop running and enter safe mode | Stop running and enter safe mode | Alarm, reset, or stop running according to the specific conditions of the fault | Stop running and enter safe mode | Stop running and enter safe mode |
| ESR | 1 | 1 | 6 | 4 | 3 | 4 | 6 |
| OPR | 1 | 1 | 1 | 1 | 3 | 1 | 2 |
| RPN | 1 | 1 | 6 | 4 | 93 | 4 | 12 |

| Module | Main control module, input and output module |
|--------|---------------------------------------------|
| Unit name | 50MHz clock output is out of tolerance or no output | 50MHz clock output is unstable | No 125MHz clock output or output tolerance | 125MHz clock output is unstable | 50MHz clock output is unstable or no output | Power-on reset failure |
| Circuit name | clock |
| Failure mode | 50MHz clock output is out of tolerance or no output | 50MHz clock output is unstable | No 125MHz clock output or output tolerance | 125MHz clock output is unstable | 50MHz clock output is unstable or no output | Power-on reset failure |
| the reason | Crystal degradation | Crystal or peripheral circuit drift | Crystal failure, short circuit of decoupling capacitor, open circuit of load capacitance | Crystal or peripheral circuit drift | Crystal or peripheral circuit drift | Series resistance open circuit |
| Local influence | Fpga clock out of tolerance does not work | Fpga is unstable | Fpga no clock source does not work | Fpga is unstable | Wd is unstable | Wd cannot be reset when the power is turned on or the io voltage is abnormal. |
### Detection method

|                      | Wd monitoring | Fpga clock monitoring or wd monitoring | Wd monitoring | Fpga clock monitoring or wd monitoring | no | no |
|----------------------|---------------|----------------------------------------|---------------|----------------------------------------|----|----|

### Compensation measure

|                      | Select active crystal oscillator with stable signal and good quality | Select active crystal oscillator with stable signal and good quality | Select active crystal oscillator with stable signal and good quality | Select active crystal oscillator with stable signal and good quality | no | no |
|----------------------|------------------------------------------------------------------|------------------------------------------------------------------|------------------------------------------------------------------|------------------------------------------------------------------|----|----|

### Overall impact

|                      | Stop running and enter safe mode | May cause an abnormal operation or increase the risk of communication failure | Stop running and enter safe mode | May cause an abnormal operation or increase the risk of communication failure | Arm and fpga running status monitoring abnormality, diagnostic ability is degraded | Wd power-on initialization error, voltage cannot be reset |
|----------------------|----------------------------------|-------------------------------------------------------------------------|----------------------------------|-------------------------------------------------------------------------|--------------------------------------------------------------------------------|------------------------------------------------------------------------|

| ESR                  | 3                               | 3                                                                       | 3                               | 2                                                                       | 2                                                                         | 2                                                                         |
| OPR                  | 1                               | 1                                                                       | 3                               | 1                                                                       | 1                                                                         | 2                                                                         |
| RPN                  | 3                               | 3                                                                       | 9                               | 2                                                                       | 2                                                                         | 4                                                                         |

### 3. Reliability Prediction

Reliability prediction refers to the quantitative estimation of product structure, function, working environment and other information in the product design stage, so as to evaluate the reliability level of its unit and system [3], which is an effective tool for product design process. The reliability prediction can be used to evaluate whether the reliability index of the product meets the design requirements, find the weak link of the design, and provide a basis for design improvement [4].

#### 3.1 Module Level is Expected

For each functional module of the neutron flux monitoring system, in the specified conditions (operating environmental conditions) and mission time (normal operating period), any condition that causes the module function to be unachieved or the performance index to decrease is classified as a fault. The basic reliability model is a series model, that is, the module must work properly to ensure that all components can work normally, and failure of any component will result in partial loss of function or performance degradation (not necessarily affecting key functions). In the detailed design phase, the reliability prediction hierarchy is set to the component level, and information such as schematics, device manuals, and expected standards are entered as basic data to calculate component and module failure rates. The results are expected to characterize reliability and risk in a probabilistic manner.

The basic reliability mathematical model of the module is as follows:

\[
R_M = \prod_{i=1}^{n} R_{Ci}, (i = 1, 2, \cdots, n) \quad (1)
\]

\[
R_M = e^{-\lambda_M t}, \quad R_{Ci} = e^{-\lambda_{Ci} t} \quad (2)
\]

\[
\lambda_M = \sum_{i=1}^{n} \lambda_{Ci} \quad (3)
\]

Among them,

- \(R_M \) - module reliability
- \(R_{Ci} \) - Reliability of the \(i\)th component
- \(\lambda_M \) - module failure rate
- \(\lambda_{Ci} \) - the failure rate of the \(i\)th component
Referring to the SN29500 standard, the reliability calculation of the integrated circuit in the main control module is taken as an example. The calculation process is as follows:

According to the above process, the failure rate of each module and the expected mtbf can be calculated. The detailed results are shown in Table 4:

| Serial number | Module                  | Failure rate (fit) | Mtbf (hours) |
|---------------|-------------------------|--------------------|--------------|
| 1             | Master module           | 3614               | 276709       |
| 2             | Power interface module  | 480                | 2084071      |
| 3             | Power adapter module    | 37                 | 27027027     |
| 4             | Communication module i/ii/iii/iv | 2677             | 373494       |
| 5             | Chassis backplane       | 2203               | 454013       |
| 6             | Expansion module        | 3349               | 298581       |
| 7             | Ai module               | 6363               | 157150       |
| 8             | Ao module               | 6676               | 149791       |
| 9             | Di module               | 4987               | 200533       |
| 10            | Do module               | 6045               | 165417       |
| 11            | Thermocouple module     | 2891               | 345949       |
| 12            | Thermal resistance module| 2693             | 371344       |
| 13            | Signal switching module | 55                 | 18115942     |
| 14            | Spmd signal processing module | 3401           | 294031       |

### 3.2 System Level Forecast

Before the system-level reliability prediction is carried out, it is necessary to establish a reliability model reflecting the reliability of the component module according to each module of the neutron flux monitoring system. The reliability model of the prefabricated neutron flux monitoring system can be represented by a reliability block diagram. Said. Each module can be represented by the box in the figure below.

![Figure 3. Neutron flux monitoring system rbd model 2](image-url)

After the reliability model is determined, the reliability prediction work can be carried out, and the reliability of each module of the prefabricated water level monitoring system is quantitatively...
predicted from the aspect of probability statistics. The method used is the component counting method and the stress analysis prediction method. The component counting method is based on the reliability prediction of the component type, quantity, and quality level. The stress analysis is expected to be performed after the mage considers the actual stress of the component. Estimated method. Because the component failure rate model and data are relatively complete; both methods can be used at the same time, which can comprehensively and correctly reflect the reliability status of each module, so that by comparing the weak links in the design, there are several basics before the prediction. Assumption:

1) During the life of the product, the failure of the component is exponentially distributed, and the failure rate is constant; the failure rate refers to the product that has not been invalidated at a certain time. After that time, the probability of failure per unit time is generally recorded. For \( \lambda \)

2) The failure of different components is statistically considered to be independent of each other;

3) The module's reliability prediction model is a series model—any component failure will cause the module to fail;

4) The module operates in a normal temperature working environment with a stable ground.

The reliability formulas of series, parallel and voting structures are as follows:

\[
R_{sys}(t) = \prod_{i=1}^{n} R_i(t) \quad (4)
\]

\[
R_{sys}(t) = 1 - \prod_{i=1}^{n} [1 - R_i(t)] \quad (5)
\]

\[
R_{n,k} = \sum_{i=k}^{n} C_n^i R^i (1 - R)^{n-i} \quad (6)
\]

Moreover, the conversion relationship between reliability and failure rate lambda and MTBF is as follows:

\[
R(t) = e^{-\lambda t} \quad (7)
\]

\[
MTBF = 1 / \lambda \quad (8)
\]

The above model and module-level parameters can be obtained by substituting them into system-level RBD calculation:

\[
R = [1-(1-R_a)^3] \cdot [1-(1-R_m)^3] \cdot R_{SP} \cdot [1-(1-R_p)^3] \cdot [1-(1-R_y)^3] \cdot \sum_{i=1}^{22} C_2^i R_{SPYD}(1-R_{SPYD})^{22-i} \quad (9)
\]

\[
MTBCF = \frac{\int_{0}^{T_o} R(t)dt}{1-R(T_o)} \quad (10)
\]
Figure 4. MTBCF of neutron cabinet

In the figure, the MTBCF has a C more than the MTBF, that is, Critical, which refers to the degree of influence on the reliability of the system when the protection design such as redundancy also fails. MTBF usually means that any component failure is considered to be a failure. MTBCF usually means that the system fails when the redundant structure fails. Sometimes MTBF is used to mean MTBCF.

In summary, the mtbcf (mtbf) of a single neutron cabinet is 121,358 hours, meeting the reliability requirements of the neutron flux monitoring system. At the same time, if the alarm function of the cabinet is considered, that is, the di and do modules are counted, the reliability index will decrease and the above requirements will not be met. It can be seen that the module-level redundancy design provides an appropriate margin for system reliability.

4. Reliability Analysis of Water Level Monitoring System

Analysis of the fmea analysis results of Table 3, together with the reliability prediction results of Table 4, for the neutron flux monitoring system, the module with the highest failure rate is the main control module, the signal processing module and the input and output module, and the signal processing module part is also the most harmful, and the system cannot complete the critical work, and the signal processing function is completely lost and the system is crashed.

Among them, the thermocouple module and the thermal resistance module have a large number of boards, and there are many thermocouples and thermal resistance channels, etc., and the possibility of failure is relatively large. The design can consider the use of better quality, corrosion-resistant boards, in addition, can be periodically tested in non-operating state, the signal processing chassis of each board, thermocouple and RTD channels, heating current channels Checksum detection to determine possible faults. For example, su uses the signal generator to inject the corresponding check signal to determine whether the thermocouple and the thermal resistance channel meet the requirements; forcibly, the corresponding board outputs the corresponding logic quantity, and judges whether the do board has a fault through the do feedback value; The channel switching forces the reference temperature change to control the heating current change and compares whether the heating current channel meets the requirements. Through design and periodic testing and improved reliability.

For input and output modules with high failure rate, since these two units adopt full hardware design and many interfaces, it is important to improve the reliability from the design, selection and operation of the board. From the design, you can choose a better quality board, pay attention to heat dissipation and timing cleaning to prevent the board from overheating. At the same time, it should pay attention to the standard operation during the use process, and also increase the external current protection device to ensure the acquisition and output of the cabinet signal.

According to the above analysis, it can be found that there is a coupling correspondence between
the fmea analysis and the reliability prediction of the neutron flux monitoring system. The reason is that the more important the module function is, the more complicated the corresponding structure is, and the more components are. The more complex the reliability model of the structure, the higher the failure rate of the whole module; on the other hand, the reliability analysis is related to the importance of the module and the probability of failure. In the water level monitoring system, the core modules need different types. Electronic devices such as boards are used to implement functions, making them more likely to malfunction. Therefore, whether using the fmea analysis at the beginning of the project design or the mid-term reliability prediction of the project, it has an extremely important guiding role in the reliability analysis of the prefabricated water level monitoring system.

5. Conclusion
Reliability focuses on the ability to evaluate the normal operation of the item. Considering the actual situation, this paper adopts the risk priority method to carry out fmea analysis on the core neutron flux monitoring system. The minimum agreed level of fmea is defined as each component. At the same time, the reliability model is given, and the reliability prediction calculation is carried out on this basis. The result is used as the basis for quantitative analysis, and the simulation of mtbcf is carried out based on the results. The results show that the mtbcf of the system meets the reliability requirements, and points out the key parts of the system and the failure mode. The failure mode of fpga is not working properly and the failure mode is more harmful. At the same time, for the various failure modes of the prefabricated water level monitoring system, some design improvement suggestions and some test methods are proposed, which provides a powerful reference for improving the reliability of the system.

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