17th International Conference on Probabilistic Safety Assessment and Management &
Asian Symposium on Risk Assessment and Management (PSAM17&ASRAM2024)
7-11 October, 2024, Sendai International Center, Sendai, Miyagi, Japan

Tianwan Nuclear Power Plant Units 1-4 Configuration Risk Management Application

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Abstract: Since the establishment of the configuration risk management system at Tianwan Nuclear Power Plant, the risk monitor has been used to monitor the unit status in real time and predict the future risks of the unit, track and monitor the instantaneous risk and the cumulative risk increment during equipment maintenance, determine whether additional risk control operations are needed, and make reasonable plans based on risk management requirements during the production plan (daily plan, long-cycle plan), outage plan (including minor outage plan) and other maintenance plans, providing technical support for safe and reliable operation of the plant.

Keywords: Configuration risk management; Risk Monitor; CDF; LERF

1. INTRODUCTION

In December 2019, the National Nuclear Safety Administration issued the "Technical Policy for Configuration Risk Management at Nuclear Power Plants (Trial)", which requires operational units of nuclear power plants to establish and optimize the configuration risk management system. This aims to enhance the scientific nature and effectiveness of nuclear safety management decisions, ensuring the safe operation of nuclear power plants [1]. As the first units in the country to implement configuration risk management, Units 1-4 at Tianwan Nuclear Power Station have established a set of risk thresholds and a corresponding risk management matrix for VVER units. By utilizing a risk monitoring system, these measures meet the requirements of the configuration risk management system, categorize management according to different risk levels, ensure the safe and stable operation of the units, and effectively control multiple equipment failures, thereby improving the scientific nature and effectiveness of nuclear safety management decisions.

2. Monitoring System

The Risk Monitor(RM) is a tool based on the PSA model for evaluating the impact of various production and operational activities on the nuclear risk at the power station. It utilizes a real-time risk model to calculate quantitative risk indicators such as core damage frequency, which are used for configuration risk management at the power station, maintenance planning risk management, and plant condition control [2].

3. Operational Configuration Risk Management

Operational configuration risk management is applicable to Units 1-4 during power operation (POS 1), the minimum detectable power level (POS 2), hot state (POS 3), heating (POS 7), and cooling (POS 8). It covers PSA equipment and addresses unplanned equipment unavailability scenarios.

Taking Unit 1 in April 2023 as an example, the unit maintained POSA (Power Operation from 100% Nnom to 5% Nnom) conditions throughout the month. Besides scheduled maintenance tasks such as safety system dual channel and XKA60 (unit diesel engine) online maintenance, there were also two random unavailability incidents of PSA equipment. These incidents had a significant impact on the unit's Core Damage Frequency (CDF) and Large Early Release Frequency (LERF). During the equipment maintenance period, the risk monitoring system was used to perform real-time monitoring of the unit's risk. The changes in the core damage frequency and early large radioactive release frequency are illustrated in Figures 1 and 2, and the risk calculation results are presented in Table 1.

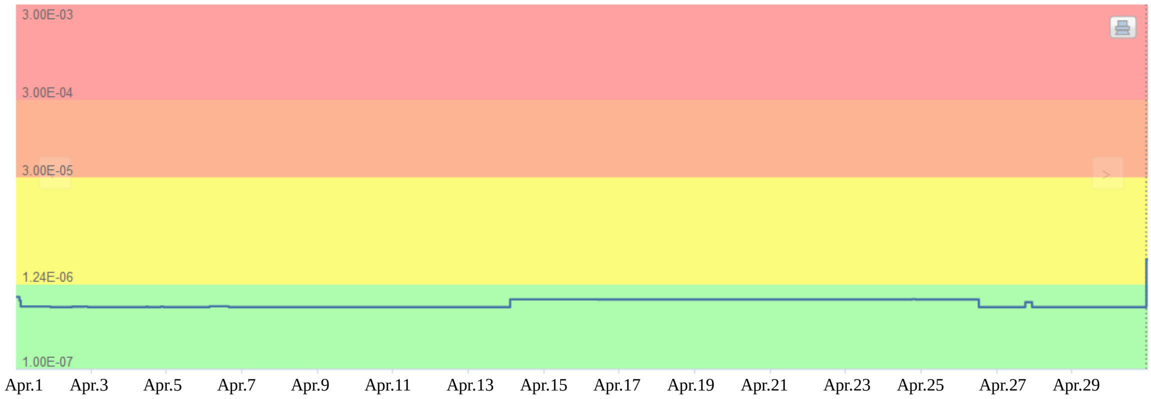


Figure 1. Real-time monitoring CDF curve for Unit 1 during the month

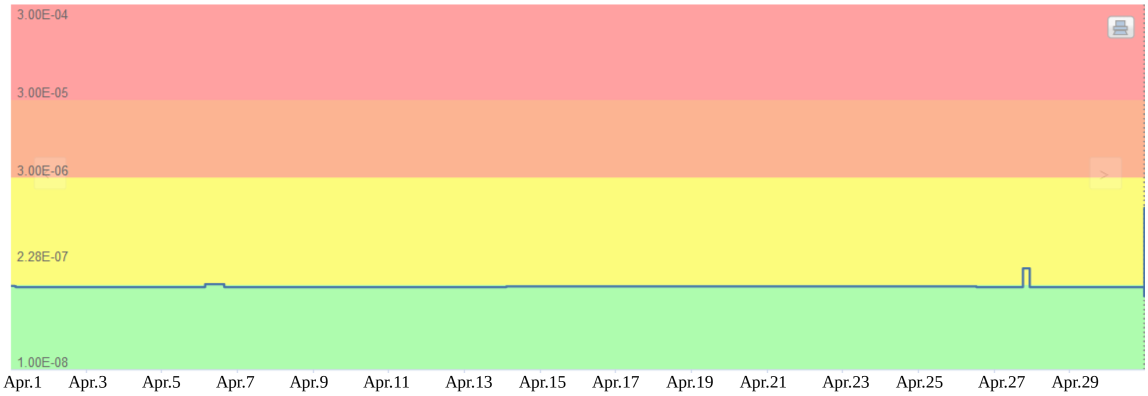


Figure 2. Real-time monitoring LERF curve for Unit 1 during the month

Table 1. Risk calculation results for Unit 1 in April

Date	Maintenance Work	(CDFmax)/per reactor-year	(LERFmax)/per reactor-year	ICDP	ILERP

Mar 14 - Apr 1	Safety system dual channel online maintenance	8.58E-7	1.19E-7	1.14E-8	2.27E-10
Apr 14 - Apr 26	1XKA60 online maintenance	7.90E-7	1.16E-7	5.44E-9	8.10E-11
Apr 24, 17:56 to 19:58	1JNG43AA102 maintenance（1）				
Apr 27, 17:58 to 22:16	1LAS10AP001 maintenance（2）	7.22E-7	1.99E-7	4.83E-11	4.19E-11

(1) April 24, 2023, 17:56, Reactor Operator of Unit 1 performed routine testing on 1JNG43AA102 (low-pressure safety injection system 40-line circulation pipeline valve). During the valve opening, a flash torque and timeout alarm were triggered, and the valve did not open, which was recorded as a demand failure.

(2) April 27, 2023, 17:58:36, during the routine test of the emergency feedwater pump 1LAS10AP001, the pump failed to start. A timeout alarm XB87 occurred for 1LAS10AP001, and a step 2 timeout alarm occurred for 1LAR10EC001, which was recorded as a demand failure.

1JNG43AA102 and 1LAS10AP001 are included in the configuration risk management list. Both random unavailability incidents entered the Technical Specifications Operating Limit Conditions (LCO). Apart from implementing the measures specified in the Technical Specifications, the operating personnel, after confirming the configuration and stabilizing the unit, entered the equipment unavailability information into the risk monitoring system within one hour. A configuration risk evaluation was completed. Since there were redundant backup options available, a common cause failure quantification was also performed. According to the calculation results, the instantaneous risks CDF and LERF for both incidents were within the normal control zone (green zone). According to the risk management matrix, normal production activities could proceed without additional risk management requirements.

4. Maintenance Configuration Risk Management

Maintenance configuration risk management applies to Units 1-4 during power operation (POS 1), the minimum detectable power level (POS 2), hot state (POS 3), cold state (POS 4), maintenance cold shutdown (POS 5), heating (POS 7), and cooling (POS 8). The management focus is on PSA equipment, primarily utilized during the development of production plans (daily plans, long-term plans), and major maintenance schedules (including minor maintenance plans). Production and major maintenance plan engineers use configuration risk management to control the unavailability of multiple pieces of equipment during plan formulation, allowing for more efficient and intuitive acquisition of quantitative analysis results. Plans are approved or adjusted based on risk values.

4.1 Daily Plan Maintenance Configuration Risk Management Application

According to the three-day rolling plan, on May 22 from 13:00 to 17:00, Unit 2 will conduct maintenance work on the nearly detached fixing screws of the water baffle ring of bearing number 4 of 2PGB12AP001 (non-critical user intermediate loop system pump number 2). The calculated CDF during this corrective maintenance period is 6.23E-7 per reactor-year, and LERF is 1.14E-7 per reactor-year, with instantaneous risks both in the green zone. According to the risk management matrix, normal production activities can proceed without additional risk management requirements. The predicted changes in the unit's core damage frequency and early large radioactive release frequency are illustrated in Figures 3 and 4 (solid lines represent operational historical risk, dashed lines represent planned predictive risk).

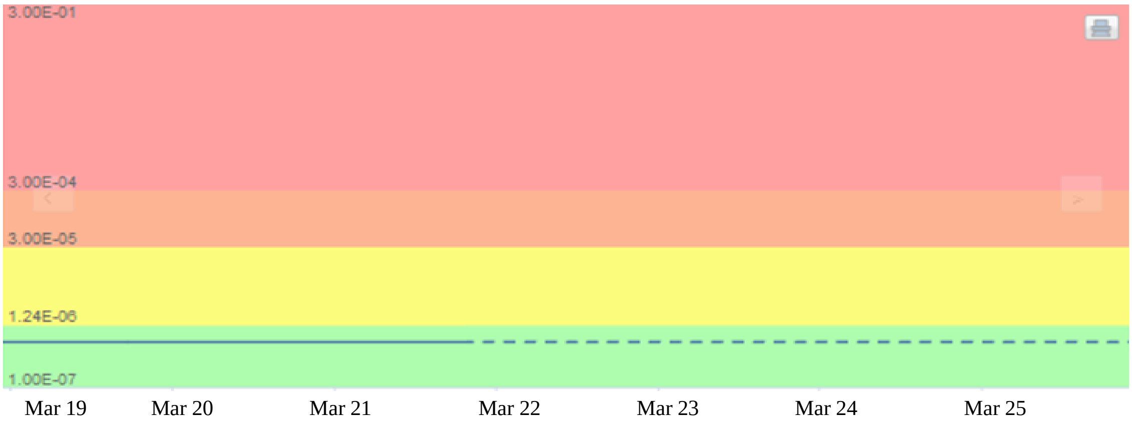


Figure 3. Daily Plan CDF Prediction Curve for Unit 2

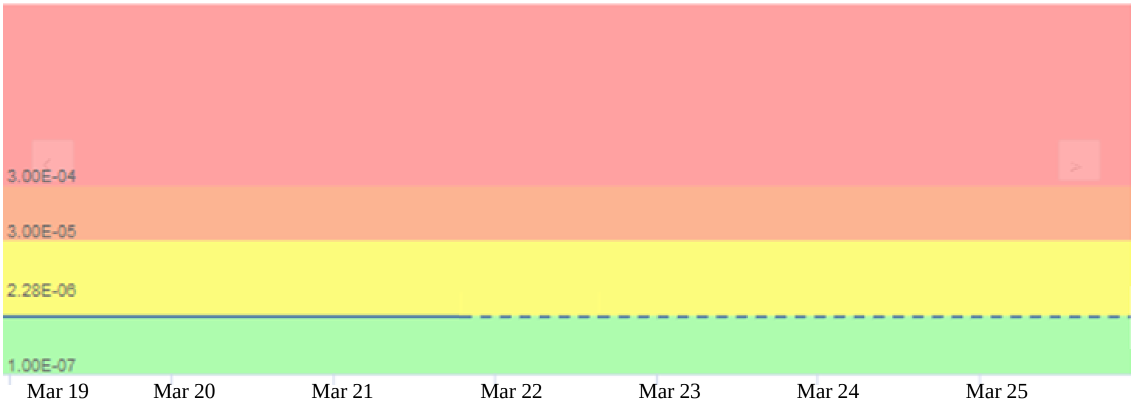


Figure 4. Daily Plan LERF Prediction Curve for Unit 2

4.2 Long-Term Plan Configuration Risk Management Application

The current acceptable criteria avoids the problem of overly lenient performance indicators, which may not accurately reflect the historical status of equipment and cannot effectively improve the maintenance effectiveness.

The acceptable criteria for performance indicators is to compare the increased CDF value with the benchmark CDF value, reflecting the characteristics of nuclear power units.

2.3. Disadvantage Analysis

Taking the online maintenance of the safety system before the major overhaul of Unit 1, OT114, as an example, risk predictions for the maintenance schedule were performed using the risk monitoring system before implementation. The predicted curves for the core damage frequency (CDF) and early large radioactive release frequency (LERF) are shown in Figures 5 and 6 (dashed lines represent estimated planned risk; numbers 1-6 on the curves represent safety channel numbers). The risk prediction results are summarized in Table 2.

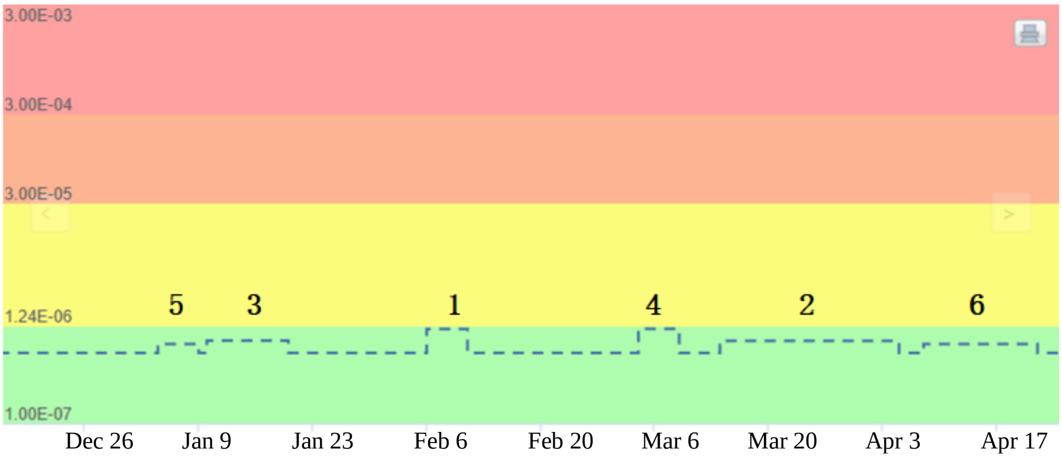


Figure 5. Pre-maintenance CDF Prediction Curve for Unit 1 OT114 Major Overhaul

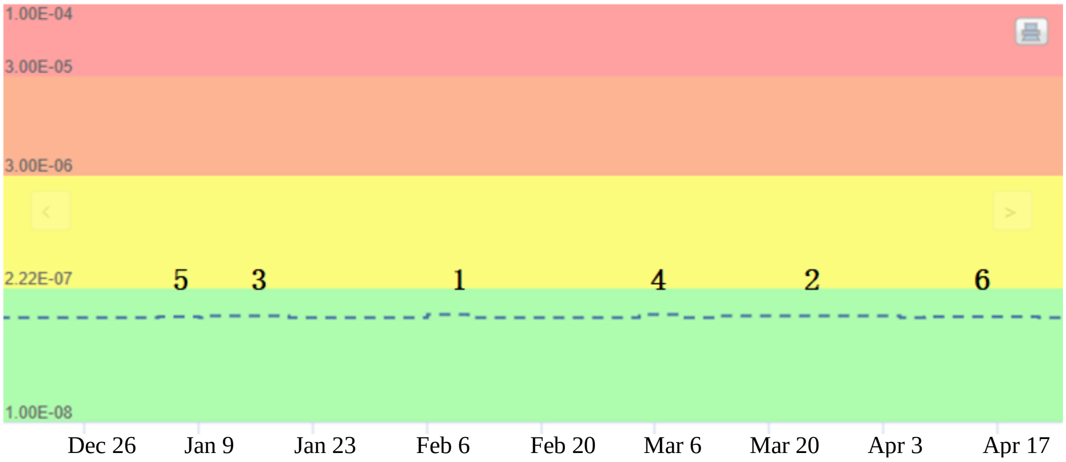


Figure 6. Pre-maintenance LERF Prediction Curve for Unit 1 OT114 Major Overhaul

Table 2. Pre-maintenance Risk Prediction Values for Unit 1 OT114

Date	**Maintenance Work**	**CDFmax per reactor-year**	**ICDP**	**LERFmax per reactor-year**	**ILERP**
Jan 4 - Jan 8	Unit diesel engine 50	7.79E-07	2.18E-09	1.13E-07	3.36E-11

	series				
Jan 10 - Jan 19	Safety system three channels	8.51E-07	6.33E-09	1.16E-07	1.30E-10
Feb 6 - Feb 10	Safety system one channel	1.15E-06	7.28E-09	1.19E-07	1.16E-10
Mar 4 - Mar 8	Safety system four channels	1.16E-06	7.36E-09	1.19E-07	1.16E-10
Mar 14 - Apr 4	Safety system two channels	8.45E-07	1.36E-08	1.16E-07	2.82E-10
Apr 8 - Apr 22	Unit diesel engine 60 series	7.79E-07	6.11E-09	1.13E-07	9.38E-11

Based on the analysis of the online maintenance plan, the following conclusions and risk insights can be drawn:

1) Risk Management During the Online Maintenance of the Safety System Before the Major Overhaul of Unit 1 OT114 During the online maintenance of the safety system before the major overhaul of Unit 1 OT114, the instantaneous risks (CDF, LERF) and cumulative risks (ICDP, ILERP) are all within the green zone. Maintenance work can be scheduled as planned, and normal work controls can be executed without the need for additional risk management measures.

2) If the Duration of the Online Maintenance of the Safety System Before the Major Overhaul of Unit 1 OT114 Exceeds the Planned Duration or if Unplanned Safety-Related System Equipment Failures Occur Should the online maintenance time exceed the planned duration or if unplanned safety-related system equipment failures occur, it will be necessary to re-analyze the risks, assess the allowable maintenance time limits, and, if necessary, establish risk management measures.

4.3 Major Overhaul Maintenance Configuration Risk Management Application

The major overhaul plan for TW-OT114 is scheduled to disconnect from the grid on April 30, 2023, at 22:00, and the generator is set to reconnect on May 28, 2023, at 22:00, with an expected duration of 28 days. According to the "Configuration Risk Management Outline" SR-TW-2, the Risk Monitoring System (RM) is used to predict risks for the overhaul plan and to manage the configuration risks of the maintenance plan. The overhaul management uses the risk monitoring system's planning module to perform risk predictions on the original plan, identifying the need for adjustments in the following items:

(1) 1LBU10AA201 (Steam Generator Atmospheric Emission System Atmospheric Release Valve) was originally scheduled to begin inspection and maintenance at 08:00:00 on May 3, 2023 (normal cold shutdown condition), but the instantaneous risk CDF would enter the red zone (unacceptable area) under this condition. The project has been rescheduled to start at the beginning of the maintenance cold shutdown.

(2) 1LAA10BB001 (Deaerator Water Tank) was originally scheduled to begin dismantling for major repairs at 08:30:00 on May 3, 2023 (normal cold shutdown condition), but the instantaneous risk CDF would enter the orange zone under this condition. The project has been postponed to start at the beginning of the maintenance cold shutdown.

(3) 1KBA61AA801/802 and 1KBA62AA801/802 (Isolation of the blow-up pipeline for the volume and boron concentration control system outside the containment shell) were originally scheduled to begin dismantling for major repairs at 22:30:00 on May 4, 2023 (maintenance cold shutdown condition), with the instantaneous risk CDF entering the orange zone. Exiting a single column would not lead to a sudden increase in risk, so the plan has been adjusted to stagger the maintenance windows for the two columns.

After adjustments, the revised major overhaul project plan was recalculated, resulting in the core damage frequency and core damage probability increment prediction curves shown in Figure 7, and the early large radioactive release frequency and early large radioactive release probability increment prediction curves shown in Figure 8 (black lines represent planned predictive risk curves; May 8 to 13 is the refueling cold shutdown, PSA risk analysis is not applicable). The major overhaul risk prediction values are presented in Table 3.

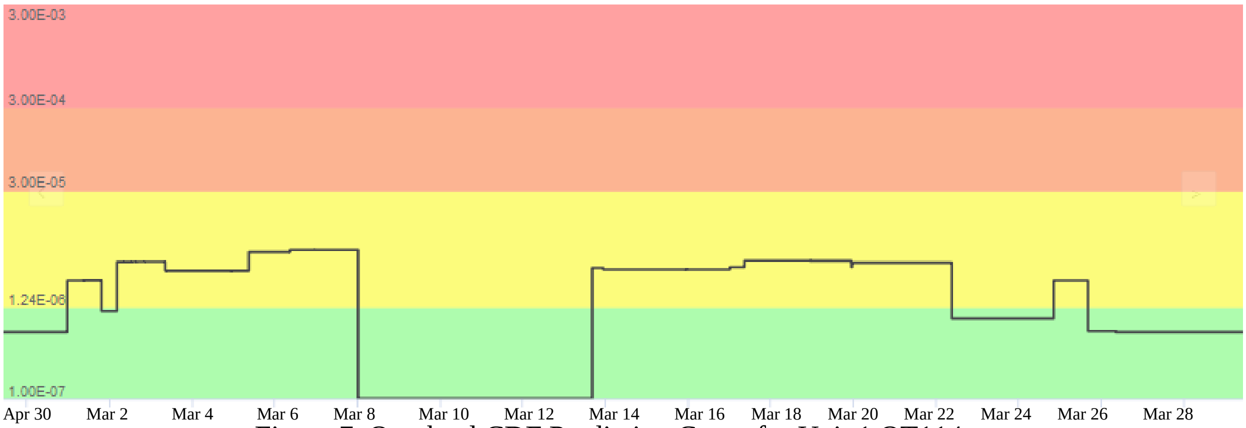


Figure 7. Overhaul CDF Prediction Curve for Unit 1 OT114

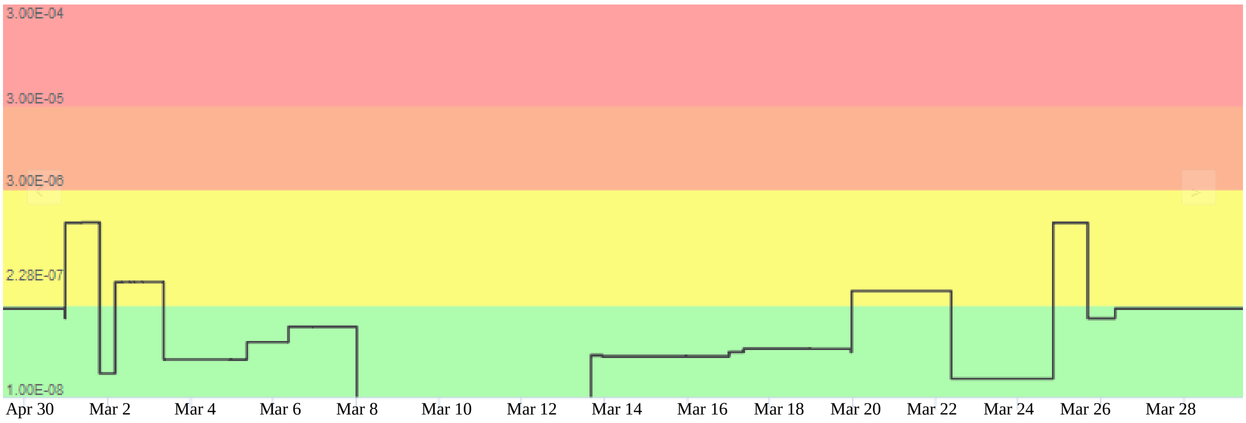


Figure 8. LERF Prediction Curve for Unit 1 OT114 Overhaul

Table 3. Planned Risk Predictions for Unit 1 OT114 Overhaul

Start Time	**Plant Operation State**	**CDFmax / per reactor year**	**LERFmax / per reactor year**	**Start Time**	**Plant Operation State**
April 30, 2023, 23:00	POS B (Power reduced from 5% to minimum detectable level)	6.40E-07	8.69E-08	April 30, 2023, 23:00	POS B (Power reduced from 5% to minimum detectable level)
April 30, 2023, 23:05	POS C (Minimum detectable power level to primary loop 150 ℃)	2.60E-06	1.21E-06	April 30, 2023, 23:05	POS C (Minimum detectable power level to primary loop 150 ℃)
May 1, 2023, 11:00	POS D (Primary loop 150 ℃ to start of normal cooldown)	1.11E-06	1.93E-08	May 1, 2023, 11:00	POS D (Primary loop 150 ℃ to start of normal cooldown)
May 2, 2023, 04:00	POS E (Normal cooldown (residual heat removal system connected to disengage the middle three control rod drive mechanisms))	4.31E-06	2.37E-07	May 2, 2023, 04:00	POS E (Normal cooldown (residual heat removal system connected to disengage the middle three control rod drive mechanisms))
May 3, 2023, 08:00	POS F (Maintenance cooldown (disengage the middle three control rod drive mechanisms to dismantling of the 106 sluice gate))	5.99E-06	6.94E-08	May 3, 2023, 08:00	POS F (Maintenance cooldown (disengage the middle three control rod drive mechanisms to dismantling of the 106 sluice gate))
May 8, 2023, 00:00	Refueling cooldown	/	/	May 8, 2023, 00:00	Refueling cooldown
May 13, 2023, 16:00	POS G (Maintenance cooldown (completion of the 106 sluice gate installation to sealing control rod drive mechanisms))	4.44E-06	3.78E-08	May 13, 2023, 16:00	POS G (Maintenance cooldown (completion of the 106 sluice gate installation to sealing control rod drive mechanisms))
May 19, 2023, 23:00	POS H (Normal cooldown (sealing control rod drive mechanisms to 130 ℃))	4.19E-06	1.84E-07	May 19, 2023, 23:00	POS H (Normal cooldown (sealing control rod drive mechanisms to 130 ℃))
May 22,	POS I (Normal cooldown to primary loop 150 ℃)	9.05E-07	1.66E-08	May 22,	POS I (Normal cooldown to primary loop 150 ℃)

2023, 09:00				2023, 09:00	
May 24, 2023, 20:00	POS J (Primary loop 150 ℃ to minimum detectable power level)	2.58E-06	1.20E-06	May 24, 2023, 20:00	POS J (Primary loop 150 ℃ to minimum detectable power level)
May 25, 2023, 16:00	POS K (Minimum detectable power level increased to 5% power)	6.41E-07	8.69E-08	May 25, 2023, 16:00	POS K (Minimum detectable power level increased to 5% power)
May 26, 2023, 08:00	POS L (5% power increased to full power)	6.23E-07	1.14E-07	May 26, 2023, 08:00	POS L (5% power increased to full power)

Based on the results of the overhaul plan calculations, the following conclusions and risk insights can be derived:

(1) It is expected that during the OT114 overhaul period, the maximum CDF (Core Damage Frequency) will be 5.99E-6 per reactor year, and the maximum LERF (Large Early Release Frequency) will be 1.21E-6 per reactor year, placing the maximum instantaneous risk in the yellow zone. The cumulative risk ICDP is 2.02E-8, which is less than the normal control area threshold of 3E-7, and ILERP is 2.37E-10, which is less than the normal control area threshold of 3E-8. Maintenance work can proceed as scheduled, with normal work controls sufficient and no additional risk management measures necessary.

(2) During the modeling of the shutdown conditions, systems not required by technical specifications were used as mitigation measures. For example, the Volume and Boron Concentration Control System (KBA) has no requirements in POS 5 (maintenance cooldown) according to the technical specifications [3]. Risk monitoring systems calculated that the risk recovery factor for KBA69AA101 (Volume and Boron Concentration Control System pressure regulator auxiliary spray pipeline electric valve) is significant during maintenance cooldown conditions. The failure mode of this valve is "erroneous opening." Maintenance personnel should establish risk management measures to prevent bypass flows from top filling to bottom draining.

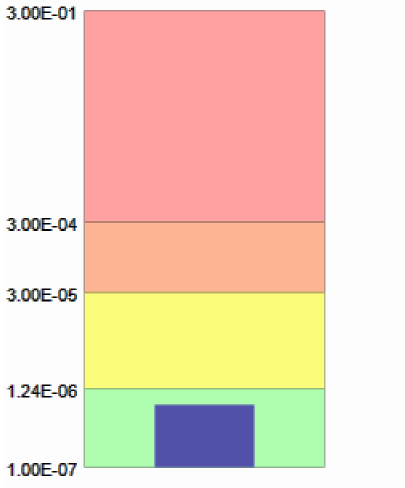
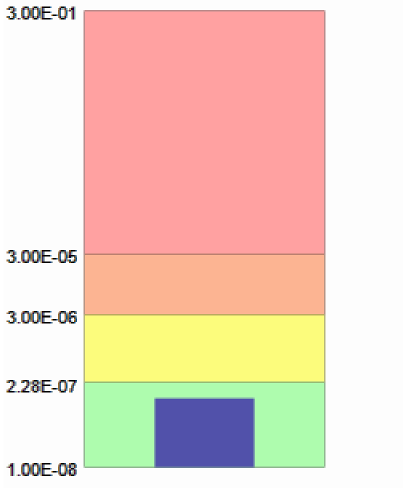
(3) If the duration of the OT114 overhaul of Unit 1 exceeds the originally planned time or if unplanned exits of safety-related system equipment occur, a re-evaluation of the risk analysis is required to assess the permissible maintenance time limits. If necessary, risk management measures should be formulated.

5. Case Study on the Application of Configuration Risk Management to Optimize Maintenance Work

Configuration risk management uses risk monitoring systems to provide quantitative bases for enhancing the economic efficiency of power stations, increasing maintenance flexibility, and reasonably optimizing overhaul durations.

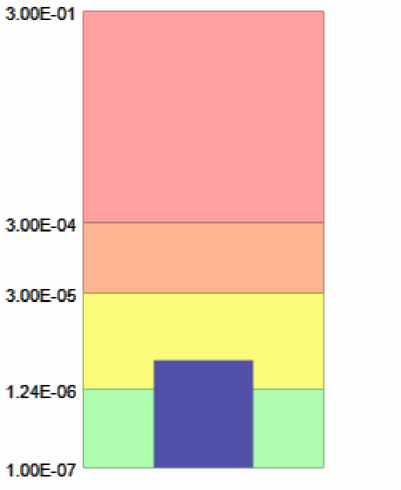
Taking the adjustment of the startup transformer maintenance window as an example, risk analyses were conducted using the risk monitoring system for the maintenance of the startup transformer (BCT) under both power operating conditions and maintenance cooldown conditions. The maintenance involves electrical isolation of the startup transformer and is expected to take 7 days, with the precondition that the main transformer/high factory transformer, safety systems channels one to four, unit diesel engines, and emergency diesel engines are available. The analysis results are as follows:

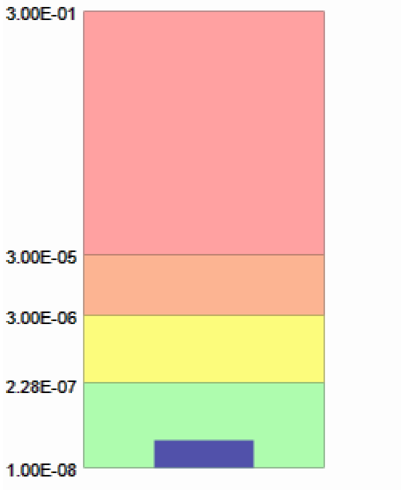
(1) Maintenance of the Startup Transformer under Power Operating Conditions

<table>
<tr><td>
</td><td>
</td></tr>
<tr><td>Predicted Risk CDF = 7.98E-07</td><td>Predicted Risk LERF =1.35E-07</td></tr>
<tr><td>Baseline Risk CDF = 6.23E-07</td><td>Baseline Risk LERF = 1.14E-07</td></tr>
<tr><td>Risk Increment ICDF = 1.75E-07</td><td>Risk Increment ILERF = 2.15E-08</td></tr>
<tr><td>Risk Area: Normal Control Area</td><td>Risk Area: Normal Control Area</td></tr>
<tr><td colspan="2">Allowed Configuration State Duration (ACT) = More than 30 days</td></tr>
</table>

Equipment Outage	2BCT02	#02 Startup Transformer

(2) Maintenance of the Startup Transformer under Maintenance Cooldown Conditions





<table>
<tr><td colspan="3">Predicted Risk CDF = 3.41E-06</td><td colspan="3">Predicted Risk LERF =2.87E-08</td></tr>
<tr><td colspan="3">Baseline Risk CDF = 3.28E-06</td><td colspan="3">Baseline Risk LERF = 2.87E-08</td></tr>
<tr><td colspan="3">Risk Increment ICDF = 1.26E-07</td><td colspan="3">Risk Increment ILERF = 4.44E-12</td></tr>
<tr><td colspan="3">Risk Area: Risk Management Area (Medium Risk)</td><td colspan="3">Risk Area: Normal Control Area</td></tr>
<tr><td colspan="6">Allowed Configuration State Duration = More than 30 days</td></tr>
<tr><td colspan="2">Equipment Outage</td><td colspan="2">2BCT02</td><td colspan="2">#02 Startup Transformer</td></tr>
</table>

From the above results, it is evident that the increments in core damage frequency and early large release frequency are small during both power operating and maintenance cooldown conditions. The planning department can flexibly arrange maintenance work based on actual site conditions or needs.

6. Advantages and Challenges in Practical Application

In the practical application of configuration risk management and risk monitoring systems at the Tianwan Nuclear Power Plant, continuous optimization and improvement have led to the following good practices:

(1) Automation of Unit Data Retrieval: The risk monitoring system has been integrated with real-time data management systems, isolation ticket systems, and overhaul management platforms. This integration automatically inputs equipment status information into the risk monitoring system, enhancing the accuracy and timeliness of risk analysis.

(2) Training Beyond PSA Professionals: Extensive training on configuration risk management has been provided not only to PSA professionals but also to departments such as operations, maintenance, production planning, overhaul management, and nuclear safety. This training has helped various departments understand the concept of configuration risk, update management procedures and plans, and tightly integrate configuration risk management with departmental management requirements. It also fosters collective brainstorming to identify improvements in the PSA model and risk monitoring system, continuously optimizing the model to better serve the power station.

However, there are also some technical challenges in the application of configuration risk management that need to be addressed:

(1) Modeling During Shutdown Conditions: Systems not required by technical specifications have been used as mitigation measures to reduce the baseline risk during shutdown conditions. The PSA model needs to be further refined based on the actual operating conditions of the power plant, optimizing initiating event parameters and equipment failure probability data. Plant personnel should use the results of configuration risk management analysis to reasonably optimize the maintenance duration of various projects during overhauls and implement appropriate risk control measures.

(2) System Interface Stability: The stability of the interfaces between the risk monitoring system and various data sources, the calculation speed, and the usability of the human-machine interface still have room for improvement.

7. SUMMARY

Since its development, the configuration risk management system at Tianwan Nuclear Power Plant has accumulated significant technical and operational experience through practical feedback and continuous optimization. By conducting nuclear power plant risk management through both operational and maintenance aspects, the system provides quantitative technical support and assurance for the units. Combined with the risk monitoring system, it enables real-time risk monitoring and future risk prediction, assisting managers in making informed decisions, which plays a crucial role in enhancing the safety and economic efficiency of the nuclear power plant.

Moreover, while the risk monitoring system serves as a tool for applying PSA model calculations of core damage frequency and other quantitative risk indicators, there is still room for improvement in its use for configuration risk management at the power station. Tianwan Nuclear Power Plant will continue to refine the configuration risk management and application tools in future practices, aiming to serve the station more efficiently and enhance the accuracy and effectiveness of nuclear risk management at the power plant.

References

[1] Technical Policy for Configuration Risk Management at Nuclear Power Plants (Trial), National Nuclear Safety Administration, December 2019.

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