Using condition-based maintenance and reliability-centered maintenance to improve maintenance in nuclear power plants

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Abstract: Maintenance optimization process in nuclear power plants (NPPs) has, in recent decades, been driving the transition of maintenance strategies from time-based preventive maintenance to systematic strategies depending on both equipment condition and reliability analysis. Starting with a comparison of various types of maintenance strategies in current NPPs, this paper highlights the evident advantages of condition-based maintenance (CBM) in both technical feasibility and cost-effectiveness. This paper also expounds the theoretical foundation and application methodology of CBM, as well as the complementary relationship between CBM and RCM. Taking Daya Bay nuclear power base as a case example, we introduce in detail the experience of using Reliability-centered Maintenance (RCM) and CBM to drive maintenance improvement in NPPs, which serves as a cornerstone for the application of RCM analysis-based CBM maintenance in other plants.

Keyword: reliability-centered maintenance (RCM); condition based maintenance (CBM); maintenance optimization; equipment reliability; nuclear power plants (NPPs)

1 Introduction

The objective of maintenance in nuclear power plants (NPPs) is to ensure that structures, systems and components (SSCs) always operate long-term on a safe, reliable and economic manner, and to provide the society with safe, clean, and good quality power at a competitive price. Since the introduction of Reliability- centered Maintenance (RCM) to the field of maintenance management in NPPs from the aviation industry by Electric Power Research Institute (EPRI) in 1983, the advanced maintenance optimization methodology for determining the maintenance requirements of equipment in its current operating context has been widely used in a large number of NPPs around the world in recent decades, and has conferred significant benefits in many aspects, such as enhancing the safety of the unit, improving equipment reliability and reducing maintenance costs, *etc* [1, 2]. Strictly speaking, RCM is not a specific maintenance strategy, but rather a decision-making process based on reliability analysis to determine an optimized combination of different types of maintenance strategies in order to meet the maintenance requirements of equipments [3]. Such maintenance strategies (shown in Fig. 1) also include time based maintenance (TBM) (also known as preventive maintenance (PM)), condition-based maintenance (CBM) (also known as predictive maintenance (PdM)), and run to failure (also known as corrective maintenance (CM)). As a scientific methodology for formulation and optimization of maintenance strategies (for a long time), RCM has been promoting the maintenance strategies for equipments in NPPs. It has changed from the early periodical maintenance or planned maintenance mode to an integration of different types of maintenance strategies through a comprehensive analysis which considers many aspects, such as working age, equipment condition, technical feasibility, and economic efficiency, *etc*.

Daya Bay Nuclear Power Base, which was the first to pioneer in the introduction of RCM in Chinese nuclear power field in 1998 [4], has completed the maintenance strategies optimization analysis and field application of about 160 critical systems in Daya Bay NPP and Ling'ao NPP. It has become the most successful nuclear power base to implement RCM in domestic NPPs. Daya Bay has also started to introduce condition-monitoring technologies and implement CBM in initial commercial operation stage, for example, the introduction of online vibration monitoring and diagnosis system from ENTEK-IRD Corporation for equipment condition

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management of rotary machinery in 1998. With the implementation of RCM in Daya Bay, a significant increase in the ratio of CBM in proactive maintenance work was apparent. As a matter of fact, while carrying out RCM, many aspects related to maintenance are significantly increased, including determination of equipment which applies CBM and its monitoring parameters, selection of condition-monitoring technologies, decision-making process of failure diagnosis and trending analysis, *etc*. After implementation of RCM analysis-based CBM, field feedback indicates remarkable improvements in the safety of utilities, equipment reliability, as well as the cost-effectiveness of maintenance. Likewise, the level of maintenance management and equipment reliability management in Daya Bay nuclear power base also had seen considerable development.

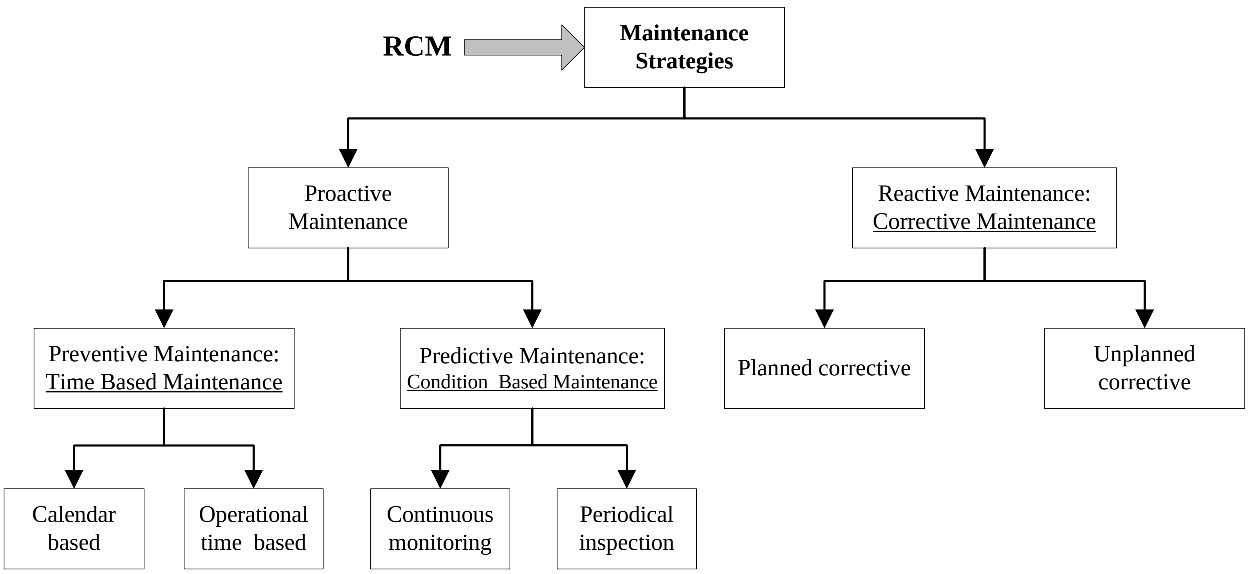

Fig.1 Various types of maintenance strategies.

With the aim of expounding the theoretical foundation and methodology of CBM, and combined with experience in Daya Bay, this paper discusses in detail the implementation process of RCM analysis-based CBM which integrates theory with practice in the field of nuclear power. The implementation of RCM analysis-based CBM provides a base for maintenance optimization, as well as reliability management of CBM applications and equipment in NPPs.

2 Comparison of different maintenance strategies in NPPs

As shown in Fig.1, there are many types of maintenance strategies in current NPPs, including proactive maintenance and reactive maintenance (also known as Corrective Maintenance (CM), or run to failure). Here, proactive maintenance can be divided into time-based maintenance (TBM) and condition-based maintenance (CBM). At the same time, CM, TBM and CBM also constitute the main options of maintenance decision-making of RCM.

The theoretical foundation supporting RCM optimization, is the conclusion of failure characteristics with a lot of evidences from researches launched by American aviation and navy industry, which also has been verified in a number of other fields. Results of these investigations indicate that (as shown in Fig.2) equipment failure modes of which conditional failure rate increases along with working age only accounts for about 8-29%, while the failure modes which are independent of working age accounts for a majority[3, 5] (*viz.* 71-92%). For the management of most of these failure modes (which have no evident relationship with the working age), it is inappropriate to use TBM strategies, because it cannot bring about improvement in equipment reliability and availability. On the contrary, it may result in early failures during the disintegration and re-assembly of equipments. In such a case, it is a sagacious choice to apply CBM strategies, within which we can realize the prevention of failure modes or avoid the corresponding failure consequences through the mastery of equipment condition, diagnosis of potential failure, forecast of tendencies of defects, and adoption of timely and effective intervention measures. Thus, it can be seen that CBM is bound to be the preferred option in maintenance and equipment management. Certainly, it does not always mean that CBM is the best choice for equipment maintenance, because it depends on the application methodology of CBM strategies, and will be further discussed in the later part of this paper.

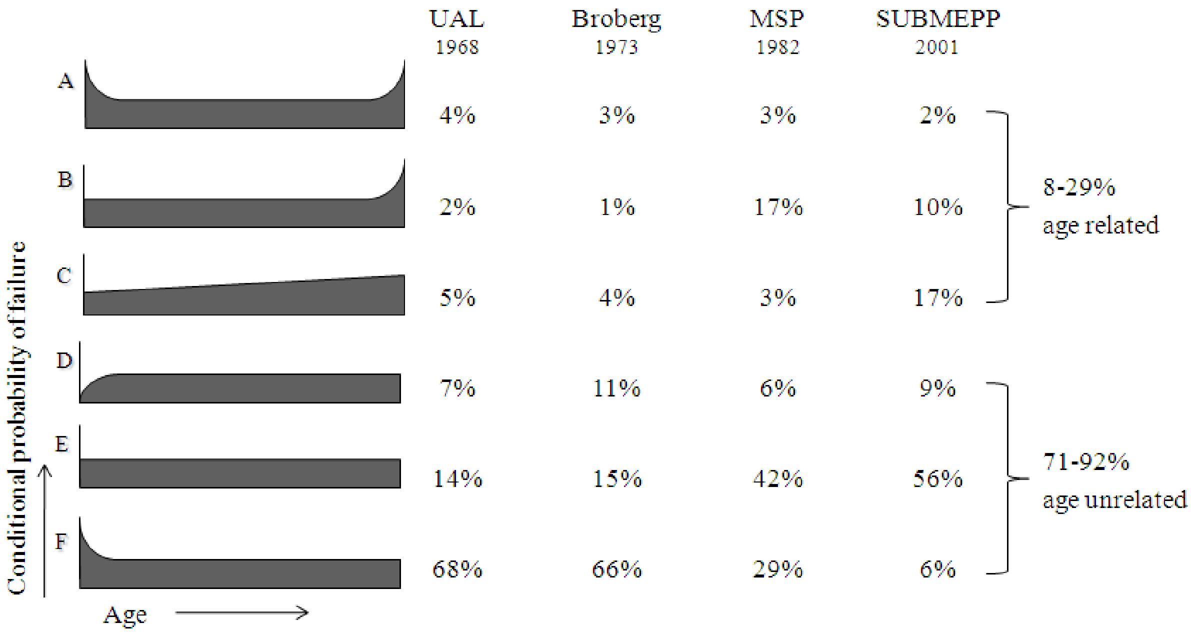

Fig.2 Age and equipment failure characteristic categories. [3, 5]

Note that: the four studies from which failure profiles and statistics are taken are:

a) The "UAL Study" - DOD Report on Reliability-Centered Maintenance by Nowlan & Heap of United Airlines, dated December 29,1978, which used data from the 1960's and 1970's and earlier papers and studies referenced therein;

b) The "Broberg Study" believed to be done under NASA sponsorship (reported in 1973) and cited in Failure Diagnosis & Performance Monitoring Vol. 11 edited by L.F. Pau, published by Marcel-Dekker, 1981;

c) The "MSP Study" - long title "Age Reliability Analysis Prototype Study"- done by American Management Systems under contract by U.S. Naval Sea Systems Command Surface Warship Directorate reported in 1993 but using 1980's data from the Maintenance System (Development) Program;

d) The "SUBMEPP Study" reported in 2001, using data largely from 1990's, and summarized in a paper dated 2001, entitled "U.S. Navy Analysis of Submarine Maintenance Data and the Development of Age and Reliability Profiles" by Tim Allen, Reliability Analyst Leader at Submarine Maintenance Engineering, Planning and Procurement (SUBMEPP) a field activity of the Naval Sea Systems Command at Portsmouth NH.

The figure above is merely a comparative analysis of three maintenance strategies from the theoretical perspective of applicability of the methodology. In practice, both technical requirements and overall cost should also be considered when determining which strategies or a combination of these strategies to adopt. As for technical requirements and related costs, Table 1 shows a comparison of various maintenance strategies, including CM, TBM and CBM, as well as the combination of a variety of maintenance strategies using RCM analysis. It is clear that, compared to CM and TBM, CBM can obtain a targeted, timely and effective maintenance, which will make a good contribution to reduce the overall cost. In conclusion, reasonable application of CBM basing on RCM analysis has merits such as improving equipment reliability and reducing maintenance cost for NPPs.

Table 1 Comparison on technical requirements and relative cost of maintenance strategies

Maintenance strategies	Technical requirements		Relative costs		
	Specialized knowledge	Specialized equipment	Maintenance activities	Repairs after failure	Downtime and extended damages
CM	Minimal	Minimal	None	Very large	Extensive
TBM	Extensive	Moderate	Extensive	Moderate	Moderate
CBM: Off-line	Extensive	Moderate	Moderate	Minimal	Minimal
CBM: On-line	Moderate	Extensive	Moderate	Minimal	Minimal pus
RCM (CM+TBM+CBM)	Extensive	Extensive	Moderate plus	Minimal	Minimal plus

Based on feedback from nuclear power fields worldwide, correct implementation of RCM analysis-based CBM in NPPs could bring about great benefits in many aspects, such as:

a) To optimize resource allocation, and improve the cost-effectiveness of maintenance

Intervention measures are determined by the assessment of equipment condition. Therefore it is worthwhile to maintenance staff out of blind overhaul, so as to make full use of maintenance resources. Meanwhile, it is available to avoid excessive maintenance or insufficient maintenance to raise the efficiency of maintenance work, which is particularly important to the NPPs with limited human, material and financial maintenance resources.

b) To improve the operational reliability of equipment

In most cases, CBM has minimum disturbance and destruction to the equipment, so as to avoid early failures in the periodic disintegration or replacement which may include the improper disassembly operation, inappropriate use of spare parts, entry of foreign matter, *etc*. Furthermore, the fact that potential failure of equipment can be detected early before the occurrence of functional failure of operating equipment, it allows effective measures to be taken to prevent functional failure or avoid failure consequences. According to RCM philosophy, shutdown or breakdown of equipment for maintenance is a failure in a sense. This is because these activities result in unavailability of the equipment, and thus it is clear from this point that the implementation of CBM can bring about improvement in reliability and availability of equipments.

c) To make full use of the effective service life of equipment

Drawn from failure characteristics, equipments always have a long period of stable operating period. With the aid of condition monitoring, we can grasp the actual condition of equipments, and cannot shut them down until the detection of potential failure or attaining the end of stable operating period. Almost all the effective service life of equipment could be fully used, and thus extending the actual service time.

d) To reduce maintenance costs

The adoption of CBM is conducive to the arrangements of maintenance work in order to become more scientific and meet the actual needs. Compared to the original maintenance programme (which is mainly based on the manufacturer's suggestion), the maintenance programme based on RCM analysis can significantly reduce the number of periodical disintegration or replacement for equipments, so as to decrease the human cost, spare parts cost and the corresponding management cost, thus lowering the overall maintenance cost. According to the feedback from different enterprises, the magnitude of this cost can generally reach 20% to 40% or even more [6].

e) To reduce overhaul burden and shorten overhaul period

With the implementation of some CBM tasks, such as online monitoring and calibration for critical valves during the daily operation of the unit, the number of equipments requiring repair and relative workload could be curtailed during the overhaul period in NPPs. As a result, it is possible to mitigate the burden from human resource and managements during the overhaul, and shorten the duration of the overhaul, which would bring about considerable economic benefits to power generation enterprises.

3 Theoretical foundation and methodology of CBM

CBM is a maintenance strategy based on condition monitoring and the evolution rules of equipment failure, which mainly include condition monitoring, data analysis, failure diagnosis and trend forecasting, and the implementation of corresponding corrective action and its relevant feedback. The core of the CBM is nested in condition monitoring and failure diagnosis, which can be divided into on-line monitoring and off-line monitoring in accordance with the equipment operating condition during monitoring. It can also be divided into continuous monitoring and periodic monitoring in accordance with monitoring frequency.

NPPs implement CBM, mainly with input from process parameters in the system process (such as pressure, temperature, flow, vibration, *etc*.), results of sample analysis (such as oil, water, gas, rubber debris, *etc*.), discoveries in testing and inspections, as well as the records of internal and external operation and maintenance experience in the same or similar equipments. Thereafter, based on personnel experience, expertise and many other support technologies such as intelligent technology, RCM, risk and reliability analysis, intelligent reasoning, root cause analysis (RCA), *etc*., CBM could implement health assessment for its function, performance, and integrity, failure diagnosis and prediction of the equipment, in order to point out the potential failure and defect location, and determine the trend of the defect. Specific suggestions should be put forward to take timely, appropriate and requisite interventions to prevent function failure or to avoid failure consequences before the occurrence of functional failure or drastic decline in economic performance of equipment [7]. Figure 3 shows a flowchart of CBM implementation process in NPPs.

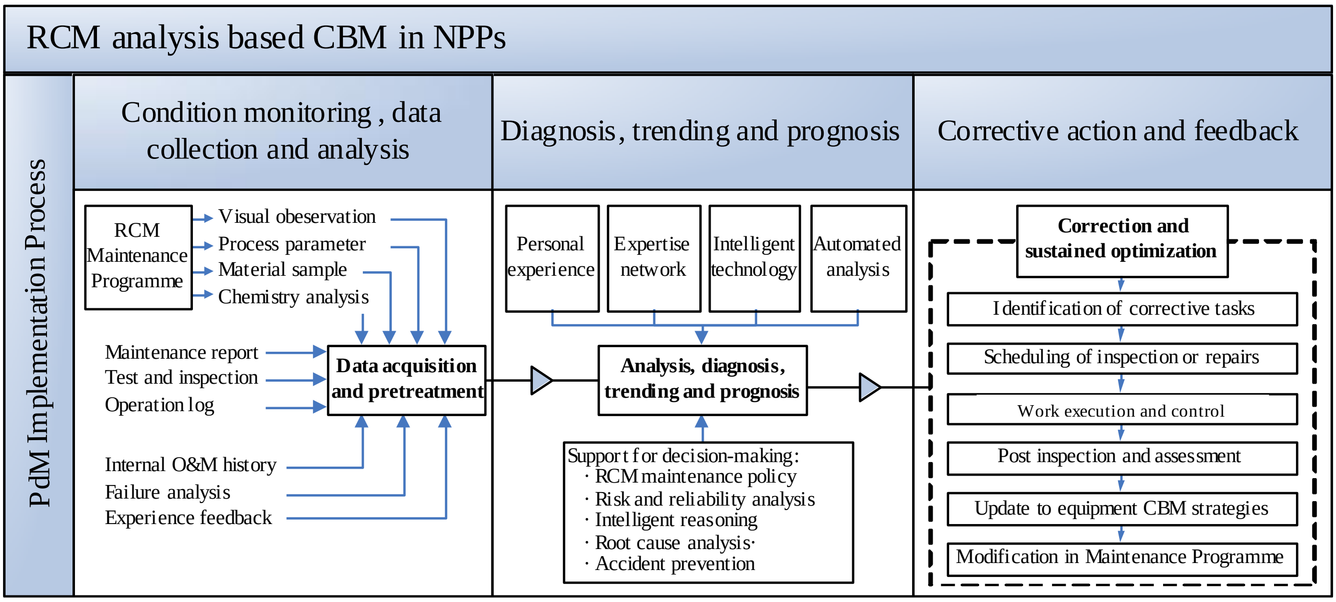

Fig.3 Schematic diagram for CBM implementation process in NPPs.

CBM is based on the P-F (Potential failure - Functional failure) interval principle [3]. Practice has proved that equipment failure has a developing process, because one can monitor relevant parameters, which can identify the existing potential failure. On the basis of this result, we first assume that the failure would not occur instantly, that is, if we can identify a potential failure during its developing process, measures can be taken to prevent the identified failure or to mitigate relevant consequences. P-F curve is usually used to describe the evolution process of a failure, as shown in Fig.4. Point P indicates the potential failure, point F the functional failure, and P-F interval the spacing between P and F during the failing process. The purpose of condition monitoring of CBM is to detect potential failure in the P-F interval, and to take corresponding preventive maintenance measures to prevent functional failure or avoid related failure consequences.

According to the P-F interval principle, and considering the technical feasibility, the rules of CBM applicability and its availability should satisfy the conditions hereunder:

a) Instead of occurring instantly, the failure develops in a certain pattern, which means that the interval between P and F is long enough to prevent the failure. Otherwise, the initiation of CBM activities is meaningless.

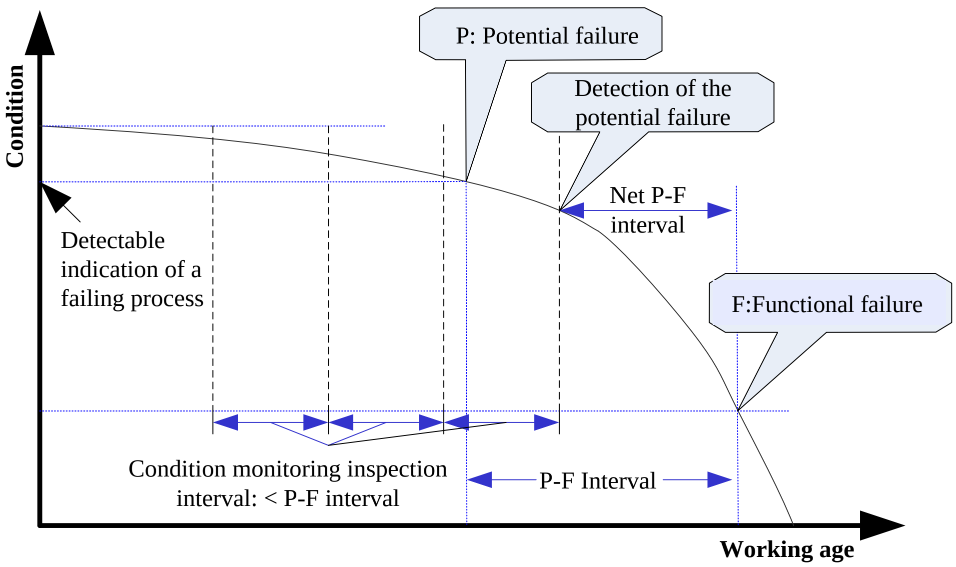

Fig.4 P-F Curve.

b) The potential failure (point P) corresponding to a detectable definite condition during the degradation process can be identified, which is based on the monitoring technology and the failure characteristics.

c) The interval between P and F is definite and relatively stable, or at least the variation range of the interval is estimable.

d) The inspection interval of CBM must be shorter than the possible minimum value of P-F interval. Only in this case can we run at least one inspection during the P-F interval to detect the defect.

e) Considering the fact that it will take some time for implementing corresponding intervention measures, the response time of which should be shorter than the P-F interval, which means that the CBM inspection period must be shorter than the distance of P-F interval excluding the response time (so as to prevent the identified failure from happening or mitigate the relevant consequences).

During the maintenance practice in NPPs, it is essential to correctly understand the complementary relationship between RCM and CBM, so as to make the best choice of CBM strategies [8, 9]. The developments and applications of a variety of advanced CBM technologies, have greatly enriched the connotation of RCM methodology and maintenance strategy choices, and also improved the operability of equipment reliability management in NPPs [10]. While selecting CBM tasks through RCM decision-making, we can take full account of all aspects of reliability, risk and economic factors, *etc.*, This is important so as to optimize the overall process of CBM applications, including the screening of objects for condition monitoring, the selection of condition monitoring technologies, the setting of monitoring parameters and relative thresholds, and the criteria for failure diagnosis, as well as decision-making process of preventive measures, thus improving the effectiveness and efficiency of the CBM. It should be noted that, although the CBM is always the preferred option in RCM decision-making logic tree [3], it does not necessarily mean that it is the best option for the management of all failure modes. This is because, when considering economic factors in RCM decision-making for the management of non-safety or non-environment related failure modes, we may prefer PM or CM strategies for their technical feasibility and lowering the overall costs, and in such circumstances then CBM task might not be the best choice. Concurrently, condition monitoring provides a plethora of data reflecting the equipment reliability, especially the real-time data, which can be taken as an important input for maintenance decision-making and optimization. Complemented with analysis on field feedback and experience in similar plants, it is feasible and necessary to update maintenance strategies in a dynamic and closed loop manner.

4 Application experience of CBM in Daya Bay nuclear power base

Daya Bay nuclear power base, including Daya Bay, Ling'ao and Lingdong NPPs, there are 6 units capable of generating a total of 6000MW. The operation performances of these units have kept with the world's advanced level in recent years [11]. Undoubtedly, the implementation of equipment reliability management has successfully contributed to the good operation performance of these units, and one of the most important practices is the application of RCM analysis based CBM. The applications of advanced CBM technologies in Daya Bay, such as pump vibration monitoring and diagnosis, motor current analysis, on-line monitoring and calibration for air-operated and motor-operated valves, partial discharge detection for major electrical equipments, on-line dissolved gas analysis for larger transformers, *etc.*, has brought about improvement in equipment reliability and availability on site. The following three cases, which focus on the practical experience of appropriate integration and applications of RCM and CBM in Daya Bay, provide a good reference for the field of maintenance management in nuclear power plants.

4.1 Optimization of equipment maintenance programme by introducing CBM methodologies

The changes of equipment maintenance programme of feedwater heaters drain recovery system (ACO) before and after the implementation of RCM analysis are shown in detail in Table 2. Before the maintenance optimization, the maintenance of pumps and motors in ACO system mainly adopt the periodical PM strategies. However, after introduction of RCM and CBM, a large number of CBM strategies are adopted. The main changes include:

① for pumps, the cycle of a complete overhaul is extended from 1 year to 4 years;

② for motors, a complete overhaul is taken every 3 years, the cycle of a complete overhaul for motor being not defined in the new maintenance programme, but only in the provisions of the maintenance tasks depending on the inspection results during the operation maintenance history, and the corresponding indications.

Field experience feedback in recent years indicates that the failure rate of ACO pump sets as well as the maintenance cost decreases significantly. It is clear from the comparison that the annual average maintenance workload of the ACO system reduced by 240 man-days and the number of required spare parts also decreased significantly, as a consequence of adoption of optimized maintenance strategies. The number of required spare parts decreased due to regular inspection of equipment, for example, the monthly vibration monitoring and trend analysis for pump or motor, replacing sealing and bearing according to seal leakage and condition of bearing, thus helpful for grasping the actual state by maintenance personal. Moreover, through targeted detection of early defects, and condition-based replacement or repair, the utilities could take full advantage of the useful life of equipment. To improve equipment reliability it is necessary to reinforce the management of equipment condition, which consequently fully embodies the advantages of CBM strategies. Implementation of RCM maintenance optimization in Daya Bay, which can make a scientific and effective integration of CBM and TBM, results in significant decrease in the number and workload of periodical maintenance, longer maintenance cycle, longer useful life of equipment, and decrease in the overall maintenance costs, *etc*.

Table 2 Optimization of maintenance programme of pumps and motors in ACO system

Serial number	Before optimization maintenance programme based on PM		After optimization maintenance programme after introducing of CBM	
	Maintenance task	Frequency	Maintenance task	Frequency
1	Check the oil level	Monthly	Check the oil level, sealing condition, and record the temperature of bearing indicated in instruments	Daily
2			Monitor the vibration, and make a trending analysis	Monthly
3			Lubricating, examine the alignment, and check the insulation of motor; Replace sealing and bearing according to seal leakage and condition of bearing	Every 2 years
4	Make a complete overhaul to pump; and visual inspection and insulation check-up to motor	Annually	Make a complete overhaul to pump	Every 4 years, and may be extended according to component condition
5	Make a complete overhaul to motor	Every 3 years	Make a complete overhaul to motor or not based on condition evaluation	Depending on components' condition

4.2 The development of PdM management system

In order to meet the requirements for the implementation of health monitoring and CBM for critical equipments, predictive maintenance management system (PdM SYStem, or 'PdMSYS' in short) was developed in 2002, which established a complete technical process for CBM implementation, analysis, assessment, and tracking in Daya Bay nuclear power base [12]. As is apparent in the flowchart of PdMSYS (see Fig.5), a centralized management of CBM activities for critical equipment could be achieved via the aid of the software platform. Based on the RCM analyses results, the maintenance progarmmes, system engineers first upload CBM tasks and the corresponding P-F interval, alarm threshold (P point) and other parameters. They then input the various condition information of equipment, and make a rapid diagnosis and prognosis using parameters alarm criterion and internal intelligent failure diagnosis module, and then executed maintenance decision-making. The field information management and tracking of the repair process and performance during the later operating period are also included in PdMSYS, so that the failure mode could give feedback to RCM analysis for continuous improvement in equipment maintenance strategies. PdMSYS was designed to cover main mechanical and electrical systems, including main transformer, main generator, safety-injection system, emergency diesel generator, and condenser system, *etc*. All related process signal, for example, temperature, vibration, voltage / current, and action time, and corresponding early warning value, *etc*., also would be included in the platform.

PdMSYS has the following features:

① All the condition monitoring information of systems and equipment is uniformly collected and managed so as to ensure that database is comprehensive, complete and symmetrical, thus providing managers with a direct means for grasping the important equipment condition;

② Whether to repair equipment or not, usually depends on the condition monitoring and relative reliability analysis, which improves the rationality and effectiveness of maintenance in a real sense;

③ Linking with RCM analysis results, PdMSYS provides a platform for the effective conversion to field applications, and promotes CBM in the entire system, in order to organize all related works from dispersion to unity, from mess to specification, from chaos to order.

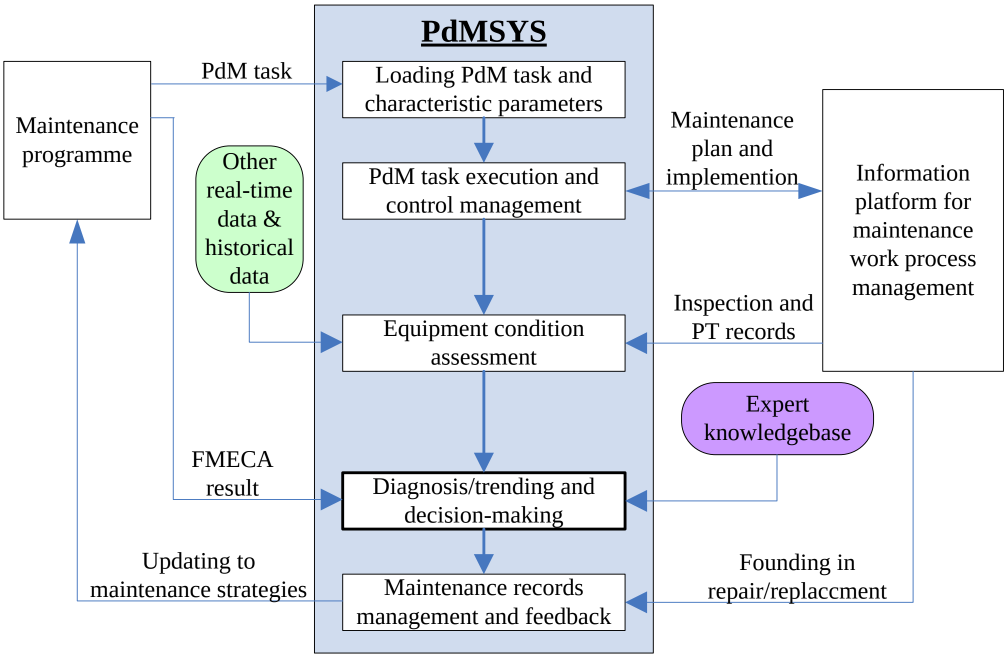

Fig.5 Process flowchart of PdMSYS.

4.3 The development of intelligent failure diagnosis expert system

In order to fully utilize and convey the relevant experience of condition monitoring and fault diagnosis in a nuclear power field in recent years, it is indeed a popular research topic to found expert knowledge database for summary and consolidation of the previous understanding of the equipment failure characteristics and maintenance requirements .

Figure 6 shows the schematic diagram for intelligent failure diagnosis expert system which is developing, and this expert system is an important part of a comprehensive intelligent system for operation and maintenance management [13]. The expert system can obtain the equipment condition information from the on-line data (distributed control system (DCS), supervisory information system (SIS)), off-line data (maintenance reports, periodical testing results, field inspection by operators, *etc.*), and trigger intelligent inference engine automatically as required after data screening by the communication module. The inference engine, which is in conjunction with the expertise base, could process all these information, and carry out trend forecasting of potential failure for forward direction as well as root cause analysis and fault location for backward direction. The inference rules set in the expertise module include logic rules, mathematics algorithm, as well as equipment operation and maintenance strategies pertinent to different levels of equipments. After diagnosis and trending for the anomaly phenomena, the expert system can provide field operators and system engineers with operating tips or recommendations for maintenance decision-making, such as strengthening surveillance of equipment condition, taking an intervention to prevent failure immediately, early warning and alarm indicating the potential failure or functional failure.

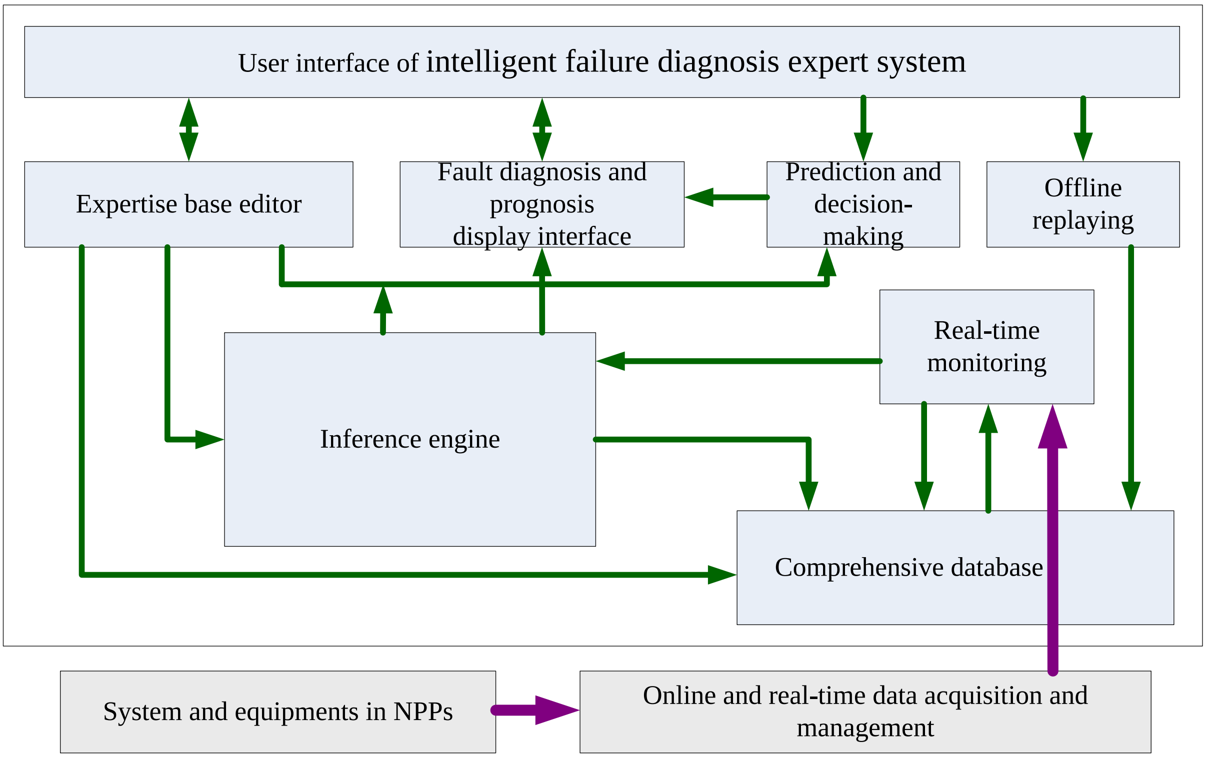

Fig.6 Schematic diagram for intelligent failure diagnosis expert system.

5 Conclusion

With a full understanding of these complementary roles, it is clear that the applications of CBM and RCM have brought about great improvement in maintenance and equipment management in NPPs worldwide. CBM provides a favorable condition for applying RCM methodology to carry out maintenance optimization in NPPs. At the same time, RCM such as maintenance strategies decision-making process, which is reliability-centered and integrates risk and economic aspects, also offers guidance and guarantee for the application of CBM. During the equipment reliability management process in NPPs, it is necessary to actively implement RCM analysis based CBM, (which is in line with the utilities) so as to ensure generation safety, improve equipment reliability, enhance the cost-effectiveness, *etc.*, and to realize a safe, healthy, effective and sustainable development of nuclear power.

Nomenclature

CBM	Condition-Based Maintenance
CM	Corrective Maintenance
DCS	Distributed Control System
PdM	Predictive Maintenance
PdMSYS	Predictive Maintenance Management SYStem
RCA	Root Cause Analysis
RCM	Reliability Centered Maintenance
SIS	Supervisory Information System
TBM	Time-Based Maintenance

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