Research and analysis of the availability of nuclear power units during the design phase

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Abstract. Safety and economy are important criteria for measuring new type of nuclear power units. How to preliminarily calculate and improve the availability of NPP at the design phase becomes the main goal in the future, which can avoid a lot of resources consumption due to design defects to increase the availability of units during the follow-up operation. At present, European Utility Requirements (EUR) and Utility Requirement Document (URD) all require the availability of more than 90% in third-generation nuclear power units. Therefore, based on the existing operation and maintenance data of nuclear power units, a dynamic calculation model of availability of nuclear power units applicable to the design phase is constructed. Adapting to the design improvements of nuclear power units, the dynamic calculation model simulates a possible outage critical path of nuclear power units through iterative calculation and evaluates the availability of the units during the design phase, so as to improve the availability of the units, which is forward-looking and practical in the power generation of nuclear power units in the future.

1. Introduction

With the increase of experience in nuclear power unit design and operation, nuclear power companies are constantly pursuing and developing nuclear power units of high safety and high economic efficiency. For nuclear power units in operation, they mainly explore and optimize outage critical path to increase the availability of the units, such as the nuclear power plants in France in 1990, the United States nuclear power plants in 2002, etc... China General Nuclear Power Group (CGN) Daya Bay Nuclear Power Operations and Management Co., Ltd. has been undertaking the outage critical path optimization since 2004 and has got some economic benefits.

With the emergence of third-generation and four-generation nuclear power units concepts, the safety and design requirements of the third-generation nuclear power plants proposed by the URD and EUR have become guidelines for new nuclear power units in many countries. At present, there are few studies on unit availability for new nuclear power units during the design phase. There are many uncertainties in the unit during the design phase, such as the uncertainty of equipment type and the lack of upstream files, which restricts the estimate of the unit availability. From the perspective of exploring the availability of the new nuclear power units in the design phase, the paper actively learns from the outage experience data of nuclear power units in operation, overcomes the lack of outage data, and simulates and establishes a set of prediction methods for the estimate of nuclear power unit availability in the design phase. The prediction methods can be used as a reference for estimating the availability of a new type of nuclear power unit.

2. General Technical Route

Based on the extensive investigation and study of nuclear power units in operation, calculate the availability of nuclear power units at the design phase. Firstly, it needs to establish the calculation
model of unit availability, and then determine the resources needed for the calculation of relevant parameters. Secondly, it is necessary to identify the related systems and equipment involved in outage, and to formulate preventive maintenance strategies. The strategy not only includes preventive maintenance items prescribed by laws and regulations, such as in-service inspection (In-Service Inspection Rule for Mechanical Components of PWR NI, short for RSEM) items, periodic tests surveillance (PTS) items, but also includes mechanical and electrical equipment preventive maintenance items which is resulting from analysis method of reliability centered maintenance (RCM) theory to ensure equipment reliability. Finally, a software platform is necessary to evaluate the outage items implementation time and simulate the outage critical path of various outage types. The whole process is also limited by many factors in the design phase, such as lack of equipment information, unidentified maintenance strategies of units, etc., which needs to perform functional analysis and comparison, and refer to the experience feedback of nuclear power plants and implement analogy, etc.

The specific steps include: availability model construction, systems and equipment identification, systems and equipment maintenance strategies formulation, strategies implementation schedule analysis, strategies implementation time estimation, unit outage strategies scheduling, availability calculation and verification, and improvement measures formulation and iterative calculation and other links. The following is a detailed description of each specific implementation process.

2.1 Construction of Availability Analysis Model

According to the definition of World Association of Nuclear Operators (WANO), the unit capacity factor is the ratio of the power generation that can be generated in a certain period of time to the reference power generation. It is determined by the planned maintenance time and unplanned maintenance time. This can be calculated as follows in Equation 1:

\[
UCF(\%) = \left(\frac{REG - PEL - UEL}{REG}\right) \times 100
\]

(Eq.1)

Where, REG is the unit in-service time; PEL is the unit planned power generation loss time, namely the unit planned maintenance time; UEL is the unplanned power generation loss time.

According to EUR documents, the planned maintenance time (PEL) is related to the planned shutdown maintenance time (Si) and the equivalent unavailable time (I3) from connection to the grid to 100% rated power. Unplanned maintenance time (UEL) is related to forced shutdown duration (I1) and outage delay (I2) caused by maintenance or major equipment replacement. With the lifetime of 60 years for the unit operating at full power, relevant parameters are brought into Equation 1, and then the new nuclear power unit availability calculation model after rearrangement is obtained. This can be calculated as follows in Equation 2:

\[
Unit\ availability\ % = \frac{365 \times N - \sum_{i=1}^{n} S_i + n \times I_3 + (I_1 + I_2) \times N}{365 \times N} \times 100
\]

(Eq.2)

Where, N is the unit in-service time/year; Si is the planned shutdown maintenance time, namely the outage duration; n is the planned shutdown maintenance number during the in-service period of the unit, which is related to the outage scheduling; I1 is duration of forced shutdown; I2 is outage delay resulting from maintenance or major equipment replacement; I3 is the equivalent unavailable time from connection to the grid to 100% rated power.

Assume that the new nuclear power unit complies with the design standard of the third or fourth generation nuclear power unit standards which have specified the duration of forced shutdown, outage delay due to maintenance or major equipment replacement, and the equivalent unavailable time from connection to the grid to 100% rated power, therefore, as long as the sum of the unit outage time within 60 years is calculated, substituting them into Equation 2 can obtain the availability.
2.2 System Identification and Equipment Screening

2.2.1 Primary screening. The purpose of system identification and equipment screening is to determine the analysis equipment of the new nuclear power unit related to outage, and provide input for the subsequent development of reliability maintenance strategies. The specific process is shown in Figure 1. It mainly identifies whether the system or function is allowed to put out of service under the Reactor in Power (RP) mode, and analyzes the effects and consequences of the system or function out of service under RP mode. If the consequences are acceptable and isolation and maintenance can be implemented on the relate equipment, the system is excluded, and vice versa. The equipment that is finally screened out is the equipment that can only perform maintenance under NS/SG (Normal Shutdown with Steam Generator cooling), NS/RIS-RHR (Normal Shutdown on RIS-RHR), RCS (Reactor cold shutdown for refuelling), MCS (Maintenance Cold Shutdown) and RCD (Reactor Completely Discharged), as the equipment for the formulation of subsequent reliability maintenance strategies.

![Figure 1. System and equipment identification process](image)

2.2.2 Secondary screening. In order to eliminate as much equipment as possible that may not affect the outage critical path and narrow the analysis equipment, referring to the outage experience of the nuclear power units in operation, the equipment that is not important from the equipment list after the evaluation is removed, such as drain valves, vent valves, local instruments and auxiliary facilities, etc.

Through system analysis, the number of systems to be analyzed and relevant equipment are determined and included in the analysis equipment of reliability maintenance strategies, such as, production systems like Reactor Coolant System, and Chemical and Volume Control System, etc., safety systems like Safety Injection System and Reactor Cavity and Spent Fuel Pit Cooling and Treatment System, and auxiliary systems like ventilation system and handling system, etc.

2.3 Formulation of Reliability Maintenance Strategies

Through the investigation and analysis of reliability maintenance strategies, reliability maintenance strategies for the unit are established, covering the periodic test surveillance (PTS) items, in-service inspection items (In - Service Inspection Rule for Mechanical Components of PWR NI, short for RSEM), and reliability-centered maintenance (RCM) strategies. The stable operation of the unit is ensured through periodic implementation of these strategies.
The reliability maintenance strategies include maintenance contents and implementation cycles. The specific formulation process is as follows:

1) For the PTS items, because the new nuclear power unit has some similarities with the referenced operating nuclear power unit, they can be formulated through the analogy of the operating surveillance program for periodic test: If the function design is the same, then directly reference the operating unit system documents to establish the surveillance items. If there are differences in the function design, carry out the difference analysis and analogy, and conservatively formulate the surveillance test items for the new nuclear power unit related systems.

For the calculation where the periodic test cycle cannot be determined, based on the availability of the expected system function, it can be expressed as FFI (Failure Finding Interval) using the empirical data of the units in operation, and FFI can be expressed as follows in Equation 3:

$$FFI = \frac{2 \times M_{TIVE}}{1/M_{TED1} + 1/M_{TED2} + \cdots + 1/M_{TEDn}} \times M_{MF}$$

(Eq.3)

Where, FFI is the failure-finding task interval, MTIVE is the mean time between failures of the protective equipment, MTED is the mean time between failures of the protected equipment, MMF is mean time between multiple failures. FFI depends on three factors: the acceptable multiple failure probability, the reliability of the protected equipment, and the reliability of the protective equipment.

2) For in-service inspection items, the in-service inspection branch shall formulate in accordance with the requirements of relevant regulatory documents. During the process, reference may be made to the in-service inspection program of operating nuclear power plants, and the equipment analogy and process analogy analysis of the design features of the new nuclear power unit equipment are performed, such as the number of welds, the availability of inspection tools, etc... The specific process requires in-service inspection department to provide technical support and make conservative decisions.

3) RCM strategy development is referring to the United States SAE JA1011 Evaluation Criteria for Reliability-Centered Maintenance (RCM) Processes. Maintenance strategy can be formulated through equipment importance analysis and failure mode analysis. To improve the rationality of the strategy analysis, similar plant equipment maintenance experience can be referred to formulate maintenance strategy. The basic analysis ideas are as shown in Figure 2:

![Figure 2. RCM analysis process](image)

In addition, according to power plant outage and maintenance experience, a simple inspection and maintenance task is proposed, which can reduce the number of reliability maintenance strategies, simplify strategies, and improve the scheduling efficiency of the maintenance strategies during the outage.

4) During the formulation of RCM strategies, for the items that can only be implemented during the outage based on the existing design, the improved suggestion is to implement in routine maintenance, so as to reduce the workload of outage. For example, the sealing face of the valve can be checked only through disassembly, it is possible to add a pressure test line, so that the pressurizing can be performed
in daily maintenance, and the internal leakage of the valve monitored by condition monitoring technology is preferred. The disassembly for inspection can be performed as required instead of periodic maintenance, so as to avoid the introduction of maintenance risks.

2.4 Maintenance Implementation Schedule Analysis
After formulation of the unit reliability maintenance strategies that may affect the outage critical path, it is necessary to perform schedule analysis for the reliability maintenance strategies of the equipment (maintenance schedule is related to process configuration, design layout, etc.). This process needs to integrate the upstream documents of the new nuclear power unit, such as existing System Design Manual, Technical Specifications, and the Maintenance Schedule Analysis for Main Safety Systems, etc., and finally provides a specific schedule for the implementation of reliability maintenance strategies in the form of a list, including NS/SG, NS/RIS-RHR, RCS, MCS, and RCD modes and related limiting conditions.

2.5 Estimate of Maintenance Strategies Implementation Time
In addition to reliability maintenance strategies, unit availability calculation also needs to estimate the implementation time of reliability maintenance strategies. The implementation time estimation methods of the reliability maintenance strategies for the new nuclear power unit are as follows:

1) Compare the equipment with the same function as the reference unit, consider the combination of the equipment model, equipment type, maintenance environment, and accessibility and other factors, and refer to the reference unit “standard man-hours management document” and historical outage data for analogy analysis and conservative estimate. For example, the same model and manufacturer's pressurizer safety valve can refer to the maintenance time of operating units to estimate the maintenance time of the new nuclear power unit equipment.

2) For the equipment of the new nuclear power unit different from the reference unit from the perspective of system design, maintenance environment and other factors, and equipment unique to the new nuclear power unit, conservative estimation can be performed using the parameter estimation method and the three-point estimation method:

Parameter estimation method: Estimate based on the project's workload and productivity. If the number of the new nuclear power unit’s steam generator tube bundle increases, the eddy current test time is increased in proportion.

Three-point estimation method: The average time T of the project is estimated by the project's most likely duration t2, optimistic duration t1 and pessimistic duration t3, the average time T can be expressed as follows: T=(t1+4t2+t3)/6.

In addition, it is necessary to add the weight of maintenance time based on the specific conditions in the field, such as the number of equipment or tools, the impact of high temperature or high radiation, etc., and comprehensively evaluate the maintenance time.

2.6 Unit Maintenance Strategies Scheduling
After estimate of the implementation time of maintenance strategies, multiple strategies need to be scheduled according to the execution status, execution sequence, execution cycle, etc. The scheduling mainly depends on the database.

In the database, each reliability maintenance strategy is seen as an activity with an internal logical relationship (see M02 in Figure 3). After scheduling, an overall activity network is formed. From the beginning to the end, the longest connecting line (duration) is the outage critical path. The total time for the project will form the project duration, as shown in Figure 3.
The specific steps of the reliability maintenance strategies scheduling for the new nuclear power unit are as follows:

1) Establish the basic framework of outage scheduling in the database according to the new nuclear power unit's refuelling outage path, which includes the duration, the start and end points of each project during the outage, and the state transition point of the unit.

2) According to the implementation cycle of the unit outage strategy and the unit status, combined with the technical team expert's recommendations, various maintenance strategies will be integrated into the refuelling outage path.

In addition, in order to reduce the workload of scheduling, prior to scheduling, it is suggested to identify the relationship between maintenance strategies and optimize their scheduling, such as the covering relationship between maintenance strategies: If the project A plan is implemented, its time length can cover that of the project B, the project B can be excluded in the scheduling. For example, a 6C full inspection time of a pump can cover the disassembly maintenance time of the front and rear isolation valves, therefore, the 6C disassembly for inspection task of the valves does not affect the outage path and may not be included in the scheduling.

2.7 Unit Availability Analysis and Calculation

After one by one scheduling of the outage strategies for each unit during the 60-year life of the unit, the database automatically counts the critical path for each outage and the duration of the project, then the duration of outage is obtained, and the sum of all outage duration is calculated, then the unavailable time of the unit due to normal outage during the lifetime, including the number of outage, types and duration.

According to the differences in outage types, the availability calculation model is further refined. Substituting each outage type and each outage duration into Equation 2 gives Equation 4:

\[
\text{unit availability} (\%) = \frac{365 \times N \times (S_1 \times S_2 + N_1 \times T_1 + T_2 \times T_3 \times (N_2 + N_3) + (I_1 + I_2) \times N)}{365 \times N} \times 100
\]  

(Eq.4)

According to the outage type and the duration of each outage, entering the calculation model (4) can get the estimated availability of the unit within 60 years, so as to analyze whether the newly designed nuclear power unit meets the empirical indicators of the availability of the third-generation nuclear power unit. If the calculated availability is too small, it is necessary to redesign the equipment related to the outage critical path’s maintenance strategies or improve the system on the premise of meeting the system safety operation indicators, reanalyze maintenance strategies and calculate the availability until the availability meets the requirements of design availability index.

Notes: N is the unit in-service time/year, 365 days a year; ST is a short outage duration/day; Sn is the number of short outage; NT is a normal outage duration/day; Nn is the number of normal outage; TT is ten-year outage duration /day; Tn is the number of ten-year outage; I1 is the duration of forced shutdown; I2 is the outage delay caused by maintenance or major equipment replacement; I3 is the equivalent unavailable time from connection to the grid to 100% rated power.
3. Conclusions and Prospects

The new nuclear power unit availability calculation model and estimation methods can be used as evaluation and reference for the analysis of availability of the third-generation nuclear power units in the design phase, which is forward-looking and practical in the power generation of nuclear power units in the future. In the analysis process, the suggestion for modification to improve equipment reliability can also be put forward on the basis of satisfying the safety and economic indicators, which can be used as reference for subsequent equipment type selection and equipment procurement, so as to ensure equipment reliability and achieve the goal. Otherwise, the determined system process will affect the frequency and time of equipment maintenance and the outage duration, which results in reduction of availability of the unit.

Because there are few operation and maintenance data in the initial design phase of the new unit, and it mainly refers to the operation and maintenance experience of similar nuclear reactor types, the accuracy of the prediction needs to be improved. With the continuous enrichment of operating data of the operating units, further advancement of design depth of the new nuclear power unit systems, and under the gradually perfect equipment information conditions, the accuracy of the new nuclear power unit calculation will be improved and eventually satisfy the requirements of the availability of the unit.

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