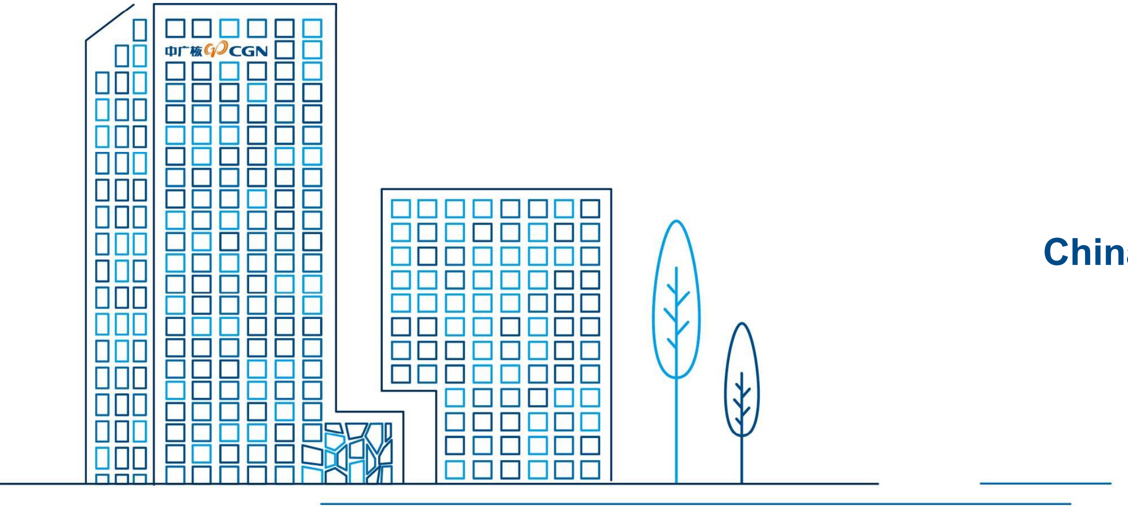
中广核 CGN

严 · 慎 · 细 · 实

Dose Optimization of Outage Critical Work Orde: A Pilot Study and Risk Assessment



China General Nuclear Power (Shenzhen) Operational Technology & Radiation Monitoring Co., Ltd.,

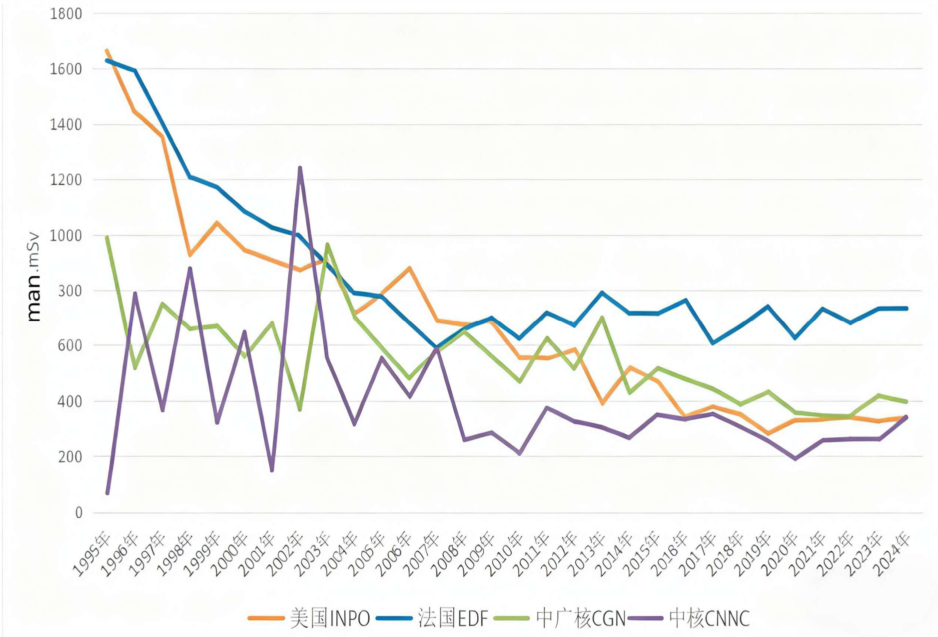
I. Introduction

Collective dose metric

Collective dose serves as a key metric for optimizing radiation protection

- Quantitative assessment of radiation risk
- Guiding the optimization of radiation protection measures
- Evaluating the effectiveness of radiation protection programs

This study proposes a normalized analysis model for work order dose during nuclear power plant outages, establishing a radiation dose evaluation methodology for maintenance operations.

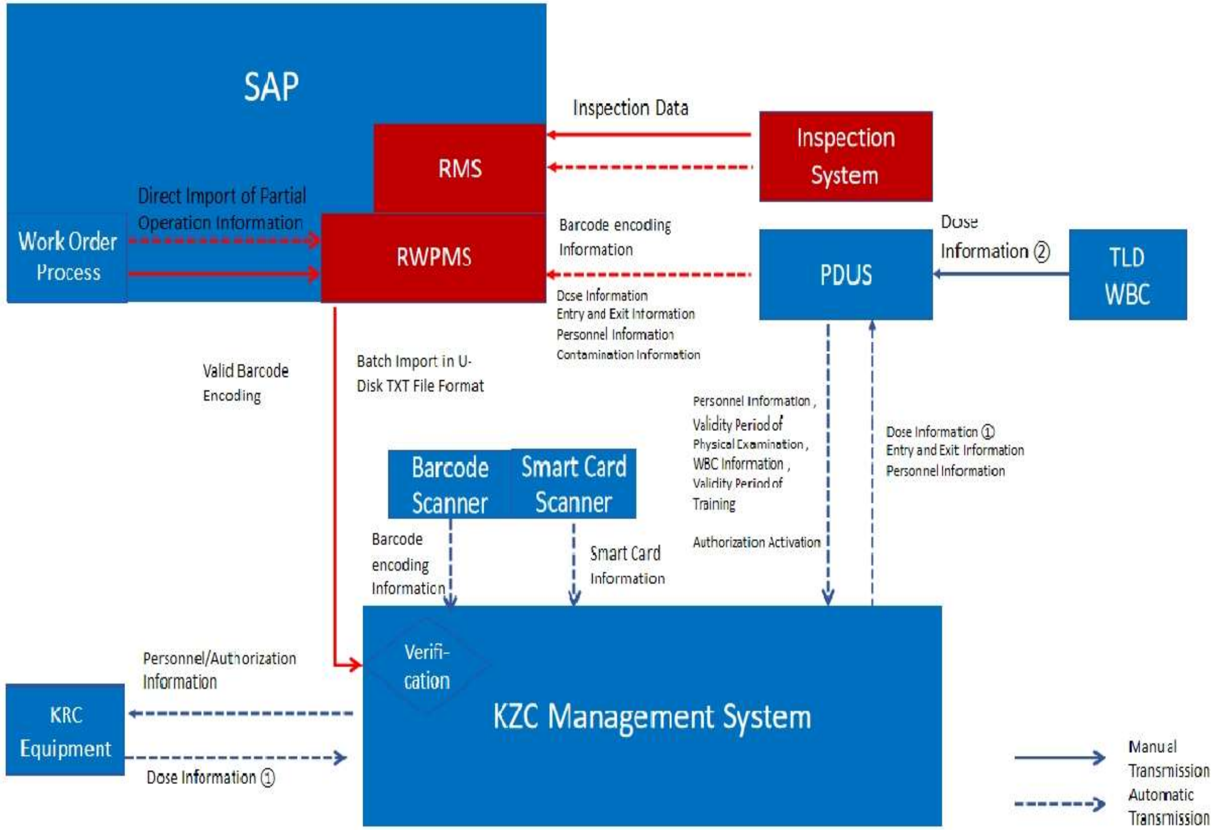


Average Annual Collective Dose Trend for a Single PWR Unit

Dose management systems

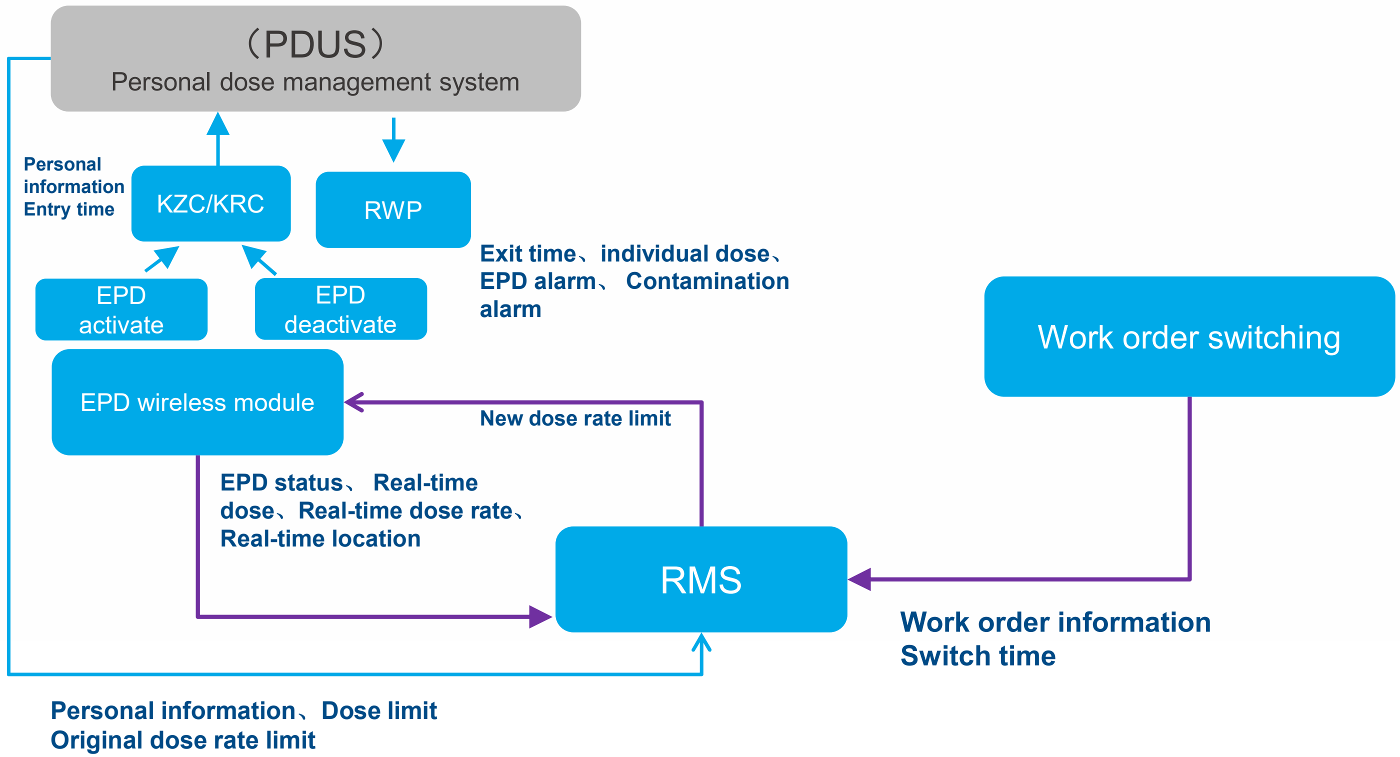
CGN has established multiple dose management systems

- SAP Work Order Management System
- PDUS CGN Personal Dose management System
- KZC/KRC Controlled Area Access System
- RWPMS Radiation Work Permit Management System
- RMS Remote Monitoring System
- TLD Thermoluminescent Detector
- WBC Whole Body counter



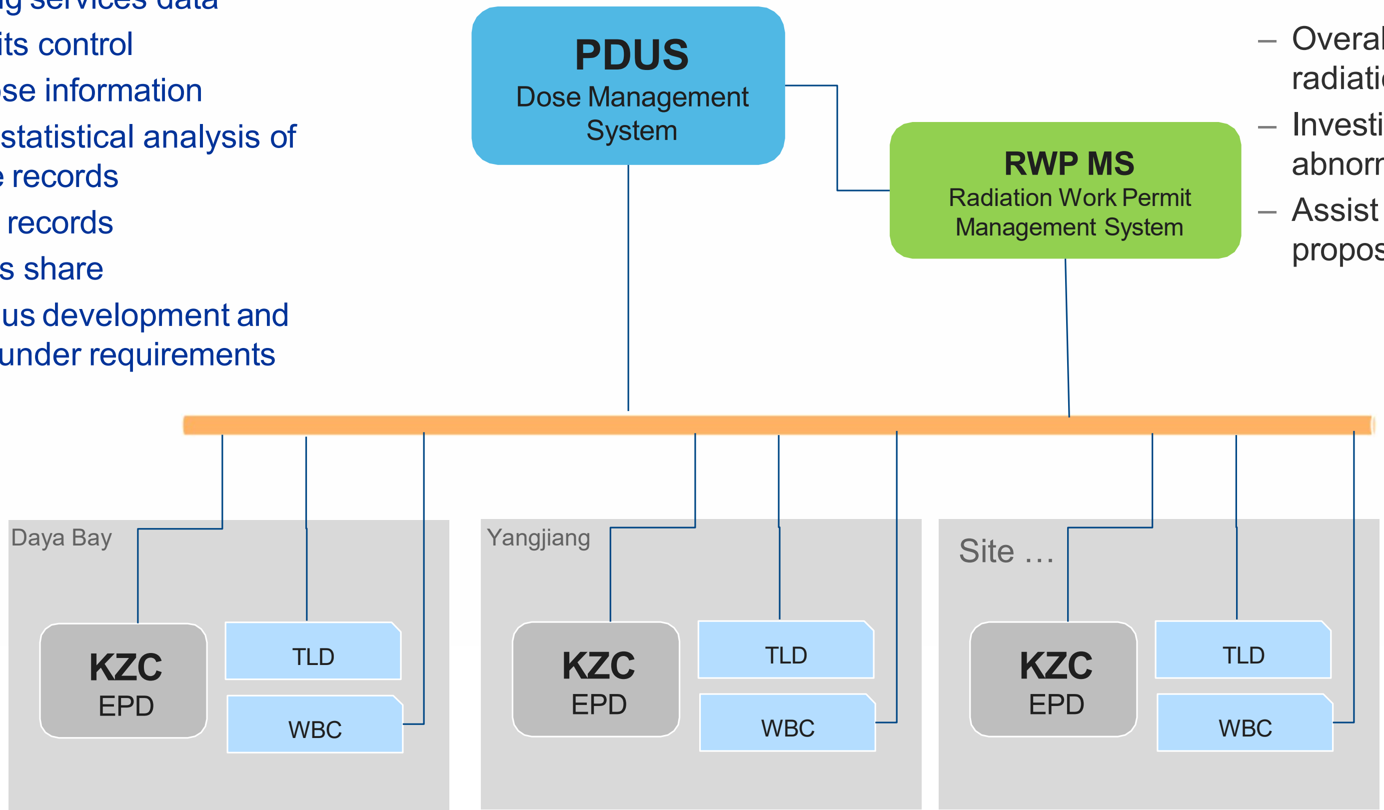
Work order switch

Work order switching:【To achieve accurate dose statistics】



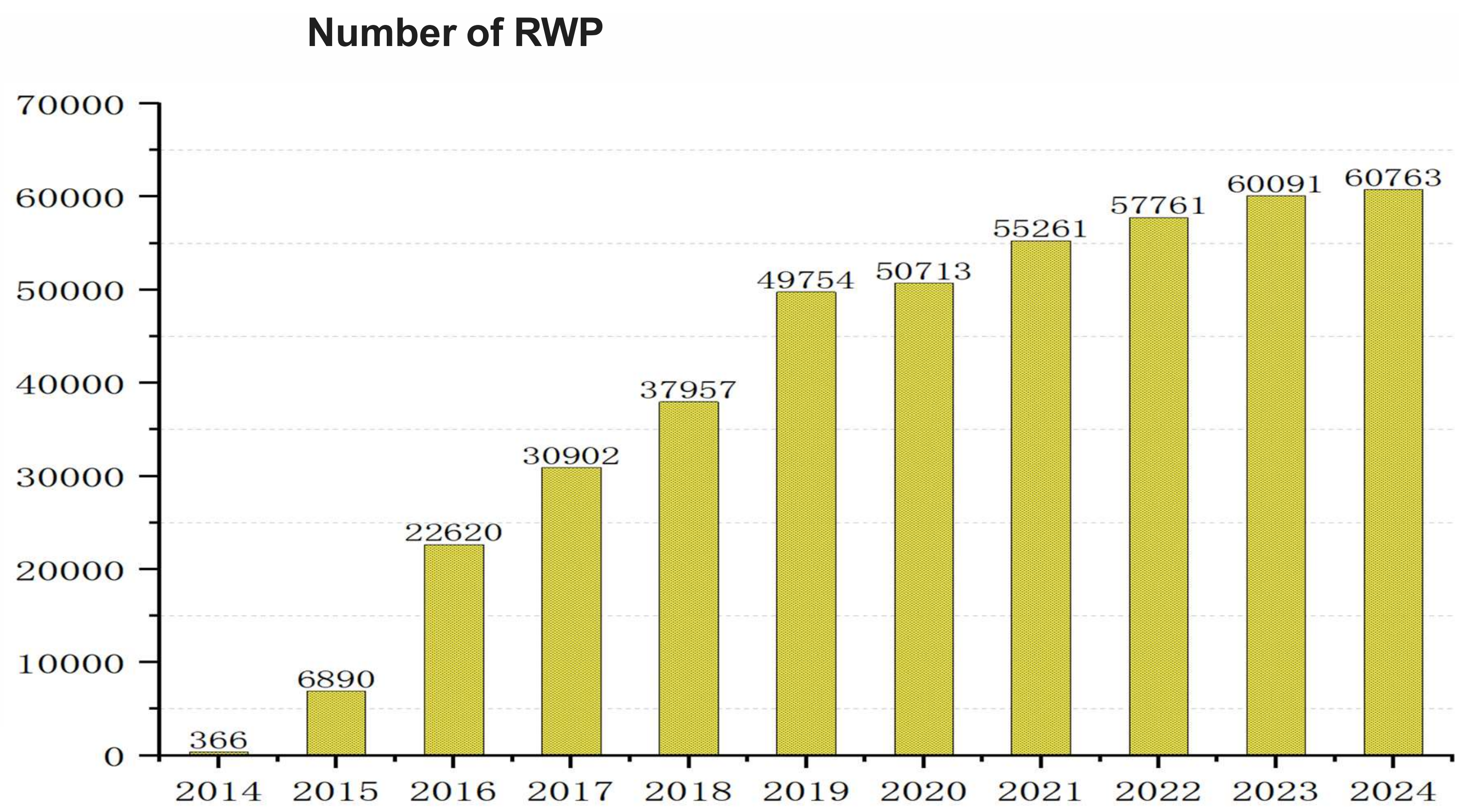
Systems functions

- Manage, process and store individual monitoring services data
- Dose limits control
- Share dose information
- Assist in statistical analysis of exposure records
- Personal records
- RCA pass share
- Continuous development and upgrade under requirements



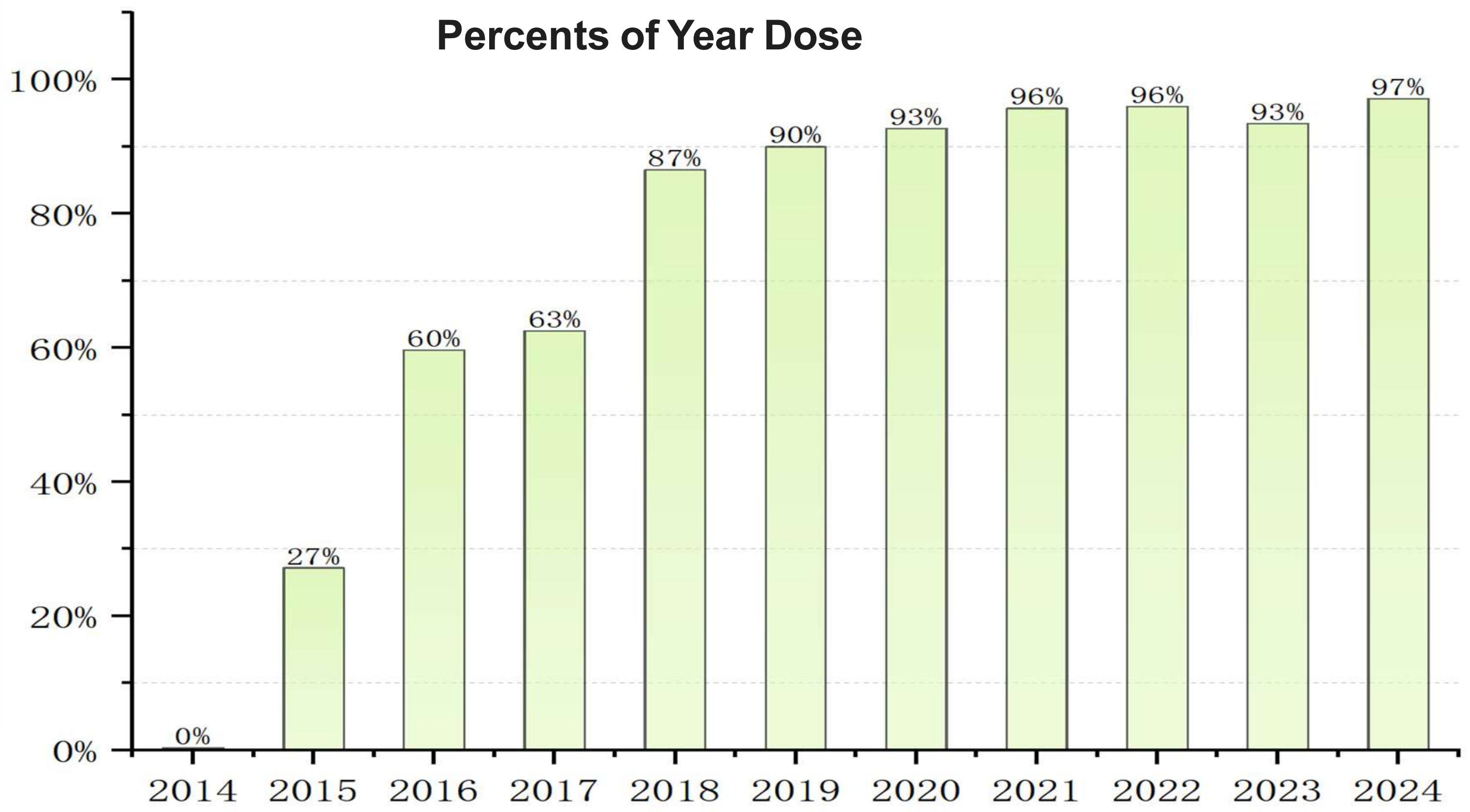
- Overall monitoring of radiation risks
- Investigate abnormalities in time
- Assist in making ALARA proposals

Work Permits (RWP) Usage Since 2014



From 2014,CGN Fleet start to using RWP system with Significant increasing in number of RWP by years.

Radiation Work Permits (RWP) dose proportion



By the end of 2024, the proportion of RWP dose to total dose is higher than 97%. and starting in 2025，All of the power plants have run RWP system.

II. Research Methods

Overview of Dose Management Methods for Critical Work Orders

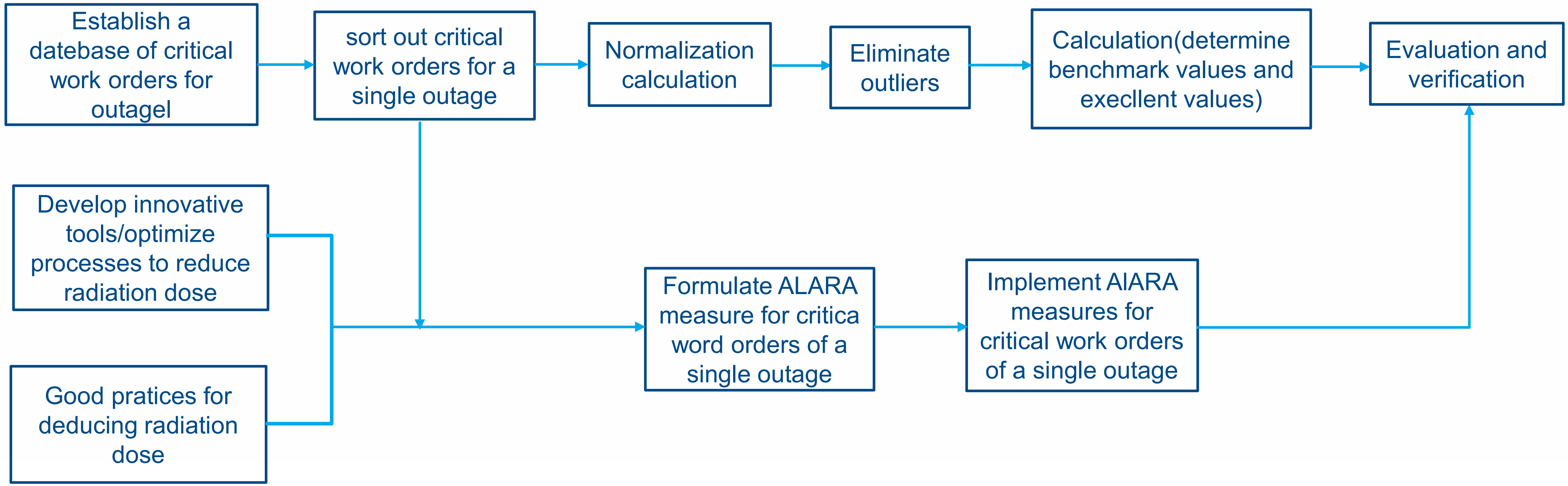
Strategy for Controlling Doses from Critical Work Orders

A statistical analysis of the collective dose distribution revealed that work orders exceeding 100 μSv were responsible for over 80% of the total outage dose, despite representing only about 20% of the total work orders in the controlled area. In line with the Pareto Principle (the 80/20 Rule), we have decided to focus our efforts on **reducing the collective outage dose by prioritizing these Critical work orders with doses above 100 μSv.**

【Data Analysis Support】

Outage Category	Outage Collective Dose (man・mSv)	Total Dose from Work Orders >100 μSv (man・mSv)	Proportion of Work Orders >100 μSv to Collective Dose	Number of Work Orders >100 μSv
Annual Outage	285	234	82%	326
Annual Outage	418	351	84%	441
10-year Outage	1030	860	83%	756

Flowchart of the normalized evaluation model



Establishment of Key Outage Work Order Database

Relying on cumulative outage data from 82 outage cycles across four nuclear power bases of CGN's CPR units, a total of 34,676 work orders meeting this threshold requirement were screened to form the core database of critical work orders for this study.

The key fields used for work orders include:

RWP Code	Work Order Number	Equipment Functional Location	RWP Description	Keyword Description	Version	Maintenance Center	Room Functional Location	Total Number of Workers	Actual Maximum Individual Dose	Actual Collective Dose	Maximum Dose Rate at Work Point	Actual Collective Man-Hours	PM Operation Type

Review of Critical Work Orders for a Single Outage

Each professional department conducts a systematic review based on their division of labor, forming a critical work order list for the single outage, and accordingly compiles the "Execution Table of ALARA Measures for Outage Work Orders."

Professional Department	RWP Code	Work Order Number	Equipment Functional Location	Work Content Description	ALARA Measure
MIC	3653892	800004816 227	LA-2-02-RPN	L2RPN-9978MA Annual Visual Inspection of RPN Probes and Cables in Reactor Pit after Reactor Vessel Closure	Arrange at most 8 personnel for the water pool work
					Measure the radiation dose in the work area, and stay away from the high-dose area
					Control the working time of the water pool according to the RP requirements
					Clarify the distribution of the working dose rate, and stay away from the high-dose area as much as possible
					Confirm that the tools are fully prepared before work to avoid repeated work.

Sort out the collective dose of historical identical activities

Historical dose work orders are matched based on the equipment functional location "02-RPN" and keywords"Annual Visual Inspection of RPN Probes and Cables in Reactor Pit after Reactor Vessel Closure"

Professional Department	RWP Code	Work Order Number	Equipment Functional Location	Work Content Description
MIC	3653892	800004816227	LA-2-02-RPN	L2RPN-9978MA Annual Visual Inspection of RPN Probes and Cables in Reactor Pit after Reactor Vessel Closure

RWP Code	Equipment Functional Location	Work Content Description	Version
3653892	LA-2-02-RPN	L2RPN-9978MA Annual Visual Inspection of RPN Probes and Cables in Reactor Pit after Reactor Vessel Closure	LA113
3040163	LA-1-02-RPN	L1RPN-9978MA	LA114
3342140	LA-1-02-RPN	L1RPN-9978MA	LA117
3459813	LA-1-02-RPN	L1RPN-9978MA	LA118
3470130	LA-2-02-RPN	L2RPN-9978MA	LA217
3595100	LA-1-02-RPN	L1RPN-9978MA	LA119
3561851	LA-2-02-RPN	L2RPN-9978MA	LA218
3595640	HY-1-02-RPN-040MA	H1RPN-9978MA	H108
3462322	HY-2-02-RPN-040MA	H2RPN-9978MA	H206
3616835	HY-4-02-RPN-040MA	H4RPN-9978MA	H406
3365654	DY-1-02-RPN	D1RPN-9978MA	DY121
3538607	LA-4-02-RPN	L4RPN-9978MA	LD410

Normalized Calculation

In actual operations, human behavioral factors (such as not switching RWP codes promptly or using generic codes) may lead to deviations in collective dose records. Meanwhile, the environmental maximum dose rate is also influenced by dynamic factors like process improvements and local shielding, making it difficult to accurately reflect the actual radiation levels during work; thus, it is not suitable as a direct basis for evaluation.

"Work Order Collective Dose" and "Maximum Dose Rate corresponding to the RWP" were identified as two highly credible basic data points. This study proposes constructing a normalized evaluation indicator (normalization factor) H_{RWP} centered on the ratio of these two. Based on this coefficient, historically matched work orders can be normalized, thereby eliminating the impact of differences in radiation fields and enabling comparable analysis of dose levels across outage cycles. The specific calculation method for HRWP is as follows:

$$H_{RWP} = \frac{COE_{RWP}}{R_{max}}$$

In the formula, COE_{RWP} is the collective dose for each work order; R_{max} is the maximum dose rate for that *RWP*.

Outlier Removall

For abnormal data processing, this study adopts the Grubbs' test from the national standard Statistical Interpretation of Data—Detection and Handling of Outliers in Normal Samples (GB/T 4883-2008) for outlier removal. According to GB/T 4883-2008, for datasets conforming to a normal distribution with a sample size n ≥ 3, the Grubbs' test is used for outlier judgment and handling. The critical values for this method can be found in Appendix A, Table A.2 Critical Values for Grubbs Test, of the standard.
For the matched historical samples of a work order, this method can be used to remove outliers in the normalization factor and maximum dose rate. Specifically, the test statistic Gn for each data point is calculated as:

$$G_n = \frac{|x_i - \bar{x}|}{S}$$

Where the sample standard deviation S is calculated as:

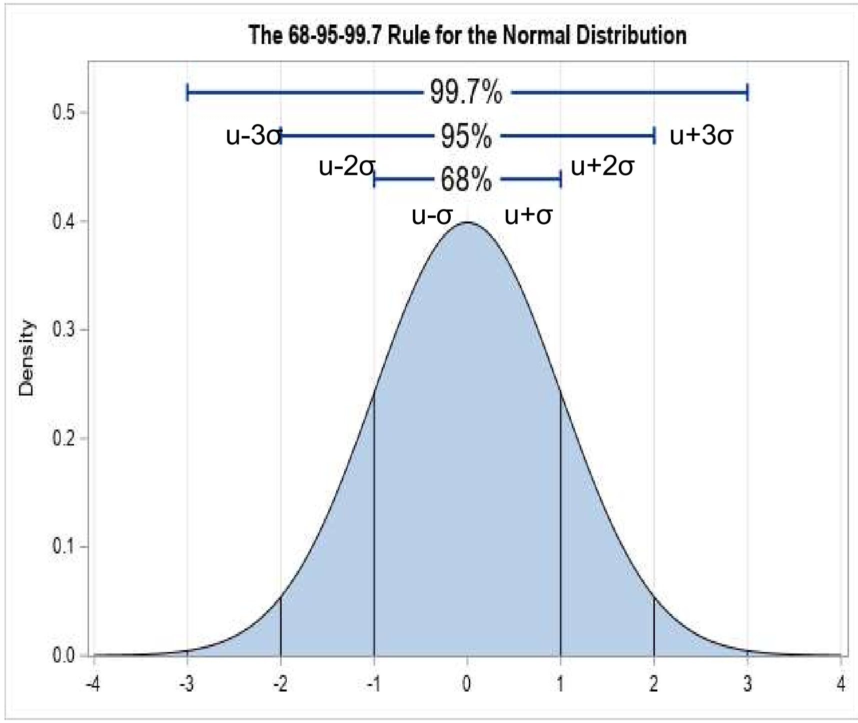
$$S = \left[\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2\right]^{1/2}$$

And compared with the corresponding critical value Gp(n). When Gn > Gp(n), the data point is judged to be an outlier.

Calculation (Determining Benchmark Value and Excellence Value)

When establishing the graded evaluation system for work order doses, two key thresholds are first set based on the normal distribution characteristics of the sample data: the probability point corresponding to sample values less than (μ - 2σ) (2.5%) is defined as the "Excellence Value," and the probability point corresponding to sample values less than (μ - σ) (16%) is defined as the "Benchmark Value." In the practical application of this paper, a tiered processing principle is adopted based on the effective sample size (n) of the historically matched work orders:

(1) When n > 5, after outlier removal, the Benchmark Value and Excellence Value are taken as (μ - σ) and (μ - 2σ), respectively.
(2) When 2 < n ≤ 5, only the Benchmark Value is set, taken as the third value in the ascending sorted sample.
(3) When n ≤ 2, no qualification evaluation is performed for now, but the normalization result of this outage is recorded to accumulate data for subsequent analysis.



Implementation Status of ALARA Work Order Measures

When establishing the graded evaluation system for work order doses, two key thresholds are first set based on the normal

Professional Department	RWP Code	Work Order Number	Equipment Functional Location	Work Content Description	ALARA Measure	Implemented
MIC	3653892	80000481 6227	LA-2-02-RPN	L2RPN-9978MA Annual Visual Inspection of RPN Probes and Cables in Reactor Pit after Reactor Vessel Closure	Arrange at most 8 personnel for the water pool work	☐YES ☐NO
					Measure the radiation dose in the work area, and stay away from the high-dose area	☐YES ☐NO
					Control the working time of the water pool according to the RP requirements	☐YES ☐NO
					Clarify the distribution of the working dose rate, and stay away from the high-dose area as much as possible	☐YES ☐NO
					Confirm that the tools are fully prepared before work to avoid repeated work.	☐YES ☐NO

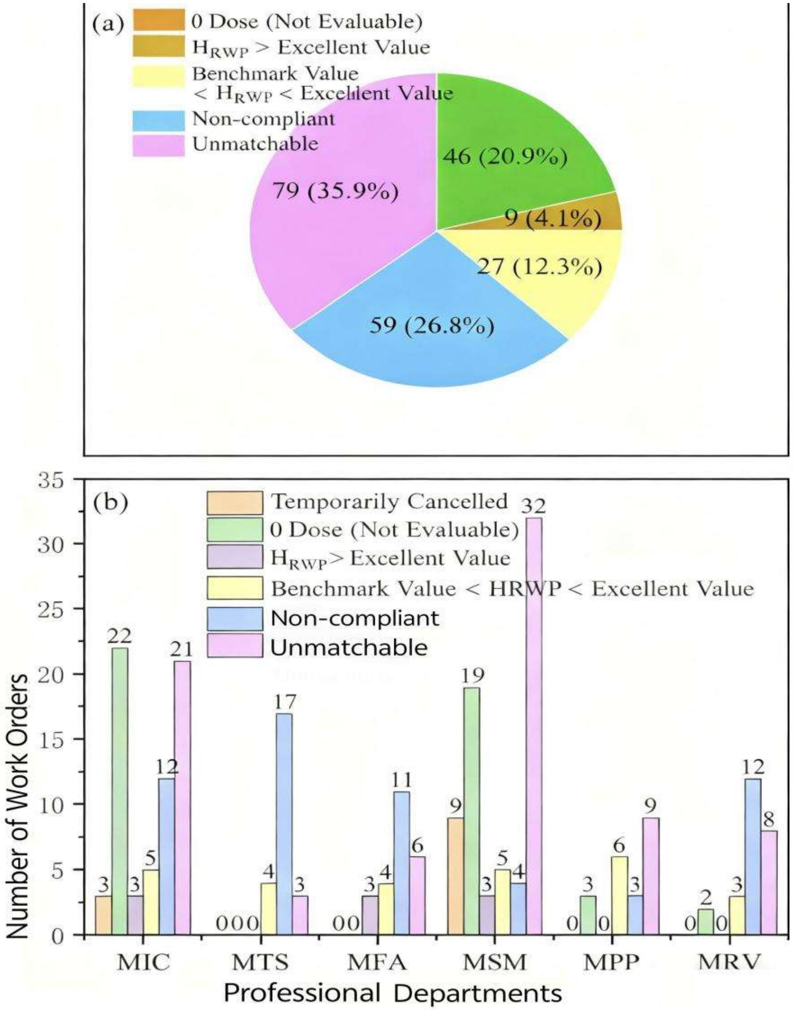
Normalized Calculation Results for Sample Work Order

Based on the 12 matched historical work orders, the established evaluation benchmark is: Excellence Value 0.036, Benchmark Value 0.193.

Actual Collective Dose	Max Dose Rate at Work Point	Normalized Calculation	Sample Size n	Statistic G_n	Critical Value	Benchmark Value μ-1σ	Excellence Value μ-2σ	This Outage Norm. Factor
0.276	0.845	0.327	12	-0.229	2.285	0.193	0.036	0.205
0.105	0.968	0.108	12	-1.557	2.285	0.193	0.036	
0.286	0.51	0.561	12	1.196	2.285	0.193	0.036	
0.328	0.613	0.535	12	1.039	2.285	0.193	0.036	
0.105	0.541	0.194	12	-1.036	2.285	0.193	0.036	
0.105	0.526	0.200	12	-1.002	2.285	0.193	0.036	
0.119	0.536	0.222	12	-0.866	2.285	0.193	0.036	
0.123	0.306	0.402	12	0.229	2.285	0.193	0.036	
0.373	0.64	0.583	12	1.330	2.285	0.193	0.036	
0.117	0.239	0.490	12	0.762	2.285	0.193	0.036	
0.25	0.565	0.442	12	0.476	2.285	0.193	0.036	
0.107	0.446	0.240	12	-0.757	2.285	0.193	0.036	

III. Results and Discussion

Results and Analysis



Among these 220 work orders, the actual compliance rate was 16.4%. 59 critical work orders did not meet the Benchmark Value, indicating that the formulation of ALARA measures for these critical work orders was not strict enough or there were deviations during field implementation.

It is recommended that the relevant professional departments re-evaluate the ALARA measures and pursue continuous improvement. For 46 critical work orders, both the actual number of workers and the dose showed as 0, indicating that the work crew did not swipe the RWP work order code as required, affecting the dose statistics and evaluation of critical work orders.

79 work orders could not be matched, indicating that the database of 34,676 key work orders is still relatively small and needs continuous accumulation and improvement.

Results and Analysis

The compliance rates for departments MIC, MSM, and MRV were less than 16%, indicating that although ALARA optimization measures (such as clarifying dose rate distribution, working away from high-dose areas, controlling valve calibration time) were implemented by these three departments, the effectiveness was not significant, and the compliance rate compared to historical similar operations is relatively low, suggesting there is still room for further improvement.

The compliance rate for MTS was slightly above 16%, indicating that the ALARA optimization measures (such as RP practical training reinforcement, selecting low-dose areas for standby, strictly controlling the number of inspection personnel) achieved the expected effect.

The compliance rates for MPP and MFA were greater than 25%, indicating that their ALARA optimization measures (such as specialized tools for opening blind flange seals, optimization of the PMC41 test procedure, use of smart glasses or intercom equipment, setting up lead shielding) were clearly effective.

The proportion of unmatched work orders for MSM and MIC exceeded 30%, highlighting the issue of incorrect RWP code usage.

Discussion

This outage evaluation relied on the core database of key work orders from four nuclear power bases operating CGN's CPR units and did not include Hualong/EPR units.

There is a need to continuously improve the construction of the key work order dose database to cover over 90% of CGN's operational units. During the analysis, the work order data missing rate reached 21%.

Improvements are needed regarding factors affecting the completeness of the key work order database and the standardization of staff RWP usage. Furthermore, efforts should be promoted to develop AI prediction and analysis models for key work order doses, enabling intelligent predictive analysis and evaluation of dose work orders.

IV. Conclusion

Conclusion

Focusing on the optimization needs of radiation protection during nuclear power outages, constructed a normalized evaluation model for work order dose and established a full-process methodological system covering data collection, analysis evaluation, and measure optimization.

By establishing and continuously improving CGN's critical outage work order database and integrating multi-site, multi-cycle outage data, a systematic plant-group evaluation system for dose optimization of key outage work orders has been formed.

At the practical application level, through verification in multiple outage cycles, the method for determining benchmark doses based on normalized calculation has been gradually refined: by normalizing similar maintenance tasks under different radiation levels, using the Grubbs criterion to remove significant outliers, scientifically setting benchmark and excellence values based on normal distribution theory, systematically evaluating and verifying work order dose reduction measures.

Application practices on typical work orders show that this method significantly improves the accuracy of dose evaluation and provides reliable technical support for continuously reducing collective doses and effectively implementing the ALARA principle.

Thank You！